

Flexible Salt Marsh Vegetation: Model-Driven Replication of Stem Biomechanics across Seasonal and Regional Scales

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^{*)} Either the German or the Canadian form of the degree may be used.

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Coastal protection strategies have shifted from structural measures toward more integrated approaches that combine traditional engineering elements with nature-based solutions provided by coastal ecosystems. Among these coastal ecosystems, salt marshes play a key role by offering multiple ecosystem services such as wave energy dissipation, sediment stabilization, and erosion reduction. A critical process governing their protective function is the near-stem flow field, which describes the local interaction between vegetation and hydrodynamic forcing. However, the influence of seasonal and regional variations in the biomechanical properties of salt-marsh vegetation on these flow dynamics remains largely unexplored. This thesis addresses this gap by incorporating *in situ* measured biomechanical properties of live stems into physical and numerical modeling approaches, enabling a detailed analysis of the fluid–vegetation interaction.

The replication of live vegetation properties in physical hydrodynamic experiments is enhanced in accuracy compared to traditional surrogate materials with 3D printing utilizing flexible filament. The developed surrogates are tested in a flume under unidirectional and oscillatory flow conditions, with particle image velocimetry enabling the measurement of the flow field alterations and the stem-induced turbulence. Next, this thesis employs the fluid-structure interaction solver in the open-source model REEF3D::CFD to quantify the role of salt marsh vegetation in coastal protection numerically, implementing a two-way coupling between vegetation stems and hydrodynamic forcing from unidirectional and oscillatory flow conditions. This extends one-way coupling approaches and provides more accurate solutions compared to previous fluid-structure interaction solvers to model flexible submerged vegetation. The application of field data from various European salt marsh studies at different times during the growing season, together with the first measurements of biomechanical stem properties from a Canadian salt marsh, enables an assessment of both seasonal and regional effects on the stem-induced flow field alterations.

The 3D printed surrogate stems have been confirmed as similar to the *in situ* measured biomechanical stem properties of live vegetation through a statistical evaluation. The fluid-structure interaction solver has been validated to replicate stem motion and forces of flexible vegetation within a maximum deviation of 10 % for most tested conditions. Based on the provided extensive validation, the solver was shown to be a valuable approach to simulate various stiffnesses. The results from both numerical and physical modeling suggest that the stem-induced turbulence varies to a greater extent between the different replicated plant species than the seasonal influence within a species. Due to seasonal variations of the stems' flexural stiffnesses across the investigated species and regions, distinctions regarding the stem bending and extent of motion have been observed, resulting in seasonal differences for the derived drag coefficients.

In conclusion, the accurate replication of *in situ* measured biomechanical stem properties in model approaches reveals the difference in flow field alterations depending on the season and region of a salt marsh. Drag coefficients provided through single-stem simulations enable future investigations of the seasonal and regional variation of salt marshes in a simplified model at the meadow scale. Numerical models would then allow for an assessment

of ecosystem services, such as the wave attenuation capacity. By incorporating seasonal field data in modeling strategies, this study enhances the understanding of fluid-vegetation interaction, contributing to reliable nature-based coastal protection strategies.

Strategien zum Küstenschutz haben sich von baulichen Maßnahmen hin zu integrierten Ansätzen entwickelt, die traditionelle technische Elemente mit naturbasierten Lösungen aus Küstenökosystemen kombinieren. Unter diesen Küstenökosystemen spielen Salzwiesen eine Schlüsselrolle, da sie Ökosystemleistungen wie Wellenenergiedissipation, Sedimentstabilisierung und Erosionsminderung bieten. Ein entscheidender Prozess, der ihre Schutzfunktion bestimmt, ist das Strömungsfeld in der Halmnähe, welches die lokale Wechselwirkung zwischen Vegetation und hydrodynamischen Kräften beschreibt. Der Einfluss saisonaler und regionaler Schwankungen der biomechanischen Eigenschaften der Salzwiesenvegetation auf das Strömungsfeld ist jedoch noch weitgehend unbekannt. Diese Arbeit schließt die Lücke, indem sie *in situ* gemessene biomechanische Eigenschaften lebender Halme in physikalische und numerische Modellierungsansätze einbezieht und so eine detaillierte Analyse der Wechselwirkung zwischen Fluid und Vegetation ermöglicht.

Die Nachbildung der Eigenschaften lebender Vegetation in Laborversuchen wird im Vergleich zu herkömmlichen Ersatzmaterialien durch den Einsatz von 3D-Druck mit flexiblem Filament in der Genauigkeit verbessert. Die entwickelten Ersatzmaterialien werden in einem Versuchskanal unter unidirektionalen und oszillierenden Strömungsbedingungen getestet. Mit Hilfe der Particle Image Velocimetry können die Veränderungen des Strömungsfeldes und die vom Halm induzierten Turbulenzen gemessen werden. Europäische Feldstudien zu verschiedenen Zeitpunkten während der Vegetationsperiode sowie erstmalige Messungen der biomechanischen Eigenschaften von Halmen aus einer kanadischen Salzwiese ermöglichen eine Quantifizierung sowohl der saisonalen als auch der regionalen Auswirkungen auf die Halm-induzierte Veränderung des Strömungsfeldes. Darüber hinaus wird der Fluid-Struktur-Interaktions-Löser des Open-Source-Modells REEF3D::CFD angewendet, um den Einfluss der Salzwiesenvegetation auf das Strömungsfeld numerisch zu quantifizieren. Hierbei werden Halme und die hydrodynamischen Kräfte von Strömungen und Wellen bidirektional gekoppelt. Dies erweitert vorherige Kopplungsansätze und verbessert die numerische Genauigkeit bei der Modellierung flexibler Vegetation. Die Verwendung von Felddaten aus verschiedenen europäischen Salzmarshenstudien zu unterschiedlichen Zeitpunkten der Vegetationsperiode, zusammen mit den ersten Messungen biomechanischer Halmeigenschaften aus einer kanadischen Salzwiese, ermöglicht eine Bewertung sowohl saisonaler als auch regionaler Einflüsse auf die durch Halme verursachten Veränderungen des Strömungsfeldes.

Die 3D-gedruckten Halmmodelle wurden durch einen statistischen Vergleich als ähnlich wie die *in situ* gemessenen biomechanischen Halmeigenschaften lebender Salzwiesenvegetation bestätigt. Der Fluid-Struktur-Interaktions-Löser wurde validiert, um die Bewegung und Kräfte flexibler Vegetation innerhalb einer maximalen Abweichung von 10 % für die meisten getesteten Bedingungen nachzubilden. Basierend auf der umfangreichen Validierung hat sich der Löser als zuverlässiger Ansatz zur Simulation verschiedener Materialsteifigkeiten erwiesen. Die Ergebnisse sowohl der numerischen als auch der physikalischen Modellierung deuten darauf hin, dass die durch die Halme verursachte Turbulenz je nach replizierter Pflanzenspezies stärker variiert als der saisonale Einfluss innerhalb einer Pflanzenspezies. Aufgrund saisonaler Unterschiede der Biegesteifigkeit der Halme bei den untersuchten Pflanzenspezies und Re-

gionen wurden Unterschiede bezüglich der Halmbiegung und dessen Bewegungsausmaßes beobachtet, weshalb sich unterschiedliche abgeleitete Widerstandskoeffizienten ergeben.

Zusammenfassend lässt sich sagen, dass die akkurate Nachbildung der *in situ* gemessenen biomechanischen Eigenschaften der Halme in Modellansätzen die Unterschiede in den Veränderungen des Strömungsfelds in Abhängigkeit von der Jahreszeit und den regionalen Unterschieden einer Salzwiese aufzeigt. Die durch Einzelhalm-Simulationen ermittelten Widerstandskoeffizienten ermöglichen als nächsten Schritt die Untersuchung der saisonalen und regionalen Variation von Salzwiesen in einem vereinfachten numerischen Modell als Wiese, wodurch eine Bewertung von Ökosystemdienstleistungen wie der Wellenenergiedissipation ermöglicht wird. Durch die Einbeziehung saisonaler Felddaten in Modellierungsstrategien verbessert diese Studie das Verständnis der Wechselwirkungen zwischen Fluid und Vegetation und trägt so zu zuverlässigeren naturbasierten Küstenschutzstrategien bei.

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Symbol	Description
ABS	acrylonitrile butadiene styrene
ALE	arbitrary Lagrangian-Eulerian
AWA	active wave absorption
BC	boundary condition
CFD	computational fluid dynamics
DNS	direct numerical simulation
EPDM	ethylene propylene diene monomer
FD	finite difference
FEM	finite element method
FSI	fluid-structure interaction
HDPE	high-density polyethylene
IBM	immersed boundary method
LES	large eddy simulations
MPI	message passing interface
NbS	nature-based solution
RANS	Reynolds-averaged Navier-Stokes
RO	research objective
PE	polyethylene
PIV	particle image velocimetry
PVC	cylindrical polyvinyl chloride
SGS	subgrid scale
SPH	smoothed-particle hydrodynamics
spp.	<i>species pluralis</i>
WALE	wall-adapting local eddy-viscosity
TI	turbulence intensity
TKE	turbulent kinetic energy
URANS	unsteady Reynolds-averaged Navier–Stokes
VARANS	volume averaged Navier-Stokes
XLPO	cross-linked polyolefin
1D	one-dimensional
3D	three-dimensional

Symbol	Description	Unit
a	acceleration	m/s^2
A	surface area	m^2
B	buoyancy parameter	-
C_D	drag coefficient	-
c_{Elymus}	correction coefficient for the calculation of I	-
c_k	rotational damping coefficient	-
C_M	mass coefficient	-
C_S	Smagorinsky constant	-
c_t	translational damping coefficient	-
Ca	Cauchy number	-
d_S	stem diameter	m, mm
d	water depth	m
E	Young's modulus	Pa
EI	flexural stiffness	$\text{Nm}^2, \text{Nmm}^2$
f	flow variable	-
F_D	drag force	N
F_{ext}	external (length-specific) force	N/m
F_G	gravitational force	N/m
F_I	inertia force	N
F_{int}	internal force	N
F_{Γ}	coupling force, per unit length	N/m
g	gravitational acceleration	m/s^2
H	wave height	m
i	element center point	-
$I, (I_c)$	(corrected) second moment of inertia	m^4, mm^4
j	node between the adjoining elements	-
k	turbulent kinetic energy (k - ω model)	m^2/s^2
KC	Keulegan-Carpenter number	-
L_S	stem length	m
M_{ext}	external (length-specific) moment	N
M_{int}	internal moment	Nm
p	pressure	N/m^2
P_k	production term of the k - ω model	m^2/s^2
r	distance vector	m

Symbol	Description	Unit
R^2	coefficient of determination	-
Re	Reynolds number	-
$ \bar{S} $	magnitude of the strain rate tensor	1/s
S_{ij}	strain rate tensor	1/s
t	time	s
T	wave period	s
T_S	stem thickness	m, mm
TI	turbulence intensity	%
TKE	turbulent kinetic energy	m ² /s ²
u	velocity	m/s
u_w	wave orbital velocity	m/s
W_S	stem width	m, mm
x, y, z	Eulerian coordinates	m
$\partial x, \partial y, \partial z$	cell size	m
X	Lagrangian coordinate	m
$\mathcal{E}$	enstrophy	1/s ²

Symbol	Description	Unit
α	constant of the k - ω model	-
α_B	slope angle of beam	$^\circ$
β	constant of the k - ω model	-
β^*	constant of the k - ω model	-
Δ	length scale	m
$\Delta\rho$	relative density	kg/m ³
δ_{ij}	Kronecker delta	-
ϵ	dissipation rate of turbulence kinetic energy	m ² /s ³
λ	geometrical scale factor	-
λ_E	Young's modulus scale factor	-
μ	dynamic viscosity	Ns/m ²
ν	kinematic viscosity	m ² /s
ν_t	eddy viscosity	m ² /s
ξ	distance from Lagrangian points to element centers	m
ρ	fluid density	kg/m ³
ρ_S	stem density	kg/m ³
σ_k	constant of the k - ω model	-
σ_S	strain vector	-
σ_t	surface tension	N/m
σ_ω	constant of the k - ω model	-
τ_{ij}	Reynolds/ subgrid-scale stress	N/m ²
τ_{kk}	trace of Reynolds stress	N/m ²
ϕ	bending angle	$^\circ$
ω	turbulent energy dissipation	1/s
ω_B	beam displacement	m
ω_S	angular velocity	Hz
ω_v	vorticity	1/s



Symbol	Description
ext	external
<i>f</i>	fluid
int	internal
<i>n</i>	normal
<i>r</i>	relative
<i>S</i>	stem
<i>t</i>	tangential

Twice a day, the water level rises during the tidal cycle on most coasts and floods the adjacent shore. Parts of the shore are covered by grass meadows, where different halophytic vegetation species have adapted to survive in the saline, frequently flooded, and wave-exposed environment (Angus and Dargie, 2024). These meadows are referred to as salt marshes, covering an area of approximately 5.5 Mha worldwide (Mcowen et al., 2017). The vegetation growing in the salt marsh obstructs the tidal flow and the occurring waves, thus reducing the flow velocity in the water column. The interaction between vegetation and the fluid dissipates wave energy, reduces erosion, and promotes sediment deposition, collectively representing the ecosystem services provided by salt marshes (Shepard et al., 2011; Anderson and Smith, 2014; Rupprecht et al., 2017).

Integrating ecosystem services into coastal protection strategies through nature-based solutions (NbSs), such as salt marshes, mangroves, or dunes, has gained attention from researchers, engineers, and coastal managers. Salt marshes provide ecosystem services concerning impacts with varying frequencies: from the daily tidal cycle to storm surges occurring several times per year (Marin-Diaz et al., 2023). During storm surges, salt marshes provide benefits in addition to gray infrastructure in coastal protection strategies, such as reducing the impact of waves on a dike, for example, through breaking of the waves further offshore due to their elevated ground levels (Baker et al., 2022; Wei et al., 2022).

More frequently, the ecosystem services of salt marshes provide benefits to humans during high tide (Temmerman et al., 2023). During each tidal cycle, the below-ground biomass of the salt marsh vegetation mitigates erosion by increasing the soil stability (Kosmalla et al., 2022; Gillis et al., 2022; Carrasco et al., 2023). Simultaneously, the above-ground biomass accelerates sedimentation accretion by reducing the flow velocity in the water column, resulting in sediment accretion (Cahoon et al., 2021; Bass et al., 2022). In contrast to gray infrastructure, salt marshes therefore can grow along with the projected sea level rise and thereby maintain their provided ecosystem services (Vuik et al., 2019; Dunlop et al., 2023; Cassalho et al., 2023; Liu et al., 2024b). The extent and conditions of salt marsh growth are under active investigation, especially if the accretion rate can compete with the projected sea level rise (Bass et al., 2022; Carrasco et al., 2023; Robson et al., 2024). Rayner et al. (2021) estimated that a surpassing of the accretion rate of coastal wetlands by the sea level rise will increase open water coverage and a significant shift in vegetation species composition. With the projected climate change across Europe, Paprotny et al. (2021) calculated that the reduction of salt marsh area due to erosion can be quantified by a loss of ecosystem services worth 14 to 17 billion euro per year by 2100, which is the greatest

absolute loss of ecosystem services compared to other NbSs.

Integrating salt marshes into today's and future coastal protection strategies requires tools able to quantify and predict the provided ecosystem services reliably, such as accurate modeling approaches (Radfar et al., 2024). The ecosystem services provided by salt marshes depend on vegetation properties, such as vegetation height, stem diameter, and its flexibility, as well as the resulting frontal area obstructing the flow and the submergence ratio (Gillis et al., 2022; Bass et al., 2022; Carrasco et al., 2023). Stem height and diameter are comparably easy to quantify, and their influence on ecosystem services is well studied (Anderson and Smith, 2014; Keimer et al., 2021; Zhao et al., 2021). In contrast, the influence of the stems' flexibility has not been fully understood, partially due to a lack of extensive field measurements as well as the common simplification of the vegetation as rigid elements during physical and numerical modeling approaches (Rooijen et al., 2020; Gillis et al., 2022). Furthermore, vegetation properties within one meadow vary due to different vegetation species found in salt marshes (Baaij et al., 2021; Bass et al., 2022), as indicated in Figure 1.1.

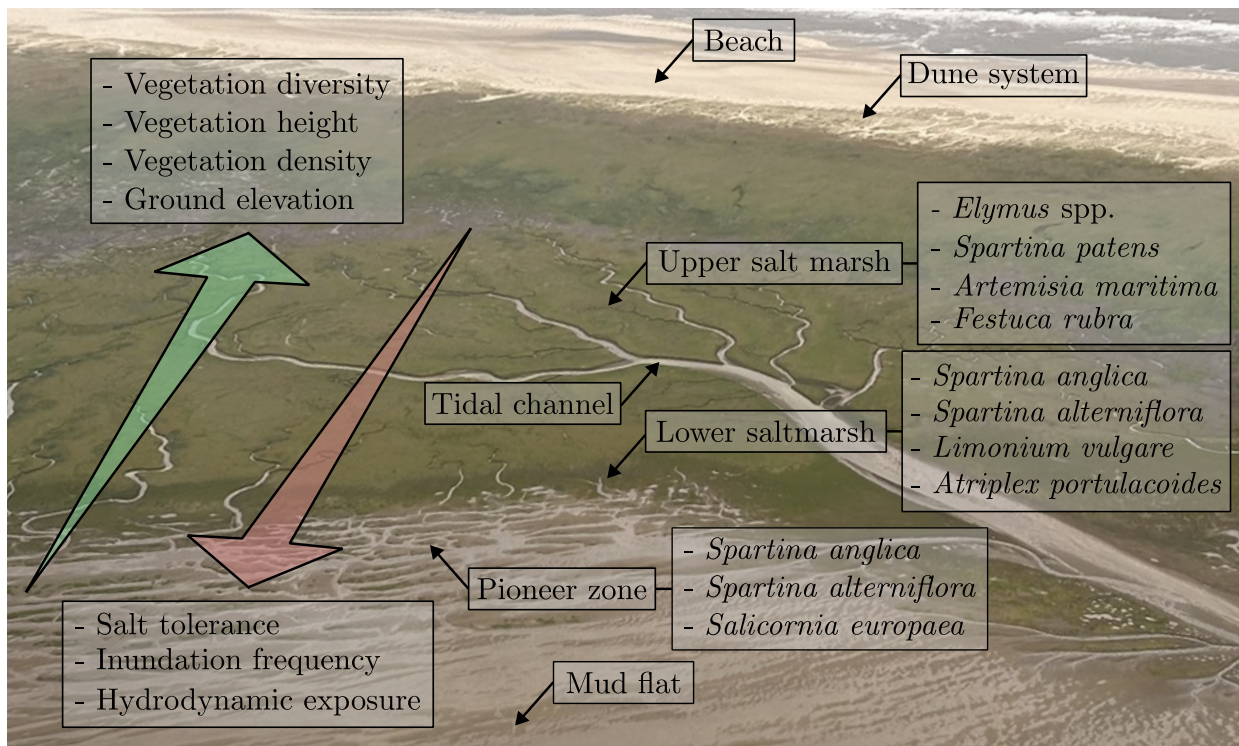


Figure 1.1. Overview of the salt marsh on Spiekeroog, a barrier island in Lower Saxony, Germany, showing key geomorphological and ecological elements as well as typical salt marsh species. Green arrows indicate increasing trends, and red arrows indicate decreasing trends of parameters from the pioneer zone toward the upper salt marsh (photo courtesy of Constantin Schweiger).

Vegetation properties of the same species might vary at specific locations depending on the age of the salt marsh, environmental conditions, such as their distance to the tidal channel, depicted in Figure 1.1, or anthropogenic influence (Meixler et al., 2018). For instance, wave conditions and salinity of the water differ if a salt marsh is established in an estuary, along a mainland coastline, or in the sheltered part of a barrier island (Temmerman et al., 2023; Angus and Dargie, 2024). Furthermore, salt marsh vegetation is susceptible to seasonal changes and is typically dormant during the winter months (Keimer et al., 2023b), which in

the Northern Hemisphere coincides with the period of largest storm surges (Bromirski et al., 2017; Kettle, 2019). As a result, elevated water levels and increased wave heights often impact a salt marsh when its above-ground biomass is at its seasonal minimum (Liu et al., 2024a). However, seasonality might not affect all salt marsh species to the same extent. For example, *Spartina anglica*, dominant in the zone of the lower salt marsh (see Figure 1.1), has been observed to undergo significant seasonal variation regarding its biomechanical stem properties (Keimer et al., 2023b). In contrast, *Elymus species pluralis* (spp.), growing in the upper salt marsh zone (see Figure 1.1), was found to be less affected by seasonal variation (Keimer et al., 2024), suggesting less seasonal variation of their provided ecosystem services.

When neglecting the salt marshes' heterogeneity, ecosystem services might be under- or overestimated if assessed through simplified meadow-scale modeling approaches, such as rigid stems in physical hydrodynamic experiments or bed friction coefficient formulations in numerical simulations (Radfar et al., 2024). Stem-scale investigations are essential for resolving the fluid-vegetation interaction that drives sediment mobilization and turbulence generation around individual stems (D'Ippolito et al., 2023; El Rahi et al., 2024). They further enable the quantification of biomechanical variability and seasonal changes in properties such as stem diameter and flexural stiffness (Vuik et al., 2017), which remain difficult to represent at the meadow scale (Radfar et al., 2024). This thesis integrates the *in situ* measured biomechanical stem properties of salt marsh vegetation, provided for instance by Keimer et al. (2023b, 2024), into physical and numerical modeling approaches, enabling a more profound analysis of the fluid-vegetation interaction at the stem scale. Physical modeling approaches offer the advantage of replicating salt marsh vegetation under controlled laboratory conditions, allowing direct observation of fluid-vegetation interactions, whereas numerical modeling provides flexibility in exploring parameter variations that are difficult to achieve experimentally. Such a numerical modeling approach is the fluid-structure interaction (FSI) solver within the open-source hydrodynamic toolbox REEF3D::CFD (Bihs et al., 2016). The model couples a three-dimensional (3D) finite-difference Navier-Stokes solver with one-dimensional (1D) Cosserat rod equations to capture bending, twisting, stretching, and shearing of flexible structures. Two-way fluid-structure coupling is achieved through an immersed boundary method, enabling detailed simulation of vegetation motion and flow interaction.

It can be summarized that advanced modeling approaches allow the comparison of the influence of both seasonally and regionally varying stem properties on their surrounding flow field. Further, this comparison enables the investigation of ecosystem services provided by salt marshes during storm surges and when the high tide inundates the land along the coastline – twice a day.

1.1 Research objectives, scope, and novelty

This section introduces the research objectives of this thesis, explores the scope of the thesis, and elaborates on its novelty to the research area.

1.1.1 Objectives

The thesis aims to provide knowledge concerning the fluid-vegetation interaction occurring in salt marshes. Flexible vegetation stems are physically and numerically modeled, incorporating *in situ* measured vegetation properties. To achieve this, the following four specific research objectives (ROs) are introduced:

RO 1



To evaluate the integration of *in situ* measured vegetation properties in physical and numerical modeling approaches

RO 2



To develop surrogate materials that can replicate the biomechanical stem properties of live vegetation for physical hydrodynamic experiments

RO 3



To assess the capability of a fluid-structure interaction solver to accurately replicate vegetation stem motion and resulting forces

RO 4



To examine the impact of fluid-structure interaction on the flow field, considering seasonal and regional variation in modeled live vegetation

1.1.2 Scope

Addressing the previously introduced research objectives, the research scope can be divided into three topics. The proposed replication of the fluid-vegetation interaction is here separated by physical and numerical modeling approaches.

Physical modeling: Surrogates that can accurately replicate live stem properties are essential for analyzing the FSI in physical hydrodynamic experiments. Therefore, a workflow based on 3D printing with flexible filament is developed, focusing on the resemblance of the biomechanical properties to those measured in the field. After confirming replicability with a statistical similarity evaluation, the surrogates can be utilized in physical hydrodynamic experiments, exposing them to unidirectional and oscillatory flow conditions.

Numerical modeling: Numerical modeling approaches with *in situ* measured vegetation properties require validation of the resulting stem motion and forces in unidirectional and oscillatory flow conditions. The herein validated numerical model is the FSI solver in REEF3D::CFD, accounting for the structural motion based on the exact Cosserat rod equations. Damping coefficients are utilized in the structural solver to account for structural

damping and inner vibrations; however, their influence on the time-dependent stem motion remains to be evaluated. Applicable ranges of damping coefficients are to be determined based on the comparison to the stem motion in established physical reference studies. Then, conclusions regarding the suitability of the damping coefficients concerning their application for live vegetation properties can be derived.

Evaluation of fluid-vegetation interaction based on in situ measured stem properties: Application of field data for selected salt marsh species to numerical and physical modeling approaches allows for an estimation of the ecosystem services that salt marsh vegetation provides at the stem level. Seasonal and regional differences are investigated, emphasizing the heterogeneity of salt marshes. Based on that, drag coefficients for meadow-scale modeling approaches can be provided.

1.1.3 Novelty

Building on the previously introduced research objectives, this thesis advances the following novel research contributions. To the best of the candidate's knowledge, this is the first investigation regarding the resemblance of biomechanical properties of 3D printed filament surrogates to *in situ* measured live vegetation properties in physical hydrodynamic experiments, building upon previous work of 3D printed flexible resin surrogates (Keimer et al., 2024). Furthermore, experiments including unidirectional and oscillatory flow conditions with consistent material properties are scarce, providing valuable insights into the FSI for various flow conditions and a benchmark for further numerical modeling approaches. Based on the experimental results, this thesis is one of the few to link differences in vegetation stiffness to surrounding flow field characteristics, such as turbulence intensity and the turbulent kinetic energy.

Regarding the numerical modeling approaches, this is the first investigation aiming to validate and evaluate the performance of the FSI solver in REEF3D::CFD. Particularly, previous studies have not addressed the influence of different turbulence models on the FSI replicating vegetation stem dynamics, while being potentially decisive for the FSI. Furthermore, this is the first investigation to address the influence of the structural solver's damping coefficient on the time-dependent stem motion and resulting forces, ensuring an accurate replication of physical processes.

The availability of relevant biomechanical stem properties, such as the flexural stiffness, varies across different regions worldwide, especially concerning their seasonal variability. For example, for Canadian salt marshes, the flexural stiffness of salt marsh stems had previously to this thesis not been measured *in situ* for any species. On the application level, this is the first study to evaluate to what extent the FSI of salt marsh vegetation and their corresponding ecosystem services are comparable across different regions. Furthermore, this thesis investigates the influence of the seasonality of biomechanical stem properties on its surrounding flow field based on the fluid-vegetation interaction, which has been largely unaddressed in the literature to date.

1.2 Candidate's contributions

The candidate's research contributions are here separated by journal articles, published research data sets, conference contributions, and public outreach events.

1.2.1 Journal articles constituting this cumulative thesis

The following articles have been either published in or submitted to peer-reviewed journals:

- **Prüter, I.**, Visscher, J., Lojek, O., Schürenkamp, D., Nistor, I., Goseberg, N.: Flexible 3D-printed models of salt marsh vegetation to investigate unidirectional and oscillatory flow dynamics, *under review* in: Physics of Fluids (AIP Publishing).
- **Prüter, I.**, Spröer, F., Keimer, K., Lojek, O., Windt, C., Schürenkamp, D., Bihs, H., Nistor, I., Goseberg, N. (2025): A comprehensive numerical study on the current-induced fluid–structure interaction of flexible submerged vegetation in: Journal of Fluids and Structures (Elsevier), vol. 133, doi: 10.1016/j.jfluidstructs.2024.104232.
- **Prüter, I.**, Spröer, F., Lojek, O., Windt, C., Schürenkamp, D., Nistor, I., Goseberg, N. (2025): Vegetation stem dynamics under wave load: insights from a coupled fluid-structure model, in: Applied Ocean Research (Elsevier), vol. 159, doi: 10.1016/j.apor.2025.104597.
- **Prüter, I.**, Markov, A., Lojek, O., Schürenkamp, D., Stolle, J., Nistor, I., Goseberg, N.: Linking biomechanical stem properties of salt marsh vegetation to flow field alterations: a regional and seasonal analysis, *under review* in: Coastal Engineering (Elsevier).

1.2.2 Co-authored journal articles

The following list includes articles that have been published in peer-reviewed journals with the candidate's contribution as a co-author:

- Keimer, K., Kind, F., **Prüter, I.**, Kosmalla, V., Lojek, O., Schürenkamp, D., Prinz, M., Niewerth, S., Aberle, J., Goseberg, N. (2024): From seasonal field study to surrogate modeling: Investigating the biomechanical dynamics of *Elymus* sp. in salt marshes, in: Limnology and Oceanography: Methods (Wiley), doi: 10.1002/lom3.10616.
- Keimer, K., Kosmalla, V., **Prüter, I.**, Lojek, O., Prinz, M., Schürenkamp, D., Freund, H., Goseberg, N. (2023): Proposing a novel classification of growth periods based on biomechanical properties and seasonal changes of *Spartina anglica*. in: Frontiers in Marine Science (Frontiers), vol. 10, doi: 10.3389/fmars.2023.1095200.

1.2.3 Published research data

The following research data sets have been assembled and published as part of the research project "Gute Küste Niedersachsen":

- Keimer, K., Kind, F., **Prüter, I.**, Lojek, O., Schürenkamp, D., Prinz, M., Niewerth, S., Aberle, J., Goseberg, N. (2024). From seasonal field study to surrogate modeling: Investigating the biomechanical dynamics of *Elymus* sp. in salt marshes [Data set], doi: 10.24355/dbbs.084-202311010949-0.
- Keimer, K., Kosmalla, V., **Prüter, I.**, Schönebeck, J.-M., Lojek, O., Schürenkamp, D., Goseberg, N. (2023). Mini Buoy measurements to evaluate flooding frequency and duration in the salt marsh from January 2022 to March 2023 (Spiekeroog and Butjadingen, Germany) [Data set], doi: 10.24355/dbbs.084-202311010959-0.
- Keimer, K., Kosmalla, V., **Prüter, I.**, Lojek, O., Schürenkamp, D., Goseberg, N. (2023). Field measurements of geometrical and mechanical properties of *Spartina anglica* on Spiekeroog, Germany, from December 2021 to December 2022 [Data set], doi: 10.24355/dbbs.084-202311010949-0.

1.2.4 Conference contributions with peer-reviewed abstracts

The following list contains oral presentations of the candidate on the thesis topic at international conferences:

- **Prüter, I.**, Lojek, O., Nistor, I., Goseberg, N.: Advancing coastal protection: comparative analysis of salt marsh stem dynamics in Canada and Germany. *CZC 2025 (Coastal Zone Canada Conference)*. 09-11.06.2025, Charlottetown, Canada.
- **Prüter, I.**, Spröer, F., Keimer, K., Lojek, O., Windt, C., Nistor, I., Goseberg, N.: The impact of damping coefficients on dynamics blade motion of flexible submerged vegetation. *ICCE 2024 Rome (38th International Conference on Coastal Engineering)*. 08-14.09.2024, Rome, Italy.
- **Prüter, I.**, Lojek, O., Nistor, I., Goseberg, N.: Integrating Field Biomechanics with Advanced Numerical Modeling for Salt Marsh Vegetation Analysis. *YCSEC-A 2024 (10th Young Coastal Scientists and Engineers Conference – Americas)*, 03-06.06.2024, Québec City, Canada.
- **Prüter, I.**, Spröer, F., Keimer, K., Lojek, O., Windt, C., Nistor, I., Goseberg, N.: Numerical validation and assessment of Flow-Vegetation Interaction for Nature-Based Solutions. *ISE-FP 2024 Québec City (15th International Symposium on Ecohydraulics and Fish Passage)*, 05-09.05.2024, Québec City, Canada.
- **Prüter, I.**, Keimer, K., Lojek, O., Nistor, I., Goseberg, N.: Flexible salt marsh vegetation - from field data to numerical modelling. *CEW 2023 (Coastal Ecology Workshop)*, 27.11-01.12.2023, Coltishall, United Kingdom.

1.2.5 Other conference contributions and public outreach events

The following list contains non-peer-reviewed conferences and public outreach contributions of the candidate, including oral and poster presentations:

- **Prüter, I.**, Lojek, O., Nistor, I., Goseberg, N.: From field to model: Using biomechanical stem properties in experimental and numerical analyses of salt marsh vegetation. *1. Forum Küstenforschung*, 11.-12.09.2025, Hannover, Germany (Poster).
- **Prüter, I.**, Spröer, F.: Ökosystemstärkender Küstenschutz. „Watt - ein Seminar“ from the Dr. Hans Riegel-Stiftung, 16.08.2025, Spiekeroog, Germany (Presentation).
- **Prüter, I.**, Lojek, O., Nistor, I., Goseberg, N.: From field to model: Using biomechanical stem properties in experimental and numerical analyses of salt marsh vegetation. *GROWTH Symposium 2025 (Graduate Research on Water Technology and Hydraulics Symposium)*, 08-09.05.2025, Ottawa, Canada (Presentation)
- **Prüter, I.**, Lojek, O., Nistor, I., Goseberg, N.: Modeling the Flowfield: Insights into Flexible Vegetation Dynamics. *Engineering Research Celebration Day, University of Ottawa*, 06.03.2025, Ottawa, Canada (Poster).
- **Prüter, I.**, Keimer, K., Spröer, F., Lojek, O., Nistor, I., Goseberg, N.: Dynamik flexible Vegetation in Wellen und Strömung. *Gute Küste Niedersachsen Fachtagung*, 19.-20.09.2024, Hannover, Germany (Poster).
- **Prüter, I.**, Keimer, K., Lojek, O., Schürenkamp, D., Goseberg, N.: Ecosystem-based coastal protection: Modeling of biomechanical properties of salt marsh vegetation. *Universidad Nacional de Colombia meets TU Braunschweig*, 18.10.2023, Braunschweig, Germany (Presentation).
- **Prüter, I.**, Ahrenbeck, L.: Ökosystemstärkender Küstenschutz. „Watt - ein Seminar“ from the Dr. Hans Riegel-Stiftung, 12.08.2023, Spiekeroog, Germany (Presentation).
- Wie sicher sind Deutschlands Küsten? So bereitet sich der Norden auf den steigenden Meeresspiegel vor, *NDR online (Ines Bellinger)*, 23.07.2023 (Report/Interview).
- Naturnaher Küstenschutz: Mit Salzwiesen gegen Klimafolgen, *NDR Info (Ines Bellinger)*, 17.07.2023 (Radio interview).
- Keimer, K., Bunzel, D., **Prüter, I.**, Schönebeck, J.-M., Schlurmann, T., Goseberg, N.: Using scientific methods to enhance the appreciation of ecosystem-based coastal protection in Lower Saxony, Germany, *FZK meets UTwente*, 07.02.2023, Hannover, Germany (Presentation).

1.3 Thesis outline

This cumulative thesis is structured based on four studies, provided in published or submitted versions in the appendix, including their respective research questions, methodologies, and results. Figure 1.2 shows the contributions of each study and their connectivity.

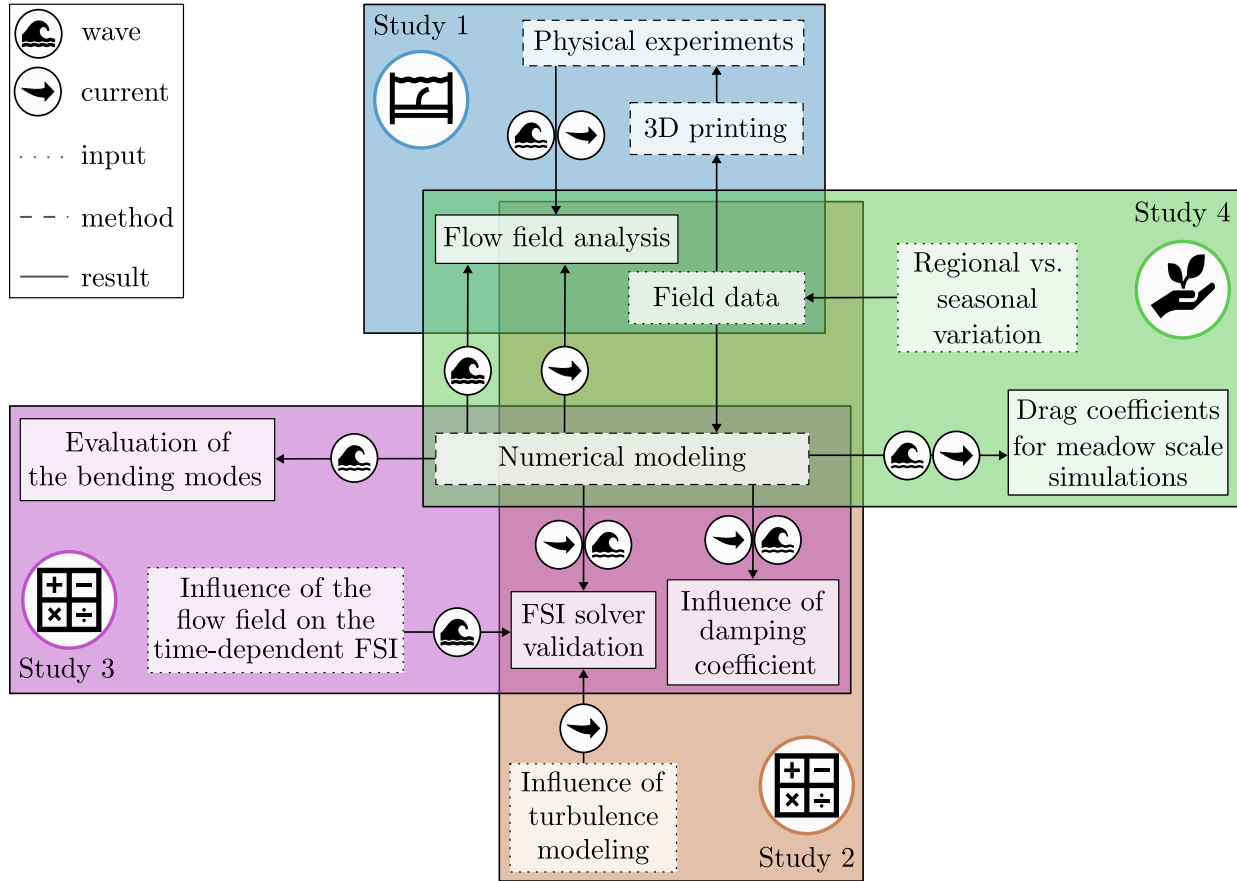


Figure 1.2. Outline of the cumulative thesis through individual studies and their connection

The first study (cf. appendix A) aims to use *in situ* measured vegetation properties for stem surrogate development for physical hydrodynamic experiments. Such an approach allows for investigating the stem-induced turbulence in unidirectional and oscillatory flow conditions. The second study and the third study (cf. appendix B and C) focus on the numerical validation and investigation of the FSI solver in REEF3D::CFD, for unidirectional and oscillatory flow conditions, respectively. The fourth study (cf. appendix D) simulates the fluid-vegetation interaction, based on the previously validated and evaluated numerical model, utilizing field measurements representing both seasonal and regional variation in salt marsh stem properties. A novel comparison of the flow field resulting from the FSI is provided, followed by the determination of parameters such as the drag coefficient, suitable for modeling approaches at the meadow scale.

This thesis is organized into chapters as follows:

- Chapter 2 includes a literature review of relevant processes in salt marshes and their provided ecosystem services, previous investigations to replicate salt marsh stems in the laboratory, and numerical modeling methods to achieve the fluid-vegetation interaction.
- Chapter 3 summarizes the main components of the published or submitted studies, including their motivation, research objectives, results, conclusions, and conceptualization.
- Chapter 4 discusses the research objectives posed in Chapter 1 based on the findings of Chapter 3, connecting the individual studies into the general framework of the thesis.
- Chapter 5 provides answers to the research objectives discussed in Chapter 4 and gives recommendations for future work.
- The appendix consists of the full text of submitted or published studies, including the rebuttal letters to the reviewers.

The literature review is structured into four sections. First, the relevance of salt marsh vegetation in coastal protection strategies, the ecosystem services it provides, and the relevance of investigating the fluid-vegetation interaction at the stem level are elaborated. Second, the relevance of different parameters to describe the fluid-vegetation interaction and previously used surrogates replicating live vegetation in physical modeling are evaluated. Third, numerical modeling approaches suitable for simulating the fluid-structure interaction and the relevant literature on replicating flexible vegetation through simulations are introduced. The literature review concludes by highlighting the derived research needs addressed in this thesis.

2.1 Significance of salt marsh vegetation in coastal engineering

Traditionally, inhabitants of the coast have built and relied on gray infrastructure, such as dikes or seawalls, as protection against incoming tides and storm surges (Shepard et al., 2011). Hard infrastructure, especially when oriented orthogonal to the coastline, such as groins, can disrupt the natural sediment transport (Griggs and Patsch, 2019; Schoonees et al., 2019). Nowadays, coastal engineering solutions, such as NbSs, aim to utilize the natural sediment transport to their advantage. One example of using NbSs is the sediment accumulation capability of salt marshes due to the reduction of the flow velocity in the water column from the vegetation stems (Shepard et al., 2011; Bass et al., 2022).

Thus, salt marshes have the potential to enhance vertical growth of the soil, rendering them of great value for coastal protection in the light of the projected sea level rise (D’Alpaos et al., 2011; Vuik et al., 2019; Dunlop et al., 2023). To date, the uncertainties of climate change projections pose challenges for the design of gray and thus static infrastructure in coastal protection plans (Vinent et al., 2019; Vuik et al., 2019). NbSs like salt marshes require continuous evaluation instead of initial designs, such as ensuring sufficient sediment supply for accretion processes (D’Alpaos et al., 2011; Dunlop et al., 2023). Further research and accurate modeling of the processes salt marshes are involved in are required to provide reliable information for decision-makers.

2.1.1 Ecosystem services provided by salt marshes

Salt marshes provide various ecosystem services, including water purification through the retention of nutrients and metals (up to 50 % over multi-year periods), nursery habitats for fish, and substantial carbon sequestration, with global average carbon accumulation rates of about $245 \text{ gC}/(\text{m}^2 \text{ yr})$ (Leendertse et al., 1996; Barbier et al., 2011; Ouyang and Lee,

2014; Liu et al., 2024b). Salt marshes are effective NbS for coastal protection, significantly attenuating incoming waves by up to 92 % over distances of 310 m (Möller and Spencer, 2002). They also reduce erosion, with interventions capable of decreasing shoreline retreat from 1.3 to 0.2 m per year (van Loon-Steensma and Slim, 2013), and promote sediment entrapment, achieving vertical accretion rates of 0.9 to 2.2 mm per year (Arriola and Cable, 2017).

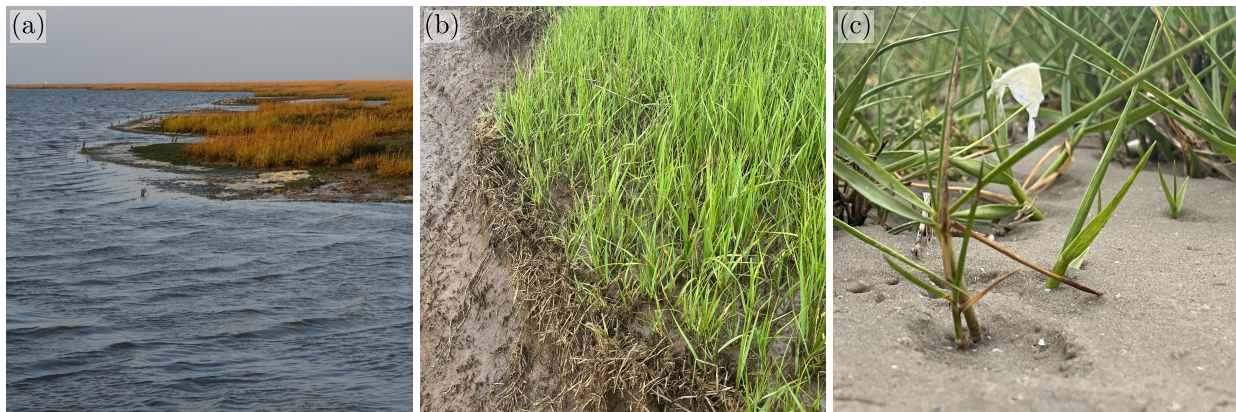


Figure 2.1. Field impressions of (a) attenuation of incoming waves by a salt marsh on Spiekeroog (Germany) (photo courtesy of Kara Keimer), (b) a salt marsh edge in the Bay of Fundy (Canada), and (c) an individual stem and resulting sediment patterns in a salt marsh on Spiekeroog (Germany)

Figure 2.1 (a) to (c) emphasizes the different scales on which processes are occurring within a salt marsh. Indicating the salt marsh's wave attenuation potential, Figure 2.1 (a) shows the incoming high tide arriving at the elevated bed level of a salt marsh. In Figure 2.1 (b), a salt marsh edge is pictured, including the below-ground and above-ground biomass of salt marsh vegetation, referring to the salt marsh's capability of soil stabilization. The third photograph in Figure 2.1 (c) depicts an example of how a salt marsh vegetation stem influences sediment patterns. Furthermore, the variability of salt marsh stems is evident, as their color varies depending on the photograph's location and the time within the season.

On the process level, the ecosystem services of salt marshes relevant for coastal protection are shown in Figure 2.2. Here, it is differentiated between ecosystem services that can be primarily quantified at the meadow scale, depicted in Figure 2.2 (a), such as the wave attenuation capacity and erosion resistance. Figure 2.2 (b) shows the fluid-vegetation interaction at the stem scale and indicates the resulting sediment deposition process.

The wave attenuation potential of salt marshes has been frequently studied (Keimer et al., 2021; Baker et al., 2022; Taylor-Burns et al., 2023; Zhu et al., 2024; Markov et al., 2025). Wave attenuation is related to vegetation obstructing the incoming flow, thus dissipating its energy and altering flow velocities. For example, Baaij et al. (2021) modeled with XBeach a 7.5 times increase in wave attenuation for a salt marsh with natural vegetation compared to the bare topography. Depending on several factors, such as the submergence ratio (d/L_S), frontal area A , vegetation density, and incoming wave conditions, the wave attenuation capacity of a salt marsh varies (Lowe et al., 2007; Pujol et al., 2013; Tempest et al., 2015; Zhao et al., 2021; Baker et al., 2022; Ye and Hu, 2023). Even in storm surge conditions, resulting in a large submergence ratio and large incoming waves, physical flume experiments show that salt-marsh vegetation can attenuate wave heights by up to 60 % over

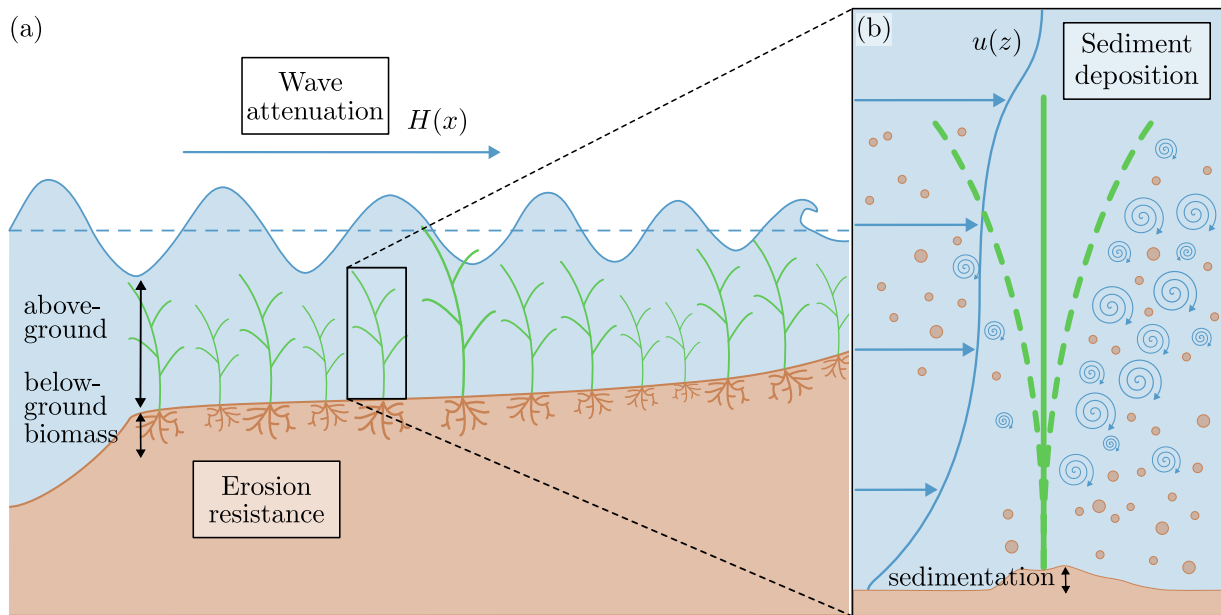


Figure 2.2. Ecosystem services provided by salt marsh vegetation for coastal protection at (a) the meadow scale, including the above- and below-ground biomass of the vegetation, and (b) the stem scale, including indicated stem movement, stem-induced turbulence in the flow field, with the wave height H and the horizontal flow velocity component u

a 40 m-long, and 1 m-wide meadow section (Moeller et al., 2014); however, the dependence of wave attenuation on marsh width was not investigated, and its transferability to wider or narrower natural marshes therefore remains uncertain. Recent studies suggest that salt marshes attenuate waves less effectively in the early season (Caldera et al., 2025), but further research is required to quantify the seasonal variability.

The abundance of vegetation and its adjunct below-ground biomass in salt marshes can reduce erosion processes by up to 80 % (Moeller et al., 2014; Lo et al., 2017; Vuik et al., 2019). The dense root system of the plants, delineated in Figure 2.2 (a), increases the shear strength of the soil (Cahoon et al., 2021; Kosmalla et al., 2022; Stoorvogel et al., 2024). While the above-ground biomass of salt marsh vegetation undergoes seasonal changes and becomes dormant during winter (Keimer et al., 2023b), the root systems are generally considered stable throughout the year, providing consistent erosion resistance (Vuik et al., 2019). However, further studies are needed to reliably quantify this effect and to account for differences among dominant plant species and local environmental conditions.

Another crucial ecosystem service provided by salt marshes for coastal protection strategies is the enhanced sediment deposition (Bass et al., 2022; Carrasco et al., 2023). The process is illustrated in Figure 2.2 (b) by example for one individual stem. It is reported that sediment deposition is increased within a salt marsh by 42 % over a period of two weeks compared to an unvegetated mudflat (Baaij et al., 2021). However, it is not fully understood yet to what extent the stiffness of the vegetation contributes to the sedimentation process (Gillis et al., 2022; D'Ippolito et al., 2023). Generally, stiff stems have the strength to tolerate high mean flow velocities (Puijalon et al., 2011), leading potentially to a larger velocity gradient behind the stem, which is associated with an increased sediment deposition. Stem-induced turbulence increases with the flow obstruction and the velocity gradient, potentially triggering sediment re-suspension (Deitrick et al., 2023). In contrast,

flexible vegetation provides less resistance to the incoming flow, resulting in smaller velocity gradients (Puijalon et al., 2011). The so-called avoidance behavior leads to less turbulence in the proximity of the stem (Gillis et al., 2022). Table 2.1 summarizes the ecosystem services for coastal protection provided by salt marshes, including the scale at which each service is investigated and key influencing parameters.

Table 2.1. Summary of selected ecosystem services and their principal influencing parameters, based on the findings reported by Boorman et al. (1998); Feagin et al. (2009); Shepard et al. (2011); Yang et al. (2012); Rupprecht et al. (2015); Brooks et al. (2021), and Marin-Diaz et al. (2023)

Ecosystem service	Investigation scale	Influencing parameters
Wave attenuation	Meadow	Vegetation density, biomass, height, thickness, stiffness, marsh extent, incident wave height, water depth, submergence ratio
Erosion resistance	Meadow	Incident wave height, water depth, organic and water content of the soil, bulk density, vegetation's fine root density
Sediment deposition	Meadow and stem	Incident wave height, water depth, vegetation height, thickness stiffness, micro-topography and elevation, sediment availability

2.1.2 Investigation of fluid-vegetation interaction at the stem level

The dynamics of salt marsh vegetation can be studied either at the meadow or stem scale, with methods including *in situ* investigations, numerical modeling or physical experiments (El Rahi et al., 2024). While the wave attenuation capacity is negligible at the stem scale, the dynamics of an individual stem highly influence the local sediment mobilization process (D'Ippolito et al., 2023), being less relevant at the meadow scale.

Previous studies on fluid-vegetation interaction, both physical and numerical (Yin et al., 2020; Keimer et al., 2021; Zhang and Zhang, 2023), utilized stiff cylinders to represent aquatic vegetation, simplifying the FSI. However, the flexural stiffness of halophyte stems enables them to grow in exposed areas subject to frequent flooding and wave impact by allowing the plants to follow the wave motion and thereby reduce the acting forces (Puijalon et al., 2011). This motion simultaneously decreases the plant's frontal area and the relative velocity between plant and water, both of which depend on the magnitude of the stems' flexural stiffness (van Veelen et al., 2020). A limited number of studies have investigated the influence of plant flexibility on wave attenuation, reporting reductions of 30 to 70 % with increasing flexibility (Mullarney and Henderson, 2010; van Veelen et al., 2020). Further, it remains challenging to accurately incorporate the effect of the stems' flexibility into modeling frameworks at the meadow scale (Radfar et al., 2024).

Approaches like the effective length, introduced by Luhar and Nepf (2016), have, for instance, been applied by Markov et al. (2025) to investigate a flexible vegetation meadow in flume experiments. However, such an approach cannot replicate processes like the turbulence induced by stem swaying. For numerical modeling at the meadow scale, approximation through empirical values, like the drag coefficient, is utilized, rendering the replication of regional or seasonal differences of the plant characteristics challenging (van Veelen et al., 2020; D'Ippolito et al., 2023). Therefore, the complex interaction between the fluid and

the vegetation, influenced by the variation of biomechanical properties and seasonal effects, requires its investigation at the stem level as a first step. Seasonal differences in salt marsh properties are predominantly measured at a stem level, as done by Vuik et al. (2017); Schulze et al. (2019), and Keimer et al. (2023b, 2024). The findings of these studies suggest that seasonality affects all biomechanical vegetation properties, such as the stem diameter, height, and flexural stiffness. It is therefore required to first accurately replicate the observed seasonal and regional variation in a model at the stem level before providing upscaling approaches. Further, stem-scale investigations provide insights into flow field modifications and the generation of stem-induced turbulence (El Rahi et al., 2024).

Generally, the interaction of fluid and vegetation is rarely investigated in the field (see Mullarney and Henderson (2010) or Garzon et al. (2019) as examples) due to limited visibility in the water column and complex hydrodynamic conditions. These challenges can be avoided by conducting physical experiments in a wave flume. Laboratory investigations require an adequate representation of the vegetation, which has been addressed in previous studies either by using live plants (Markov et al., 2023; Lara et al., 2016; Moeller et al., 2014) or surrogates (Baker et al., 2022; Keimer et al., 2021; Zhang et al., 2022). Live plants either need to be sampled from nature, which leaves an impact on often protected areas and requires challenging logistics, such as plant transportation and immediate use in experiments (Lara et al., 2016). Alternatively, they can be grown in the laboratory, which may lead to differing growing conditions compared to the field and thus to variations in stem properties. Instead, stem surrogates or numerical modeling approaches can be utilized to replicate live vegetation, allowing further assessment of how variation in live vegetation stems, based on field measurements, influences the fluid-vegetation interaction (Rupprecht et al., 2017; Liu et al., 2021; Keimer et al., 2023b; Schulze et al., 2019). However, simplified models (Bouma et al., 2007; Okamoto and Nezu, 2010; Yin et al., 2020; Zhang and Zhang, 2023) can not replicate plant flexibility and thus are limited in representing the biomechanical stem properties and correspondingly their seasonal variation. To overcome these challenges, advanced modeling approaches are required for both physical experiments and numerical simulations to replicate the stem dynamics of salt marsh vegetation accurately.

2.1.3 Regionality in salt marsh vegetation properties

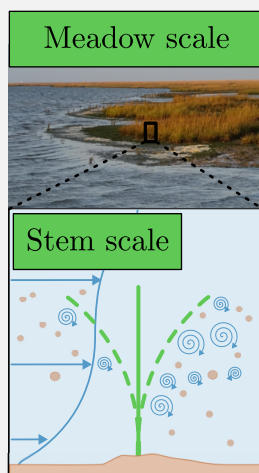
Salt marshes can be found worldwide in temperate climates (Mcowen et al., 2017), including the German coastline along the North Sea and the Canadian coast, with the highest abundance along its southern East coast. The previously discussed ecosystem services are generally independent of geographical location (Barbier et al., 2011). Nevertheless, which species dominate within a salt marsh varies regionally, thus potentially influencing the effectiveness of the ecosystem services. For example, *Spartina alterniflora* is commonly growing in North American salt marshes compared to *Spartina anglica*, which is widely distributed in European salt marshes (Keimer et al., 2023b; Markov et al., 2023). Both plant species occupy the same ecological niche in the lower salt marsh (Zhi et al., 2007). However, *S. alterniflora* has a larger stem diameter and grows taller compared to its European counterpart (Zhang and Nepf, 2021). The extent to which such differences affect local sedimentation processes, and thereby the capacity of salt marshes to grow with projected sea level rise, has not yet been fully established. In colder regions, such as the Canadian east coast, the implications of a shorter growing season for the biomechanical properties

of the vegetation also remain insufficiently assessed, which may constrain the ecosystem function of these salt marshes.

The combination of population density and extent of low-lying areas along the German and Dutch coastline resulted in a long history of coastal protection strategies and corresponding research (Esselink et al., 2017). Therefore, biomechanical properties of salt marsh vegetation along the North Sea coast have been frequently determined in the field, for example by Bouma et al. (2007); Vuik et al. (2017); Schulze et al. (2019); Zhu et al. (2020b); Baaij et al. (2021); Steinigeweg et al. (2025) and Keimer et al. (2023b, 2024), with some studies including their seasonal variation. In contrast, the remoteness of the Canadian coastline due to the lower population density leads to more challenging conditions for field studies (Rabinowitz and Andrews, 2022). Therefore, field measurements of biomechanical vegetation properties for Canadian salt marshes are scarce. It remains essential to assess to what extent biomechanical stem properties and the quantification of ecosystem services derived from European field studies can be transferred to other regions, such as, for example, Canadian salt marshes, to avoid under- or overestimating the provided ecosystem services.

Overall, the variance of hydrodynamic and environmental conditions found in nature complicates the quantification of ecosystem services provided by salt marshes for specific locations. Furthermore, the seasonal variation of ecosystem services is largely unaddressed in the literature, as field studies are often conducted during the summer period (Riffe et al., 2011; Meixler et al., 2018; Schoutens et al., 2020) and both numerical and physical modeling approaches frequently rely on idealized vegetation characteristics (D'Ippolito et al., 2023).

Concluding remarks of Section 2.1



- Salt marshes provide ecosystem services such as wave attenuation, erosion resistance, and sediment deposition
- Investigation of ecosystem services requires accurate replication of stem properties, such as the flexural stiffness
- Fluid-vegetation interaction can be analyzed at either the meadow or the stem scale
- Investigations at the stem scale allow for the incorporation of *in situ* measured stem properties of live vegetation and insights regarding flow field alterations and stem-induced turbulence
- Biomechanical stem properties vary regionally and seasonally, requiring appropriate modeling considerations

2.2 Physical modeling of flexible vegetation

As outlined in the previous section, accurate modeling of live vegetation, both numerically and physically, is crucial to gain further knowledge of the fluid-vegetation interaction and investigate salt marsh ecosystem services. Surrogate materials have the advantage that their material properties can be controlled and are replicable (Paul et al., 2016). Considering the processes involved, the set of parameters necessary to characterize fluid-vegetation interaction is evaluated in the following.

2.2.1 Replication of live vegetation properties

When investigating fluid-vegetation interactions in hydrodynamic flume experiments using surrogate vegetation, it is essential to ensure that the governing processes of the interaction are accurately reproduced. The focus lies on both directions of the interaction, the influence of the fluid on the vegetation and, conversely, the influence of the vegetation on the fluid. Accordingly, the obstruction of the flow field by the stem and the resulting fluid-induced stem motion must resemble those observed in nature, as these represent the dominant processes of the fluid-vegetation interaction (Blackmar et al., 2014; van Veelen et al., 2020). Depending on the scope of the experiments, this can be achieved either without scaling, by aligning the relevant dimensions and material properties (Anderson and Smith, 2014), by matching derived parameters that characterize the fluid-vegetation interaction (van Veelen et al., 2020), or by applying appropriate scaling laws (Baker et al., 2022).

Several parameters must be carefully selected in flume experiments to ensure a representative fluid-vegetation interaction: hydrodynamic conditions, fluid properties, stem geometry, and material characteristics. Scaling is often not required in single-stem experiments, as the interaction can typically be investigated at a prototype scale. Then, surrogate dimensions, such as stem length, L_S , and diameter, d_S , should align with those measured for live vegetation (van Veelen et al., 2020). Some studies have modeled vegetation stems with a rectangular cross-section, either as a simplification or to represent seagrass species, defined then by the stem width W_S and thickness T_S (Wu and Cox, 2016; Paul et al., 2016; Jacobsen et al., 2019). The morphological influence of the stem cross-section on the FSI is parameterized through the second moment of inertia I . Assuming a perfectly circular, homogeneous, and isotropic cross-section, I can be calculated from d_S using

$$I = \frac{\pi}{64} d_S^4. \quad (2.1)$$

While most surrogate models simplify vegetation stems as solid cylinders, stems are known to be hollow for some salt marsh species or even rectangular for *Bolboschoenus maritimus* (Zhu et al., 2020b; Liu et al., 2021; Keimer et al., 2023b). Geometry-dependent alternatives of Equation (2.1) can therefore be applied to account for varying geometries found in natural vegetation stems, such as the triangular or ring-shaped cross sections. However, for irregular shapes found in natural vegetation, assuming a circular or ring-shaped cross-section can lead to deviating values of I for a surrogate stem compared to the prototype. A binary image analysis of a live vegetation stem by Keimer et al. (2023b) revealed that the cross-sectional area is about 6 % smaller if a ring structure is assumed and 13 % smaller if a circular shape is assumed compared to the observed stem morphology. Correspondingly, I differs by 5 % for the ring structure and 6 % for the circular structure compared to the cross-section

incorporating mesoscopic morphology. Keimer et al. (2024) therefore utilized a refined approach to calculate I for the salt marsh species *Elymus* spp. A correction coefficient, c_{Elymus} , to calculate the corrected I_c was applied, based on Liu et al. (2021), who analyzed 84 *Elymus* spp. cross-sections. A correction coefficient c_{Elymus} of 0.79, whose coefficient of determination for the fit was $R^2 = 0.97$, can be integrated into the equation to compute I_c under the assumption of a solid circular morphology

$$I_c = c_{Elymus} \frac{\pi}{64} d_S^4. \quad (2.2)$$

An accurate determination of the stem's cross-sectional morphology is therefore crucial for the determination of I . The stem's flexural stiffness EI can then be calculated as the product of the Young's modulus E , determined for example through three-point bending tests, and the previously calculated second moment of inertia I or I_c .

It can be concluded that the projected frontal area, characterized by the stem diameter d_S or width W_S , must be aligned between prototype and surrogate to achieve a comparable obstruction of the flow field. Likewise, the flexural rigidity EI must be matched to reproduce similar stem motion under hydrodynamic loading. If the surrogates are manufactured with rectangular cross sections or the live vegetation exhibits an irregular geometry, the second moment of area I might differ between the two. Then, the surrogate material should be chosen with a Young's modulus E such that the resulting flexural rigidity EI corresponds to that of the natural vegetation. When the biomechanical properties of the surrogate have been designed in alignment with those found in live vegetation, it is logical to investigate wave or current conditions similar to what can be observed in the field (van Veelen et al., 2020).

When an exact match of all relevant physical properties or stem geometries cannot be achieved, the fidelity of the fluid–vegetation interaction can be maintained by ensuring similarity in key dimensionless parameters, such as the Cauchy number Ca , the Buoyancy parameter B , the Reynolds number Re , and the Keulegan–Carpenter number KC .

Many studies aimed to replicate the swaying motion of live vegetation (Lima et al., 2006; Anderson and Smith, 2014; van Veelen et al., 2020; Markov et al., 2025). Such stem motion is dominantly influenced by the vegetation flexural stiffness (Luhar and Nepf, 2016; Koftis et al., 2013), which can be described based on the relation of external drag and elastic forces by the Cauchy number Ca , here expressed for a rectangular cross-section

$$Ca = \frac{\rho u^2 W_S L_S^3}{EI}. \quad (2.3)$$

with ρ as the fluid density and u as the flow velocity. Accordingly, if hydrodynamic conditions and the geometry of the stem have been accurately reproduced in the experimental setup, utilizing a material for the surrogate stem with a flexural stiffness in alignment with the one measured for live vegetation is crucial. However, if no stem movement is expected for the tested flow conditions, surrogates might be simplified as stiff, as done by van Veelen et al. (2025). Several studies aimed to replicate the buoyancy of live vegetation as well, meaning that the stem initially maintains a vertical upright position (Lima et al., 2006; Koftis et al., 2013; Ozeren et al., 2014). The buoyancy is particularly relevant for the investigation of emergent vegetation (Anderson and Smith, 2014), and can be described by the relative

density difference between water and vegetation ($\Delta\rho = \rho_S - \rho$), with ρ_S as the material density of the stem. Alternatively, the buoyancy parameter B can be utilized, here provided by way of example for a rectangular cross-section,

$$B = \frac{(\rho - \rho_S)gW_S T_S L_S^3}{EI}, \quad (2.4)$$

with g as the gravitational acceleration. Unfortunately, the scarcity of *in situ* measurements reporting the material density ρ_S of live vegetation limits the ability to accurately reproduce the density, and thus the buoyancy, of surrogate materials.

Further, the influence of the vegetation on the hydrodynamics should be well replicated (van Veelen et al., 2020), which can be, for example, achieved by keeping a comparable magnitude of Re between field conditions and the test facility. The Reynolds number Re has been utilized in the literature to ensure comparable flow conditions between the flow field of the model and prototype fluid-vegetation interaction (Blackmar et al., 2014; Wu and Cox, 2016; Baker et al., 2022; Keimer et al., 2024), calculated as:

$$Re = \frac{\rho u d_S}{\mu} \quad (2.5)$$

with μ as the dynamic viscosity of the fluid. The most direct approach, ensuring comparable Reynolds numbers, matches d_S as the characteristic length to the stem properties observed in nature. However, replicating the stem diameter of live vegetation presents certain challenges. For live vegetation, d_S varies along the plant height (Rupprecht et al., 2015), but is often simplified in surrogate stems (Keimer et al., 2024; Markov et al., 2025). Furthermore, field investigations show that thicker vegetation stems tend to exhibit larger diameter variation along their height, compared to thinner stems (Keimer et al., 2023b, 2024). An additional non-dimensional parameter describing the relationship between wave conditions and vegetation properties is the Keulegan-Carpenter number KC , describing the ratio of drag to inertia

$$KC = \frac{u_w T}{W_S} \quad (2.6)$$

with u_w describing the wave orbital velocity and T as the wave period.

Figure 2.3 illustrates the key properties for accurately replicating fluid-vegetation interactions in physical wave or current flume experiments using surrogate materials. As previously elaborated, not every parameter necessarily aligns between surrogates and live vegetation, depending on the focus of a particular study. However, studies should clearly state which properties are replicated or possibly scaled and which are not, elucidating potential limitations of the study.

In most experimental facilities, the fluid properties are those of fresh water and remain unchanged. However, specialized facilities can utilize saline or brackish water (e.g., Goseberg et al. (2025)). Suppose stem dimensions and hydrodynamic conditions are chosen in agreement with the field observations, it is crucial to utilize a material for the surrogate that has a comparable Young's modulus and thus, flexural stiffness to the live vegetation properties. Furthermore, if the stem diameter differs or a rectangular surrogate is chosen, selecting a surrogate material that results in comparable flexural stiffness is critical. In

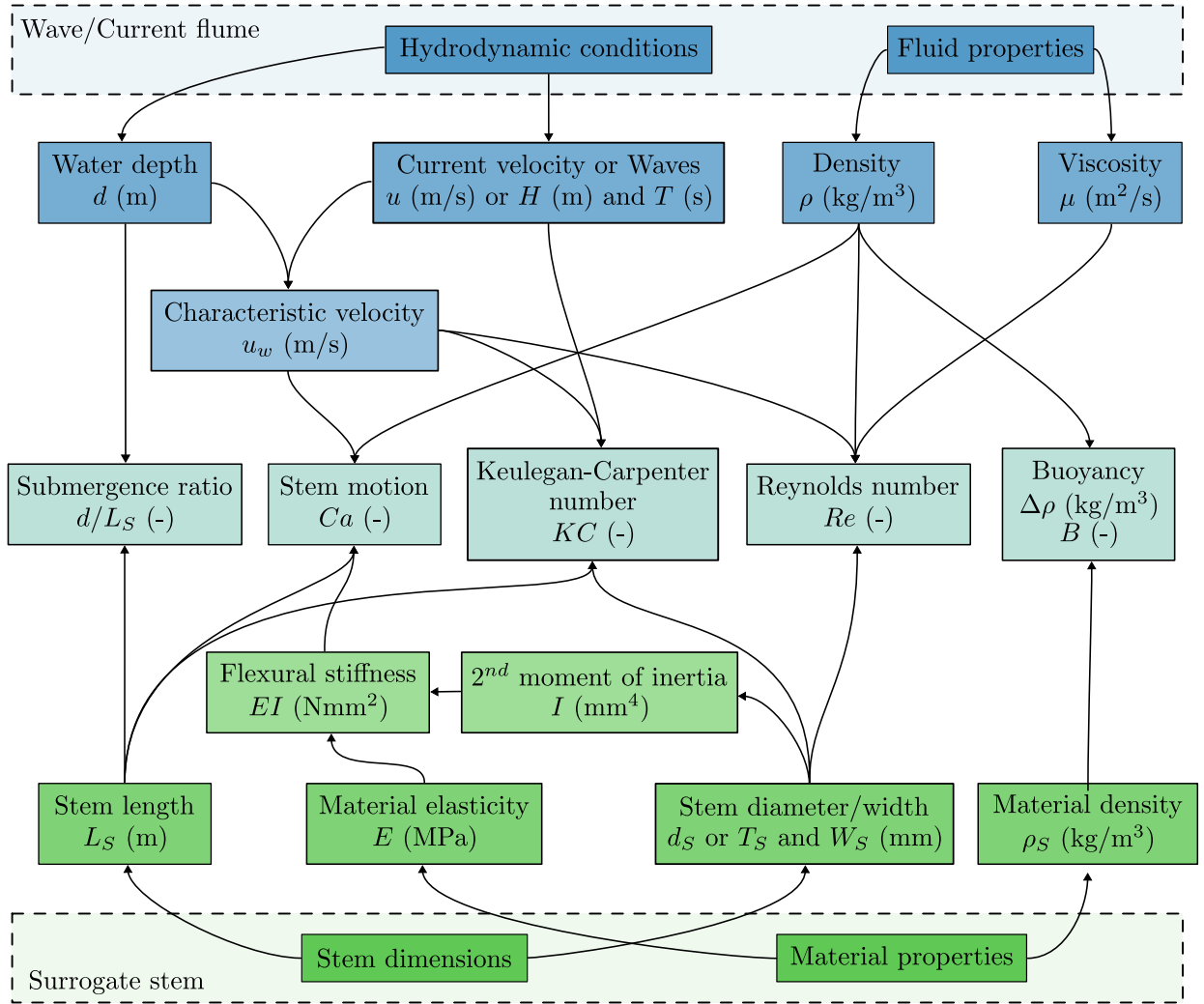


Figure 2.3. Material properties to consider for an accurate replication of the fluid-vegetation interaction

practice, selected current velocities or wave conditions, as well as the water depth d , are dependent on the available flume facility. Based on the submergence ratio relevant to the study's objectives, the stem length of the surrogate can then be determined.

When a vegetation meadow is investigated or only a small flume facility is available, scaling laws need to be considered (Bouma et al., 2007). Commonly applied in hydrodynamic experiments, the Froude scaling law relates model and prototype conditions by preserving the ratio of inertial to gravitational forces, ensuring dynamic similarity in free-surface flow experiments. The traditional Froude scaling law has its limitations for flexible vegetation, as scale effects are expected concerning both Re and Ca , meaning that neither the flow conditions around the stem, nor the stem motion are accurately replicated (Blackmar et al., 2014; Wu and Cox, 2016). Applying the exact Froude scaling law, which requires scaling both fluid and stem properties, could resolve this issue. However, in most cases, simultaneously scaling air and water properties is considered too complex for practical implementation. Instead, traditional Froude-Cauchy scaling is often utilized, including the scaling of the Young's modulus to ensure the Cauchy similitude between the model and the prototype (Baker et al., 2022; Keimer et al., 2024). However, it may be challenging to find materials with a magnitude of E that follows the scaling law, and the flow conditions (Re) are still

subject to scale effects. For example, Zhang and Nepf (2021) compared a surrogate stem and live vegetation in a test flume, ensuring comparable dimensions concerning stem height, diameter, and flexural stiffness, leading to comparable Ca in the test flume. However, compared to fully grown *S. alterniflora* plants, their 1:5 model has limitations as the Re is not scaled accordingly.

Alternatively, Attali et al. (2023) proposed a new scaling law to replicate flexible wave-structure interaction, with the scaling adapted for the governing equation of such interaction, as detailed in Table 2.2. Here, an appropriate material with a given Young's modulus can be utilized, requiring only the scaling of the structural width. This proposed scaling law remains to be applied and investigated for the replication of live vegetation properties. Some of the most frequently applied scaling laws concerning structural flexibility are summarized in Table 2.2 based on the elaboration of Attali et al. (2023), including the geometrical scale factor, λ , and the Young's modulus scale factor, λ_E .

Table 2.2. Scaling laws for all relevant parameters concerning the fluid-vegetation interaction, including flexibility under different scaling approaches, adapted after Attali et al. (2023), with wave height H , the wave period T , the density of the water ρ , the viscosity of the water ν , the surface tension σ_t , the Young's modulus E , the structural density ρ_S , the structural thickness T_S , the length of the structure L_S , the gravitational acceleration g , the geometrical scale factor λ and the Young's modulus scale factor λ_E

Parameter	Unit	traditional Froude	precise Froude	traditional Froude–Cauchy	proposed by Attali et al. (2023)
H	m	λ	λ	λ	λ
T	s	$\lambda^{1/2}$	$\lambda^{1/2}$	$\lambda^{1/2}$	$\lambda^{1/2}$
ρ	kg/m ³	1	1	1	1
ν	m ² /s	1	$\lambda^{3/2}$	1	1
σ_t	N/m	1	λ^2	1	1
E	N/m ²	1	λ	λ	λ_E
ρ_S	kg/m ³	1	1	1	1
T_S	m	λ	λ	λ	$\lambda^{3/4}/\lambda_E$
L_S	m	λ	λ	λ	λ
g	m/s ²	1	1	1	1

Last, in case of a vegetation meadow, stems can be scaled based on the frontal area or solid volume fraction to overcome the discrepancy of Re due to the difference in stem diameters, as shown by Baker et al. (2022) and Markov et al. (2025). It follows the assumption that wave attenuation mainly depends on the vegetation drag, which depends on the vegetation frontal area rather than the stem diameter.

2.2.2 Surrogates replicating salt marsh vegetation

In the literature, materials like rubber, plastic, or foam are frequently used to replicate salt marsh vegetation stems (Lima et al., 2006; Augustin et al., 2009; Anderson and Smith, 2014; Markov et al., 2025). The associated tested surrogate properties, such as material density and Young's modulus, vary greatly, as summarized in Table 2.3. While some studies aim to replicate a specific vegetation species, others investigate the behavior of generalized and often idealized vegetation (Paul et al., 2016; Jacobsen et al., 2019; Keimer et al., 2021). Table 2.3 includes only the parameters reported in each study. Missing quantities (such as

E or EI , declared as n/a) were not calculated to maintain consistency with the data and comparisons originally presented by the authors.

Comparing natural and surrogate stems, stem diameters are usually straightforward, while approaches to achieve similitude regarding the flexural stiffness of the vegetation differ between studies. For example, Markov et al. (2025) noted the considerable natural variability of their target species (*S. alterniflora*) in terms of EI and the derived Ca reported in the literature. Consequently, they focused on testing surrogate stems representative of a specific region and/or season rather than attempting to capture the full variability of the species for physical experiments. As a verification, Markov et al. (2025) compared the stem movement of different surrogate materials under wave load to previous experimental observations with live vegetation. The most similar material (latex rubber tubing) was selected without finding an exact agreement regarding the stem's movement. While this methodology provides an approach to estimate the replication of the stem movement, it is unsuitable for vegetation that has not been previously tested in physical hydrodynamic experiments.

Alternatively, the similarity of the bending behavior between live vegetation and surrogate stems can be confirmed by comparing the flexural stiffness. Earlier research (Lima et al., 2006; Augustin et al., 2009) hypothesized the agreement of material properties between their surrogate and the target species without providing field measurements. Other studies have aimed at achieving similar stem diameters and Young's modulus for their surrogate stem compared to their target species (Anderson and Smith, 2014; Ozeren et al., 2014). Nevertheless, minor deviations in both parameters still led to a difference in the resulting flexural stiffness between live vegetation and the surrogate stem. Ozeren et al. (2014) argued that while the elasticity of their material differed from that observed in the field, the mass density is comparable. However, as discussed in the previous section, the objective should be to align the surrogate's material properties with those of the prototype to ensure, together with the hydrodynamic conditions, an accurate replication of all relevant fluid-vegetation interaction processes.

The study of van Veelen et al. (2020) aimed at generally replicating vegetation properties measured in a salt marsh in South Wales, including a variation of different species, and exposed them to hydrodynamic conditions in alignment with those measured in the field. While the properties of their surrogate material agree with the measurement range of the live vegetation, the authors did not accurately replicate all properties of one species. For example, the surrogate stem made of silicon sealants has a diameter of 5 mm, which is similar to the *in situ* measured stem diameter of *Aster tripolium* with 5.5 mm, but differs from the diameter of *Puccinellia maritima* ($d_s = 0.85$ mm). In contrast, their determined flexural stiffness for the surrogate stem with 1.7×10^{-11} Nmm² is similar to the one obtained for *P. maritima* with 1.9×10^{-11} Nmm² but not for the one of *A. tripolium* ($EI = 2.6 \times 10^{-8}$ Nmm²). In conclusion, the surrogate stems do not fully meet the requirements (similarity of plant dimensions, incoming wave dynamics, hydrodynamic impact on the waves by the vegetation, and plant swaying) set by van Veelen et al. (2020). While the study provides valuable insights into flexible and stiff fluid-vegetation interactions, the tested surrogates do not fully characterize an *in situ* measured salt marsh plant. Alternatively, Keimer et al. (2024) utilized 3D resin printing for their surrogate fabrication, including various flexibilities, to replicate *in situ* measured stem stiffness. They mixed two different flexible resins to achieve

Table 2.3. Summary of studies in the literature replicating salt marsh vegetation, with the stem density ρ_S , diameter d_S , width W_S , thickness T_S , the Young's modulus E , the flexural stiffness EI , and PE = Polyethylene, EPDM = Ethylene propylene diene monomer, ABS = acrylonitrile butadiene styrene, PVC = cylindrical polyvinyl chloride, XLPO = cross-linked polyolefin

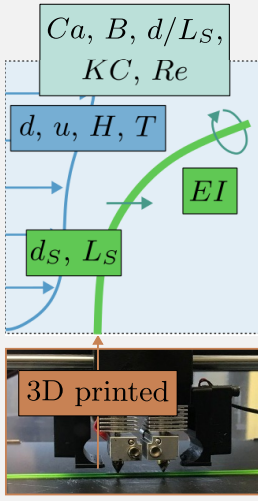
Study	Target species Surrogate material	Dimensions (mm)	ρ_S (kg/m ³)	E (MPa)	EI (Nmm ²)
Lima et al. (2006)	<i>Brachiaria subquadri-para</i> Braided nylon rope	n/a $d_S = 6$	n/a 681.4	n/a n/a	n/a n/a
Augustin et al. (2009)	<i>Spartina alterniflora</i> PE foam tubing	$d_S = 10$ $d_S = 12$	n/a 32	n/a 0.345*	n/a n/a
Anderson and Smith (2014)	<i>Spartina alterniflora</i> XLPO tubing	$d_S = 8, 4.5$ $d_S = 6.4$	n/a 1350	159.8, 1410 172.4	n/a
Ozeren et al. (2014)	<i>Spartina alterniflora</i> EPDM foam-rubber cords	n/a $d_S = 9.4$	n/a 368	100 - 10000 4	n/a
Baker et al. (2022)	<i>Spartina alterniflora</i> tygon tubing	$d_S = 8.7$ $d_S = 7.9$	n/a n/a	n/a 4.5 (90**)	n/a n/a
Markov et al. (2025)	<i>Spartina alterniflora</i> latex rubber tubing	$d_S = 4.47$ $d_S = 9.5$	n/a n/a	230 n/a	5.1×10^{-8} n/a
Blackmar et al. (2014)	<i>Schoenoplectus pungens</i> n/a	n/a $d_S = 1, 5$	n/a n/a	n/a n/a	n/a n/a
Wu and Cox (2016)	<i>Schoenoplectus pungens</i> Plastic strips (zip ties)	n/a $W_S = 5,$ $T_S = 1$	n/a n/a	n/a n/a	n/a n/a
van Veelen et al. (2020)	<i>Puccinellia maritima</i> <i>Aster tripolium</i> Silicon sealants	$d_S = 0.85$ $d_S = 5.5$ $d_S = 5.0$	n/a n/a 998	0.98 2343 0.56	1.9×10^{-11} 2.6×10^{-8} 1.7×10^{-11}
Keimer et al. (2024)	<i>Elymus</i> spp. flexible resin	$d_S = 1.63$ $d_S = 1.60$	n/a n/a	5364.2 8.6 - 1708.4	1447.9 2.72 - 549.6
Paul et al. (2016)	Plastic strips (Lexaan plates)	$W_S = 5.5,$ $T_S = 1, 2, 4$	1240	n/a	$1.4 \times 10^{-9},$ $9.0 \times 10^{-9},$ 6.6×10^{-8}
Jacobsen et al. (2019)	Polystyrene ABS	$W_S = 10.0,$ $T_S = 0.5$ $W_S = 8.0,$ $T_S = 1.6$	1030 1090	3300 2200	n/a n/a
Keimer et al. (2021)	PVC rods	$d_S = 3.00$	n/a	n/a	13.1

*tensile strength, **at full scale

six surrogates with varying flexibilities to provide a proof-of-concept for 3D-printed surrogate vegetation. However, while the 3D-printing allowed for an accurate replication of the stem diameter, the corresponding Young's moduli and thus flexural stiffness were lower than those measured in the field. Furthermore, the material properties of resin vary with environmental conditions, such as water saturation and light exposure (Mudhaffer et al., 2024), posing additional challenges compared to other surrogate materials.

Overall, replicating all relevant parameters describing the fluid-vegetation interaction in surrogate stems remains challenging. Novel fabrication techniques, such as 3D printing, should be considered to achieve biomechanical stem properties for a surrogate comparable to those measured *in situ* of salt marsh vegetation.

Concluding remarks of Section 2.2



- The replication of the fluid-structure interaction in physical experiments can be characterized and scaled by the non-dimensional parameters $Ca, B, d/L_S, KC$, or Re
- To achieve a comparable fluid-structure interaction without scaling, the hydrodynamic conditions (d and u or H, T), the stem's obstruction to the flow field (d_S and L_S), and its flexural stiffness (EI) need to be in alignment with the prototype
- Previous investigations with surrogate stems often failed to replicate all relevant processes due to differences in biomechanical stem properties, often EI , between model and prototype
- 3D printing is a promising approach for accurate replication of all relevant biomechanical stem properties

2.3 Numerical modeling of flexible vegetation stems

Accurately replicating the fluid-vegetation interaction numerically requires several model considerations. Figure 2.4 provides an overview of some of the relevant components, such as the fluid and structural solver, and choices for different coupling approaches involved in FSI simulations, aligning with the structure of this section.

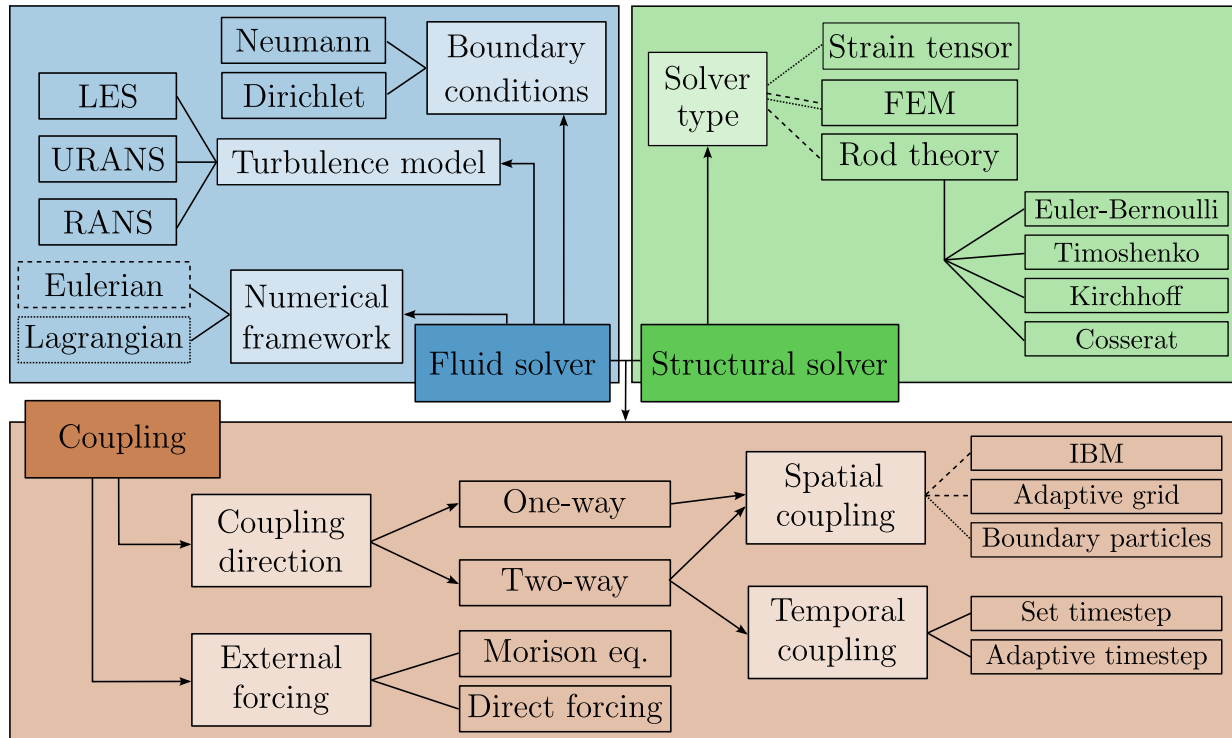


Figure 2.4. Overview of components and corresponding approaches required to achieve a coupled fluid-structure interaction involving slender and flexible bodies, with dashed lines indicating suitability with Eulerian, and dotted lines with Lagrangian fluid solvers and their corresponding coupling methods

2.3.1 Fluid solver

The simulation of the interaction between a fluid and flexible vegetation requires an accurate representation of the surrounding fluid domain. Most computational fluid dynamics (CFD) solvers can handle some aspects of FSI; however, modeling the interaction of a fluid with vegetation, which can be characterized as a slender and flexible body at the stem scale, requires specific model capabilities. O'Connor and Rogers (2021) emphasized that the fluid solver must accommodate free-surface flows and surface-piercing structures when emergent vegetation is investigated. Enabling the simulation of application scenarios, the model should also be computationally efficient and scalable, potentially through the use of the message passing interface (MPI) or other parallel computing architectures. The following section introduces the numerical treatment of the fluid flow, including the governing equations, turbulence modeling, and spatial discretization schemes applied in FSI studies of vegetated flows.

First, appropriate boundary conditions (BCs) must be defined for the computational domain to replicate either flume or field conditions in a numerical model. Here, an overview of the most relevant BCs is provided in Figure 2.5 to simulate unidirectional and oscillatory

flow conditions in hydraulic engineering. As indicated in Figure 2.5, numerical studies aiming to replicate physical hydrodynamic experiments commonly define one side of the domain as the inflow boundary, and the other side as the outflow. The remaining boundaries can be specified as either symmetry planes or solid walls. The flow velocity at the wall is enforced either through the grid discretization, with explicit representation of wall roughness, or via a wall law (e.g., logarithmic profile) that accounts for surface roughness in the first grid cell. At a wall boundary, the velocity can be prescribed using a slip or a no-slip BC, as visualized in Figure 2.5.

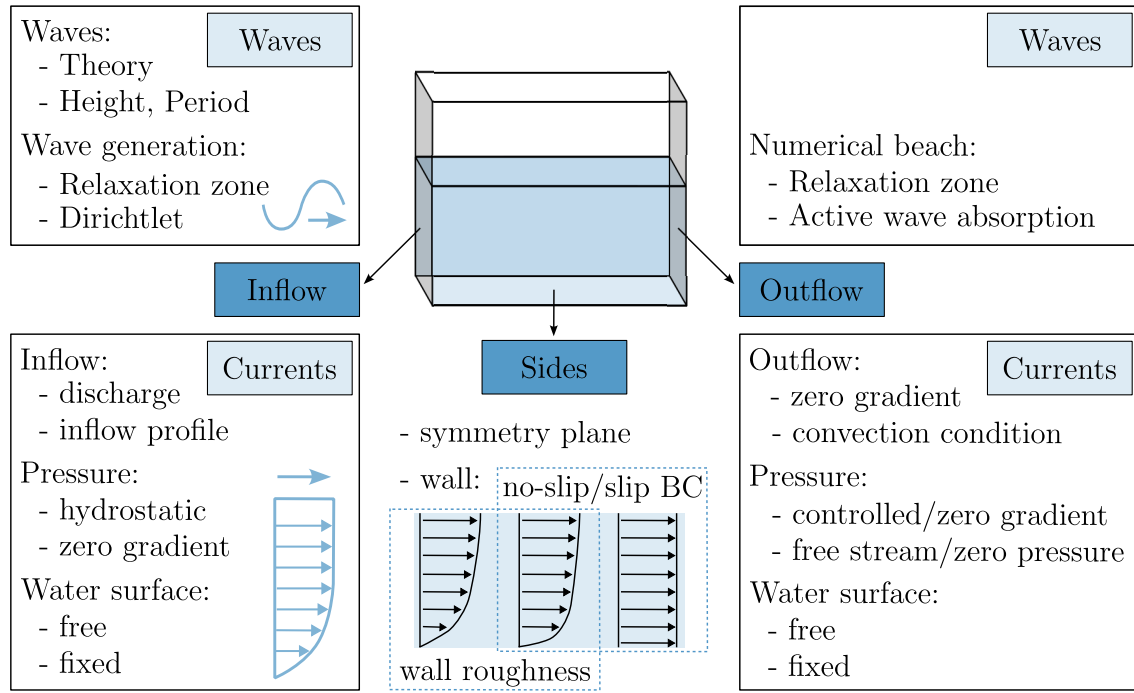


Figure 2.5. Definition sketch of boundary conditions (BC) for the numerical flume, for unidirectional and oscillatory flow conditions and configurations for the side of the flume

For the simulation of unidirectional flow with multiphase solvers, in hydrodynamic simulations usually involving the phases air and water, the pressure at the inflow can be defined using either a hydrostatic BC, which assumes a vertical pressure distribution in balance with gravity and is suitable for open-channel or free-surface flows, or a zero-gradient boundary condition, where no pressure variation is considered across the boundary. At the outflow boundary, a zero-gradient or convection condition allows the fluid and momentum to exit the domain naturally. Pressure at the outflow may also be defined as zero-gradient, enabling the pressure field to be governed by the interior solution, or as a zero-pressure BC, which sets the pressure to atmospheric and is appropriate for free-surface outflows (Ferziger et al., 2020). The water level at the outflow can be treated as either fixed or free at the in- and outflow, depending on whether a controlled or dynamically responsive boundary is desired.

Different methods of wave generation and absorption are elaborated and compared by Miquel et al. (2018) and Windt et al. (2018). Waves can be introduced into the domain using either a relaxation zone, in which the computed flow variables are gradually blended with the target wave solution to smoothly ramp up the wave motion, or a Dirichlet BC, where velocity and wave elevation are directly imposed. In multiphase simulations, the choice

of boundary conditions for velocity and pressure depends on the free-surface algorithm, as different approaches may require either a fixed velocity with zero-gradient pressure or vice versa. Several strategies can be employed at the outflow to prevent wave reflection and ensure numerical stability. One common method involves the implementation of a relaxation zone or numerical beach, where the solution is gradually blended with a predefined target state (e.g., still water), thus absorbing the outgoing wave energy smoothly. Another approach is the active wave absorption (AWA), in which the solver detects incoming wave energy near the boundary and calculates a reverse flow at the boundary condition to cancel the incoming wave.

The definition of suitable boundary conditions is closely tied to the governing equations of motion. For hydrodynamic applications, CFD solvers in hydraulic engineering are usually governed by the incompressible Navier–Stokes equations, which include the continuity Equation (2.7) and the incompressible momentum Equation (2.8), here provided in Einstein notation:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2.7)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + g_i. \quad (2.8)$$

In Equations (2.7) and (2.8), u_i represents the velocity vector in three dimensions (x, y, z), t denotes time, p the pressure, and ν the molecular kinematic viscosity of the fluid, which describes the ratio of the fluid's dynamic viscosity to its density and characterizes the diffusion of momentum within the fluid. The Navier–Stokes equations represent the conservation of mass and momentum for a Newtonian fluid and are capable of describing a wide range of free-surface and internal flow phenomena relevant to fluid–vegetation interaction. Despite their generality, the Navier–Stokes equations rely on continuum mechanics assumptions, neglecting molecular-scale effects, and require turbulence modeling when flow structures become smaller than the spatial resolution of the numerical grid. Direct numerical simulations (DNSs), which resolve the entire flow field down to all relevant turbulent length and time scales, require extremely fine spatial and temporal resolutions and therefore exceed the computational resources available for most practical applications (Ferziger et al., 2020). To reduce this computational demand, various approaches have been developed that modify the Navier–Stokes equations through averaging or filtering. These methods resolve only the larger, energy-containing flow structures while modeling the smaller, less energetic turbulent motions through approximations. The averaging or filtering process decomposes the velocity field into mean and fluctuating components, $u_i = \bar{u}_i + u'_i$, where $\bar{u}_i$ denotes the mean velocity and u'_i the fluctuating component. The influence of the unresolved fluctuations, introduced by this decomposition, must then be represented by additional terms in the Navier–Stokes equations, requiring suitable turbulence models to close the system of equations. The effect of the unresolved component of the fluctuating velocity on the mean flow is referred to as Reynolds stress ($\tau_{ij} = -\rho \overline{u'_i u'_j}$). Since the filtered product of the velocity is not equal to the product of the filtered velocities ($\overline{u_i u_j} \neq \bar{u}_i \bar{u}_j$), the Reynolds stress requires an alternative determination. The Reynolds stress can be quantified through the Boussinesq approximation, which assumes that the Reynolds stress can be associated with increased transport and dissipation due to viscosity, similar to the function of the molecular viscosity (Ferziger

et al., 2020). These turbulent effects can be summarized by the term eddy viscosity, which is approximated through turbulence models, depending on the utilized adaptation of the Navier-Stokes equations. The three most common options are detailed in Figure 2.6 with (b) large eddy simulations (LES), (c) unsteady Reynolds-averaged Navier-Stokes (URANS), and (d) Reynolds-averaged Navier-Stokes (RANS). Differences to the DNS solution are visualized by example of the flow variable f , with $\langle f \rangle$ as the conditionally averaged and $\bar{f}$ as the Reynolds-averaged value, each over the time t .

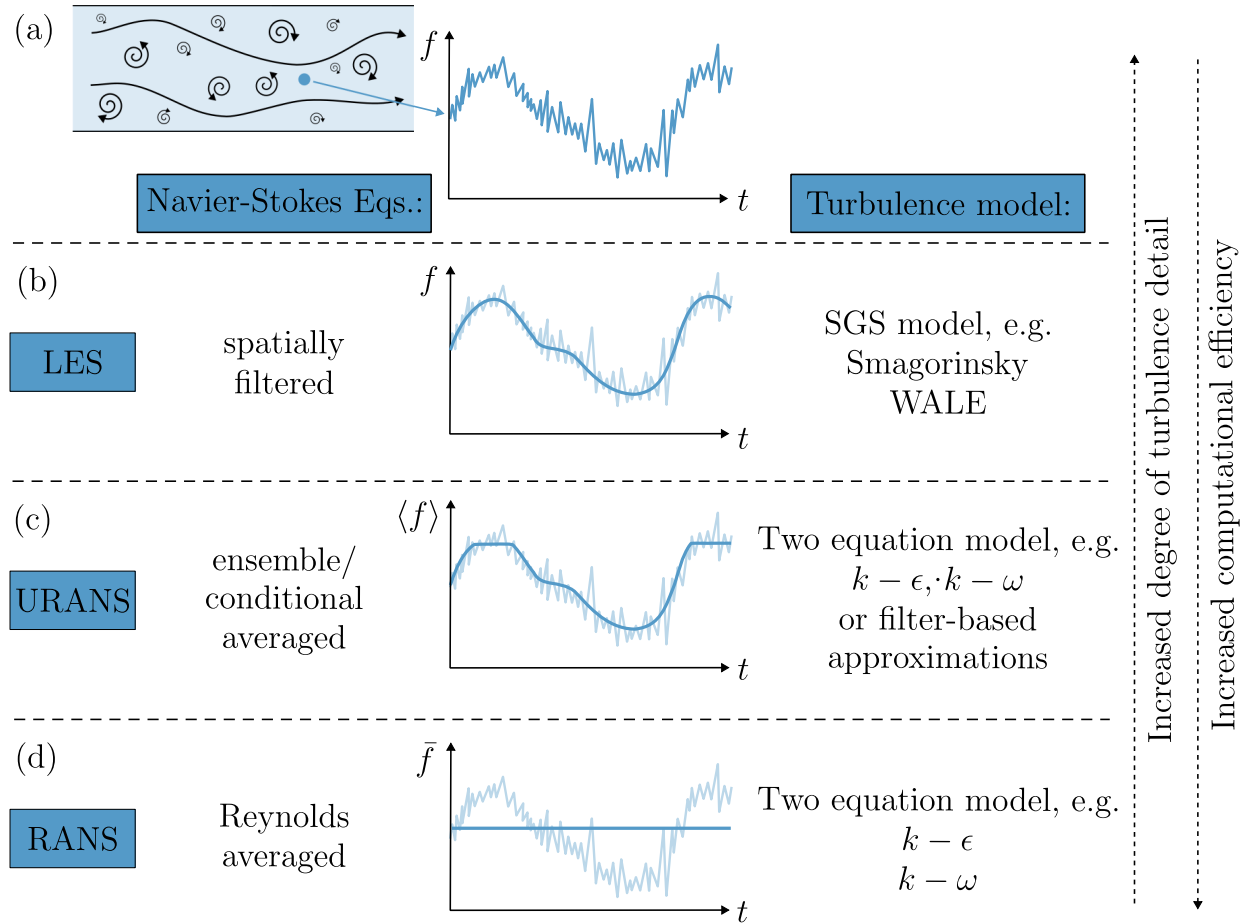


Figure 2.6. Numerical models to approximate turbulence with (a) overview of a flow field and fluctuations over time, (b) Large eddy simulations (LES), (c) unsteady Reynolds-averaged Navier-Stokes approach (URANS), and (d) Reynolds-averaged Navier-Stokes approach (RANS) and their respective commonly utilized turbulence models, where f denotes a flow variable, $\langle f \rangle$ its conditionally averaged and $\bar{f}$ its the Reynolds-averaged value and the time t (adapted and extended based on Chen and Jaw (1997); Ferziger et al. (2020))

Figure 2.6 highlights furthermore the increase in simplification of the turbulent flow field from LES to RANS, which is the result of a decreasing complexity of the applied turbulence approaches and thus leads to increasing computational efficiency. Which turbulence model is suitable for a problem depends on the complexity of the resulting flow field and the investigated scale (Ferziger et al., 2020).

Of the options shown in Figure 2.6, a solution closest to the flow field of a DNS simulation can be achieved with the LES approach. Here, a spatially filtered Navier-Stokes equation, commonly based on the cell size ($\Delta = \sqrt[3]{\partial x \partial y \partial z}$), can be used to resolve larger eddies in the

flow field and model turbulence smaller than the filter size. Due to the spatially dependent filtering process, the governing equations of the LES are never independent of the numerical grid (Ferziger et al., 2020). The influence of the unresolved scale on the flow field is expressed through the so-called subgrid scale (SGS) Reynolds stress $\tau_{ij}^s = -\rho(\overline{u_i u_j} - \bar{u}_i \bar{u}_j)$ (Ferziger et al., 2020). Correspondingly, the Boussinesq approximation in LES is only applied to the SGS (Ferziger et al., 2020) through

$$\tau_{ij} - \frac{1}{3}\tau_{kk}S_{ij} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) = 2\nu_t \bar{S}_{ij} \quad (2.9)$$

including the subgrid-scale stress $\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j$, τ_{kk} as the trace of Reynolds stress and S_{ij} as the strain-rate tensor. The eddy viscosity ν_t , added to the molecular kinematic viscosity in Equation (2.8) ($\nu + \nu_t$), can then be approximated with a subgrid-scale model as the subgrid-scale eddy viscosity. The subgrid-scale eddy viscosity can be modeled, for example, using the Smagorinsky model, which approximates it as $\nu_t = C_S^2 \Delta^2 |\bar{S}|$. Here, $|\bar{S}| = (\bar{S}_{ij} \bar{S}_{ij})^{\frac{1}{2}}$ represents the magnitude of the strain-rate tensor, which quantifies the rate of fluid deformation due to velocity gradients, and C_S is the Smagorinsky constant, typically taken as 0.20 (Smagorinsky, 1963; Ferziger et al., 2020). The Smagorinsky model has been further developed by Nicoud and Ducros (1999) to enhance its functionality in the proximity of walls. In contrast to the Smagorinsky model, which typically approaches zero near walls, the so-called wall-adapting local eddy-viscosity (WALE) model incorporates the rotational rate of the strain rate tensor.

Alternatively, the Navier-Stokes equations can be Reynolds-averaged, resulting in the representation of mean velocity terms in Equations (2.7) and (2.8), depicted in Figure 2.6 (d), and the modeling of the turbulent velocity component. Here, the Reynolds stress ($\overline{\rho u'_i u'_j}$) is determined throughout the flow field by the Boussinesq approximation

$$\tau_{ij} = -\overline{\rho u'_i u'_j} = 2\mu S_{ij} - \frac{2}{3}\rho k \delta_{ij} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3}\rho k \delta_{ij} \quad (2.10)$$

with k as the turbulent kinetic energy and δ_{ij} as the Kronecker delta. The eddy viscosity ν_t is then modeled with approximations, for example, through the k - ϵ or the k - ω model, whereas ϵ represents the dissipation rate of turbulence kinetic energy and ω the turbulent energy dissipation. Commonly referred to as two-equation models, small-scale turbulence effects of the flow field are expressed through the eddy viscosity ν_t . In the k - ω model, as detailed first by Wilcox (1998), ν_t is determined based on the ratio of the turbulent kinetic energy k and the specific dissipation rate ω . The parameters k and ω are described through two coupled transport equations:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_k \nu_t) \frac{\partial k}{\partial x_j} \right] \quad (2.11)$$

$$\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_t) \frac{\partial \omega}{\partial x_j} \right] \quad (2.12)$$

with model constants $\alpha = 0.553$, $\beta = 0.075$, $\beta^* = 0.09$, $\sigma_k = 2.0$, $\sigma_\omega = 2.0$ typically applied for the k - ω model (Versteeg and Malalasekera, 2007). Following the Boussinesq approximation, the production term P_k in Equations (2.11) and (2.12) is given by

$$P_k = \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}. \quad (2.13)$$

These equations describe the transport of turbulent kinetic energy k and its specific dissipation rate ω . The left-hand side represents the temporal and convective transport of turbulence, while the terms on the right-hand side account for its production, dissipation, and diffusion. The coupling between k and ω enables the model to capture local turbulence and length scales.

Figure 2.6 (d) highlights the stationary nature of the RANS approach. In the past, various solutions have been explored to extend the RANS equations for in-stationary flow properties, referred to as URANS (Nakayama and Miyashita, 2001; Celik et al., 2006; Ferziger et al., 2020). URANS approaches aim to represent unsteady trends in the flow field or coherent flow structures through adapted averaging of the Navier-Stokes equations, such as ensemble averaging, density-weighted averaging, or conditional averaging (Chen and Jaw, 1997). Ensemble averaging is a statistical approach used to separate the mean flow from random turbulent fluctuations, as illustrated in Figure 2.6 (c). However, it is discussed in the literature how well the ensemble-averaged flow field represents the actual turbulent conditions (Nakayama and Miyashita, 2001; Wyngaard, 2011; Ferziger et al., 2020). An alternative formulation of the RANS equations involves conditional averaging, as utilized by Johansen et al. (2004), which leads to a filter-based description of turbulence. In this approach, a spatial or temporal filter is applied to the Navier-Stokes equations, typically through the eddy viscosity term, so that turbulent motions smaller than the filter size are not explicitly resolved but instead modeled using established closures such as the k - ϵ or k - ω model. When the filter scale is chosen smaller than the characteristic length scales of conventional RANS models, the simulation can resolve a larger portion of the flow's unsteady structures, limited only by the turbulence closure, numerical discretization, and grid resolution.

The performance of any turbulence model depends not only on its formulation but also on how the governing equations are discretized in space. The choice between Eulerian, Lagrangian, or hybrid schemes determines how the fluid-structure interface can be represented and coupled to the motion of flexible vegetation. In this thesis, Lagrangian refers to a grid that moves with the simulated object, such as fluid particles or structural elements, as applied, for instance, in the studies by O'Connor and Rogers (2021) and El Rahi et al. (2023). In contrast, the Eulerian framework employs a fixed spatial grid through which the fluid flows and is commonly adopted in FSI simulations, for example by Tschisgale and Fröhlich (2020); Martin and Bihs (2021b); Agrawal et al. (2024) and Hagmeyer et al. (2024). Here, the fluid solver typically operates in the Eulerian domain, while the structure is represented in a Lagrangian framework. Mixed Eulerian-Lagrangian formulations are also possible, combining the advantages of both approaches for problems involving strong interactions between moving structures and the surrounding flow.

The turbulence characteristics of the resulting flow field can be described by different parameters. In unidirectional flow conditions, the turbulence intensity (TI) can be utilized, in oscillatory flow conditions, the turbulent kinetic energy (TKE) can then be determined for each phase of the oscillatory cycle as, and in both flow conditions, the enstrophy ($\mathcal{E}$), describing the intensity of rotational motion within the flow, can be determined (Saeedipour,

2023), as:

$$TI = \frac{\sqrt{\frac{1}{3} \overline{u'_i u'_i}}}{\bar{u}}, \quad TKE = \frac{1}{2} \overline{u'_i u'_i}, \quad \mathcal{E} = \frac{1}{2} \omega_{v,i} \omega_{v,i}, \quad (2.14)$$

where $(u'_i = u_i - \bar{u}_i)$ correspond to the fluctuating components of the velocity field, the mean horizontal velocity $(\bar{u})$ is used as the reference due to its dominance in the unidirectional flow, and the vorticity vector components $(\omega_{v,i})$ describe the velocity gradients of the flow field.

2.3.2 Structural solver

While the fluid solver captures the hydrodynamic forcing, an equally important component of the FSI is the structural response of the vegetation. The following section, therefore, focuses on structural modeling approaches, which provide a simplified yet physically consistent representation of flexible stems under unidirectional and oscillatory flow conditions. Structural solvers suitable for replicating vegetation often rely on established beam or rod theories (O'Reilly, 2017). Alternative modeling approaches, such as the 3D FEM solvers applied by El Rahi et al. (2023, 2024), are not further detailed here, but represent promising directions for future work aiming to capture three-dimensional structural responses in greater detail. Alessi et al. (2024) identified four of the most common rod theories and their respective motion regimes, illustrated in Figure 2.7. The most simplistic model is known as the Euler-Bernoulli theory, which only represents structural bending (Figure 2.7 (a)). The Euler-Bernoulli beam can be extended to the Timoshenko theory, shown in Figure 2.7 (c), which includes shearing and bending. Alternatively, the Kirchhoff model (Figure 2.7 (b)) accounts for bending and twisting motion. The most complex model is the Cosserat rod theory, depicted in Figure 2.7 (d), which captures bending, shearing, twisting, and stretching.

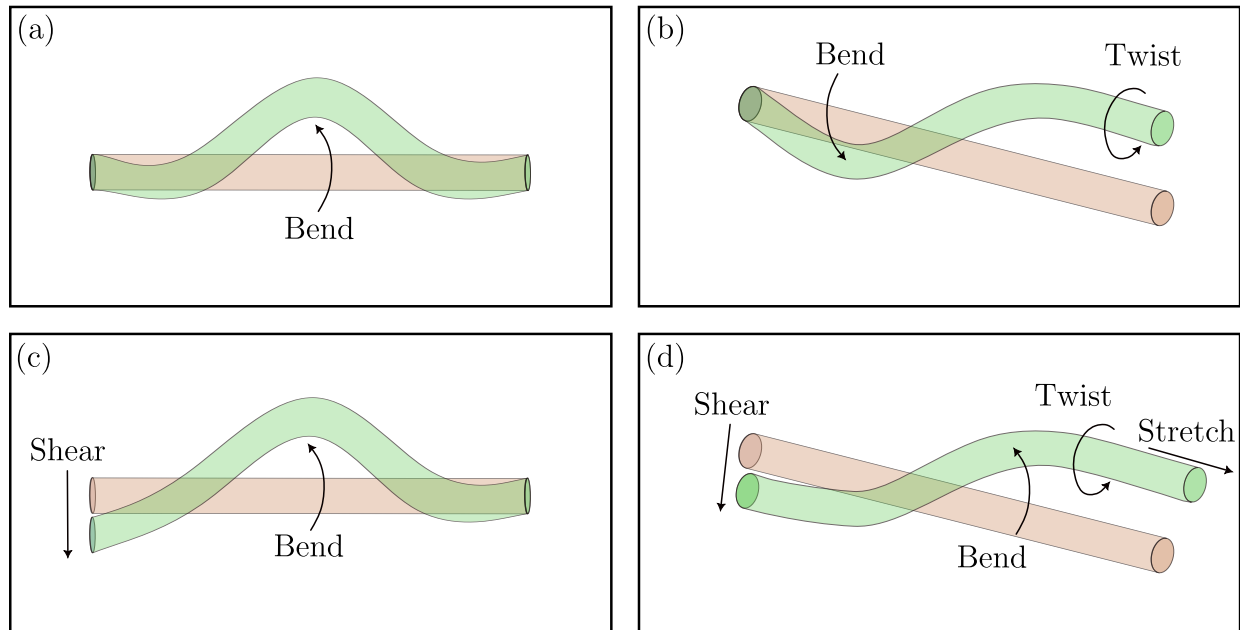


Figure 2.7. Comparison of different rod theories with (a) the Euler-Bernoulli rod theory, (b) the Kirchhoff rod theory, (c) the Timoshenko-Ehrenfest rod theory, and (d) the Cosserat rod theory, adapted from Alessi et al. (2024)

The Euler-Bernoulli rod theory, as depicted in Figure 2.7 (a) and described by Timošenko (1983), accounts only for bending around one axis. It is assumed that the rod's slope angle equals the tangent angle of the backbone curve. For the linear Euler-Bernoulli model, a rod in the x-y plane can be described by the displacement $\omega_B(x, t) \in \mathbb{R}$ from the x-axis. The slope angle $\alpha_B(x, t) \in \mathbb{R}$ of the beam can then be written as

$$\alpha_B(x, t) = \frac{\partial \omega_B}{\partial x}, \quad (2.15)$$

and minimizing the strain energy yields the equation of motion for the rod

$$EI = \frac{\partial^4 \omega_B(x, t)}{\partial x^4} + \rho_S A \frac{\partial^2 \omega_B(x, t)}{\partial t^2} = M_{\text{ext}, z}(x, t), \quad (2.16)$$

where $M_{\text{ext}, z}(x, t)$ is the distributed external moment around the z-axis. Equation (2.16) incorporates material properties, such as E , I , ρ_S , and the frontal area exposed to the flow A . Equation (2.16) assumes a constitutive law for the bending moment $M_z(x, t)$ as

$$M_z = EI_z \frac{\partial^2 \omega_B}{\partial x^2}, \quad (2.17)$$

where $M_z \in \mathbb{R}$ is the z -component of the internal moment M_{int} . In the literature, an inextensible, nonlinear Euler-Bernoulli beam has been applied by He et al. (2022) to model a meadow with flexible vegetation stems, with stem bending limited to the streamwise-vertical plane. Alternatively, Kim et al. (2024) applied the Euler-Bernoulli beam for a finite-element structural solver to study the flow dynamics of a vegetation patch.

The Timoshenko-Ehrenfest rod theory (Timošenko and Goodier, 1951) extends the Euler-Bernoulli theory by allowing for shear deformations. This extension, visualized in Figure 2.7 (c), treats the tangent angle and the cross-section angle as independent variables, meaning $\alpha_B(x) \neq \partial \omega_B / \partial x$. Consequently, the equations of motion need to include $\alpha_B(x, t)$ as a separate variable. However, applications of the theory to model flexible vegetation stems are not yet traceable in the literature.

The two geometrically exact Cosserat rod equations, with a corresponding stem illustrated in Figure 2.7 (d), describe a broad range of motion. The model has been introduced by Cosserat and Cosserat (1896) and is here described based on its application by Tschisgale and Fröhlich (2020) with Equations (2.18) and (2.19). Equation (2.18) entails the translational motion of the rod's distance vector $r(X, t)$ by computing the centerline acceleration for each Lagrangian coordinate $X \in [0; L_S]$, while Equation (2.19) governs the rod's rotational motion.

$$\rho_s A \frac{\partial^2 r_i}{\partial t^2} = \frac{\partial F_{\text{int}, i}}{\partial X} + F_{\text{ext}, i} \quad (2.18)$$

$$\rho_s I_i \frac{\partial \omega_{S, i}}{\partial t} + \omega_{S, i} \times \rho_s I_i \omega_{S, i} = \frac{\partial M_{\text{int}, i}}{\partial X} + \frac{\partial r_i}{\partial X} \times F_{\text{int}, i} + M_{\text{ext}, i} \quad (2.19)$$

In Equations (2.18) and (2.19), ω_S represents the rods angular velocity, $F_{\text{int}, i}$ and $F_{\text{ext}, i}$ are internal and external forces, $M_{\text{int}, i}$ and $M_{\text{ext}, i}$ are internal and external moments, respectively. Assuming a Kelvin-Voigt type material, which represents a viscoelastic solid in which an elastic spring and a viscous damper are connected in parallel (Keshavarz et al.,

2021), the internal force $F_{\text{int},i}$ and internal moment $M_{\text{int},i}$ are determined based on material characteristics, such as A , E , and I and include contributions from both elasticity and internal friction, described by the translational damping coefficient c_t and the rotational damping coefficient c_k (Martin and Bihs, 2021b; Tschisgale and Fröhlich, 2020). The Cosserat rod theory, studied extensively in theoretical mechanics (Cao and Tucker, 2008; Lang et al., 2011; Jung et al., 2011), has been applied to various fields, such as robotics, for modeling cables or actuators (Rucker and Webster III, 2011; Renda et al., 2014; Till et al., 2019). In the context of flexible vegetation, both Tschisgale and Fröhlich (2020) and Agrawal et al. (2024) employed the geometrically exact Cosserat rod successfully.

The Kirchhoff rod theory (Love, 1906) is related to the Cosserat model but assumes an unstretchable, unshearable rod, as illustrated in Figure 2.7 (b). This theory introduces a directed curve with a unique reference system at each cross-section, enforcing an unstretchable and unshearable constraint as $\sigma_S = [1, 0, 0]^T$ and is considered particularly well-suited for FSI problems involving bending around any axis and twisting (Meier et al., 2019; Alessi et al., 2024). While the Kirchhoff rod theory has not yet been utilized to model fluid-vegetation interaction, it is considered promising, since bending and twisting can be regarded as the dominating processes in fluid-vegetation interaction. In addition, this approach features increased numerical stability (Meier et al., 2019). For example, Hassani et al. (2017) simulated flexible elements under wind and gravity influence based on the Kirchhoff rod theory.

In summary, different beam theories are utilized in the literature to model the fluid-vegetation interaction. The choice of the structural solver depends on the required complexity of the motion and the computational efficiency requirements of the FSI application.

2.3.3 Forcing and coupling considerations

With both the fluid and structural solvers defined, the coupling between the two separate solvers determines how hydrodynamic forces are transferred and how structural motion feeds back to the flow field. The following section elaborates on how these interactions are represented, ranging from empirical force formulations to direct numerical coupling approaches. Complex beam theories, such as the previously introduced Kirchhoff or Cosserat rod theory, utilize external forces and moments to describe the vegetation's motion. The forces exerted by a fluid on vegetation can be either modeled through semi-empirical or direct forcing approaches, compared in Figure 2.8. In Figure 2.8 (a), a fictional rod is illustrated, which represents a vegetation stem and can be modeled with either approach. The semi-empirical approach is shown based on the notation of Martin and Bihs (2021b), see Figure 2.8 (b). The direct forcing approach is demonstrated based on the notation utilized by Tschisgale and Fröhlich (2020) and depicted in Figure 2.8 (c).

In Figure 2.8 (b), semi-empirical formulations are utilized to establish a force balance, including forces such as drag, inertia, and gravity. Semi-empirical methods commonly follow the assumptions of Morison et al. (1950) for hydrodynamic transparent structures, defining the total force as the sum of hydrodynamic and static components. The hydrodynamic forces include drag and inertia acting along the structure's centerline (Martin and Bihs, 2021b), while the static component accounts for gravitational or buoyancy effects on the structure. Examples of the utilization of such a semi-empirical approach in the literature for flexible vegetation are illustrated by Dijkstra and Uittenbogaard (2010); Mullarney and

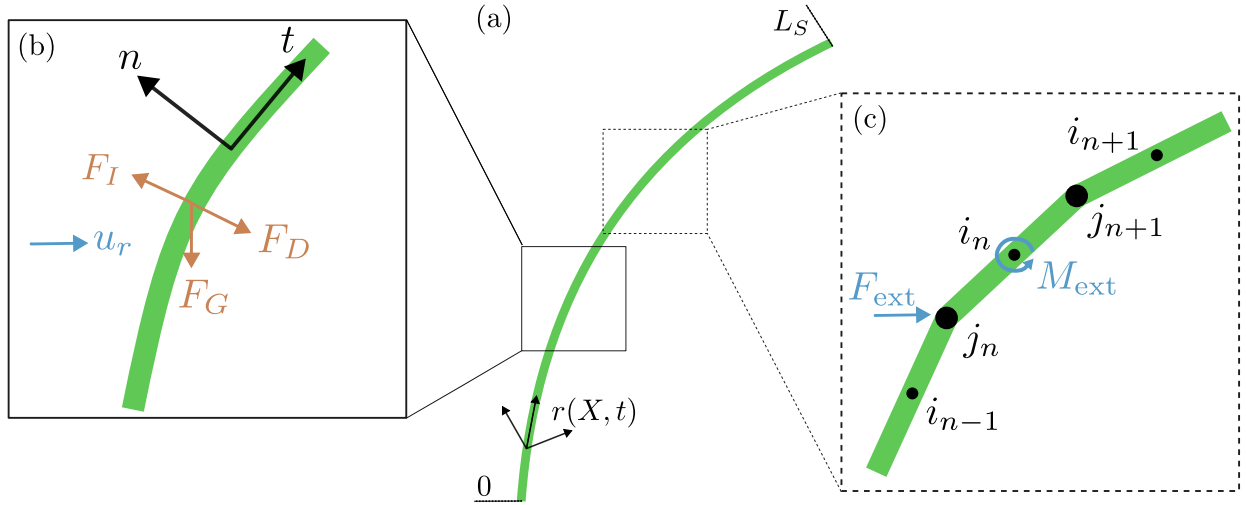


Figure 2.8. Comparison of different forcing approaches for a slender and flexible body (a) with (b) detailing the force balance of semi-empirical formulations and (c) external forces and moments utilized in direct forcing approaches, with i as the element center points and j as the nodes between the adjoining elements, adapted from Zhu et al. (2020a); Martin and Bihs (2021b); Tschisgale and Fröhlich (2020)

Henderson (2010); Maza et al. (2013) and Jin and Zhang (2022). The specific formulations in the force balance vary across the applied numerical models, depending on model complexity, for example, with the incorporation of skin friction (Dijkstra and Uittenbogaard, 2010; Zhu et al., 2020a). In Figure 2.8 (c), the forces, determined by the local velocity or pressure fields, are transferred from the fluid to the structural solver. Examples of direct forcing approaches for the simulation of fluid-vegetation interaction include works by Tschisgale and Fröhlich (2020); Agrawal et al. (2024); Hagmeyer et al. (2024).

The primary force balance using the Morison equation is illustrated in Figure 2.8 (b), where F_I , F_D , and F_G represent the inertia force, drag force, and gravitational force, respectively. At each time step, the force exerted by the fluid on the stem is determined based on the relative velocity. In Figure 2.8 (b), arrows labeled n and t indicate the normal and tangential directions, serving as reference directions for calculating the force balance. The arrow labeled u_r indicates the relative velocity between the structure and the surrounding fluid, utilized to calculate the drag force. The static gravitational and buoyancy forces are calculated assuming an equally distributed mass per unit length:

$$F_{G,i} = \rho_S A g_i \cdot \frac{\rho_S - \rho}{\rho_S}. \quad (2.20)$$

Here, g_i is the gravitational acceleration vector, typically oriented in the negative z -direction. The inertia forces can be calculated as follows (Martin and Bihs, 2021a), differentiated by normal and tangential direction:

$$F_{I,i} = \rho A \cdot \left[a_{f,i} + C_{M,t} (a_{r,i} \cdot n_i) n_i + C_{M,n} \left(\frac{\partial^2 r_i}{\partial t^2} - (a_{r,i} n_i) n_i \right) \right]. \quad (2.21)$$

In Equation (2.21), $a_{f,i}$ denotes the fluid acceleration, $a_{r,i}$ represents the relative acceleration between the fluid and the structure, n_i denotes the unit normal vectors along $r(X)$. C_M corresponds to the added mass coefficients in the normal and tangential directions. The

added mass coefficients $C_{M,t}$ and $C_{M,n}$ can be, for example following Palm et al. (2017), set equal to 3.8 and 0, respectively. The velocity-dependent drag forces can then be calculated as follows (Martin and Bihs, 2021b):

$$F_{D,i} = \frac{1}{2} \rho d_S \cdot \left[C_{D,t} (u_{r,i} \cdot n_i) |u_{r,i} \cdot n_i| \cdot n_i + C_{D,n} (u_{r,i} - (u_{r,i} \cdot n_i) n_i) |u_{r,i} - (u_{r,i} \cdot n_i) n_i| \right]. \quad (2.22)$$

In Equation (2.22), $C_{D,n}$ and $C_{D,t}$ are the drag coefficients in the normal and tangential directions. The Morison equation (2.22) includes specific values for the drag coefficient (C_D), which are often correlated with the Reynolds number Re (cf. Equation (2.5)). The dependency of C_D on Re has been previously investigated for vegetation stems by Losada et al. (2016) and van Veelen et al. (2020), among others, however, usually without considering structural flexibility. While Whittaker et al. (2015) incorporated stem flexibility in calculating the drag force, the lack of comprehensive empirical C_D values specific to plant species and their seasonal variability (e.g., Keimer et al. (2023b, 2024)) poses challenges for accurate numerical representation. Consequently, the assumption of a uniform drag coefficient describing different vegetation species, including their geographical and seasonal variability, may oversimplify the system and limit model reliability (van Veelen et al., 2020; Caroppi and Järvelä, 2022). Thus, simplified semi-empirical methods relying on coefficients like C_D may not accurately simulate FSI with flexible vegetation stems. Addressing the variability of flexible vegetation with drag coefficients would require extensive field and laboratory data collection, covering different vegetation species, stem-leaf configurations, seasonal factors, and biomechanical variability within a stem. Alternatively, forcing approaches, where exerted forces, flow velocities, or pressures are transferred directly from the fluid to the structural solver, offer potentially better accuracy by eliminating empirical coefficients. However, such approaches are numerically complex and require robust coupling of the fluid and structure solvers. An example of direct forcing implementation is shown in Figure 2.8 (c), based on the utilization of Tschisgale and Fröhlich (2020). Their flexible stem model consists of multiple rigid elements, each subjected to external force and corresponding external moment, calculated based on the local velocity field. The external force $F_{\text{ext},i}$ combines the gravitational force ($F_{G,i} = (\rho_s - \rho) A g_i$) and the coupling force $F_{\Gamma,i}$ from the fluid-structure boundary. Appropriate coupling approaches are detailed in the following.

Generally, numerical models simulating flexible structures in varying hydrodynamic conditions can be either one-way coupled, where only the impact of the fluid on the structure is considered, as employed by Luhar and Nepf (2016), or two-way coupled, allowing the structure to influence the surrounding flow field, as implemented by Tschisgale and Fröhlich (2020) or Agrawal et al. (2024) for flexible vegetation (cf. Figure 2.4). One-way coupled FSI models require a time discretization to advance in time, such as a third-order Runge-Kutta scheme (Martin and Bihs, 2021b). Two-way coupled approaches require further temporal coupling since both the fluid and the structural solver influence the interface velocity and are dependent on each other. In the application presented by Tschisgale and Fröhlich (2020), the temporal coupling of the interaction force $F_{\Gamma,i}$ is realized using a five-stage implicit Runge-Kutta scheme. First, a preliminary velocity field is computed for the upcoming time step. This velocity is then transferred to the structural solver (second step), which calculates the corresponding structural response. In the third step, the interface velocity for the next

numerical time step is obtained for each element based on the coupling force $F_{T,i}$. To improve computational efficiency, the fluid velocity field is replaced by the integral quantities, thereby reducing the communication between solvers to six points per rod element. In the fourth step, the coupling force at the current time level is updated from the difference between the preliminary and corrected velocities. Finally, in the fifth step, the velocity field for the next time level is advanced using the resulting coupling force. Further information, including the analogous computation of external moments, can be found in Tschisgale and Fröhlich (2020). Considering the amount of calculations required for each time step, computational efficiency can be increased by utilizing adaptive time-stepping approaches, such as those proposed by Mayr et al. (2018). Their temporal coupling considers the flow field, the structure, and the fluid-structure interface for an error estimation to determine suitable time step intervals.

Most commonly, FSI modeling that includes structural flexibility employs an Eulerian approach for the fluid solver and a Lagrangian approach for the structural solver. To achieve coupling between these, the Eulerian grid must communicate with the Lagrangian grid of the structural solver in a one-way coupling, and vice versa for a two-way coupling. Alternatively, both fluid and structural solvers can follow a Lagrangian approach. Selected applications of such spatial coupling are illustrated in Figure 2.9.

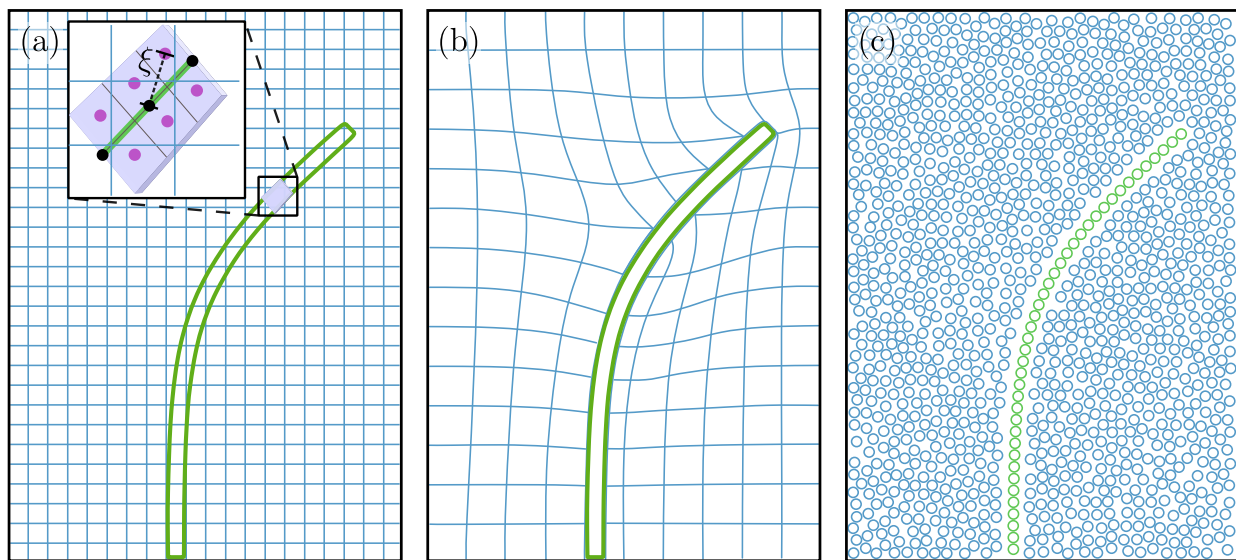


Figure 2.9. Comparison of different spatial coupling approaches for FSI modeling, including (a) the immersed boundary method (IBM), (b) an adaptive grid, and (c) smoothed-particle hydrodynamics (SPH) approach, adapted after Döllinger et al. (2023)

The IBM has emerged as a versatile approach for modeling interactions between fluid flow and flexible or moving structures. It is increasingly popular to achieve the spatial coupling of FSI (Tschisgale and Fröhlich, 2020; Agrawal et al., 2024), illustrated in Figure 2.9 (a). In this framework, each component of the FSI problem retains its own computational grid, while the interface at which flow properties are exchanged is defined as the immersed boundary. The key idea of the IBM is to represent the structural surface implicitly within the fluid grid, allowing forces to be communicated between the fluid and the structure without requiring the grids to conform. As shown in the zoom box of Figure 2.9 (a), the three-dimensional immersed boundary can be locally approximated by a 1D beam representation. The coupling between fluid and structure is typically achieved by introducing a coupling or boundary force

term into the Navier–Stokes equations, which enforces the no-slip condition at the immersed interface. For a detailed introduction to the IBM, the interested reader is referred to Roy et al. (2020). An example implementation employing the IBM is described in the work of Tschisgale and Fröhlich (2020). The authors use the Eulerian coordinates for the fluid solver (x -, y -, and z -directions) and the Lagrangian coordinates (X) for the structural solver. Flexibility is achieved by dividing the structure into rigid elements (cf. Figure 2.8 (c)). Such an element is depicted in Figure 2.9 (a) with a gray block. The spatial coupling of f_Γ accounts for the differences between the immersed boundary’s 3D shape and the 1D Cosserat rod, linking Lagrangian marker points to Eulerian grid cells via regularized delta functions. Each marker point represents a Lagrangian volume, which should be equal to or smaller than the Eulerian fluid cell to maintain the impermeability of the structural solver. The vector ξ , indicated by the dotted line in Figure 2.9 (a), determines the distance of the Lagrangian points to each element’s center. Recent IBM applications for the simulation of flexible vegetation stems are detailed by Tian et al. (2014), Tschisgale and Fröhlich (2020), Wang et al. (2020), He et al. (2022), Wang et al. (2022), Ni et al. (2023), Kim et al. (2024), Hagmeyer et al. (2024), Wei et al. (2024), and Agrawal et al. (2024). The IBM accommodates large deformations of the structural solver using an Eulerian grid for fluid stability, and its extensive literature application highlights its promising accuracy for fluid-vegetation interaction studies.

Alternatively, a body-fitted mesh can facilitate communication between the fluid and the vegetation stem, as visualized by way of example in Figure 2.9 (b). Using methods like arbitrary Lagrangian-Eulerian (ALE), which ensure a strong coupling, allows the Lagrangian structure to integrate with the Navier-Stokes equations in ALE coordinates, such that the ALE reference configuration aligns with the Lagrangian structural configuration (Richter, 2017). A recent body-fitted grid implementation by Chourdakis et al. (2023) identified issues in OpenFOAM simulations, where mesh deformations led to distorted cells, requiring advanced mesh motion techniques. Accordingly, deformation constraints can limit body-fitted meshes, requiring high computational power for re-meshing during significant structural deformations. Nevertheless, if re-meshing is numerically stable and fast, it can assure strong coupling between the fluid and the structure (Chourdakis et al., 2023).

A third coupling method utilizes the fluid and structural solvers within a Lagrangian model, as shown in Figure 2.9 (c). DualSPHysics is a commonly used SPH model, demonstrated for its FSI by O’Connor and Rogers (2021). Alternatively, El Rahi et al. (2023) proposed recently the coupling of a Lagrangian fluid model in DualSPHysics with an external finite element method (FEM) solver to replicate flexible vegetation dynamics. Generally, SPH approaches eliminate the need for communication boundaries in Eulerian grids and previously described grid deformation challenges. However, slender body simulations remain computationally demanding as a small particle size across the domain is required, increasing simulation expense. Research on variable particle sizes across domains is ongoing and anticipated to become standard practice (Sun et al., 2018; Ricci et al., 2025), rendering SPH approaches promising for future FSI applications.

Together, these methods form the numerical framework for simulating FSI in vegetated coastal environments. However, challenges remain in capturing the combined effects of turbulence, vegetation flexibility, and wave-induced unsteadiness at realistic scales. To date, few numerical models offer a strongly coupled fluid–structure interaction approach

capable of reproducing the range of motion resulting from the variability in flow velocity and stiffness observed in submerged flexible vegetation. In the literature, prospective FSI solvers have often been validated for either unidirectional (Tschisgale and Fröhlich, 2020; He et al., 2022) or oscillatory flow conditions (El Rahi et al., 2023; Wei et al., 2024). However, both hydrodynamic regimes are considered relevant for the coastal environment and only a few studies, for example Jin and Zhang (2022) and Agrawal et al. (2024), tested their solver in unidirectional and oscillatory flow conditions. Furthermore, the validated range of material parameters in previous studies is often limited to conclude their applicability to *in situ* measured live vegetation properties. For example, Jin and Zhang (2022) and El Rahi et al. (2023) validated their model in oscillatory flow conditions only based on the stiffer material of the experimental campaign by Luhar and Nepf (2016). Wei et al. (2024) mimicked highly flexible vegetation, thus simulating relatively large deformations through a truss-spring model to represent the vegetation stem. Unfortunately, the application to salt marsh vegetation might be eliminated as their utilized critical time step size of the structural solver is related to the Young's modulus of the stem, leading to a decreased efficiency for more stiff vegetation species, including typical salt marsh vegetation.

It can be summarized that two-way coupled FSI solvers are, to date, either limited by their applicable hydrodynamic or structural property range. Moreover, previous numerical models have seldom accounted for the seasonal dynamics of vegetation. These limitations motivate the modeling approach adopted in this thesis. Therefore, alternative FSI solvers, able to replicate the expected property range in live vegetation, such as sea grass or salt marsh, and hydrodynamic conditions they are facing, such as unidirectional and oscillatory flow, need to be validated, allowing for future investigations and the incorporation of *in situ* measured biomechanical stem properties.

Concluding remarks of Section 2.2

Structural solver

Fluid solver

Coupling

Coupling
direction

One-way

Two-way

External
forcing

Morison eq.

Direct forcing

Structural solver:

→ Different rod theories governing the motion of the structural solver are applicable depending on the desired complexity and expected range of movement

Fluid solver:

→ Modeling choices, such as turbulence model and boundary conditions, are required to represent the flow field appropriately

Coupling considerations:

→ The fluid-structure interaction can be either one- or two-way coupled

→ Forcing of the fluid to the structure can be either achieved through semi-empirical approaches, such as the Morison equation, or direct forcing

→ Temporal and spatial coupling depend on the utilized solvers and the desired complexity of the fluid-structure interaction

2.4 Research Needs

The literature review highlights that salt marshes provide valuable ecosystem services, such as wave attenuation, erosion resistance, and sediment deposition, which can support coastal protection strategies. However, reliable quantification of these services requires accounting for regional and seasonal variability in live vegetation. In particular, incorporating variation in plant flexibility, often neglected in both physical and numerical models, is essential to avoid under- or overestimating these ecosystem services. Additionally, flow field modifications at the stem level, which are expected to influence sediment dynamics in the proximity of the stems, remain underexplored. Therefore, investigating the influence of regional and seasonal variation in stem properties on fluid–vegetation interactions is considered crucial, yet remains underexplored in the literature.

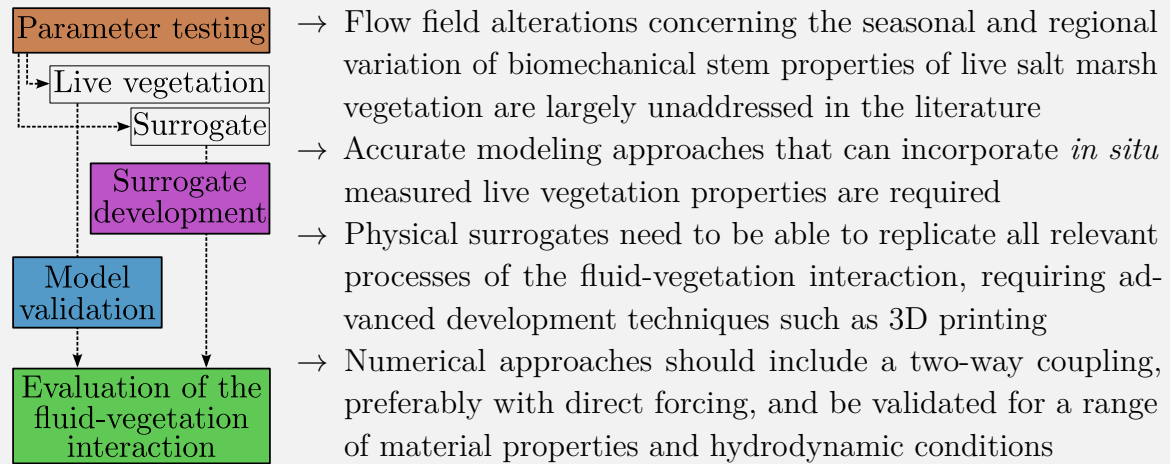
Salt marshes cover extensive areas of coastlines in temperate climates and are increasingly recognized as NbS for mitigating climate change–induced sea level changes. To illustrate the broader question of regional transferability of insights regarding the fluid–vegetation interaction in salt marshes, this study compares biomechanical stem properties in Canadian and European salt marshes as an example. Projected climate changes threaten salt marsh ecosystems in both regions, reinforcing the need for modeling approaches that integrate field data and account for regional and seasonal variability.

Previous studies using generalized or idealized vegetation in physical hydrodynamic experiments are limited in their applicability to specific salt marshes and related coastal protection strategies. In particular, the influence of seasonal and regional variation in stem properties on ecosystem services remains largely unaddressed, highlighting the need for more accurate modeling approaches. Accurately replicating *in situ* vegetation properties in physical experiments is crucial to bridge the gap between conceptual studies and practical coastal protection applications. Surrogate stems used in earlier studies often fail to capture key characteristics such as flexural stiffness or buoyancy, emphasizing the need for a structured approach to develop surrogates based on *in situ* measurements of biomechanical stem properties, confirmed by statistical similarity evaluation. Advances in flexible 3D printing now allow fabrication of stems with adjustable material properties, enabling replication of different salt marsh species and their biomechanical characteristics. Such surrogates can be used to investigate fluid–vegetation interactions, including stem-induced turbulence, under both unidirectional and oscillatory flow conditions typical of coastal environments, providing a more realistic experimental basis for future studies.

Last, gaining further insights into fluid–vegetation interactions requires numerical tools capable of replicating the motion of flexible vegetation. Models relying on empirical coefficients to calculate external forces are rendered as less suitable, as they cannot directly incorporate measured field data; thus, direct coupling of the forces for the FSI is preferred. Previous numerical models have often not been validated for both flow regimes relevant at the coast, unidirectional and oscillatory, and rarely account for seasonal variations in vegetation, leaving values of C_D for different species and seasons unavailable. Accurately assessing climate change impacts on salt marshes thus requires predictive models that integrate *in situ* vegetation properties rather than simplified approximations. In this thesis, a FSI tool is applied to incorporate measured stem properties and investigate fluid–vegetation interactions and derived drag forces. The model should be validated against physical experiments under both unidirectional and oscillatory flow, ensuring a realistic simulation of stem motion and

fluid forces. Resulting seasonal drag coefficients can then provide crucial input for further numerical models and future studies.

Concluding remarks of Section 2.4



This chapter summarizes the studies forming the core of this cumulative thesis, highlighting how their combined outcomes address the research objectives of the thesis.

3.1 Physical modeling of 3D-printed flexible stems

This section summarizes the study submitted as:

Study 1

Prüter, Inga, Visscher, Jan, Lojek, Oliver, Schürenkamp, David, Nistor, Ioan, Goseberg, Nils: Flexible 3D-printed models of salt marsh vegetation to investigate unidirectional and oscillatory flow dynamics, *under review* in: Physics of Fluids.

3.1.1 Motivation and Objectives

The assessment of ecosystem services of salt marsh vegetation requires accurate replication of their biomechanical properties, for example, with surrogate stems in flume experiments. Advanced surrogate stems should entail the representation of different salt marsh species in physical hydrodynamic experiments. Quantifying the FSI through particle image velocimetry (PIV) measurements in physical hydrodynamic experiments enables the determination of the extent of stem-induced flow field alterations, differentiating between salt marsh species and their seasonal variation in stem properties. In summary, the following research objectives are addressed in this study:

- To develop a method for distinguishing stem-induced flow field alterations from the surrounding flow field.
- To investigate how stem-induced flow field alterations vary with material characteristics under unidirectional and oscillatory flow conditions.
- To evaluate the extent to which 3D printing with flexible filament can replicate *in situ* measured properties of live vegetation.

3.1.2 Material and Methods

Based on the versatility of 3D printing, this study employs flexible filaments to replicate biomechanical stem properties measured *in situ*. The similarity of the biomechanical properties of the surrogates with those measured *in situ* of live vegetation is determined through statistical evaluation. The stems are then tested in unidirectional and oscillatory flow conditions to investigate the near-stem alteration of the surrounding flow field, as

depicted in Figure 3.1. Based on PIV measurements, flow field properties such as the velocity magnitude $\langle |\mathbf{u}| \rangle$, turbulence intensity TI , and enstrophy $\mathcal{E}$ are derived, enabling the investigation of the stems' influence on their surrounding flow field.

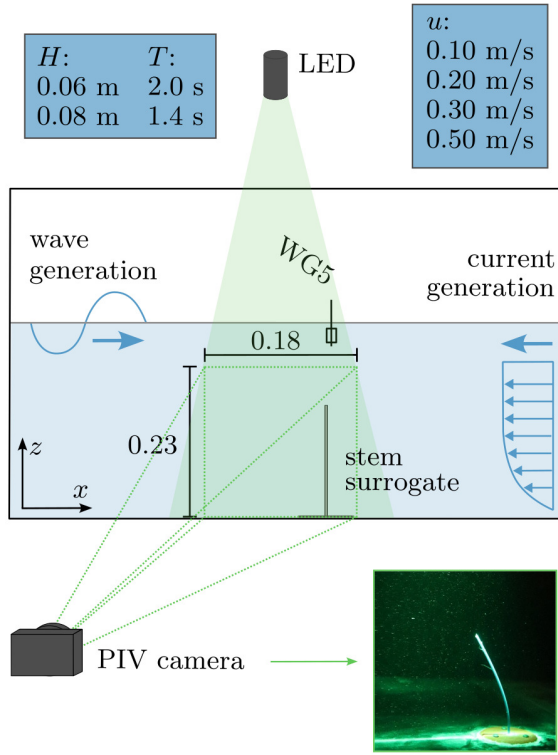


Figure 3.1. Sketch of the wave flume including the location of the stem surrogate, of the wave gauge (WG), of the particle image velocimetry measurement system (in meters, not to scale), and a picture captured by the camera as an example; flow velocities (u) are provided for the unidirectional tests and wave heights (H) and periods (T) for oscillatory test conditions

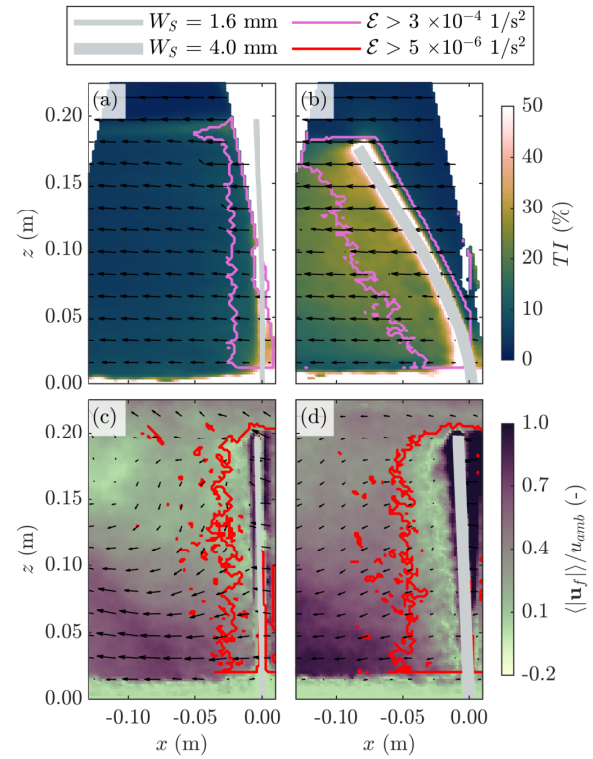


Figure 3.2. Comparison of the turbulence intensity TI in unidirectional flow ($u = 0.20$ m/s) with stem surrogates representing (a) *Elymus* spp. and (b) *S. anglica* and the fluctuating horizontal velocity in oscillatory flow conditions ($H = 0.06$ m and $T = 1.40$ s) at $t/T = 0.60$ with (c) *Elymus* spp. and (d) *S. anglica* and the area of stem influence defined through an enstrophy threshold $\mathcal{E}$

3.1.3 Results

Statistical evaluation confirms that the surrogate stems, fabricated with flexible filament with shore hardness of 85A and 95A, replicate the biomechanical stem properties of the targeted salt marsh species (*Elymus* spp. and *S. anglica*). The surrogates depicted in Figure 3.2 (a) and (c) are representative of *Elymus* spp., and in Figure 3.2 (b) and (d) are representative of *S. anglica*. The area of extent of the influence of the stem is quantified through an enstrophy threshold of $\mathcal{E} \geq 3 \times 10^{-4} \text{ s}^{-2}$ for unidirectional and $\mathcal{E} \geq 5 \times 10^{-6} \text{ s}^{-2}$ for oscillatory flow conditions, rendering the enstrophy as a suitable differentiator between unsteady state conditions of the fluid and the stem's alterations to the surrounding flow field. Last, the correlation between the Cauchy number Ca and the stem position resulting from the fluid-structure interaction of all tested surrogate stems in both unidirectional (R^2

= 0.62) and oscillatory ($R^2 = 0.78$) flow conditions is presented in the study.

3.1.4 Conclusions

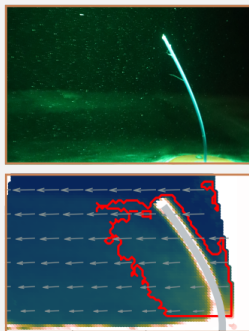
Overall, 3D printing with flexible filaments is confirmed as a suitable approach to replicate the biomechanical properties of live vegetation in physical hydrodynamic experiments, paving the way for future studies to address more complex geometries or varying material properties found in salt marshes. This study's research objectives have been addressed as follows:

- The enstrophy is a suitable indicator of near-stem influence on its surrounding flow field and differs in spatio-temporal extent, depending on biomechanical stem properties.
- The non-dimensional parameter Ca correlates well with the resulting bent stem position in both unidirectional and oscillatory flow conditions.
- Surrogates have been shown to accurately reproduce *Elymus* spp. and *S. anglica* and represent the range of biomechanical parameters measured *in situ* in salt marshes.

3.1.5 Contextualization

This study utilizes the biomechanical stem properties from field measurements of Keimer et al. (2023b) and Keimer et al. (2024), building upon previous work conducted within the research project "Gute Küste Niedersachsen", to assess the FSI of the salt marsh species *S. anglica* and *Elymus* spp. To achieve that, this study provides the first investigation to explore 3D printed flexible filament as a promising tool to replicate *in situ* measured biomechanical stem properties. The physical hydrodynamic experiments demonstrated the importance of studying FSI at the stem scale across different plant species. However, replicating the seasonal variation of biomechanical stem properties within a single salt marsh species was not achieved, indicating the need for alternative approaches in future studies.

Concluding remarks of Section 3.1



- 3D printed surrogate stems with flexible filament are exposed to unidirectional and oscillatory flow conditions in a flume
- The area of extent of flow field alterations due to the fluid-structure interaction can be quantified through an enstrophy threshold
- Similarity to *in situ* measured biomechanical properties of live salt marsh vegetation is confirmed with statistical evaluation

3.2 Fluid-structure interaction in unidirectional flow

This section summarizes the study published as:

Study 2

Prüter, Inga; Spröer, Felix; Keimer, Kara; Lojek, Oliver; Windt, Christian; Schürenkamp, David et al. (2025): A comprehensive numerical study on the current-induced fluid–structure interaction of flexible submerged vegetation. In: Journal of Fluids and Structures, vol. 133, doi: 10.1016/j.jfluidstructs.2024.104232.

3.2.1 Motivation and Objectives

Submerged vegetation provides ecosystem services, such as wave attenuation, and is therefore a valuable component of NbSs in coastal protection plans. Accurate replication of live vegetation through solutions obtained by numerical models permits the investigation of the provided ecosystem services. High-fidelity numerical models, such as the FSI coupling in REEF3D::CFD solving the Cosserat rod equations, enable the incorporation of seasonally varying biomechanical stem properties and the elaboration of their implications for the FSI. Comprehensive validation with various material properties and hydrodynamic conditions regarding the motion of and forces exerted on flexible vegetation under unidirectional flow conditions is required to ensure reliability when applying *in situ* measured live vegetation properties in numerical models. The following research objectives are addressed in this study:

- To test the model sensitivity to numerical parameters, including its temporal and spatial resolution, and to numerical parameters of the structural solver, such as the number of elements of a stem.
- To investigate the effect of different turbulence models and their model parameters on the resulting drag force exerted on single, flexible stems.
- To compare the model predictions regarding different materials, varying stem lengths, and current velocities to physical (Luhar and Nepf, 2011) and numerical (Tschisgale and Fröhlich, 2020) results.

3.2.2 Material and Methods

The FSI solver within the finite difference model REEF3D::CFD, coupled with the IBM and employing the direct forcing approach, depicted in Figure 3.3, is comprehensively evaluated for the simulation of stem motions and forces exerted on flexible vegetation under varying unidirectional flow conditions. The performance of the FSI is investigated concerning different turbulence models, such as RANS, URANS, and LES, and further numerical modeling parameters, such as the spatial discretization. The validation of the FSI is based on the flexible soft foam and more stiff high-density polyethylene (HDPE) material exposed to various unidirectional flow velocities by Luhar and Nepf (2011). Afterward, the biomechanical stem properties, following the classified growth states of *S. anglica* by Keimer et al. (2023b), are incorporated to explore a first example of simulations based on live vegetation properties.

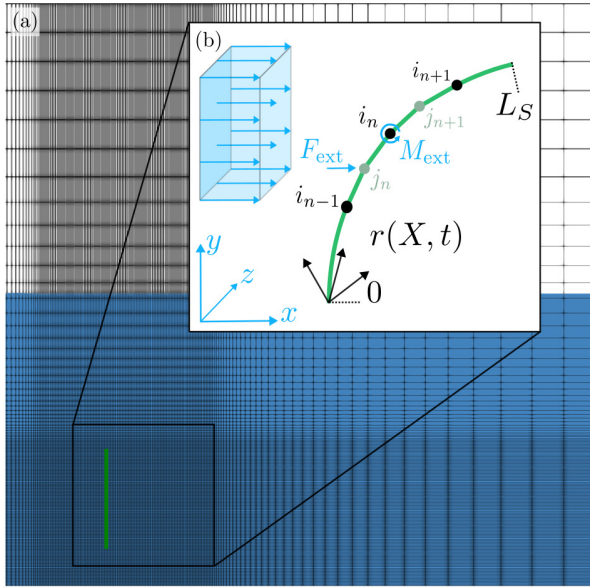


Figure 3.3. (a) Excerpt from the numerical non-uniform grid, with a refined resolution of 1.5 mm, utilized to simulate the fluid-structure interaction, and (b) definition sketch of the coupling of the structural and the fluid solver with the Eulerian and Lagrangian system, the external forces (F_{ext}) and moments (M_{ext}) calculated for each element center (i_n) and element edge (j_n)

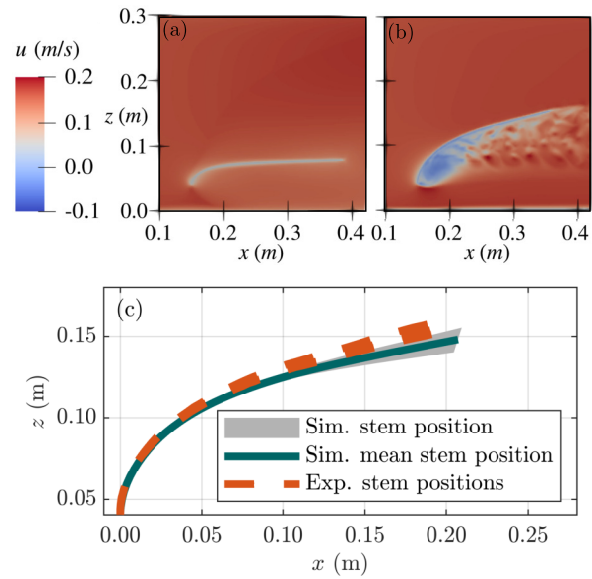


Figure 3.4. Simulated flow field for the 0.25 m long stem with HDPE material and a current velocity u of 0.16 m/s, including the comparison of different utilized turbulence models with (a) $k-\omega$ model (RANS) and (b) Smagorinsky model (LES), and (c) the comparison of the stem bending for the simulated and experimental stem from Luhar and Nepf (2011)

3.2.3 Results

The sensitivity of the FSI solver in REEF3D::CFD to replicate the motion of submerged vegetation stems has been evaluated. Thresholds for numerical parameters, such as a minimum number of 25 rigid elements composing the stem, are identified for accurate solutions. The necessity of using LES and a Smagorinsky coefficient of 0.1, compared to traditional or adapted RANS approaches, to simulate the turbulent FSI is demonstrated, as shown in Figure 3.4 (a) and (b). The study confirms the accuracy of the implemented FSI model to replicate stem bending (less than 10 % deviation relative to the stem length), depicted by example in Figure 3.4 (c), and forces across varying hydrodynamic conditions. The first application of *in situ* measured live vegetation properties in the numerical model reveals that the distribution of the TI in the wake of the stem varies for each stem, representing the different growth states of *S. anglica* (sprouting, flowering, and broken).

3.2.4 Conclusions

A first validation of the FSI solver in REEF3D::CFD to replicate stem bending and resulting forces of submerged aquatic vegetation in unidirectional flow conditions has been presented, enabling the application of *in situ* measured stem properties of live vegetation. The research objectives of this study, previously listed in Section 3.2.1, have been addressed as follows:

- The convergence analysis of the structural solver underscores the importance of a fine

grid resolution in the proximity of the vegetation stem. No discernible sensitivity to temporal resolution was observed in the context of the flow velocities examined in this study. An optimal number of individual rigid elements has been determined for the simulated stem with a length of 0.25 m, totaling 200 elements per meter.

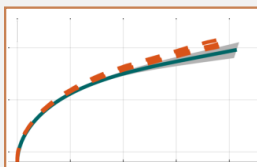
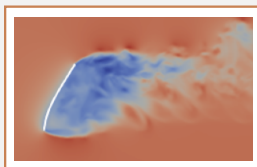
- A comparative assessment of simulated forces employing three turbulence models, namely RANS, URANS, and LES, highlighted that the wall-adapted RANS approach represents a more reasonable FSI compared to the non-adapted approach, while the utilization of LES shows the smallest deviations of simulated to experimental forces.
- The outcomes of this investigation demonstrate that the FSI implemented in REEF3D::CFD can accurately replicate both stem bending and associated forces across diverse stem lengths, current velocities, and material compositions.

3.2.5 Contextualization

Based on the research need revealed in the previous section for alternative modeling approaches to replicate *in situ* measured biomechanical stem properties across different seasons, high-fidelity numerical modeling of the FSI has been employed within this study. As the investigations of Keimer et al. (2023b, 2024) revealed a statistical significance regarding the seasonal variation for biomechanical stem properties of *S. anglica*, in contrast to *Elymus* spp., the former is utilized for a first application case in the FSI solver in unidirectional flow conditions.

Overall, the numerical modeling of the FSI has been shown as promising in replicating varying growth states within the salt marsh species *S. anglica* and the differences in the resulting flow field. Within this study, the FSI solver has been successfully validated for unidirectional flow conditions, and the sensitivity to numerical parameters and turbulence models has been analyzed. However, it remains to be determined in a subsequent study if the FSI solver can replicate the stem movement in resulting forces in oscillatory flow conditions accurately, being crucial in the context of coastal aquatic vegetation, which is elaborated in the following section.

Concluding remarks of Section 3.2



- The FSI solver of the hydrodynamic toolbox REEF3D::CFD is validated for unidirectional flow concerning the stem bending and resulting forces
- The importance of utilizing appropriate turbulence models for the FSI is emphasized
- The first application of *in situ* measured live vegetation properties to investigate seasonal variation in flow field alterations is provided

3.3 Fluid-structure interaction in oscillatory flow

This section summarizes the study published as:

Study 3

Prüter, Inga; Spröer, Felix; Lojek, Oliver; Windt, Christian; Schürenkamp, David; Nistor, Ioan; Goseberg, Nils (2025): Vegetation stem dynamics under wave loading: Insights from a coupled fluid–structure model. In: Applied Ocean Research, vol. 159, doi: 10.1016/j.apor.2025.104597.

3.3.1 Motivation and Objectives

Accurate replication of the stem motion of submerged aquatic vegetation is relevant to gain insights into its capacity for coastal protection and adaptability, such as the wave attenuation capacity and local sediment mobilization. In the literature, FSI solvers validated in oscillatory flow conditions have been limited regarding their tested material range, rendering their applicability for *in situ* measured stem properties of submerged aquatic vegetation unaddressed. Building upon the previous study concerning the FSI solver in REEF3D::CFD in unidirectional flow conditions, the analysis of the solver's performance in oscillatory flow conditions remains to be conducted. Furthermore, the models' built-in damping coefficients are expected to influence the stems' time-dependent motion in oscillatory flow, requiring a comprehensive analysis. Therefore, the following research objectives are addressed in this study:

- To evaluate the ability of the proposed FSI model to replicate wave-induced time-dependent movement and forces of an individual stem.
- To investigate the influence of the flow field in front of an individual stem on the stem motion of the proposed FSI model.
- To determine the constraints of the model's built-in damping coefficients on the wave-induced stem motion.

3.3.2 Material and Methods

The FSI solver within the numerical model REEF3D::CFD (cf. Figure 3.3) is validated in oscillatory flow conditions using reference experiments by Luhar and Nepf (2016) and Jacobsen et al. (2019), covering a wide range of material properties (referred to as Material 1, 2, and 3) and hydrodynamic conditions found in natural aquatic vegetation. The solver is then employed to analyze vegetation stem motion and resulting drag forces. To investigate possible sources of discrepancies between the numerical and experimental results, the numerical flow field in front of the stem is compared to PIV measurements of the reference experiment by Luhar and Nepf (2016). Further on, the stem motion is evaluated through its bending modes, providing further insights regarding possible deviations between the simulated and experimental stems. Finally, varying damping coefficients, required to calculate the internal moment of the Cosserat rod equations governing the structural solver (cf. Equation (2.19)), are employed across the range of previously validated material types to evaluate the damping coefficients' influence on the stem motion and resulting forces, enabling the recommendation for application ranges for future studies.

3.3.3 Results

For the simulations in oscillatory flow conditions, good agreement between simulated and experimental results is achieved for most test cases. Two examples regarding the agreement of the stem bending are depicted in Figure 3.5. The agreement is expressed by less than 10 % deviation of the simulated from the experimental forces and the stem positions relative to the stem length. The comparison of the numerical to the physical incoming flow field reveals the FSI solver's sensitivity and the need for detailed benchmark cases. Bending modes of stem movements provide further insights into the complex dynamic behavior of stems.

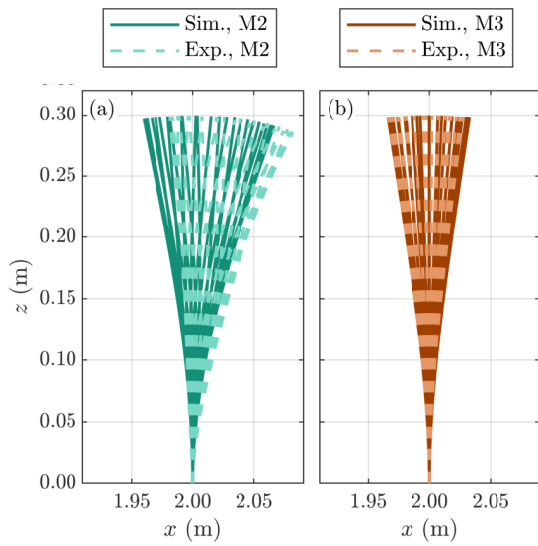


Figure 3.5. Comparison of the simulated to the experimental ensemble-averaged stem motion from $t/T = 0 - 1$ with $t/T = 0.04$ increments, resulting in 25 stem positions each for (a) Material 2 (M2) with $L_S = 0.30$ m, $H = 0.04$ m and $T = 2.0$ s, and (b) Material 3 (M3) with $L_S = 0.30$ m, $H = 0.07$ m and $T = 1.5$ s

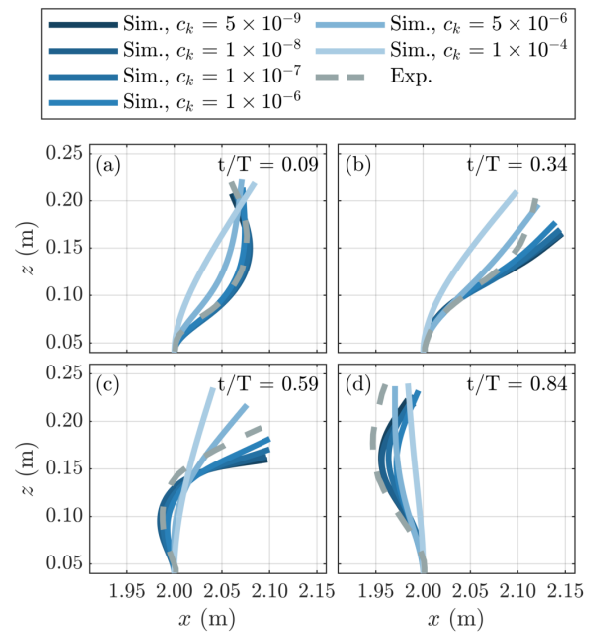


Figure 3.6. Influence of varying damping coefficients c_k on the stem position for Material 1 with the wave conditions $H = 0.08$ m and $T = 2.0$ s for selected points in time normalized by the wave period

Additionally, the study demonstrates the influence of the model's built-in damping coefficients on the time-dependent stem movement in oscillatory flow conditions and the resulting forces for different material types. The influence of varying damping coefficients on the wave-induced stem motion is shown, by example, in Figure 3.6, and compared to the stem motion of the reference experiment. For all tested material types, the findings suggest that utilizing damping coefficients ranging between 1×10^{-8} and 1×10^{-6} leads to the successful replication of the stem dynamics and the resulting drag forces.

3.3.4 Conclusions

It can be summarized that accurate predictions of vegetation response in oscillatory flow conditions require careful selection of the governing parameters in the structural model replicating the stem. Considering this, the proposed FSI solver proves highly effective for simulating a wide range of flexible, submerged vegetation stems. Based on the recommended

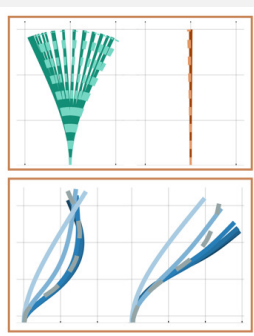
range of suitable damping coefficients, the application of *in situ* measured live vegetation properties is now enabled. This study's research objectives, listed in Section 3.3.1, have been answered as follows:

- The proposed FSI model can accurately replicate an individual stem's wave-induced motion and associated drag forces.
- The flow field in front of an individual stem was observed to have a large influence on the proposed FSI model, marking it as a source of possible model inaccuracies.
- The model's built-in damping coefficients control the time-dependent wave-induced stem motion and the resulting drag forces while ensuring numerical stability to a greater extent than previously thought. Therefore, considerate choices of damping coefficients are recommended (1×10^{-8} and 1×10^{-6}), based on the analysis presented in this study for three different materials.

3.3.5 Contextualization

This study has shown the utilization of the FSI solver in oscillatory flow conditions for various material properties and hydrodynamic conditions, extending the previous study in unidirectional flow. In combination, Section 3.2 and Section 3.3 provide the first and comprehensive validation and analysis of the FSI solver in REEF3D::CFD. The validation was conducted deliberately for structural parameters and hydrodynamic conditions representative of salt marsh vegetation. The relevance of applying appropriate damping coefficients for the time-dependent FSI in oscillatory flow conditions has been highlighted for the first time in this study. The findings suggest suitable damping coefficients within a specific range (1×10^{-8} and 1×10^{-6}), independent of the applied material properties of the stem. Utilizing this recommended range of damping coefficients enables the application of *in situ* measured live vegetation stem properties in a subsequent study.

Concluding remarks of Section 3.3



- Validation of the FSI solver in oscillatory flow conditions regarding stem motion and resulting forces for various material types and hydrodynamic conditions
- Emphasizing the influence of the incoming flow field on the time-dependent stem movement
- Determining damping coefficients ranging between 1×10^{-8} and 1×10^{-6} as appropriate to replicate the stem dynamics and the resulting drag forces for the tested material types

3.4 Investigation of the fluid-vegetation interaction with seasonally and regionally varying biomechanical stem properties

This section summarizes the study submitted as:

Study 4

Prüter, Inga, Markov, Acacia, Lojek, Oliver, Schürenkamp, David, Stolle, Jacob, Nistor, Ioan, Goseberg, Nils: Linking biomechanical stem properties of salt marsh vegetation to flow field alterations: a regional and seasonal analysis, *under review* in: Coastal Engineering.

3.4.1 Motivation and Objectives

Salt marshes provide valuable ecosystem services for coastal protection plans, but reliability depends on quantifying the seasonal and regional variation of their properties. Biomechanical stem properties determine salt marsh stems' motion and resulting forces in unidirectional and oscillatory flow conditions. *In situ* measurement of stem properties and their application in suitable modeling frameworks, as introduced in the previous sections 3.2 and 3.3, enables the evaluation of seasonal and regional variation and their implication for the fluid-structure interaction. However, to date, the biomechanical properties of Canadian salt marshes have not been investigated in the field. Therefore, the following research objectives are addressed in this study:

- To examine the seasonal variation of biomechanical stem properties from a Canadian salt marsh
- To compare the biomechanical stem properties of a Canadian salt marsh to field studies from the literature
- To evaluate the influence of the variation in biomechanical stem properties on the stem motion in unidirectional and oscillatory flow and their resulting flow field alterations
- To determine drag coefficients considering modeled salt marsh stems' seasonal and regional variation

3.4.2 Material and Methods

The first measurement of the flexural stiffness and its seasonal variation of a Canadian *S. alterniflora* has been assessed through field measurements. The location of the study site at the Petites-Bergeronnes River, adjacent to the St. Lawrence estuary in Quebec, is depicted in Figure 3.7 (a). The setup of the three-point bending tests to determine the stem's flexural stiffness is indicated in Figure 3.7 (b). The FSI solver in REEF3D::CFD (cf. Figure 3.3) is then employed to model the flow field alterations at the stem level. In combination with measurements of biomechanical properties of *S. anglica* from European salt marshes (Vuik et al., 2017; Schulze et al., 2019; Keimer et al., 2023a), locations shown in Figure 3.7 c, the influence of seasonal and regional variation of the flow field is investigated at the stem level through numerical modeling. The stems are exposed to unidirectional flow with a velocity of 0.30 m/s and oscillatory flow conditions with a wave height of 0.08 m and a period of 1.5 s.

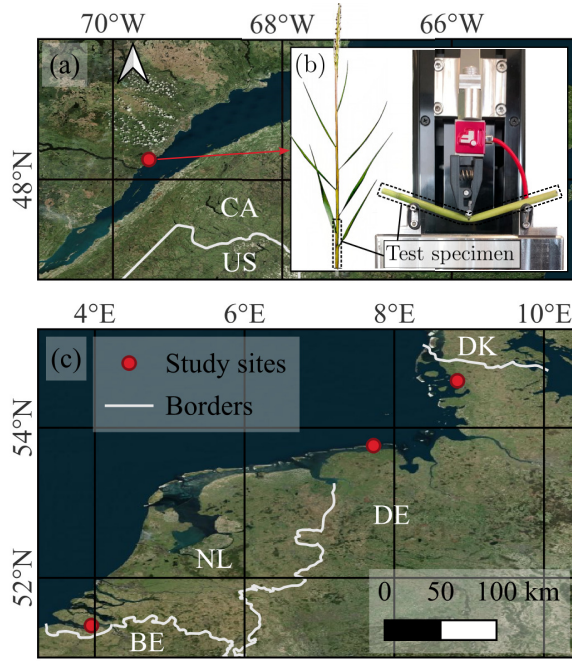


Figure 3.7. (a) Location of the study site in Quebec, Canada, with (b) the conducted three-point bending tests to determine the flexural stiffness of *S. alterniflora* and (c) gathered field measurements data, including seasonally varying measurements of biomechanical properties of *S. anglica* along the North Sea coast

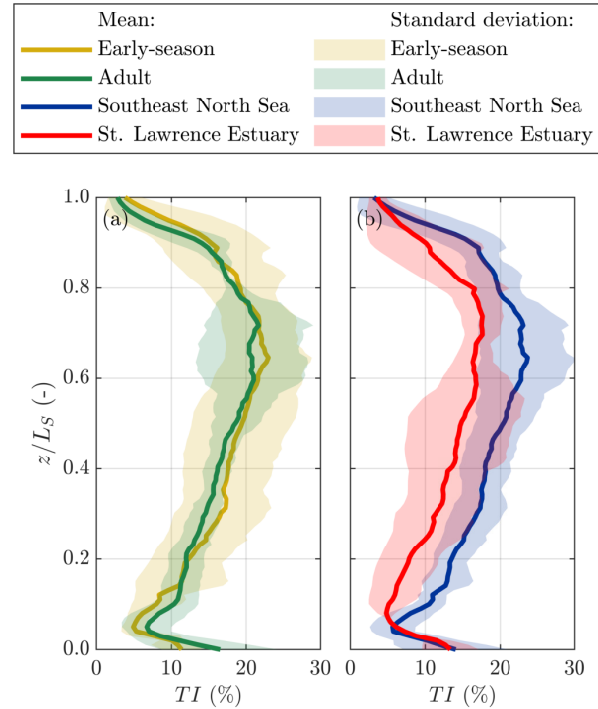


Figure 3.8. Comparison of the averaged turbulence intensity (TI) profiles, differentiated by seasonality (a) and region (b), in the wake of the stem (0.20 m behind the stem in x -direction) over the normalized stem height z/L_S

3.4.3 Results

The field investigations of the Canadian *S. alterniflora* stems show that the biomechanical stem properties vary greatly from an early-season to an adult stem. The comparison of the stem properties to the European *S. anglica* reveals that the Canadian stems are generally smaller and more flexible. The stem-influenced flow field alterations in unidirectional flow, expressed through the turbulence intensity, differ more between the two regions than due to seasonal effects, depicted in Figure 3.8. In oscillatory flow conditions, the stem tip motion varies in its extent on both the seasonal and regional scales. However, a variation of the flow field alterations in the proximity of the stem, expressed through the TKE, is solely apparent on the regional and not the seasonal scale. Drag coefficients are provided, differentiated by season and region, applicable for future large-scale modeling approaches.

3.4.4 Conclusions

In summary, both the seasonal and regional variation of biomechanical stem properties are relevant when investigating the FSI of salt marsh stems. The following conclusions can be drawn based on the in Section 3.4.1 detailed research objectives:

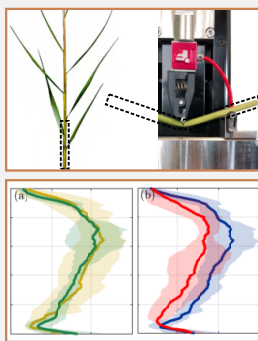
- Field measurements of *S. alterniflora* at the Petites-Bergeronnes River in Canada showed seasonal variation of biomechanical stem properties, with a lower EI in June ($101.57 \pm 97.31 \text{ Nmm}^2$) compared to July ($1279.80 \pm 255.9 \text{ Nmm}^2$) and September ($1276.22 \pm 195.00 \text{ Nmm}^2$).

- The investigated *S. alterniflora* stems at the St. Lawrence Estuary show smaller d_S (2.50 ± 0.52 mm in early-season and 2.95 ± 0.61 mm as adult stems) and a lower EI (101.57 ± 97.31 Nmm² in early-season and 1483.29 ± 1320.05 Nmm² as adult stems) compared to measurements of *S. anglica*, with $d_S = 3.31 \pm 0.67$ mm on average in early-season and 3.76 ± 0.61 mm as adult stems, and $EI = 1592.57 \pm 810.65$ Nmm² on average in early-season and 4419.42 ± 1917.28 Nmm² as adult stems.
- Regional variation exerts a stronger influence than seasonal variation on the TI in the stem wake under unidirectional flow and on the TKE under oscillatory flow.
- Derived drag coefficients under unidirectional and oscillatory flow conditions range between 1.5 and 2.0, without clear trends regarding seasonal or regional variation.

3.4.5 Contextualization

This study provides a workflow linking field measurements with numerical FSI modeling and explores the regional and seasonal differences regarding the biomechanical stem properties of salt marsh vegetation. While *in situ* measurements of biomechanical stem properties for European salt marshes are frequently published, among others by Rupprecht et al. (2015); Vuik et al. (2017); Schulze et al. (2019) and as part of the research project "Gute Küste Niedersachsen" (Keimer et al., 2023b, 2024), similar measurements for Canadian salt marsh vegetation remained unaddressed in the literature. To enable the comparison of the regional and seasonal variation of the biomechanical stem properties, measurements were conducted at the Petite-Bergeronnes River in Quebec. Combining the field measurements and published studies (Vuik et al., 2017; Schulze et al., 2019; Keimer et al., 2023a), a comprehensive database could be implemented in the FSI solver, which was previously validated in Sections 3.2 and 3.3. The simulations showed that seasonal stem properties vary regionally, reflecting unique local patterns in how salt marshes contribute to coastal protection throughout the year.

Concluding remarks of Section 3.4



- First *in situ* measurements of biomechanical stem properties of a Canadian salt marsh stem
- Canadian stems are smaller and more flexible compared to European salt marsh stems
- Simulating the fluid-structure interaction showed regionally varying flow-field alterations
- The results highlight regional differences in the seasonal cycle of biomechanical stem properties

Herein, the findings of Sections 3.1, 3.2, 3.3, and 3.4 are discussed regarding the research objectives introduced in Section 2.1. General considerations regarding the suitability of numerical and physical modeling approaches to replicate live vegetation dynamics are evaluated first in Section 4.1. Subsequently, in Sections 4.2 and 4.3, the applicability of the surrogate development based on 3D printed flexible filament and the herein proposed FSI solver are classified based on model advantages and future challenges. Last, the influence of seasonal and regional variation of biomechanical stem properties on the stem-induced flow field alterations is discussed in Section 4.4.

4.1 Comparison of modeling approaches incorporating *in situ* measured vegetation properties

The replication of *in situ* measured biomechanical stem properties in modeling approaches is crucial to accurately assess the resulting stem dynamics, as introduced in Chapter 1, before investigating ecosystem services provided by salt marshes on a broader scale (Tempest et al., 2015). The literature review in Chapter 2 highlighted some general requirements to model flexible vegetation stems incorporating *in situ* measured live vegetation properties. In summary, the following criteria apply to both numerical and physical modeling approaches:

- Representation of thin and long structures that experience large excursions
- Replication of the flexural stiffness based *in situ* measurements of vegetation stems
- Ability to represent seasonal and regional variation of the stem properties, requiring either high accuracy of the material properties for surrogates in physical modeling approaches or independence of empirical coefficients, such as C_D , to calculate the external forces for numerical modeling methods

In Chapter 2, it has been further concluded that previous modeling approaches either did not replicate all relevant biomechanical stem properties measured in salt marsh vegetation or are challenged in incorporating the range of properties and the resulting stem motion found in live vegetation. Therefore, based on the results provided in Section 3.1, Section 3.2, and Section 3.3, the advantages and disadvantages of both numerical and physical modeling approaches in replicating *in situ* measured vegetation properties are evaluated in this section.

Generally, numerical modeling approaches have the advantage of enabling the incorporation of great versatility in replicated vegetation properties, including their seasonal and regional variation, for example, as shown by Baaij et al. (2021) and in Section 3.4 of this

work. As outlined in Section 2.2.2, previous surrogates failed to reproduce the natural range of biomechanical stem properties, particularly flexural stiffness, and therefore did not capture the seasonal variation observed in salt marshes. Despite intensive efforts, the findings in Section 3.1 confirmed that the representation of seasonal variation of stem properties for physical modeling with surrogate stems remains challenging. While the seasonal variation in biomechanical stem properties measured *in situ* is often significant (Keimer et al., 2023b), its magnitude is relatively small compared to the variability of properties within the surrogate development.

The replication of salt marsh stems in physical modeling approaches, such as the surrogate development with 3D printing utilizing flexible filament explored in Section 3.1, offers several advantages over numerical simulations. First, 3D printed surrogate stems are expected to be advantageous for representing various vegetation geometries, in contrast to most numerical FSI solvers, where stems are solely represented by beam theories. Such stems without leaves are considered a good representation of, for example, *S. anglica* in its winter state. However, they cannot replicate the leaf development of the vegetation within the growing cycle or vegetation with more complex geometries, such as the salt marsh shrub *Atriplex portulacoides*, commonly found along the German North Sea coast (Stückemann and Waske, 2022). Beyond beam theories, SPH approaches offer a promising framework for simulating complex vegetation geometries and their interaction with the flow field, although their suitability for such cases remains untested to date. However, replicating thin structures like leaves (Zhang et al., 2022) in SPH approaches may still be computationally prohibitive (Vacondio et al., 2021; Huang et al., 2024).

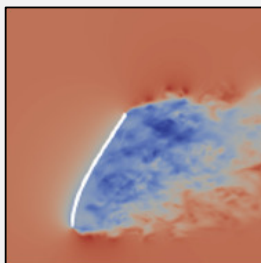
Second, numerical modeling approaches of FSI have, to date, the disadvantage of their high computational demand, resulting in a limited realizable simulation time, usually shorter compared to the time durations investigated in physical experiments. For example, in Section 3.3, the simulation time of the FSI varied between approximately 7 to 30 s. In the literature, Chen and Zou (2019) modeled approximately 28 s of FSI, El Rahi et al. (2023) simulated only 4 wave cycles, and Wei et al. (2024) simulated 20 wave cycles in total, but recorded motion and forces of the stem for the last two wave cycles only. Such computational constraints hinder the investigation of potential long-term effects or developments of the FSI. However, the investigation with high-frequency PIV measurements in physical experiments is usually likewise restricted by a limited feasible number of time frames. As shown in Sections 3.2 and 3.3, the simulation time per step in numerical models depends on vegetation stiffness, particularly under unsteady oscillatory flow. Faster computation was observed for very stiff or very flexible stems, while intermediate stiffness, typical for salt marsh vegetation, resulted in the longest runtime. Adaptive time-stepping based on stem stiffness, as proposed by Mayr et al. (2018), could help to mitigate this issue.

Depending on the spatial and temporal scales of interest, numerical simulations often rely on turbulence models to approximate unresolved flow dynamics (see Section 2.3.1). Consequently, the choice of turbulence model must be aligned with the scale and objectives of the investigation, particularly when analyzing stem-induced turbulence in the surrounding flow field (cf. Section 3.1), and wall effects concerning the coupling interface between the fluid and the structure should be taken into account. In contrast, physical modeling approaches, without scaling involved, offer the advantage of directly replicating stem-induced turbulence phenomena. However, challenges may arise when it comes to capturing and determining

the stem-induced turbulence in physical experiments, as elaborated in Section 3.1, since the velocity fields measured with PIV require separation of the moving stem from the surrounding flow (Jeon and Sung, 2011; Theunissen, 2012), thus introducing additional uncertainty compared to numerical modeling approaches.

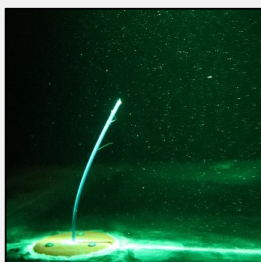
In conclusion, replicating *in situ* vegetation properties in numerical or physical experiments has method-specific advantages and limitations. Numerical models can directly use measured stem properties but face challenges with complex geometries, computational efficiency, and time constraints in FSI simulations. In contrast, surrogates currently lack accuracy regarding their biomechanical properties needed to represent the seasonal variation observed *in situ* in live vegetation, but offer greater versatility in replicating leaf structures and other geometric features. The box below summarizes the key findings of this section, highlighting the advantages of numerical and physical modeling approaches for implementing *in situ* measured biomechanical stem properties and replicating the resulting FSI. This overview can support the selection of a suitable modeling approach based on the specific focus of a study.

Concluding remarks of Section 4.1



Numerical simulations:

- Straightforward implementation of biomechanical stem properties, including seasonal and regional variation
- Enable the comparison of a large variety of stem properties
- Provide accurate (3D) information of the FSI and the surrounding flow field



Physical experiments:

- Provide physical replication of stem-induced turbulence
- Enable comparably long test durations
- Possibility to represent complex geometries, such as leaves
- Possibility to include varying flexibilities within one surrogate, for example, through dual extrusion printers

4.2 Applicability of 3D printed surrogates to replicate live vegetation

The literature review in Section 2.2.2 revealed that replicating all relevant stem properties, such as their diameter, flexural stiffness, and buoyancy, in surrogate materials is to date challenging. Based on the results provided in Section 3.1, the applicability of using 3D printed flexible filament to develop surrogate stems is discussed in terms of accuracy and versatility compared to traditionally used surrogate materials in the literature.

The evaluation in Section 2.2.1 has shown that it is crucial to replicate the obstruction of the flow field by the stem, expressed by its diameter d_S and length L_S , together with, decisive for the stem bending, the stems flexural stiffness EI , to achieve representative FSI behavior. However, most studies rely on individually comparing surrogate properties to those of live vegetation, as seen among others in Augustin et al. (2009); Anderson and Smith (2014); van Veelen et al. (2020). Comparing vegetation properties individually simplifies the interplay and dependencies between parameters and their influence on the stem behavior, such as the stem diameter d_S and the flexural stiffness EI . Therefore, the similarity of the surrogate stems to *in situ* measured biomechanical stem properties of live vegetation has been confirmed in Section 3.1 based on a statistical similarity evaluation. A comprehensive comparison ensures that similarity is only confirmed for surrogates aligning with live vegetation stems regarding both their diameter and flexural stiffness.

In Section 3.1, the experiments with stiff stems as reference cases revealed the difference in their near-stem flow field in comparison to the flow field alterations of the flexible stems. Due to their greater resistance to the incoming flow, the stiff stems generated higher wake turbulence under both unidirectional and oscillatory flow regimes. The observed higher wake turbulence for stiff stems aligns with the literature (Puijalon et al., 2011; Gillis et al., 2022) and confirms the relevance of including the stem's flexibility in the surrogate development.

Based on the elaboration in Section 3.1, 3D printing has been confirmed as a suitable approach to replicate *in situ* measured biomechanical properties of live vegetation. It remains to be evaluated how the applicability of flexible filament compares to flexible resin, which has been utilized in physical hydrodynamic experiments by Keimer et al. (2024). On one hand, 3D-printed filament has the advantage that its material properties are not sensitive to environmental exposure, in comparison to 3D-printed resin, which is known for its thermal and hydro sensitivity (Xian et al., 2024; Ci et al., 2025). On the other hand, the workflow utilized in Section 3.1 to develop a flexible surrogate relies on the material properties of the manufacturers regarding the desired flexural stiffness of the stem. The mixing approach proposed by Keimer et al. (2024) offers higher versatility in comparison. Similar versatility could be achieved with self-fabricated flexible filament, as seen in Jayswal and Adanur (2023). While the self-fabrication of the flexible filament would improve the methodology's possible range of flexibilities, it would also increase the complexity of the surrogate development, making its application less straightforward.

Furthermore, 3D printing is considered promising due to its ability to represent complex shapes and geometry of biological systems with surrogates for laboratory experiments (Behm et al., 2018; Hitzegrad et al., 2024). For vegetation, Bömer et al. (2024) have shown accurate replication of complex leaves and stem structures with 3D printing. The next step is to expose such a 3D printed surrogate to a flow field in a wave or current flume, enabling an assessment of the FSI. Overall, salt marsh species whose geometry cannot be simply described by a main stem and several leaves, such as *Limonium vulgare* or *A. portulacoides*,

may only be accurately represented as surrogates with 3D printing. However, adaptations to the printing setup and utilized printing nozzles are required to enable the printing of circular or very thin stems. Furthermore, the 3D printing process has the disadvantage compared to traditional materials that the duration of the printing process increases with larger stem dimensions and greater material flexibility, and requires iterative adaptation of the printing set-up to achieve the desired biomechanical properties.

The 3D printed surrogate stems in Section 3.1 have been shown to replicate *in situ* measured biomechanical stem properties of specific salt marsh species (*S. anglica* and *Elymus* spp.) accurately. However, with the applied development process, the seasonal variation within one salt marsh species could not be replicated, as discussed in Section 4.1. Consequently, the iterative process of stem printing and property testing needs to be refined to achieve the required level of accuracy, especially regarding the seasonal variation of the flexural stiffness observed in the live vegetation (Vuik et al., 2017; Schulze et al., 2019; Keimer et al., 2023b, 2024). A detailed understanding of how printing setup factors, such as infill density and layer thickness, affect the biomechanical properties of the stem is essential for improving the efficiency of the 3D printing process. Moreover, a comparative study involving flexible filaments from different manufacturers would support the development of more comprehensive guidelines beyond the proof-of-concept assessment presented in Section 3.1.

An improved workflow is proposed in Figure 4.1 based on the first assessment of the utility of flexible filament to develop salt marsh surrogates in Section 3.1. The iterative process involves a parameter-wise comparison to ensure similarity between surrogate and prototype properties. Each relevant parameter, such as stem length (L_S), thickness (T_S), width (W_S), flexural stiffness (EI), and material density (ρ_S), is satisfied when the desired level of similarity to the prototype is reached. Depending on the specific process under investigation, the parameters used for comparison can be adjusted. The proposed workflow ensures accurate replication of flow obstruction, stem motion, and buoyancy, with parameters considered most decisive for the FSI, such as geometry and flexural stiffness, evaluated first.

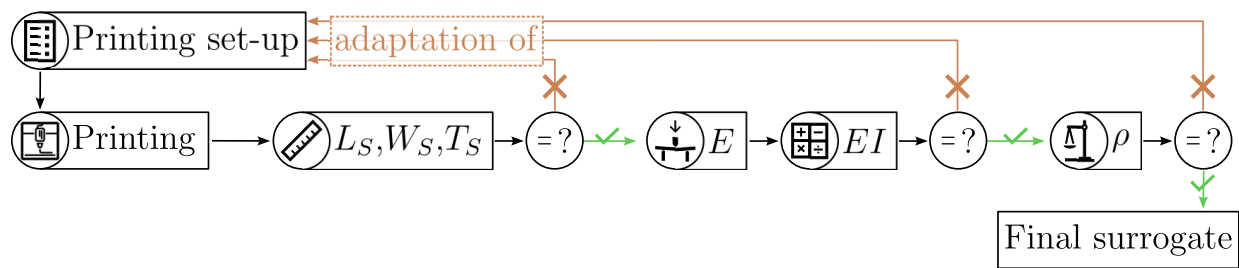


Figure 4.1. Suggested workflow for an improved 3D printing process, ensuring the accurate replication of the stem's length (L_S), width (W_S), and thickness (T_S), its flexural stiffness (EI), and material density (ρ)

Based on the previous assessment, the box below summarizes the most relevant advantages of using 3D printed flexible filament for the surrogate development, while providing an overview of the current challenges of the proposed technology.

Concluding remarks of Section 4.2

Model advantages:

- Greater versatility than traditional surrogate materials, allowing for fine-tuning of the relevant parameters
- Less sensitive to environmental exposure compared to flexible resin
- Opportunity to print complex geometries or including different flexibilities for stems and leaves

Current challenges:

- Requires an iterative process to determine material properties with the desired accuracy
- Time duration of the printing process extends with greater stem dimensions and increasing flexibility
- Adaptation to the printing process required for circular or very thin stems

4.3 Assessment of the fluid-structure interaction solver in REEF3D::CFD

Numerical approaches are considered valuable to replicate salt marsh vegetation's biomechanical stem properties accurately. Herein, the performance of the FSI solver in REEF3D::CFD, introduced and validated in Section 3.2 and Section 3.3, and applied in Section 3.4, is examined. The combined validation presented in Sections 3.2 and 3.3 offers a broad range of test cases for the FSI solver under both unidirectional and oscillatory flow conditions. In summary, the solver has been validated in unidirectional flow conditions for two different material types, silicon foam and HDPE (including varying stem thickness and flexural stiffness), five stem lengths, and eight different current velocities. In oscillatory flow conditions, the FSI solver has been validated based on three different material types (silicon foam, polystyrene, and acrylonitrile butadiene styrene), including a variation of thickness, stem length, and flexural stiffness, and in total four different wave conditions. The tested parameter range is summarized in Figure 4.2, along with a comparison to those used in related FSI solver studies by example (Jin and Zhang, 2022; El Rahi et al., 2023; Wei et al., 2024). This comparison highlights the thorough validation carried out in Section 3.2 and 3.3, while also emphasizing that studies often rely on the experimental work of Luhar and Nepf (2011) and Luhar and Nepf (2016) for their validation, resulting in similar parameter selections.

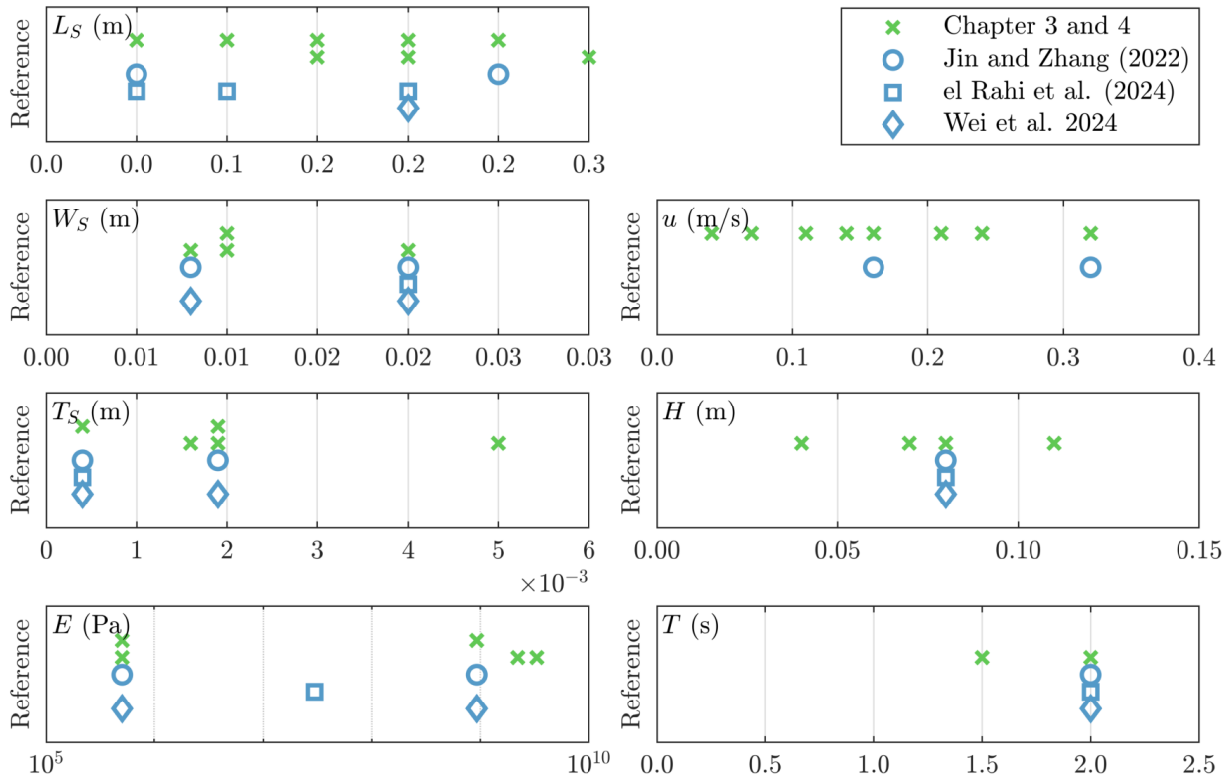


Figure 4.2. Comparison of utilized parameter ranges of the structural solver (stem length L_S , stem width W_S , stem thickness T_S , and Young's modulus E) to validate FSI solvers in unidirectional (with flow velocity u) and oscillatory (with wave height H and period T) flow conditions across different studies

Throughout the validation of the FSI solver in REEF3D::CFD in Section 3.2 and Section 3.3, the chosen accuracy threshold of less than 10% deviation compared to the reference experiments regarding the stem movement and exerted forces has been achieved

for most cases. However, the validation revealed, through grid convergence studies, the importance of choosing a small cell size for the refined grid in the proximity of the stem. While for the unidirectional flow simulations (Section 3.2), a refined cell size of 0.0015 m was determined as sufficient, a refined cell size of 0.001 m was chosen for the oscillatory flow conditions (Section 3.3). Similar magnitudes can be found for comparable FSI studies, with Henteleff et al. (2024) and Tschisgale and Fröhlich (2020) both utilizing a cell size of 0.001 m in the proximity of the stem. The herein applied ratio of stem width to the refined cell size varies between 0.26 and 1.26 for unidirectional and between 1.60 and 5.00 for oscillatory flow conditions. Accurate replication of the hydrodynamic conditions is required to allow for a reliable assessment of the resulting FSI and a realistic judgment of the model validation. In Section 3.3, where the time-dependent motion of the stem has been evaluated, the sensitivity of the FSI solver regarding the incoming flow field has been revealed. Small deviations between wave shape or incoming velocity profile of the reference experiments (here Luhar and Nepf (2011, 2016); Jacobsen et al. (2019)) influence the resulting FSI, rendering high-fidelity validation of numerical solvers in the time domain challenging. Such deviations could be avoided by including records of the wave generation in experimental data sets, which serve as reference studies. Alternatively, detailed information of the incoming flow field, for example, through PIV measurements as done in Section 3.1, could enhance the determination of differences in the flow field of the FSI compared to the physical experiments.

Largely unaddressed in the literature, the investigation in Section 3.2 showed the relevance of the utilized turbulence model. The application of the widely utilized RANS $k - \omega$ turbulence model led to a nonphysical increase of the turbulent kinetic energy, providing a potential explanation for the deviations of the FSI observed by Henteleff et al. (2024). Improved results were achieved with a modification to increase the turbulent energy dissipation on the stem's interface. Further on, LES have been shown to provide the most accurate results regarding stem movement and resulting forces compared to the adapted $k - \omega$ model and URANS simulations for FSI solver in REEF3D::CFD. Additionally, accurate wall treatment is considered essential for the application of turbulence models to simulate the FSI. The reliability of the results may be reduced if the laws of the wall are not well-suited to the flow conditions. In Sections 3.2 and 3.3, the requirements of the Cosserat rod equations to utilize damping coefficients for the calculation of the internal moments and forces have been introduced. Their application and influence on the FSI have been examined for unidirectional (Section 3.2) and oscillatory flow conditions (Section 3.3). Overall, it has been observed that while the influence of the damping coefficients is negligible for steady-state conditions, they play a crucial role in replicating the time-dependent components of the FSI due to their influence on the stem motion. Furthermore, appropriate damping coefficients are important to ensure numerical stability and can, if needed, be used to restrict the structural motion artificially. In the literature, the utilized damping coefficients varied for c_d , accounting for translational damping, between 0.02 to 200 and for c_k , accounting for rotational damping, between 1×10^{-6} to 0.04 (Lang et al., 2011; Till et al., 2019; Martin and Bihs, 2021b). The studies neither detailed their choice regarding the magnitude of damping coefficients utilized nor their influence on the FSI. In Section 3.3, a c_d equal to one has been applied, and a range between 1×10^{-6} to 1×10^{-8} was recommended for c_k , based on the comparison to physical experiments utilizing surrogate stems. In Section 3.4, the recommended range of

damping coefficients has been applied to represent live vegetation stem dynamics while ensuring numerical stability. The performance evaluation of the FSI solver facilitates the identification of potential model enhancements, with particular emphasis on improving computational efficiency and numerical robustness. To date, the broader application of the FSI solver in REEF3D::CFD and simulation of several stems to replicate a salt marsh meadow are limited by the required computational demand of the numerical implementation. Tschisgale et al. (2021) has shown in their implementation of the solver that it is possible to simulate a vegetation meadow with 800 individual stems. However, their prescribed stem length of 0.07 m is noticeably shorter than that of natural salt marsh vegetation, which typically reaches several decimeters in length (Keimer et al., 2023b, 2024). For the implementation of the FSI solver in REEF3D::CFD, Sections 3.2 and 3.3 reveal that longer stem lengths, requiring more individual rigid elements, result in increased simulation times. Furthermore, to maintain numerical stability, the coarse cell size in the non-uniform grid currently requires being twice that of the refined grid, leading to an excessive total number of cells. This issue requires further investigation to enable more effective use of the non-uniform grid and to reduce computational time. The FSI solver's efficiency could be enhanced alternatively by replacing the structural solver. Currently, the exact Cosserat rod model is solved in the framework of the FSI solver in REEF3D::CFD, accounting for a great range of motion, including bending, shearing, stretching, and twisting. Depending on the application case, it should be evaluated if a more simplistic rod theory, such as introduced in Section 2.3.2, would be sufficient to replicate the desired structural motion and thus reduce the required computational time. In its current implementation, the performance of the FSI solver in REEF3D::CFD is limited by the structural solver, whose equations, in contrast to the application of MPI for the fluid component, are solved in series. The computational time required could be either improved by applying a multithreading approach, as seen in Mosquera Michaelsen et al. (2013), or MPI parallelization, as implemented by Lorentzon and Revstedt (2020) for their structural solver. In the following, model advantages, which have been revealed throughout Section 3.2 and Section 3.3, and current challenges that limit the applicability of the FSI solver are summarized.

Concluding remarks of Section 4.3

Model advantages:

- Validated for unidirectional and oscillatory flow conditions with $< 10\%$ deviation
- Incorporation of stem properties without empirical coefficients to calculate the external forces
- Ability to represent a great range of stem flexibilities
- Capable of various motion types (bending, shearing, twisting, stretching)

Current challenges:

- Appropriate damping coefficients required for numerical stability for live vegetation properties
- Requires fine grid resolution with 1 mm refined cell size and a non-uniform grid with an excessive number of cells
- Improved efficiency of the structural solver required to model longer stems
- Adjustments to the structural solver to represent complex geometries

4.4 The effect of the regional and seasonal variation of live vegetation properties on the fluid-structure interaction

The following discusses the extent to which the replication of the variation in biomechanical stem properties is relevant for the flow field alterations, and on a broader scale. Throughout this thesis, salt marsh stems from different salt marsh species, seasons, and regions were replicated in either physical or numerical modeling approaches, with the results summarized in Sections 3.1, 3.2, 3.3, and 3.4. An overview of the different comparisons conducted throughout this thesis is provided in Figure 4.3.

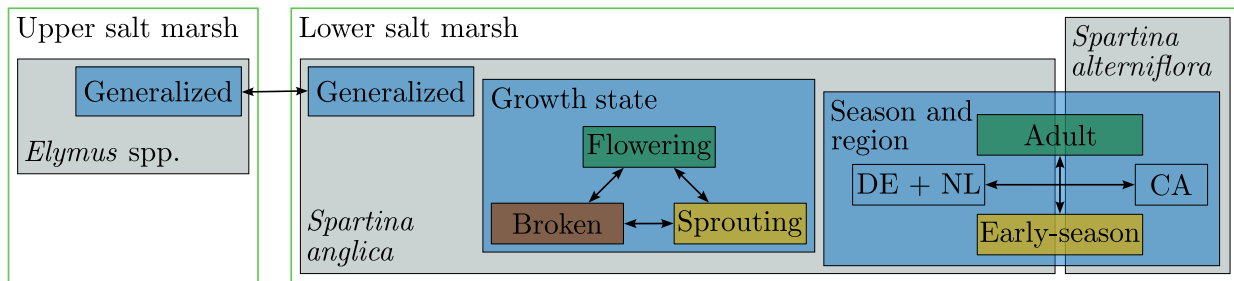


Figure 4.3. Overview of compared scenarios, differentiated by salt marsh zonation and plant species, including the variation of season and growth state for *Spartina anglica* and the seasonal variation for *Spartina alterniflora*, and different regions of the two *Spartina* species with Germany (DE), the Netherlands (NL), and Canada (CA)

As indicated in Figure 4.3, the study summarized in Section 3.1 replicates the lower salt marsh species *S. anglica* and the upper salt marsh species *Elymus* spp. in physical hydrodynamic experiments. The second study (cf. Section 3.2) compares flow field alterations based on previously defined growth states of *S. anglica* (Keimer et al., 2023b) in unidirectional flow numerically. In the study summarized in Section 3.4, biomechanical stem properties of two species located in the lower salt marsh, *S. anglica* and *S. alterniflora*, from two different regions, the Southeast North Sea coast (the Netherlands and Germany) and the St. Lawrence Estuary (Canada), were applied in numerical simulations. For both salt marsh species, seasonal variation was implemented by comparing stems replicating biomechanical properties measured in early-season and adult plants.

Tendencies can be summarized regarding the comparison between plant species and seasonal and regional influence, differentiated by the hydrodynamic regime. In unidirectional flow conditions, it has been observed that stem bending differs between plant species (Section 3.1). Correspondingly, the extent and shape of the stem-induced flow field alterations, usually relative to the stem position, vary for each plant species. The current-induced stem bending also differs depending on the replicated growth state of *S. anglica* (Section 3.2). As expected, the distribution of the normalized velocity and the *TI* profiles in the wake of the stems differs as well. While the deviation of the resulting drag force for each stem is negligible, the derived drag coefficients vary for each growth state corresponding to the bent stem position. Section 3.4 further shows for unidirectional flow conditions that the stem bending and the derived drag coefficients differ depending on the simulated season of *S. anglica* and *S. alterniflora*. In contrast, the difference in the extent of the *TI* profile in the wake of the stem is more pronounced for stems replicating different regions than the seasonal variation.

In oscillatory flow conditions, it was shown that the stem bending differs for each plant species (Section 3.1). Further, flow field alterations and their area of extent differ for each plant species, such as the normalized velocity magnitude in the proximity of the stem. The simulations, summarized in Section 3.4, show that the regional variation is more pronounced than the seasonal variation regarding stem-induced flow field alterations in oscillatory flow conditions.

Figure 4.4 shows a comprehensive summary based on the tested stems in Section 3.1, Section 3.2, and Section 3.4 in unidirectional flow conditions. The influence of the flow field on the stem is quantified through its bending position, expressed by the bending angle ϕ , relative to the upright stem position (Figure 4.4 (a)), the resulting drag force relative to the stem length (Figure 4.4 (b)), and the turbulence intensity TI (Figure 4.4 (c)).

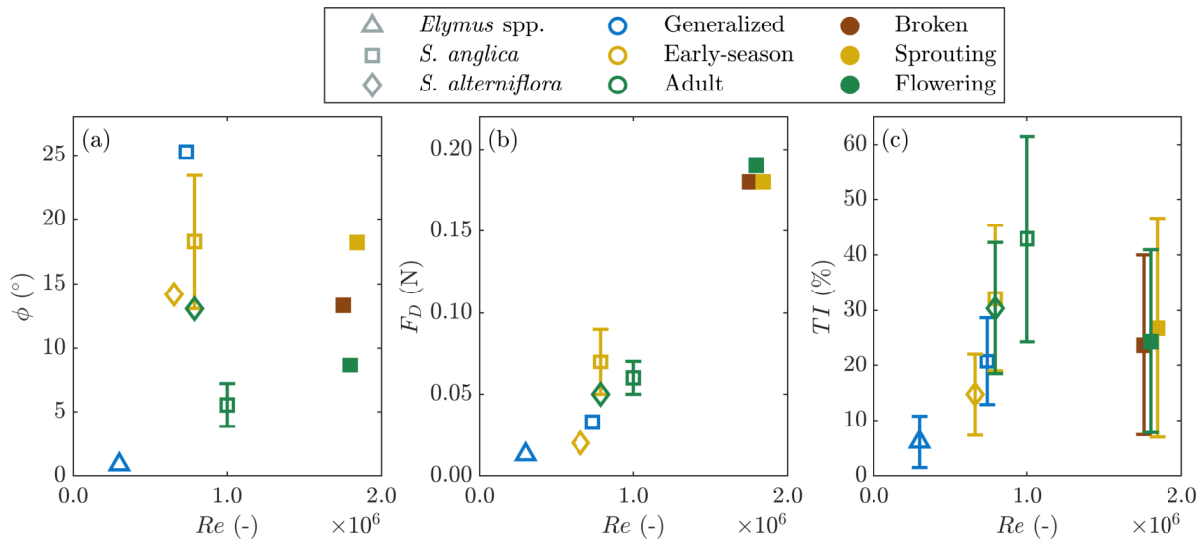


Figure 4.4. Summary of parameters describing the current-vegetation interaction presented in Sections 3.1, 3.2, and 3.4 with (a) bending angle ϕ of the bent stem position (0° corresponding to an upright stem), (b) mean drag force F_D that the flow is exerting on the stem, and (c) turbulence intensity TI of the stem wake in 0.10 m distance to the stem in x -direction, with varying flow velocities for the generalized stems ($u = 0.20$ m/s), the seasonal stems ($u = 0.30$ m/s), and the variation in growth state ($u = 0.50$ m/s) with marker shape indicating plant species, and marker color and fill representing seasonal variation

Since the drag force has not been measured in the experimental study (Section 3.1), F_D has been calculated based on the Morison equation with the effective lengths of the stems, determined through the non-dimensional parameters Ca and B as introduced by Luhar and Nepf (2011) and applied in the study summarized in Section 3.2. The influence of the stems on the flow field in their wake (at 0.10 m distance) is expressed by the mean TI over the height of the stem in Figure 4.4 (c), with the error bars indicating the standard deviation of TI over the stem height. For the stems representing spring and summer conditions of *S. anglica*, the derived ϕ , F_D , and TI were averaged across the results representing three investigated European salt marshes, with the standard deviation indicated by error bars.

Figure 4.4 enables the identification of tendencies regarding the variability within each study. Due to the different utilized current velocities ($u = 0.20$ m/s, 0.30 m/s, and 0.50 m/s),

stem lengths (0.11 to 0.25 m) and corresponding submergence ratios (0.37 to 0.83) of the stems, the results of the different studies cannot be directly compared with each other. Further, it should be noted that the results from physical and numerical investigations are included, limiting the comparability. Generally, the bending angle ϕ appears to be independent of Re in Figure 4.4 (a), while a correlation of Re with the drag force F_D and the turbulence intensity TI can be observed in Figures 4.4 (b) and (c). Different trends are apparent in Figure 4.4 regarding ϕ , F_D , and TI . For example, the generalized stems of *Elymus* spp. and *S. anglica* show the highest difference in terms of bending angle in Figure 4.4 (a), but compared to other studies, less difference in their derived drag force in Figure 4.4 (b). Further, the different growth states (broken, sprouting, and flowering) of *S. anglica* show a clear distinction regarding their stem bending in Figure 4.4 (a). In contrast, the growth states show similar orders of magnitude regarding TI in the wake of the stem in Figure 4.4 (c), while the resulting TI of the generalized *Elymus* spp. and *S. anglica* stems can be clearly distinguished. For future studies, it should be carefully evaluated if the seasonal variation within a salt marsh is relevant for the study's aim and justifies the thereby introduced level of detail. However, based on the observations provided in this thesis, it is recommended that plant species within a salt marsh should be distinguished regarding their drag forces and influence on the flow field to avoid simplified conclusions regarding the fluid-vegetation interaction.

In the study summarized in Section 3.1, differences regarding the influence range of the vegetation stems on their surrounding flow field have been observed between the replicated salt marsh species. However, such species grow with different horizontal stem densities in the field, varying seasonally. For example, Keimer et al. (2023a) measured $1933 \pm 592 \text{ m}^{-2}$ stems of *S. anglica* in December and January compared to $1246 \pm 602 \text{ m}^{-2}$ stems on average for February to June. For the upper salt marsh species *Elymus* spp., Keimer et al. (2024) counted from December to April $2108 \pm 748 \text{ m}^{-2}$ stems, from May to September $1248 \pm 600 \text{ m}^{-2}$ stems, and from October to December $1192 \pm 719 \text{ m}^{-2}$ stems, highlighting the seasonal cycle of the horizontal density. Reconsidering the observed flow field alterations in Section 3.1, the larger area of extent in distance to the stem may be compensated by lower stem horizontal densities within the salt marsh, similar to the elaboration by (Schoutens et al., 2024), linking the salt marshes' wave attenuation capacity to vegetation properties. To investigate such effects further at the meadow scale, it is important to include the heterogeneity of salt marshes observed in the field, as well as sheltering and collision effects, which have not been addressed within this thesis. Based on the varying stem-induced flow field alterations observed herein, upscaling approaches should incorporate the increased turbulence in the stems' proximity, as it has been reported to influence ecosystem services like wave attenuation and sediment deposition processes (Deitrick et al., 2023; Vettori et al., 2025).

Plant flexibility plays a larger role as the flexural stiffness of the stem decreases. With the biomechanical properties representing flexible salt marsh vegetation, the stems have a distinctive bending angle in unidirectional flow conditions but a comparably narrow extent of stem motion for the herein tested oscillatory flow conditions, highlighted in Section 3.1 in physical experiments and in Section 3.4 in numerical simulations. Correspondingly, the difference regarding flow field alterations is more pronounced in unidirectional than in oscillatory flow conditions. However, in the coastal or estuarine environment, tidal or

freshwater currents exist in combination with waves, but have only been studied separately in this thesis. Previous studies have shown that the wave attenuation within vegetation meadows is influenced by the interaction of waves and currents (Paul et al., 2012; Hu et al., 2021; Zhang and Nepf, 2024). Furthermore, the magnitude of the wave height and current velocity utilized within Section 3.1 and 3.4 were chosen to represent everyday conditions for a salt marsh at the German North Sea coast. At the barrier island Spiekeroog in the North Sea, mean current velocities of $0.13 \text{ m/s} \pm 0.09 \text{ m/s}$ were recorded, compared to a maximum current velocity of 10.71 m/s during a storm surge event (Zielinski et al., 2018). Mean significant wave heights ($H_{1/3}$) were observed with 0.03 m compared to a maximum significant height of 0.73 m during a storm surge event (Zielinski et al., 2018). While such differences between everyday and extreme hydrodynamic conditions are expected to result in a varying FSI, Leonardi et al. (2016) determined average wave conditions as the main driver for salt marsh erosion, compared to storm conditions only contributing with 1 % to the erosion processes.

Overall, it can be concluded that both seasonal and regional variation of biomechanical stem properties influence the flexural stiffness of the stem, resulting in varying bent stem positions, drag forces, and flow field alterations. Below, the discussion points are summarized, separated by the influence of the regional and seasonal variation of biomechanical stem properties.

Concluding remarks of Section 4.4

Regional influence:

- Plant species from the same salt marsh zone, but different geographic regions, vary in their biomechanical stem properties, such as stem diameter and flexural stiffness, decisive for the fluid-structure interaction and resulting in different flow field alterations
- Plant species from different salt marsh zones vary regarding their biomechanical stem properties, thus experiencing different stem motion and corresponding flow field alterations

Seasonal influence

- The difference of the fluid-structure interaction is more pronounced for stems with biomechanical properties from April and September than differentiated by their growth state
- The difference in flow field alterations is less pronounced for seasonal variation compared to plants representing different regions or salt marsh species
- The stem bending varies with the seasons, resulting in different drag coefficients

This chapter presents concluding remarks on the main findings and contributions of the thesis. It outlines recommended directions for future research, highlighting how subsequent studies could build upon the methodologies, results, and limitations discussed herein.

5.1 Concluding remarks

The significance of salt marshes as a NbS for coastal protection strategies has been detailed in Section 2.1 regarding their wave attenuation capacity, erosion resistance, and sedimentation enhancement. Numerical or physical modeling approaches can provide further insights into the fluid-vegetation interaction. Such modeling approaches are required to enable researchers and policymakers to give informed recommendations and make decisions regarding the incorporation of salt marshes into coastal protection strategies.

This study presents a comprehensive, structured approach exploring different modeling approaches, aiming at the accurate replication of *in situ* measured live vegetation stem properties. The tested modeling approaches enable the investigation of the ecosystem services provided by salt marshes at the stem level. For an accurate representation of the live vegetation, the incorporation of the seasonal and regional variation of biomechanical stem properties is required. The research objectives, introduced in Section 1.1.1, have been addressed as follows:

RO 1



To evaluate the integration of *in situ* measured vegetation properties in physical and numerical modeling approaches

Effective numerical simulations of the fluid-vegetation interaction require carefully chosen numerical methods and coupling approaches to capture the dynamic interactions between fluids and flexible structures. This interaction involves structural deformations and fluid forces, which are two-way coupled and must therefore be modeled adaptively. Effective coupling strategies should consider factors such as the choice of spatial resolution and temporal coupling to account for rapid or complex structural responses. Enabling the incorporation of live vegetation properties measured *in situ*, the FSI modeling approach should be independent of empirical coefficients, such as drag coefficients, to determine the external forces. Numerical modeling approaches have the advantage that the structural

properties can be precisely incorporated, and a larger variation of scenarios, such as varying stem flexibility or hydrodynamic conditions, can be modeled.

In contrast, physical modeling approaches have the advantage of providing a physical replication of the flow field and thus the stem-induced turbulence. Compared to currently utilized structural solvers in numerical modeling approaches, 3D printed surrogates are expected to be able to represent complex geometries, such as leaves, and to incorporate varying flexibilities within a single surrogate, for example, by using different filaments in a dual extrusion printer. However, the accuracy of replicating the biomechanical stem properties depends on the surrogate material utilized and the fabrication process.

RO 2



To develop surrogate materials that can replicate the biomechanical stem properties of live vegetation for physical hydrodynamic experiments

As it remains challenging to replicate all properties of a natural salt marsh stem accurately with traditionally utilized surrogate materials, the application of 3D printing with flexible filament is explored. The tested fabrication process offers larger versatility than traditional surrogates, enabling fine-tuning of key properties such as the stem's width and flexural stiffness, ensuring representative obstruction of the stem to the incoming flow field and fluid-induced stem motion. Furthermore, 3D printing has the advantage of enabling the development of complex geometries or varying flexibilities for stems and leaves. Additionally, filament is less sensitive to environmental exposure than the previously utilized flexible resin due to its material properties.

The approach presented in this thesis showed the ability of 3D printed surrogates to represent material properties of different salt marsh species (*S. anglica* and *Elymus* spp.), confirmed by a statistical similarity analysis. However, replicating seasonal variations based on *in situ* measured salt marsh stem properties requires a more advanced iterative printing process. Additionally, larger stem dimensions and increased flexibility lead to longer printing times, and adjustments to the printing setup are necessary for circular or very thin stems.

RO 3



To assess the capability of a fluid-structure interaction solver to accurately replicate vegetation stem motion and resulting forces

The FSI solver in the hydrodynamics toolbox REEF3D::CFD has been validated, and its potential to accurately replicate live vegetation properties has been investigated for unidirectional and oscillatory flow conditions. The approach is validated for varying material parameters with less than 10% deviation. It has been highlighted that the model can incorporate *in situ* measured live vegetation stem properties without relying on empirical coefficients to determine the external forces and captures a wide range of flexibilities and motion types. Highest accuracy between simulated and experimental stem motion and forces was achieved using LES in combination with a fine grid resolution of 1 mm in the proximity of the stem.

However, numerical stability of the FSI solver in REEF3D::CFD requires appropriate utilization of damping coefficients without artificially restricting the desired natural motion of live vegetation stems. Based on the numerical analysis presented in this thesis, damping coefficients on the order of 1×10^{-8} to 1×10^{-6} are recommended. However, careful evaluation of their influence is strongly advised for applications beyond the evaluation range provided in this thesis.

RO 4



To examine the impact of fluid-structure interaction on the flow field, considering seasonal and regional variation in modeled live vegetation

After confirming the applicability of the modeling approaches, the influence of both regional and seasonal variations in the salt marsh stem properties on the fluid-vegetation interaction remains to be investigated.

For all investigated parameters describing the FSI such as the bending angle, stem tip excursion, drag force, turbulence intensity, and turbulent kinetic energy, larger differences have been observed between regions (Southeast North Sea and the St. Lawrence Estuary) and plant species (*S. anglica*, *S. alterniflora*, and *Elymus* spp.) compared to the seasonal variation, differentiated by growth states (sprouting, flowering, broken) or timing in the seasonal cycle (early-season and adult stems). The most pronounced influence of seasonality became apparent regarding the stem bending or motion range. However, the same influence of seasonality was not reflected in the derived stem-induced flow field alterations. Therefore, ecosystem services with stem motion as a decisive factor, such as the wave attenuation capacity, might be more prone to seasonal variation than those ecosystem services where the flow-field alterations are relevant, for example, regarding the sediment deposition process.

By accurately replicating the fluid-vegetation interaction and providing approaches that can directly incorporate *in situ* measured stem properties, this work provides a critical foundation for FSI solutions to model flexible salt marsh vegetation. The techniques and insights presented here support realistic simulations of the fluid-vegetation interaction, contributing to the ongoing development and application of FSI in engineering and enabling the evaluation of the influence of regionally and seasonally varying biomechanical stem properties. This thesis provides tools that can be further applied to determine ecosystem services at the stem scale based on site-specific field properties and future upscaling approaches to the meadow scale.

5.2 Recommendations for future work

Future work should expand on different aspects explored in this thesis, including field investigations, surrogate development for physical experiments, and numerical modeling of salt marshes.

Field measurements: For all modeling approaches presented in this thesis, their ability to incorporate *in situ* measured biomechanical stem properties was emphasized. As such, standardized and representative field investigations are essential to apply the proposed modeling strategies. Field studies, often conducted by researchers from disciplines such as biology and ecology, are encouraged to include more frequently vegetation parameters derived from materials science, such as flexural stiffness and material density, to fully characterize the biomechanical aspects of the stems. As explored within this thesis by way of example for two study sites, future investigations should extend the exploration of regional differences regarding the seasonal variation in biomechanical stem properties. Then, a more comprehensive comparison of flow field alterations can be achieved in future studies based on the combination of extended available data sets, including biomechanical stem properties, and the herein proposed modeling approaches.

FSI solver: Facilitating the integration of field data into the FSI solver in REEF3D::CFD, initial efforts should focus on enhancing the solver's efficiency. Key components regarding the solver's efficiency are grid optimization and the parallelization of the structural solver. In the next step, adaptations should be developed to account for spatial variation in stem properties along the stem height, as demonstrated by Schoppmann et al. (2021). Additionally, strategies for incorporating more complex stem geometries and leaves should be explored to improve the fidelity of live vegetation replication, as shown in Marjoribanks et al. (2019). Another recommended research direction is the investigation of stem-stem interactions, as implemented by Tschisgale (2020), but not yet investigated with *in situ* measured salt marsh stem properties, to capture the collective behavior of densely growing vegetation patches more accurately.

3D printed surrogates: The 3D printing process proposed in this study should be refined through iterative development to achieve the accuracy needed to replicate seasonal variations in biomechanical stem properties, as proposed in Section 4.2, building upon the printing configurations provided in the Appendix to Section 3.1. The printing setup should then be extended to accommodate more complex plant geometries, allowing for a comprehensive representation of live vegetation properties. In contrast to the adaptations required for the FSI solver, the incorporation of complex plant geometries is expected to be more straightforward with 3D printing, highlighting the versatility and practical advantage of the proposed methodology. Building on these improvements, future studies should include investigations of the influence of the flow field by brush-type vegetation, such as *A. portulacoides*, since, compared to the frequently studied lower salt marsh species, for example *S. anglica* and *S. alterniflora*, the influence of brush-type salt marsh vegetation is underexplored to date.

Further investigations at the stem level: Future studies should integrate sediment transport processes into both numerical and physical modeling frameworks, with explicit consideration of stem flexibility, as an extension of the approach demonstrated by van Veelen et al. (2025). This would enable a comparison of flow field alterations due to the stem's obstruction and stem-induced turbulence, which are both governed by the stem motion and

therefore linked to flexural stiffness. Quantifying the relative contributions of these processes to local sedimentation and erosion in the proximity of the stem would provide valuable insight into local vegetation–sediment interactions. Subsequent investigations should extend this analysis to include sheltering effects and allow for the extrapolation to the meadow scale.

Upscaling approaches: Along the way to a predictive model, it is required to pursue an appropriate upscaling technique that bridges between simulations of individual plants to meadow-scale interaction with incoming waves and tidal currents. Upscaling could utilize the drag coefficients obtained from the individual plant simulations, serving as input parameters in meadow-scale modeling approaches. One example is the volume averaged Navier-Stokes (VARANS) approach, which simplifies an area covered by salt marshes as a porous medium block, see for example, in Hadadpour et al. (2019) or Suzuki et al. (2019). Such a porous media approach has been implemented in the REEF3D::CFD toolbox (Sasikumar et al., 2020) and applied by Spröer et al. (2025) to simulate groins and by Kelly et al. (2025) to represent mangroves but currently lacks validation for salt marsh vegetation. Similarly, vegetation effects can be parameterized using sink terms incorporating vegetation characteristics such as spatial density, stem height, diameter, and empirical friction coefficients. Such an application has been, among others, demonstrated in the modeling framework of Delft3D by Jiang et al. (2023), yet it requires the utilization of representative drag coefficients. Further refinement has previously been enabled through subgrid canopy flow models, such as the implementation in XBeach by van Rooijen et al. (2022), which remains to be evaluated regarding its applicability to represent seasonal variation of salt marsh properties. Another common method involves the application of roughness coefficients in large-scale models (e.g., Siemes et al. (2020)); however, this simplification omits complex processes such as wave attenuation and sediment entrapment within the meadow. Despite numerous efforts, all upscaling techniques face to date challenges in capturing the dynamic effects of plant swaying and fine-scale variability associated with seasonal biomechanical stem properties. Addressing these limitations remains crucial to reliably replicate salt marshes at the meadow scale.

Investigations at the meadow scale: Meadow scale investigations are essential for evaluating the ecosystem services provided by salt marshes, whether based on individual stems, if computationally feasible, or on the upscaling approaches described previously. Such studies enable, for example, the assessment of wave attenuation capacity while accounting for the seasonal and regional variability of salt marsh vegetation. The resulting insights regarding seasonal wave attenuation potential can provide useful information for guidelines, including NbS and salt marshes as coastal protection elements. Furthermore, incorporating climate change scenarios into these analyses provides a valuable understanding of potential future impacts regarding the wave attenuation capacity of salt marsh ecosystems or their potential to grow vertically in alignment with the projected sea level rise.

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- Agrawal, V., Kulachenko, A., Scapin, N., Tammisola, O., and Brandt, L. (2024). An efficient isogeometric/finite-difference immersed boundary method for the fluid–structure interactions of slender flexible structures. *Computer Methods in Applied Mechanics and Engineering*, 418.
- Alessi, C., Agabiti, C., Caradonna, D., Laschi, C., Renda, F., and Falotico, E. (2024). Rod models in continuum and soft robot control: a review. *tbd*.
- Anderson, M. and Smith, J. (2014). Wave attenuation by flexible, idealized salt marsh vegetation. *Coastal Engineering*, 83:82–92.
- Angus, S. and Dargie, T. (2024). Improving the definition of a coastal habitat: Putting the salt back into saltmarsh. *Estuarine, Coastal and Shelf Science*, 309:108954.
- Arriola, J. M. and Cable, J. E. (2017). Variations in carbon burial and sediment accretion along a tidal creek in a florida salt marsh. *Limnology and Oceanography*, 62(S1).
- Attili, T., Heller, V., and Triantafyllou, S. (2023). Scaling approaches and scale effects in wave–flexible structure interaction. *Journal of Fluids and Structures*, 123:103987.
- Augustin, L. N., Irish, J. L., and Lynett, P. (2009). Laboratory and numerical studies of wave damping by emergent and near-emergent wetland vegetation. *Coastal Engineering*, 56(3):332–340.
- Baaij, B. M., Kooijman, J., Limpens, J., Marijnissen, R. J. C., and van Loon-Steensma, J. M. (2021). Monitoring impact of salt-marsh vegetation characteristics on sedimentation: an outlook for nature-based flood protection. *Wetlands*, 41(6).
- Baker, S., Murphy, E., Cornett, A., and Knox, P. (2022). Experimental study of wave attenuation across an artificial salt marsh. *Front. Built Environ.*, 8.
- Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, 81(2):169–193.
- Bass, J., Granse, D., Hache, I., Jensen, K., Karius, V., Minden, V., Stock, M., Suchrow, S., and Kleyer, M. (2022). Plant traits affect vertical accretion of salt marshes. *Estuarine, Coastal and Shelf Science*, 276:108010.
- Behm, J. E., Waite, B. R., Hsieh, S. T., and Helmus, M. R. (2018). Benefits and limitations of three-dimensional printing technology for ecological research. *BMC ecology*, 18(1):32.
- Bihs, H., Kamath, A., Alagan Chella, M., Aggarwal, A., and Arntsen, Øivind. (2016). A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. *Computers & Fluids*, 140:191–208.
- Blackmar, P. J., Cox, D. T., and Wu, W.-C. (2014). Laboratory observations and numerical simulations of wave height attenuation in heterogeneous vegetation. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 140(1):56–65.
- Bömer, J., Esser, F., Marks, E., Rosu, R. A., Behnke, S., Klingbeil, L., Kuhlmann, H., Stachniss, C., Mahlein, A.-K., and Paulus, S. (2024). A 3D printed plant model for accurate and reliable 3D plant phenotyping. *GigaScience*, 13.
- Boorman, L. A., Garbutt, A., and Barratt, D. (1998). The role of vegetation in determining patterns of the accretion of salt marsh sediment. *Geological Society, London, Special*

- Publications*, 139(1):389–399.
- Bouma, T. J., van Duren, L. A., Temmerman, S., Claverie, T., Blanco-Garcia, A., Ysebaert, T., and Herman, P. (2007). Spatial flow and sedimentation patterns within patches of epibenthic structures: Combining field, flume and modelling experiments. *Continental Shelf Research*, 27 (8):1020–1045.
- Bromirski, P. D., Flick, R. E., and Miller, A. J. (2017). Storm surge along the pacific coast of north america. *Journal of Geophysical Research: Oceans*, 122(1):441–457.
- Brooks, H., Möller, I., Carr, S., Chirol, C., Christie, E., Evans, B., Spencer, K. L., Spencer, T., and Royse, K. (2021). Resistance of salt marsh substrates to near-instantaneous hydrodynamic forcing. *Earth Surface Processes and Landforms*, 46(1):67–88.
- Cahoon, D. R., McKee, K. L., and Morris, J. T. (2021). How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Estuaries and Coasts*, 44(4):883–898.
- Caldera, G., Stolle, J., van Pham Bang, D., Murphy, E., and Knox, P. (2025). Seasonal and inter-annual changes in wave attenuation by a constructed salt marsh on a sloping bed. *Ecological Engineering*, 221:107758.
- Cao, D. Q. and Tucker, R. W. (2008). Nonlinear dynamics of elastic rods using the cosserat theory: Modelling and simulation. *International Journal of Solids and Structures*, 45 (2).
- Caroppi, G. and Järvelä, J. (2022). Shear layer over floodplain vegetation with a view on bending and streamlining effects. *Environ Fluid Mech*, 22 (2-3):587–618.
- Carrasco, A. R., Kombiadou, K., and Matias, A. (2023). Short-term sedimentation dynamics in mesotidal marshes. *Scientific reports*, 13(1):1921.
- Cassalho, F., de Lima, A. S., Coleman, D. J., Henke, M., Miesse, T. W., Coelho, G. d. A., and Ferreira, C. M. (2023). Projecting future wave attenuation by vegetation from native and invasive saltmarsh species in the united states. *Regional Studies in Marine Science*, 68:103264.
- Celik, I., Klein, M., Freitag, M., and Janicka, J. (2006). Assessment measures for urans/des/les: an overview with applications. *Journal of Turbulence*, 7:N48.
- Chen, C. J. and Jaw, S.-y. (1997). *Fundamentals of turbulence modeling*. Combustion. Taylor & Francis, Washington, DC.
- Chen, H. and Zou, Q.-P. (2019). Eulerian–lagrangian flow-vegetation interaction model using immersed boundary method and openfoam. *Advances in Water Resources*, 126:176–192.
- Chourdakis, G., Schneider, D., and Uekermann, B. (2023). OpenFOAM-preCICE: coupling OpenFOAM with external solvers for multi-physics simulations. *OpenFOAM J*, 3:1–25.
- Ci, S., Wang, B., Di, C., Wang, M., Zhu, B., and Qiao, K. (2025). Effect of ultraviolet aging on properties of epoxy resin and its pultruded fiber-reinforced composite. *Polymers*, 17(3).
- Cosserat, E. and Cosserat, F. (1896). Sur la théorie de l’élasticité: Premier mémoire. *Annales de la Faculté des sciences de Toulouse pour les sciences mathématiques et les sciences physiques 1e série*, 10 (3-4).
- D’Alpaos, A., Mudd, S. M., and Carniello, L. (2011). Dynamic response of marshes to perturbations in suspended sediment concentrations and rates of relative sea level rise. *Journal of Geophysical Research*, 116(F4):77.
- Deitrick, A. R., Hovendon, E. H., Ralston, D. K., and Nepf, H. (2023). The influence of vegetation-generated turbulence on deposition in emergent canopies. *Frontiers in Marine Science*, 10.

- Dijkstra, J. T. and Uittenbogaard, R. E. (2010). Modeling the interaction between flow and highly flexible aquatic vegetation. *Water Resour. Res.*, 46.
- D'Ippolito, A., Calomino, F., Dey, S., Gaudio, R., and Penna, N. (2023). Bedload transport through emergent vegetation: current status and its future prospect. *Environmental Fluid Mechanics*.
- Döllinger, M., Zhang, Z., Schoder, S., Šidlof, P., Tur, B., and Kniesburges, S. (2023). Overview on state-of-the-art numerical modeling of the phonation process. *Acta Acustica*, 7:25.
- Dunlop, T., Glamore, W., and Felder, S. (2023). Restoring estuarine ecosystems using nature-based solutions: Towards an integrated eco-engineering design guideline. *The Science of the total environment*, page 162362.
- El Rahi, J., Martínez-Estévez, I., Almeida Reis, R., Tagliafierro, B., Domínguez, J. M., Crespo, A. J. C., Stratigaki, V., Suzuki, T., and Troch, P. (2024). Exploring wave-vegetation interaction at stem scale: Analysis of the coupled flow-structure interactions using the SPH-Based DualSPHysics Code and the FEA Module of Chrono. *Journal of Marine Science and Engineering*, 12(7):1120.
- El Rahi, J., Martínez-Estévez, I., Tagliafierro, B., Domínguez, J., Crespo, A., Stratigaki, V., Suzuki, T., and Troch, P. (2023). Numerical investigation of wave-induced flexible vegetation dynamics in 3D using a coupling between DualSPHysics and the FEA module of Project Chrono. *Ocean Engineering*, 285.
- Esselink, P., van Duin, W. E., Bunje, J., Cremer, J., Folmer, E. O., Frikke, J., Glahn, M., de Groot, A. V., Hecker, N., Hellwig, U., Jensen, K., Körber, P., Petersen, J., and Stock, M. (2017). CWSS: salt marshes. In Kloepper, S., Baptist, M. J., Bostelmann A., Busch J.A., Buschbaum C., Gutow L., Janssen G., and Jensen K., editors, *Wadden Sea Quality Status Report*. Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany.
- Feagin, R. A., Lozada-Bernard, S. M., Ravens, T. M., Möller, I., Yeager, K. M., and Baird, A. H. (2009). Does vegetation prevent wave erosion of salt marsh edges? *Proceedings of the National Academy of Sciences of the United States of America*, 106(25):10109–10113.
- Ferziger, J. H., Perić, M., and Street, R. L. (2020). *Computational methods for fluid dynamics*. Springer, Cham, fourth edition edition.
- Garzon, J. L., Maza, M., Ferreira, C. M., Lara, J. L., and Losada, I. J. (2019). Wave attenuation by spartina saltmarshes in the chesapeake bay under storm surge conditions. *Journal of Geophysical Research: Oceans*, 124(7):5220–5243.
- Gillis, L., Maza, M., Garcia-Maribona, J., Lara, J. L., Suzuki, T., Argemi Cierco, M., Paul, M., Folkard, and Balke, T. (2022). Living on the edge: How traits of ecosystem engineers drive bio-physical interactions at coastal wetland edges. *Advances in Water Resources*, 166:104257.
- Goseberg, N., Krautwald, C., Schweiger, C., Schürenkamp, D., and Windt, C. (2025). Innovative hydrodynamic research facilities for offshore renewable energy: a case study on the effects of biofouling. In *American Society of Mechanical Engineers 2025 – Proceedings of ASME 2025 44th*.
- Griggs, G. and Patsch, K. (2019). The protection/hardening of california's coast: Times are changing. *Journal of Coastal Research*, 35(5):1051.
- Hadadpour, S., Paul, M., and Oumeraci, H. (2019). Numerical investigation of wave attenuation by rigid vegetation based on a porous media approach. *Journal of Coastal*

- Research*, 92(sp1):92.
- Hagmeyer, N., Mayr, M., and Popp, A. (2024). A fully coupled regularized mortar-type finite element approach for embedding one-dimensional fibers into three-dimensional fluid flow. *Numerical Meth Engineering*, 125 (8).
- Hassani, M., Laurin, S. M., Mureithi, N. W., and Gosselin, F. P. (2017). Bending and torsional reconfiguration of chiral rods under wind and gravity. *Extreme Mechanics Letters*, 13:91–99.
- He, S., Liu, H., and Shen, L. (2022). Simulation-based study of turbulent aquatic canopy flows with flexible stems. *J. Fluid Mech.*, 947.
- Henteleff, R., Stolle, J., Markov, A., Nistor, I., and Sriram, V. (2024). The performance of flexible fluid–structure interaction module for saltmarsh vegetation under flow and wave action. *Canadian Journal of Civil Engineering*.
- Hitzegrad, J., Brohmann, L., Herding, F., Pfennings, K., Jonischkies, S., Scharnbeck, E., Mainka, J., Mai, I., Windt, C., Kloft, H., Wehrmann, A., Lowke, D., and Goseberg, N. (2024). Surfaces of coastal biogenic structures: exploiting advanced digital design and fabrication strategies for the manufacturing of oyster reef and mussel bed surrogates. *Frontiers in Marine Science*, 11.
- Hu, Z., Lian, S., Wei, H., Li, Y., Stive, M., and Suzuki, T. (2021). Laboratory data on wave propagation through vegetation with following and opposing currents. *Earth System Science Data*, 13(10):4987–4999.
- Huang, X., Zhu, B., and Chen, Y. (2024). A coupled peridynamics–smoothed particle hydrodynamics model for fluid–structure interaction with large deformation. *Physics of Fluids*, 36(11).
- Jacobsen, N., Bakker, W., Uijttewaalt, W. S. J., and Uittenbogaard, R. (2019). Experimental investigation of the wave-induced motion of and force distribution along a flexible stem. *J. Fluid Mech.*, 880:1036–1069.
- Jayswal, A. and Adanur, S. (2023). Characterization of polylactic acid/thermoplastic polyurethane composite filaments manufactured for additive manufacturing with fused deposition modeling. *Journal of Thermoplastic Composite Materials*, 36(4):1450–1471.
- Jeon, Y. J. and Sung, H. J. (2011). Piv measurement of flow around an arbitrarily moving body. *Experiments in Fluids*, 50(4):787–798.
- Jiang, H., Chai, C., and Zhang, M. (2023). Numerical study on the influence of salt marsh plants on coastal wetland hydrodynamics and suspended sediment transport. *Frontiers in Environmental Science*, 11.
- Jin, C. and Zhang, J. (2022). Numerical investigation of the wave interaction with flexible vegetation: model setup and validation for a single stem study case. *Anthropocene Coasts*, 5.
- Johansen, S. T., Wu, J., and Shyy, W. (2004). Filter-based unsteady rans computations. *International Journal of Heat and Fluid Flow*, 25(1):10–21.
- Jung, P., Leyendecker, S., Linn, J., and Ortiz, M. (2011). A discrete mechanics approach to the cosserat rod theory—part 1: static equilibria. *Numerical Meth Engineering*, 85 (1):31–60.
- Keimer, K., Kind, F., Prüter, I., Kosmalla, V., Lojek, O., Schürenkamp, D., Prinz, M., Niewerth, S., Aberle, J., and Goseberg, N. (2024). From seasonal field study to surrogate modeling: Investigating the biomechanical dynamics of *elymus* sp. in salt marshes.

- Limnography and Oceanography Methods.*
- Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Schürenkamp, D., and Goseberg, N. (2023a). Field measurements of geometrical and mechanical properties of *Spartina anglica* on Spiekeroog, Germany, from December 2021 to December 2022. TU Braunschweig Open Research Data Repository. <https://doi.org/10.24355/dbbs.084-202311010949-0>. Dataset.
- Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Prinz, M., Schürenkamp, D., Freund, H., and Goseberg, N. (2023b). Proposing a novel classification of growth periods based on biomechanical properties and seasonal changes of *spartina anglica*. *Front. Mar. Sci.*, 10.
- Keimer, K., Schürenkamp, D., Miescke, F., Kosmalla, V., Lojek, O., and Goseberg, N. (2021). Ecohydraulics of surrogate salt marshes for coastal protection: Wave–vegetation interaction and related hydrodynamics on vegetated foreshores at sea dikes. *J. Waterway, Port, Coastal, Ocean Eng.*, 147 (6).
- Kelly, D., Mann, F., Lamei, A., Pender, D., Bellafont, F., Bihs, H., Wang, W. W., and Savant, G. (2025). CFD modelling of wave-mangrove interaction via RANS and VARANS approaches. *Coastal Engineering Proceedings*, 13.
- Keshavarz, B., Zarket, B., Amin, S., Rughani, R., Muthukrishnan, S., Holten-Andersen, N., and McKinley, G. H. (2021). Characterizing viscoelastic properties of synthetic and natural fibers and their coatings with a torsional pendulum. *Soft matter*, 17(17):4578–4593.
- Kettle, A. J. (2019). Storm tilo over europe in november 2007: storm surge and impacts on societal and energy infrastructure. *Advances in Geosciences*, 49:187–196.
- Kim, H. D., Yu, X., and Kaplan, D. (2024). Steady flow over a finite patch of submerged flexible vegetation. *Water Resources Research*, 60 (1).
- Koftis, T., Prinos, P., and Stratigaki, V. (2013). Wave damping over artificial *posidonia oceanica* meadow: A large-scale experimental study. *Coastal Engineering*, 73:71–83.
- Kosmalla, V., Keimer, K., Schürenkamp, D., Lojek, O., and Goseberg, N. (2022). Erosion resistance of vegetation-covered soils: Impact of different grazing conditions in salt marshes and analysis of soil-vegetation interactions by the novel dicoastar method. *Ecological Engineering*, 181.
- Lang, H., Linn, J., and Arnold, M. (2011). Multi-body dynamics simulation of geometrically exact cosserat rods. *Multibody Syst Dyn*, 25 (3):285–312.
- Lara, J. L., Maza, M., Ondiviela, B., Trinogga, J., Losada, I. J., Bouma, T. J., and Gordejuela, N. (2016). Large-scale 3-D experiments of wave and current interaction with real vegetation. Part 1: guidelines for physical modeling. *Coastal Engineering*, 107:70–83.
- Leendertse, P. C., Scholten, M. C., and van der Wal, J. T. (1996). Fate and effects of nutrients and heavy metals in experimental salt marsh ecosystems. *Environmental pollution*, 94(1):19–29.
- Leonardi, N., Ganju, N. K., and Fagherazzi, S. (2016). A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. *Proceedings of the National Academy of Sciences of the United States of America*, 113(1):64–68.
- Lima, S. F., Neves, C. F., , and Rosauro, N. M. L. (2006). Damping of gravity waves by fields of flexible vegetation. *Proc., 30th Int. Conf. on Coastal Engineering*.
- Liu, J., Kutschke, S., Keimer, K., Kosmalla, V., Schürenkamp, D., Goseberg, N., and Böhl, M. (2021). Experimental characterisation and three-dimensional modelling of *Elymus* for

- the assessment of ecosystem services. *Ecological Engineering*, 166.
- Liu, J., Liu, Q., Kutschke, S., Kosmalla, V., Schürenkamp, D., Goseberg, N., and Böl, M. (2024a). Seasonal variations in biomechanical properties of *Elymus* species: Implications for assessing coastal ecosystem services. *PAMM*, 24(2).
- Liu, Z., Fagherazzi, S., He, Q., Gourgue, O., Bai, J., Liu, X., Miao, C., Hu, Z., and Cui, B. (2024b). A global meta-analysis on the drivers of salt marsh planting success and implications for ecosystem services. *Nature communications*, 15(1):3643.
- Lo, V. B., Bouma, T. J., van Belzen, J., van Colen, C., and Airolidi, L. (2017). Interactive effects of vegetation and sediment properties on erosion of salt marshes in the northern adriatic sea. *Marine environmental research*, 131:32–42.
- Lorentzon, J. and Revstedt, J. (2020). A numerical study of partitioned fluid–structure interaction applied to a cantilever in incompressible turbulent flow. *International Journal for Numerical Methods in Engineering*, 121(5):806–827.
- Losada, I. J., Maza, M., and Lara, J. L. (2016). A new formulation for vegetation-induced damping under combined waves and currents. *Coastal Engineering*, 107:1–13.
- Love, A. E. H. (1906). *A treatise on the mathematical theory of elasticity*. Cambridge University Press, Cambridge, England.
- Lowe, R. J., Falter, J. L., Koseff, J. R., Monismith, S. G., and Atkinson, M. J. (2007). Spectral wave flow attenuation within submerged canopies: Implications for wave energy dissipation. *J. Geophys. Res.*, 112.
- Luhar, M. and Nepf, H. M. (2011). Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. *Limnology and Oceanography*, 56:2003–2017.
- Luhar, M. and Nepf, H. M. (2016). Wave-induced dynamics of flexible blades. *Journal of Fluids and Structures*, 61:20–41.
- Marin-Diaz, B., van der Wal, D., Kaptein, L., Martinez-Garcia, P., Lashley, C. H., Jong, K. d., Nieuwenhuis, J. W., Govers, L. L., Olff, H., and Bouma, T. J. (2023). Using salt marshes for coastal protection: Effective but hard to get where needed most. *Journal of Applied Ecology*.
- Marjoribanks, T. I., Lague, D., Hardy, R. J., Boothroyd, R. J., Leroux, J., Mony, C., and Puijalon, S. (2019). Flexural rigidity and shoot reconfiguration determine wake length behind saltmarsh vegetation patches. *J. Geophys. Res. Earth Surf.*, 124:2176–2196.
- Markov, A., Muller, M., Nistor, I., Baker, S., Stolle, J., Murphy, E., and Cornett, A. (2025). Wave interactions with *Spartina alterniflora* on a living dyke model: New insights into the use of scaled surrogate meadows. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 151(3).
- Markov, A., Stolle, J., Henteleff, R., Nistor, I., van Pham Bang, D., Murphy, E., and Cornett, A. (2023). Deformation of *Spartina patens* and *Spartina alterniflora* stems under irregular wave action. *Coastal Engineering Journal*, page 1–22.
- Martin, T. and Bihs, H. (2021a). A non-linear implicit approach for modelling the dynamics of porous tensile structures interacting with fluids. *Journal of Fluids and Structures*, 100.
- Martin, T. and Bihs, H. (2021b). A numerical solution for modelling mooring dynamics, including bending and shearing effects, using a geometrically exact beam model. *JMSE*, 9(5):486.
- Mayr, M., Wall, W. A., and Gee, M. W. (2018). Adaptive time stepping for fluid-structure interaction solvers. *Finite Elements in Analysis and Design*, 141:55–69.

- Maza, M., Lara, J. L., and Losada, I. J. (2013). A coupled model of submerged vegetation under oscillatory flow using navier–stokes equations. *Coastal Engineering*, 80:16–34.
- Mcowen, C. J., Weatherdon, L. V., van Bochove, J.-W., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C. S., Spalding, M., and Fletcher, S. (2017). A global map of saltmarshes. *Biodiversity data journal*, 5:e11764.
- Meier, C., Popp, A., and Wall, W. A. (2019). Geometrically exact finite element formulations for slender beams: Kirchhoff–love theory versus simo–reissner theory. *Archives of Computational Methods in Engineering*, 26(1):163–243.
- Meixler, M. S., Kennish, M. J., and Crowley, K. F. (2018). Assessment of plant community characteristics in natural and human-altered coastal marsh ecosystems. *Estuaries and Coasts*, 41(1):52–64.
- Miquel, A. M., Kamath, A., Alagan Chella, M., Archetti, R., and Bihs, H. (2018). Analysis of different methods for wave generation and absorption in a cfd-based numerical wave tank. *Journal of Marine Science and Engineering*, 6(2):73.
- Moeller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B. K., Wolters, G., Jensen, K., Bouma, T. J., Miranda-Lange, M., and Schimmels, S. (2014). Wave attenuation over coastal salt marshes under storm surge conditions. *Letters Nature Geoscience*, 7.
- Möller, I. and Spencer, T. (2002). Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change. *Journal of Coastal Research*, 36:506–521.
- Morison, J. R., O’Brien, M. P., Johnson, J. W., and Schaaf, S. A. (1950). The force exerted by surface waves on piles. *Petroleum Transactions*, 189.
- Mosquera Michaelsen, P., Pritz, B., and Gabi, M. (2013). A fluid-structure-interaction tool by coupling of existing codes. In Dongarra, J., editor, *Proceedings of the 20th European MPI Users’ Group Meeting*, ACM Other conferences. ACM, New York, NY.
- Mudhaffer, S., Althagafi, R., Haider, J., Satterthwaite, J., and Silikas, N. (2024). Effects of printing orientation and artificial ageing on martens hardness and indentation modulus of 3D printed restorative resin materials. *Dental materials: official publication of the Academy of Dental Materials*, 40(7):1003–1014.
- Mullarney, J. C. and Henderson, S. M. (2010). Wave-forced motion of submerged single-stem vegetation. *J. Geophys. Res.*, 115.
- Nakayama, A. and Miyashita, K. (2001). URANS simulation of flow over smooth topography. *International Journal of Numerical Methods for Heat & Fluid Flow*, 11(8):723–745.
- Ni, J., Ji, C., Xu, D., Zhang, X., and Liang, D. (2023). On Monami modes and scales of a flexible vegetation array in a laminar boundary layer. *Physics of Fluids*, 35 (7).
- Nicoud, F. and Ducros, F. (1999). Subgrid-scale stress modelling based on the square of the velocity gradient tensor. *Flow, Turbulence and Combustion*, 62:183–200.
- Okamoto, T.-a. and Nezu, I. (2010). Large eddy simulation of 3-D flow structure and mass transport in open-channel flows with submerged vegetations. *Journal of Hydro-environment Research*, 4 (3):185–197.
- O’Reilly, O. M. (2017). *Modeling Nonlinear Problems in the Mechanics of Strings and Rods: The Role of the Balance Laws*. Interaction of Mechanics and Mathematics. Springer International Publishing and Imprint: Springer, Cham, 1st edition.
- Ouyang, X. and Lee, S. Y. (2014). Updated estimates of carbon accumulation rates in coastal marsh sediments. *Biogeosciences*, 11(18):5057–5071.

- Ozeren, Y., Wren, D. G., and Wu, W. (2014). Experimental investigation of wave attenuation through model and live vegetation. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 140(5).
- O'Connor, J. and Rogers, B. D. (2021). A fluid-structure interaction model for free-surface flows and flexible structures using smoothed particle hydrodynamics on a GPU. *Journal of Fluids and Structures*, 104.
- Palm, J., Eskilsson, C., and Bergdahl, L. (2017). An hp -adaptive discontinuous Galerkin method for modelling snap loads in mooring cables. *Ocean Engineering*, 144:266–276.
- Paprotny, D., Terefenko, P., Giza, A., Czapliński, P., and Vousdoukas, M. I. (2021). Future losses of ecosystem services due to coastal erosion in Europe. *The Science of the total environment*, 760:144310.
- Paul, M., Bouma, T. J., and Amos, C. L. (2012). Wave attenuation by submerged vegetation: combining the effect of organism traits and tidal current. *Mar. Ecol. Prog. Ser.*, 444:31–41.
- Paul, M., Rupprecht, F., Möller, I., Bouma, T. J., Spencer, T., Kudella, M., Wolters, G., van Wesenbeeck, B. K., Jensen, K., Miranda-Lange, M., and Schimmels, S. (2016). Plant stiffness and biomass as drivers for drag forces under extreme wave loading: A flume study on mimics. *Coastal Engineering*, 117:70–78.
- Puijalon, S., Bouma, T. J., Douady, C. J., van Groenendael, J., Anten, N. P. R., Martel, E., and Bornette, G. (2011). Plant resistance to mechanical stress: evidence of an avoidance-tolerance trade-off. *The New phytologist*, 191 (4):1141–1149.
- Pujol, D., Serra, T., Colomer, J., and Casamitjana, X. (2013). Flow structure in canopy models dominated by progressive waves. *Journal of Hydrology*, 486:281–292.
- Rabinowitz, T. and Andrews, J. (2022). Valuing the salt marsh ecosystem: Developing ecosystem accounts.
- Radfar, S., Mahmoudi, S., Moftakhari, H., Meckley, T., Bilskie, M. V., Collini, R., Alizad, K., Cherry, J. A., and Moradkhani, H. (2024). Nature-based solutions as buffers against coastal compound flooding: Exploring potential framework for process-based modeling of hazard mitigation. *The Science of the total environment*, 938:173529.
- Rayner, D., Glamore, W., Grandquist, L., Ruprecht, J., Waddington, K., and Khojasteh, D. (2021). Intertidal wetland vegetation dynamics under rising sea levels. *Science of The Total Environment*, 766:144237.
- Renda, F., Giorelli, M., Calisti, M., Cianchetti, M., and Laschi, C. (2014). Dynamic model of a multibending soft robot arm driven by cables. *IEEE Trans. Robot.*, 30 (5):1109–1122.
- Ricci, F., Vacondio, R., Domínguez, J. M., and Tafuni, A. (2025). Three-dimensional variable resolution for multi-scale modeling in smoothed particle hydrodynamics. *Computer Physics Communications*, 313:109609.
- Richter, T. (2017). *Fluid-structure Interactions*, volume 118. Springer International Publishing, Cham.
- Riffe, K. C., Henderson, S. M., and Mullarney, J. C. (2011). Wave dissipation by flexible vegetation. *Geophysical Research Letters*, 38(18).
- Robson, G., Schoen, E., Chan, D. M., Ogrosky, H. R., Shrestha, K., and Zinnert, J. C. (2024). Modeling the interaction of vegetation and sea level rise on barrier island evolution. *PloS one*, 19(8):e0302395.
- Rooijen, A., Lowe, R., Rijnsdorp, D. P., Ghisalberti, M., Jacobsen, N. G., and McCall, R. (2020). Wave-driven mean flow dynamics in submerged canopies. *Journal of Geophysical*

- Research: Oceans*, 125(3).
- Roy, S., De, A., and Balaras, E., editors (2020). *Immersed Boundary Method: Development and Applications*. Springer eBook Collection. Springer Singapore and Imprint Springer, Singapore, 1st edition.
- Rucker, D. C. and Webster III, R. J. (2011). Statics and dynamics of continuum robots with general tendon routing and external loading. *IEEE Trans. Robot.*, 27 (6):1033–1044.
- Rupprecht, F., Möller, I., Evans, B., Spencer, T., and Jensen, K. (2015). Biophysical properties of salt marsh canopies — quantifying plant stem flexibility and above ground biomass. *Coastal Engineering*, 100:48–57.
- Rupprecht, F., Möller, I., Paul, M., Kudella, M., Spencer, T., van Wesenbeeck, K., B., Wolters, G., Jensen, K., Bouma, T., Miranda-Lange, M., and Schimmels, S. (2017). Vegetation-wave interactions in salt marshes under storm surge conditions. *Ecol. Eng.*, 100:301–315.
- Saeedipour, M. (2023). An enstrophy-based analysis of the turbulence–interface interactions across the scales. *International Journal of Multiphase Flow*, 164:104449.
- Sasikumar, A., Kamath, A., and Bihs, H. (2020). Modeling porous coastal structures using a level set method based VRANS-solver on staggered grids. *Coastal Engineering Journal*, 62 (2):198–216.
- Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T. J., Silva, R., Schlurmann, T., and Schüttrumpf, H. (2019). Hard structures for coastal protection, towards greener designs. *Estuaries and Coasts*, 42(7):1709–1729.
- Schoppmann, K., Löhrer, B., Tschisgale, S., Fröhlich, J., and Langre, E. d. (2021). An efficient solver for a cosserat rod of non-constant width applied to a problem of fluid-structure interaction. *Proc Appl Math & Mech*, 21 (1).
- Schoutens, K., Heuner, M., Fuchs, E., Minden, V., Schulte-Ostermann, T., Belliard, J.-P., Bouma, T. J., and Temmerman, S. (2020). Nature-based shoreline protection by tidal marsh plants depends on trade-offs between avoidance and attenuation of hydrodynamic forces. *Estuarine, Coastal and Shelf Science*, 236:106645.
- Schoutens, K., Silinski, A., Belliard, J.-P., Bouma, T. J., Temmerman, S., and Schoelynck, J. (2024). Wave attenuation by intertidal vegetation is mediated by trade-offs between shoot- and canopy-scale plant traits. *Journal of Applied Ecology*.
- Schulze, D., Rupprecht, F., Nolte, S., and Jensen, K. (2019). Seasonal and spatial within-marsh differences of biophysical plant properties: implications for wave attenuation capacity of salt marshes. *Aquat Sci*, 81 (4).
- Shepard, C. C., Crain, C. M., and Beck, M. W. (2011). The protective role of coastal marshes: A systematic review and meta-analysis. *PloS one*, 6(11):e27374.
- Siemes, R. W. A., Borsje, B. W., Daggenvoorde, R. J., and Hulscher, S. J. M. H. (2020). Artificial structures steer morphological development of salt marshes: A model study. *Journal of Marine Science and Engineering*, 8(5):326.
- Smagorinsky, J. (1963). General circulation experiments with the primitive equations. *Mon. Wea. Rev.*, 91 (3):99–164.
- Spröer, F., Lojek, O., Bischoff, C., Bunzel, D., Paul, M., and Goseberg, N. (2025). High fidelity numerical modelling of European brushwood groyne fluid-structure-interaction: Parametrization through Darcy–Forchheimer, reflection and transmission coefficients. *Coastal Engineering*, 197:104659.

- Steinigeweg, C. S., Siebeneicher, O. J., Schröder, B., Kleyer, M., Löhmus, K., and Löbel, S. (2025). Elevational ranges of pioneer marsh species are site specific and likely shaped by different abiotic and biotic factors. *Ecosphere*, 16(1).
- Stoorvogel, M. M., van Belzen, J., Temmerman, S., Wiesebron, L. E., Fivash, G. S., van IJzerloo, L., van de Koppel, J., and Bouma, T. J. (2024). Salt marshes for nature-based flood defense: Sediment type, drainage, and vegetation drive the development of strong sediment beds. *Ecological Engineering*, 207:107335.
- Stückemann, K.-J. and Waske, B. (2022). Mapping Lower Saxony’s salt marshes using temporal metrics of multi-sensor satellite data. *International Journal of Applied Earth Observation and Geoinformation*, 115:103123.
- Sun, P. N., Colagrossi, A., Marrone, S., Antuono, M., and Zhang, A. M. (2018). Multi-resolution Delta-plus-SPH with tensile instability control: Towards high Reynolds number flows. *Computer Physics Communications*, 224:63–80.
- Suzuki, T., Hu, Z., Kumada, K., Phan, L. K., and Zijlema, M. (2019). Non-hydrostatic modeling of drag, inertia and porous effects in wave propagation over dense vegetation fields. *Coastal Engineering*, 149:49–64.
- Taylor-Burns, R., Nederhoff, K., Lacy, J. R., and Barnard, P. L. (2023). The influence of vegetated marshes on wave transformation in sheltered estuaries. *Coastal Engineering*, 184:104346.
- Temmerman, S., Horstman, E. M., Krauss, K. W., Mullarney, J. C., Pelckmans, I., and Schoutens, K. (2023). Marshes and mangroves as nature-based coastal storm buffers. *Annual review of marine science*, 15:95–118.
- Tempest, J. A., Möller, I., and Spencer, T. (2015). A review of plant–flow interactions on salt marshes: the importance of vegetation structure and plant mechanical characteristics. *WIREs Water*, 2(6):669–681.
- Theunissen, R. (2012). Particle image velocimetry near interfaces: A moving future. *Journal of Aeronautics & Aerospace Engineering*, 01(03).
- Tian, F.-B., Dai, H., Luo, H., Doyle, J. F., and Rousseau, B. (2014). Fluid-structure interaction involving large deformations: 3D simulations and applications to biological systems. *Journal of Computational Physics*, 258.
- Till, J., Aloï, V., and Rucker, C. (2019). Real-time dynamics of soft and continuum robots based on cosserat rod models. *The International Journal of Robotics Research*, 38(6):723–746.
- Timošenko, S. (1983). *History of strength of materials: With a brief account of the history of theory of elasticity and theory of structures*. Dover, New York.
- Timošenko, S. and Goodier, J. (1951). *Theory of Elasticity*. McGraw-Hill Book Company, 2nd edition.
- Tschisgale, S. (2020). *A numerical method for fluid-structure interactions of slender rods in turbulent flow*. Dissertation, Technische Universität Dresden, Dresden.
- Tschisgale, S. and Fröhlich, J. (2020). An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid. *Journal of Computational Physics*, 423(7).
- Tschisgale, S., Löhner, B., Meller, R., and Fröhlich, J. (2021). Large eddy simulation of the fluid–structure interaction in an abstracted aquatic canopy consisting of flexible blades. *J. Fluid Mech.*, 916.

- Vacondio, R., Altomare, C., de Lefte, M., Hu, X., Le Touzé, D., Lind, S., Marongiu, J.-C., Marrone, S., Rogers, B. D., and Souto-Iglesias, A. (2021). Grand challenges for smoothed particle hydrodynamics numerical schemes. *Computational Particle Mechanics*, 8(3):575–588.
- van Loon-Steensma, J. M. and Slim, P. A. (2013). The impact of erosion protection by stone dams on salt-marsh vegetation on two wadden sea barrier islands. *Journal of Coastal Research*, 289:783–796.
- van Rooijen, A., Lowe, R., Ghisalberti, M., McCall, R., and Hansen, J. (2022). Modelling wave attenuation through submerged vegetation canopies using a subgrid canopy flow model. *Coastal Engineering*, page 104153.
- van Veelen, T. J., Fairchild, T. P., Reeve, D. E., and Karunarathna, H. (2020). Experimental study on vegetation flexibility as control parameter for wave damping and velocity structure. *Coastal Engineering*, 157.
- van Veelen, T. J., Nepf, H., Hulscher, S. J., and Borsje, B. W. (2025). The thresholds of sediment resuspension within emergent vegetation under combined wave-current conditions – a flume experiment. *Coastal Engineering*, page 104727.
- Versteeg, H. K. and Malalasekera, W. (2007). *An introduction to computational fluid dynamics: The finite volume method*. Pearson Education Ltd, Harlow England and New York, 2nd ed. edition.
- Vettori, D., Giordana, F., and Manes, C. (2025). Turbulence enhances wave attenuation of seagrass in combined wave-current flows. *Proceedings of the National Academy of Sciences of the United States of America*, 122(6):e2414150122.
- Vinent, O. D., Johnston, R. J., Kirwan, M. L., Leroux, A. D., and Martin, V. L. (2019). Coastal dynamics and adaptation to uncertain sea level rise: Optimal portfolios for salt marsh migration. *Journal of Environmental Economics and Management*, 98:102262.
- Vuik, V., Borsje, B. W., Willemsen, P. W., and Jonkman, S. N. (2019). Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. *Ocean & Coastal Management*, 171:96–110.
- Vuik, V., Suh Heo, H. Y., Zhu, Z., Borsje, B. W., and Jonkman, S. N. (2017). Stem breakage of salt marsh vegetation under wave forcing: A field and model study. *Estuarine, Coastal and Shelf Science*, 200:41–58.
- Wang, J., He, G., Dey, S., and Fang, H. (2022). Influence of submerged flexible vegetation on turbulence in an open-channel flow. *Journal of Fluid Mechanics*, 947.
- Wang, M., Avital, E. J., Bai, X., Ji, C., Xu, D., Williams, J. J. R., and Munjiza, A. (2020). Fluid–structure interaction of flexible submerged vegetation stems and kinetic turbine blades. *Comp. Part. Mech.*, 7 (5).
- Wei, W., Dai, Z., Pang, W., Wang, J., Chen, Y., and Gao, S. (2022). Frequency-dependent wave damping by tidal wetlands under storm conditions. *Journal of Hydrology*, page 128415.
- Wei, Z., Shao, Y., Kristiansen, T., and Kristiansen, D. (2024). An efficient numerical solver for highly compliant slender structures in waves: Application to marine vegetation. *Journal of Fluids and Structures*, 129.
- Whittaker, P., Wilson, C. A., and Aberle, J. (2015). An improved Cauchy number approach for predicting the drag and reconfiguration of flexible vegetation. *Advances in Water Resources*, 83:28–35.

- Wilcox, D. C. (1998). *Turbulence modeling for CFD*. DCW Industries, La Cañada, Calif., 2. ed., 2. print edition.
- Windt, C., Davidson, J., and Ringwood, J. V. (2018). High-fidelity numerical modelling of ocean wave energy systems: A review of computational fluid dynamics-based numerical wave tanks. *Renewable and Sustainable Energy Reviews*, 93:610–630.
- Wu, W.-C. and Cox, D. T. (2016). Effects of vertical variation in vegetation density on wave attenuation. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 142(2).
- Wyngaard, J. C. (2011). *Turbulence in the Atmosphere*. Cambridge University Press, Cambridge.
- Xian, G., Bai, Y., Qi, X., Wang, J., Tian, J., and Xiao, H. (2024). Hygrothermal aging on the mechanical property and degradation mechanism of carbon fiber reinforced epoxy composites modified by nylon 6. *Journal of Materials Research and Technology*, 33:6297–6306.
- Yang, S. L., Shi, B. W., Bouma, T. J., Ysebaert, T., and Luo, X. X. (2012). Wave attenuation at a salt marsh margin: A case study of an exposed coast on the Yangtze Estuary. *Estuaries and Coasts*, 35(1):169–182.
- Ye, W. and Hu, Z. (2023). A new model for quantifying wave damping by vegetation in combined wave–current flow. *Ocean Engineering*, 288:116119.
- Yin, Z., Wang, Y., Liu, Y., and Zou, W. (2020). Wave attenuation by rigid emergent vegetation under combined wave and current flows. *Ocean Engineering*, 213.
- Zhang, C. and Zhang, M. (2023). Numerical investigation of solitary wave attenuation and mitigation caused by vegetation using openfoam. *Coastal Engineering Journal*, page 1–19.
- Zhang, X., Lin, P., and Nepf, H. (2022). A wave damping model for flexible marsh plants with leaves considering linear to weakly nonlinear wave conditions. *Coastal Engineering*, 175.
- Zhang, X. and Nepf, H. (2021). Wave-induced reconfiguration of and drag on marsh plants. *Journal of Fluids and Structures*, 100:103192.
- Zhang, X. and Nepf, H. (2024). Laboratory data linking the reconfiguration of and drag on individual plants to the velocity structure and wave dissipation over a meadow of salt marsh plants under waves with and without current. *Earth System Science Data*, 16(2):1047–1062.
- Zhao, C., Tang, J., Shen, Y., and Wang, Y. (2021). Study on wave attenuation in following and opposing currents due to rigid vegetation. *Ocean Engineering*, 236.
- Zhi, Y., Li, H., An, S., Zhao, L., Zhou, C., and Deng, Z. (2007). Inter-specific competition: *Spartina alterniflora* is replacing *spartina anglica* in coastal china. *Estuarine, Coastal and Shelf Science*, 74(3):437–448.
- Zhu, L., Zou, Q., Huguenard, K., and Fredriksson, D. W. (2020a). Mechanisms for the asymmetric motion of submerged aquatic vegetation in waves: A consistent-mass cable model. *J. Geophys. Res. Oceans*, 125.
- Zhu, S., Wei, W., Zhu, Q., Wan, K., Xing, F., Yan, W., Gao, J., and Wang, Y. P. (2024). Wave attenuation and transformation across a highly turbid muddy tidal flat-salt marsh system. *Applied Ocean Research*, 147:103980.
- Zhu, Z., Yang, Z., and Bouma, T. J. (2020b). Biomechanical properties of marsh vegetation in space and time: effects of salinity, inundation and seasonality. *Annals of botany*, 125 (2):277–290.

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- Zielinski, O., Meier, D., Löhmus, K., Balke, T., Kleyer, M., and Hillebrand, H. (2018). Environmental conditions of a salt-marsh biodiversity experiment on the island of Spiekeroog (Germany). *Earth System Science Data*, 10(4):1843–1858.

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A summary of this manuscript can be found in Section 3.1 of this thesis. The following document shows the submitted study.

Flexible 3D-printed models of salt marsh vegetation to investigate unidirectional and oscillatory flow dynamics

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The assessment of ecosystem services of salt marsh vegetation requires accurate replication of their biomechanical properties, for example, with surrogate stems in flume experiments. Based on the versatility of 3D printing, this study utilizes flexible filament to achieve in situ measured biomechanical stem properties. The stems are tested in unidirectional and oscillatory flow conditions to investigate the near-stem alteration of the surrounding flow field. Statistical evaluation confirms that the surrogate stems replicate biomechanical stem properties of the tested salt marsh species. The area of extent of the influence of the stem is quantified through an enstrophy threshold of $3 \times 10^{-4} \text{ s}^{-2}$ for unidirectional and $5 \times 10^{-6} \text{ s}^{-2}$ for oscillatory flow conditions. That area of extent is shown to be a useful indicator to differentiate between unsteady state conditions of the fluid and the stem's alterations to the surrounding flow field. The correlation between the Cauchy number and the stem position resulting from the fluid-structure interaction in both unidirectional ($R^2 = 0.62$) and oscillatory ($R^2 = 0.78$) flow conditions is presented. Furthermore, the fluid-structure interaction and the resulting changes in the surrounding flow field vary depending on the salt marsh vegetation species that the surrogate stems are replicating. Overall, 3D printing with flexible filaments is confirmed as a novel approach to replicate the biomechanical properties of live vegetation in flume experiments, paving the way for future studies to address more complex geometries or varying material properties found in live vegetation in salt marshes or other ecosystems.

I. INTRODUCTION

Salt marsh vegetation is valued as a nature-based solution (NbS) in coastal protection plans for its wave attenuation capacity, erosion reduction due to soil stabilization, and accretion due to sediment entrapment^{1–3}. However, the variance of hydrodynamic and environmental conditions found in nature complicates the assessment of ecosystem services provided by salt marshes. To date, the seasonal variation of ecosystem services has been largely unexplored in the literature, as field studies were often conducted during the summer period^{4–6} and both numerical and physical modeling approaches frequently rely on idealized vegetation characteristics^{7,8}, limiting the generalization of their results.

Upon interaction, salt marsh plants can attenuate hydrodynamic forces exerted on them by swaying with the wave motion⁹ and exhibiting resistance to it, thus inducing turbulence in the surrounding flow field. Halophytes persist in exposed locations with frequent flooding and wave impact, with varying stem flexibilities. The plant motion then reduces the frontal area of the plant and the relative velocity between the plant and the water, as the flexible stem is put in motion by the external load¹⁰. The importance of including plant flexibility on the meadow scale has been shown, for example, regarding the ability of vegetation to dampen incoming waves, which reduces with increasing plant flexibility by 30 % to 70 %^{10–12}. Regarding the alteration of the flow field, Caroppi *et al.*¹³ showed that for unidirectional flow, the vegetation motion due to incorporating flexibility leads to deeper vortex penetration into the meadow along the main channel. Furthermore, Yang and Choi¹⁴ revealed that the vertical component of the turbulent intensity in the water column increases for flexible vegetation. However, these studies utilized live vegetation or idealized surrogates differing from salt marsh vegetation and, hence, their biomechanical stem properties, rendering conclusions regarding the ecosystem services of salt marshes approximate.

The ecosystem services provided by salt marsh vegetation can be studied either on a meadow scale or on the stem scale¹⁵. To date, it remains challenging to accurately incorporate the effect of the vegetation flexibility into modeling approaches on the meadow scale^{7,16}. While estimations such as the use of the effective length, developed by Luhar and Nepf¹⁷ and, for example, applied by Markov *et al.*¹⁸, for the investigation of flexible vegetation on the meadow scale exist, such an approach cannot replicate processes such as the turbulence induced by stem swaying. Overall, the complex interaction between a fluid and vegetation, influenced by the variation of biomechanical properties and seasonal effects, requires its investigation at the stem level as a first step. For

example, the dynamics of an individual vegetation stem highly influence the sediment mobilization process⁸. To date, it remains uncertain to what extent the influence of a stem on the ambient flow field depends on its flexibility and other material properties, and how to quantify its area of influence for unidirectional and oscillatory flow conditions. Furthermore, seasonal effects are usually measured on a stem level, as seen in Vuik *et al.*¹⁹, Schulze *et al.*²⁰ and Keimer *et al.*^{21,22}. These studies underline that seasonality affects all biomechanical vegetation traits, such as the stem diameter, plant height, and its stiffness. It is therefore required to first accurately replicate the observed differences in a model on the stem level, before providing upscaling approaches.

Vegetation on the stem level has been investigated by several studies^{23–27}; however, it remains challenging to represent complex shapes observed in live vegetation, such as leaves and height-dependency of stem diameters^{21,28}. Adequate representation of the vegetation in laboratory investigations has been achieved in previous studies by using live plants^{29–31} or surrogates^{32–34}. Live plants must be sampled from nature, which often requires leaving an impact on protected areas and necessitates challenging logistics, such as the transportation of the plants and their immediate use in experiments³⁰. Alternatively, the plants can be grown in the laboratory²⁹, resulting in differing growing conditions compared to the field and potentially varying material properties. Instead, stem surrogates are frequently used as a simplification of the inhomogeneous plant material regarding height, season, location within the salt marsh, and abiotic impacts^{2,20,21,35}. However, simplified models often cannot incorporate relevant factors such as plant flexibility and seasonal variation. To overcome these challenges, surrogate development advancements are necessary to accurately replicate salt marsh vegetation's stem dynamics.

In the literature, different aspects have been considered for the accurate representation of live vegetation properties with surrogates^{10,18,36,37}. Generally, when experiments do not involve scaling, surrogate dimensions, such as stem height and diameter, should align with those measured for live vegetation¹⁰. However, replicating the stem diameter of live vegetation presents certain challenges. For live vegetation, the outer stem diameter (d_v) of the plant varies along the plant height²⁸, which is often simplified in surrogate stems^{18,22}. In general, thicker vegetation stems tend to exhibit greater diameter variation along their height compared to thinner stems^{21,22}. Alternatively, vegetation stems are represented with a rectangular cross section with the width W_v and thickness T_v , as done by Wu and Cox³⁸, Paul *et al.*³⁹ and Jacobsen *et al.*⁴⁰. Either d_v or W_v are crucial to be selected identical to the stem properties found in nature to achieve comparable Reynolds numbers ($Re = \frac{uL_s\rho}{\nu}$)^{22,32,36,38}. The morphological influence of the stem cross-section is

incorporated through the second moment of inertia, I , which is usually derived from d_v . Furthermore, I is used to calculate the plants' flexural stiffness EI . The flexural stiffness is an important parameter determining the resulting stem reconfiguration and dependent processes^{41,42}. In summary, both the stem diameter, d_v , and the flexural stiffness, EI , are important parameters to align between the live vegetation and its surrogate stem.

When surrogate dimensions have been designed to replicate natural conditions, it is essential to investigate wave or current conditions similar to those observed in the field¹⁰. As a next step, the similarity of the influence of the vegetation on the hydrodynamics can be ensured by keeping a comparable magnitude of Re between field conditions and the test facility, usually applied in unidirectional flow conditions. Alternatively, the Keulegan-Carpenter number ($KC = \frac{uT}{W_S L_S}$), describing the relative importance of the drag forces over inertia forces, is used to quantify the relationship between oscillatory flow conditions and vegetation stem properties.

Furthermore, previous studies aimed to replicate the swaying motion of live vegetation^{10,18,37,43}. This stem motion is dominantly influenced by the vegetation flexural stiffness EI ^{17,44}, which influences the external drag by the Cauchy number

$$Ca = \frac{\rho W_S L_S^3 u^2}{EI}. \quad (1)$$

Furthermore, buoyancy of live vegetation may be replicated, meaning that the stem initially maintains a vertical position^{43–45}, especially relevant when emergent vegetation conditions are investigated³⁷. Either the relative density difference between water and vegetation ($\Delta\rho = \rho_S - \rho$) or the Buoyancy parameter

$$B = \frac{(\rho - \rho_S)g W_S T_S L_S^3}{EI} \quad (2)$$

can be utilized for an assessment of the similarity. However, van Veelen *et al.*¹⁰ stated that buoyancy can be neglected for test conditions with large numbers of Ca . Furthermore, investigations including the material density of live vegetation remain scarce, rendering the assessment of similarity challenging.

In summary, it was considered most relevant in this study to replicate the obstruction of a stem to the surrounding flow field, the flexural rigidity of the stem, and the hydrodynamic conditions representative of real-world applications. When these parameters were in agreement with prototype conditions, a representative fluid-structure interaction could be achieved, including swaying motion of the stem and the hydrodynamic feedback, as visualized in FIG. 1.

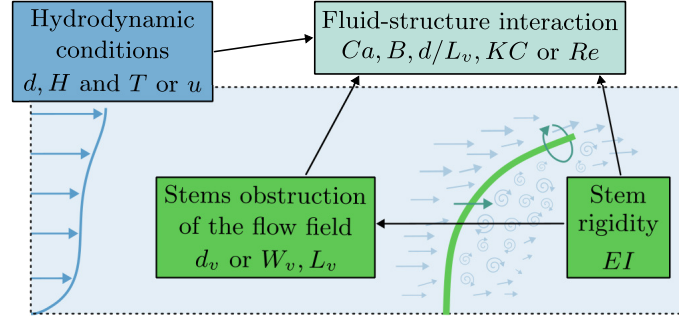


FIG. 1. Relevant processes and corresponding parameters employed to replicate the fluid-structure interaction of live vegetation using surrogate stems

Assuming that hydrodynamic conditions and the stem dimensions have been chosen in agreement with the prototype model, it is deemed crucial to utilize a material for the surrogate stem with a flexural stiffness similar to the one measured for live vegetation. If a surrogate material has been simplified as a rigid stem, the effective length theory, introduced by Luhar and Nepf¹⁷, may be applied to ensure comparable hydrodynamic forcing, as also performed by Markov *et al.*¹⁸. However, the influence of the rigid surrogate stems on their surrounding flow field, potentially differs compared to actual flexible vegetation. In contrast, van Veelen *et al.*⁴⁶ justified their choice of utilizing rigid surrogates in their experiments as they did not expect stem bending in their tested flow conditions. Most previous studies have utilized either rubber, plastic, or foam to replicate the material properties of live vegetation found in salt marshes^{18,37,43,47}. The associated material properties, such as the density and Young's modulus, vary greatly. While some studies aimed to replicate a specific vegetation species, others investigated the behavior of generalized and often idealized vegetation^{33,39,40}.

While stem diameters are usually straightforward to compare between natural and surrogate stems, the verification of the flexural stiffness differs. For example, Markov *et al.*¹⁸ did not scale EI or Ca directly due to the large variance found in nature for their target species (*S. alterniflora*). They argued that the surrogate stem should rather replicate a specific region and season instead of trying to incorporate physical properties measured for a specific species. As a verification, Markov *et al.*¹⁸ compared the stem movement of different surrogate materials under wave load to previous experimental observations with live vegetation. While no exact agreement was found, the most similar material (latex rubber tubing) was selected. While this methodology provides a reasonable approach to estimate the applicability of the stem movement, it is not suitable for vegetation that

has not been previously tested in flume experiments.

Another way of confirming the similarity in the bending behavior between live vegetation and surrogate materials is the comparison of their flexural rigidity. Earlier research^{43,47} hypothesized the agreement of material properties between their surrogate and the target species without providing any field measurement results. Other studies have aimed to achieve both similar stem diameters and Young's modulus for their surrogate stem compared to their target species, such as in the studies Anderson and Smith³⁷ and Ozeren, Wren, and Wu⁴⁵. Nevertheless, minor differences in both parameters (d_v and EI) still led to a difference in the flexural rigidity between live vegetation and surrogate material. Ozeren, Wren, and Wu⁴⁵ argued that while the elasticity of their material differed from that observed in the field, the mass density is comparable. However, surrogate materials should be able to accurately replicate all relevant processes for the fluid-vegetation interaction (cf. FIG. 1).

In contrast to the specific replication attempts of Markov *et al.*¹⁸, van Veelen *et al.*¹⁰ aimed at generally replicating vegetation properties measured in a salt marsh in South Wales, including a variation of different species. While the properties of their surrogate material fall within the measurement range in the field, they did not aim to replicate all properties of one species accurately. For example, the surrogate stem made of silicon sealants has a diameter of 5 mm, which is similar to the stem diameter of *Aster tripolium* with 5.5 mm measured in their field, but differs from the diameter of *Puccinellia maritima* ($d_v = 0.85$ mm). But in contrast, their determined flexural stiffness for the surrogate material is with 1.7×10^{-11} Nmm², similar to the one obtained for *P. maritima* with 1.9×10^{-11} Nmm² and not for the one of *A. tripolium* ($EI = 2.6 \times 10^{-8}$ Nmm²). None of the vegetation species fully met their replication requirements compared to the surrogate material. While their study provided valuable insights into flexible and rigid fluid-vegetation interactions, it did not accurately replicate all characteristics measured in salt marsh vegetation yet.

Introducing a different direction in replicating live vegetation stems, Keimer *et al.*²² utilized three dimensional (3D) resin printing to fabricate surrogates, including various flexibilities, aiming for a profound replication of in situ measured vegetation properties. They combined two different resins to achieve six surrogates with varying flexibilities to provide a proof-of-concept for 3D-printed surrogate vegetation. However, while the 3D printing allowed for an accurate replication of the stem diameter, the corresponding Young's moduli and thus flexural stiffness were lower than those measured in the field. Furthermore, resin's material properties vary with environmental conditions, such as water saturation and light exposure^{48,49}, posing additional challenges compared

to other surrogate materials. Therefore, the proposed 3D printing technology by Keimer *et al.*²² requires refinement to ensure accurate and reliable representation of live vegetation properties. Overall, it is expected that 3D-printed flexible filament is more suitable and reliable to replicate the in situ measured stem properties.

Overall, plant flexibility plays a crucial role in the stem motion and corresponding processes, such as wave attenuation or vortex penetration. However, it is not known to what extent alterations of an individual stem's flow field depend on stem parameters and how to quantify their extent. Furthermore, accurate replication of all relevant vegetation properties with surrogates for physical modeling studies remains scarce. 3D printing has been shown as a promising approach to fill that research gap. If the presented 3D printing process proves as suitable to replicate live vegetation properties, it is a promising approach to represent more complex shapes found in live vegetation, such as the incorporation of branches or leaves in subsequent studies. In conclusion, the following specific objectives will be addressed within this study:

- To develop a method for distinguishing stem-induced flow field alterations from the surrounding flow field.
- To investigate how stem-induced flow field alterations vary with material characteristics under unidirectional and oscillatory flow conditions.
- To evaluate the extent to which 3D printing with flexible filament can replicate in situ measured properties of live vegetation.

II. METHODOLOGY

A. Development and assessment of the surrogate stems

Surrogate stems were developed in a 1:1 scale to represent live vegetation stems. The stem dimensions and their flexibility have been chosen to replicate in situ measured salt marsh vegetation properties. Specifically, the salt marsh species *S. anglica* and *Elymus* spp. from the barrier island Spiekeroog, located in the German Wadden Sea, were used as the target prototype. The field campaign conducted by Keimer *et al.*²¹ and Keimer *et al.*²² resulted in an average measured outer stem diameter d_v of $4.1 \text{ mm} \pm 1.0 \text{ mm}$ ($n = 1150$) for *S. anglica* and $1.63 \text{ mm} \pm 0.31 \text{ mm}$ ($n = 1645$) for *Elymus* spp. A diameter of 4.0 mm for *S. anglica*, and of 1.6 mm for *Elymus* spp.

were accordingly chosen as the width, W_S , and thickness, T_S , of the surrogate stem, which required a rectangular shape of the stem to facilitate the 3D printing process. Throughout the growing season, the vegetation stems of *S. anglica* exhibited a great variation of stem lengths ranging from 0.07 m to 0.30 m, while the averaged stem lengths of *Elymus* spp. were constant throughout the year with about 0.37 m to 0.38 m. However, for this study, shorter stem lengths L_S have been selected (0.10 and 0.20 m) to represent two different lengths while staying in a reasonable limit for the investigated printing technology and flume facilities. The target vegetation species also vary in their flexural stiffness EI . For example, *S. anglica* measured on Spiekeroog had EI values (mean) of 2216.15 Nmm² in April and 4342.97 Nmm² in September 2022. In contrast, *Elymus* spp. exhibited a flexural stiffness of 1823.97 Nmm² in April and of 1979.48 Nmm² in September 2022. To achieve a wide range of rigidity for the surrogate stems, 3D printing technology utilizing flexible filament was applied^{50,51}.

Flexible filament has been chosen for the 3D printing process due to its consistency in material properties compared to, for example, flexible resin^{48,49}. Three filament types were selected based on their difference in rigidity for the printing of the surrogate stems. The first filament consists of polylactic acid (PLA), which can be classified as stiff and is utilized as a reference case in this study. The other two filaments are made of thermoplastic polyurethane (TPU) and differ in their shore hardness classification. Based on the manufacturer's specifications, one is classified with a shore hardness of 95A and the other with a shore hardness of 85A, corresponding to the upper and lower end of the category "hard". In the following, the PLA filament is referred to as "Stiff", the 95A TPU as "Flex1", and the 85A TPU as "Flex2". Each filament type required a specific printing setup to achieve a desirable printing quality. Generally, with increasing flexibility of the filament, higher temperatures and slower printing speeds were required. The detailed printing setup utilized for this study is provided in TABLE V in Appendix A.

The geometry and material properties of the 3D-printed surrogate stem were determined to allow for an assessment of their similarity to in situ measured vegetation stem properties and a precise evaluation of their influence on the surrounding flow field. First, the dimensions such as stem width, W_S , thickness, T_S , and length, H_S , were measured using a caliper (resolution of 0.05 mm), and average values were calculated. The standard deviations for the stem lengths were all smaller than 0.01 m across the specimens, and for the stem width and thickness, with 0.01 mm, smaller than the resolution of the caliper and therefore not further detailed. The stiffness of the 3D-printed surrogate stems has been determined by 3-point bending tests. For these tests, the

universal testing machine “500N zwicki” (ZwickRoell GmbH & Co KG) was utilized, following the measurement procedure applied by Keimer *et al.*²¹. The load cell was able to measure forces ranging from 0.2 to 50 N. For each test, the span between the two supports, s_l , was set to 0.04 m. The measurements began after a preload of 0.1 N was reached, with a displacement rate equal to 0.05 mm/s to achieve quasi-static deformation³⁵. Based on the measured force-displacement curves, the slope of the linear displacement range, here ranging between 0.2 and 1.0 mm, was quantified as $S = \Delta F / \Delta D$. The slope, S , and the span between the supports, s_l , were then utilized to calculate the flexural rigidity EI . The Young’s modulus was then determined based on the previously calculated flexural stiffness EI and the second moment of inertia I of the rectangular surrogate stems:

$$EI = \frac{s_l^3 \cdot S}{48}, \quad I = \frac{W_s T_s^3}{12}, \quad E = \frac{EI}{I} \quad (3)$$

The density of the surrogate material was determined with the density scale GRAM FD410 (GRAM PRECISION S.L.), which has a resolution of 0.001 g based on the manufacturer’s specifications. Depending on whether the 3D-printed surrogates exhibited a density larger or smaller than water, the concave or convex specimen holder was used.

The resulting properties for the rigid and flexible stem surrogates are summarized in TABLE I. Here, the material density, ρ_s , and the Young’s modulus, E , are considered to be independent of the chosen stem length, L_s . However, due to logistical reasons, the stiff surrogates were printed with different batches of the same filament type. To ensure accuracy, the material properties of the stiff surrogates were therefore separately determined for the 0.10 and 0.20 m long stem. The thick stem printed with the stiff filament was too stiff for the utilized load cell, exceeding the maximum force shortly after the start of the measurements. The provided values should therefore be considered as an indicator that the stems had a higher stiffness than the other surrogates, rather than for their absolute values. Correspondingly, no standard deviation is provided for them.

A multivariate similarity analysis was conducted to quantify the replication of the in situ measured live vegetation properties with the 3D-printed surrogate stems. Here, it is focused on the combination of stem diameter and width, ensuring similar obstruction to the flow, and the flexural stiffness, ensuring similar stem motion. The statistical similarity analysis involved Hotelling’s T^2 test⁵², the Mahalanobis distance^{53,54}, and a multivariate version of the two one-sided tests (TOST) procedure^{55,56}. The procedure is elaborated in detail in Appendix B.

TABLE I. Summary of the investigated material properties. L_S , W_S , and T_S denote stem length, width, and thickness, respectively; ρ_S is the material density, E the Young's modulus, I the second moment of inertia, and EI the flexural stiffness of the 3D-printed surrogate stems.

Material	L_S (m)	W_S (mm)	T_S (mm)	I (mm ⁴)	EI (Nmm ²)	E (MPa)	ρ_S (kg m ⁻³)
Stiff (0.10 m)	0.10	1.76	1.65	0.66±0.04	1927±450	2924±69	1199±26
Stiff (0.20 m)	0.20	1.79	1.68	0.70±0.08	1790±685	2542±185	1153±23
Stiff (0.10 m, wide)	0.10	4.40	4.09	25.01±1.20	56403	2255	917±37
Stiff (0.20 m, wide)	0.20	4.23	4.07	23.72±1.31	49316	2079	921±20
Flex1 (0.10 m)	0.10	1.87	1.59	0.63±0.08	52.4±38.4		1006±18
Flex1 (0.20 m)	0.20	1.98	1.67	0.77±0.11	2044±12.2		943±28
Flex2 (0.10 m)	0.10	1.82	1.74	0.80±0.07	19.0±7.3		1124±33
Flex2 (0.20 m)	0.20	1.87	1.78	0.88±0.40	498±4.7		887±23

B. Flume set up and hydrodynamic test program

In this section, the experimental flume setup, the hydrodynamic test program, and the utilized particle image velocimetry (PIV) measurement system to characterize the flow properties are introduced.

The experiments were conducted in a 32.80 m long, 0.50 m wide, and 0.80 m deep flume, referred to as the MiniGWK+, located at the Coastal Research Center in Hannover, Germany. The flume is equipped with a piston-type wave maker and a pump-driven current circulation, first described by Welzel, Schendel, and Goseberg⁵⁷. For this study, waves were generated at the left side of the flume while currents were generated from the right side of the flume. Flow straighteners, described by Goseberg⁵⁸, were utilized to minimize secondary flows in lateral or vertical direction. Further specifications, including positioning of the measurement equipment, are detailed in FIG. 2.

The hydrodynamic conditions used in the tests were selected to reflect the flow regime in front of the salt marsh at Spiekeroog, Germany, where the stem properties had been previously characterized. The hydrodynamic conditions in the field were obtained from long-term observations of the Spiekeroog Coastal Observatory⁵⁹, including wave heights and current velocity measurements in front of the salt marsh edge. Derived from the data set of Zielinski *et al.*⁶⁰, average monthly current velocities range between 0.10 and 0.26 m/s and maximum current velocities between 0.28 and 1.07 m/s from November 2013 to October 2015. The mean current velocity over all months

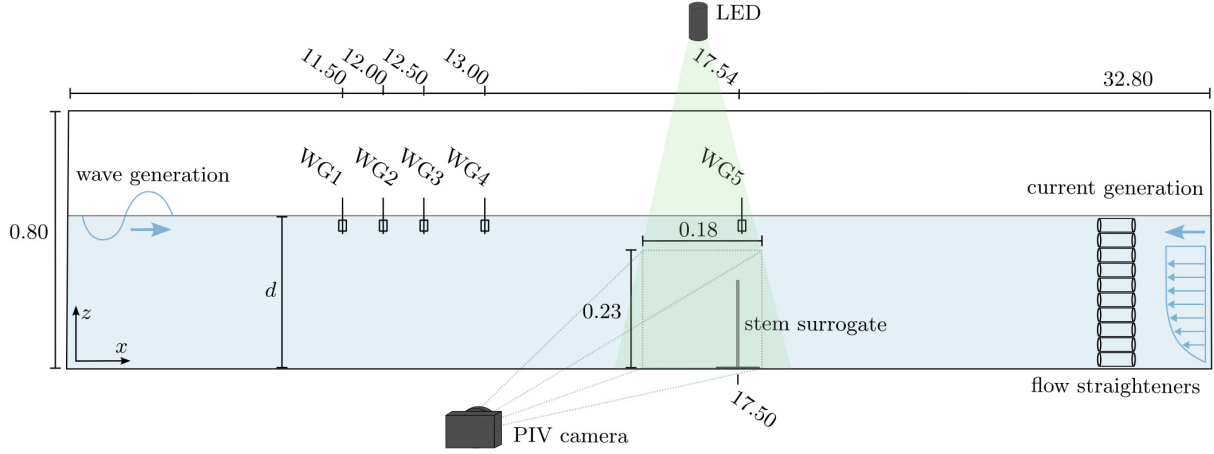


FIG. 2. Sketch of the numerical wave flume (dimensions in meters, not to scale) including the location of the stem surrogate, of the wave gauges (WG), and of the particle image velocimetry (PIV) measurement system

is 0.14 m/s and the averaged maximum current velocity is 0.46 m/s. Based on the observed mean and maximum current velocities in the field, four different current velocities (0.10, 0.20, 0.30 and 0.50 m/s) were selected for the experiments to represent the variation of unidirectional flow conditions measured in the field. They are referred to as C01, C02, C03, and C05 throughout this study. The dataset of Meier *et al.*⁶¹, including wave conditions for each month of 2019, was utilized to determine representative wave parameters. The monthly average wave height ranged between 0.05 and 0.10 m and the wave period between 1.31 and 2.96 s. The mean of the lowest and highest values concludes in wave heights of 0.06 m and 0.08 m. The means of the lowest and highest values correspond to wave periods of 1.40 s and 2.00 s. Therefore, two sets of wave conditions were selected for the experiments, with oscillatory flow to represent the range measured in the field. The combination of two different wave heights and periods were select to generate linear waves ($H_i = 0.08$ m, $T_i = 1.40$ s, referred to as W01 and $H_i = 0.06$ m, $T_i = 2.00$ s, referred to as W02). The waves have been generated based on the 2nd order Forschungszentrum Küste (FZK) Theorem, which has been adapted to ensure ideal wave generation for the specific flume. The water depth in the flume has been set constant at 0.30 m for all tests. The hydrodynamic test program based on the previous considerations is provided in TABLE II.

Water surface level elevations were measured with five ultrasonic wave gauges (WGs) (Ultra-Lab ULS HF58 from General Acoustics e.K.) with a sampling frequency of 50 Hz. The mea-

TABLE II. Summary of the hydrodynamic test program including the initial water depth, d , the target horizontal current velocity, u_i , and the target wave height, H_i , and period T_i .

Test designation (-)	d_i (m)	u_i (m/s)	H_i (m)	T_i (s)
C01	0.30	0.10	-	-
C02	0.30	0.20	-	-
C03	0.30	0.30	-	-
C05	0.30	0.50	-	-
W01	0.30	-	0.08	1.40
W02	0.30	-	0.06	2.00

measurements of the WGs were captured via data acquisition (DAQ) with the software CatmanEasy (Hottinger Brüel & Kjaer GmbH, V5.5.2) with a sampling frequency of 200 Hz. The surrogate stems were installed at a distance of $x = 17.5$ m from the wave maker. As the unidirectional current was generated at the opposite side of the flume, the distance to the installed stem was 15.3 m. The surrogate stems were positioned in the hole (0.7 mm depth) of a circular plate (diameter of 0.051 m), which was installed with three countersunk head screws to reduce impact on the flow field, ensuring the consistent positioning for all tests and surrogate stems.

The motion of the stem and the surrounding flow field were captured with a PIV system provided by ILA_5150 GmbH, based on an iLA.LPS v3 LED light source with a typical output of 7 mJ per pulse at rates of 1 kHz to generate a light sheet of about 3 mm to 5 mm thickness, see Sciacchitano⁶² for an elaboration of potential measurement uncertainties. A 2D2C setup (two-dimensional result field with two velocity components) was chosen, using a single μ EYE+ CMOS camera (ILA_5150 GmbH) with a resolution of 2448 by 2448 pixels and a sequential image rate up to 79 Hz. Synchronization of the PIV system with the WGs was achieved using a trigger signal attached to the light exposure of the light-emitting diode (LED).

Different settings for the PIV system were chosen based on the previously introduced hydrodynamic test program: The unidirectional flow conditions were captured with two different temporal resolutions in the resulting 500 flow fields (3 and 32 Hz), ensuring both a broader basis for time-independent flow statistics as well as time-resolved analyses of smaller turbulent features in the proximity of the stem. The sampling rates of the oscillatory flow conditions (20 and 14 Hz) were selected based on the wave period to ensure a constant number of 336 resulting flow field samples for each test, yielding 28 samples per wave cycle. Further specifications for the unidirectional

and oscillatory flow conditions are summarized in TABLE III. The same seeding material, hollow glass spheres, was utilized for all tests. The data was processed with PIVview (v 3.6.3) using a standard double-pass refining grid approach, yielding a final vector grid spacing of 1.8 mm in both streamwise and vertical direction.

TABLE III. Settings and resulting measurements for the PIV system utilized for each hydrodynamic condition.

Case	Pulse distance (μs)	Pulse length (μs)	Trigger rate (Hz)	Samples (-)	PIV duration (s)
C01	15.6	5.0	3	500	166.7
C01	15.6	5.0	32	500	15.6
C02	6.0	2.5	3	500	166.7
C02	6.0	2.5	32	500	15.6
C03	5.0	1.5	3	500	166.7
C03	5.0	1.5	32	500	15.6
C05	2.5	1.0	3	500	166.7
C05	2.5	1.0	32	500	15.6
W01	10.0	8.0	20	336	16.8
W02	10.0	8.0	14	336	24.0

Afterwards, temporal and spatial filtering was utilized for the velocity measurements of the PIV to reduce measurement noise. First, a centered moving average filter was applied to mitigate the impact of missing data points in the velocity fields. Subsequently, a spatial median filter was applied to each velocity field using a two-dimensional kernel of size 3×3 to suppress outliers and local noise in the spatial domain while retaining local flow structures.

C. Hydrodynamic conditions and derivation of non-dimensional parameters

In this section, ambient flow velocities for unidirectional and oscillatory tests are detailed. Non-dimensional parameters characterizing the fluid-vegetation interaction are introduced, and an overview of the hydrodynamic and non-dimensional experimental characteristics are provided.

The determination of the ambient velocity for the unidirectional flow cases is detailed in Appendix C. Utilizing the reference velocity profiles for each test case, visualized for example in

FIG. 19 (c), the ambient velocity is calculated relative to the tested stem height, L_S , indicating the characteristic depth, z , resulting in $u_{amb,c} = \langle u_{bulk} \rangle_z$.

The oscillatory flow conditions inducing the stem motion are characterized here by the ambient orbital velocity $u_{amb,w}$, which was calculated at a 0.10 m distance in front of the stem in x -direction, ensuring that the stem has not yet influenced the velocity field. Following Jacobsen *et al.*⁴⁰, the root mean square (RMS) of the depth-averaged velocity is used to calculate the ambient orbital velocity, resulting in $u_{amb,w} = \sqrt{2} \langle u_{rms} \rangle_z$. For the characteristic depth, the length of the stem was chosen, as was previously done for the unidirectional flow conditions.

It has been observed that when propagating up to the surrogate stem, the waves experienced some deformation from their originally generated linear shape. The phase-averaged water surface elevation for all test cases at WG5 (see FIG. 2) is depicted in FIG. 3 (a) for W01 and FIG. 3 (b) for W02. While deviating from linearity, the provided confidence interval for the two wave conditions shows that consistency was achieved throughout each experimental test with the same wave condition.

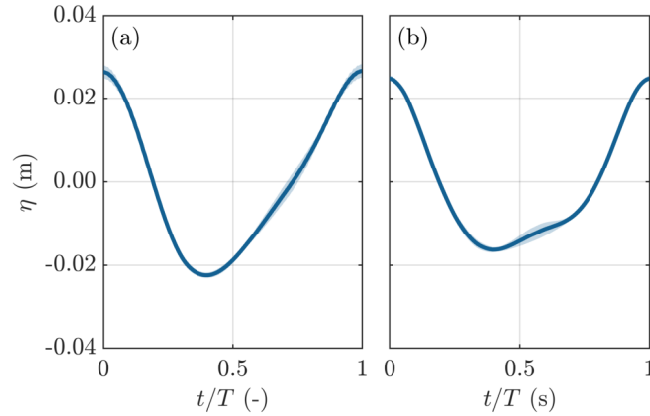


FIG. 3. Averaged profile of the waves for (a) W01 with $H_i = 0.08$ m, $T_i = 1.40$ s and (b) W02 with $H_i = 0.06$ m, $T_i = 2.00$ s

Further comparison of the test conditions was enabled by calculating non-dimensional parameters, similarly performed by Luhar and Nepf¹⁷ and Jacobsen *et al.*⁴⁰. The non-dimensional parameter Re was utilized to characterize the unidirectional flow conditions, and KC for the oscillatory flow conditions. The fluid-structure interaction (FSI) was quantified by Ca and B . For all calculations, a constant water density ρ of 1000 kg/m^3 , water viscosity ν of $1.004 \times 10^{-6} \text{ m}^2/\text{s}$ and gravitational acceleration g of 9.81 m/s^2 were utilized. The stem is characterized by its width

W_S , length L_S , thickness T_S , flexural stiffness EI , and ρ_S as the density of the stem, see TABLE I. The flow field was described by u_{amb} as the ambient velocity and the wave period, T , as stated in TABLE VI for unidirectional flow and TABLE VII for oscillatory flow conditions in Appendix D.

Utilizing the ambient velocities of each test, determined as previously elaborated based on the PIV measurements, and the material properties provided in TABLE I, the non-dimensional parameters were calculated for all tested unidirectional and oscillatory flow conditions. The results for the unidirectional flow are detailed in TABLE VI and for oscillatory flow in TABLE VII in Appendix C. It should be noted that due to time constraints, only selected surrogates were tested in oscillatory flow conditions.

D. Further analysis of the PIV measurements

Based on the raw images captured by the PIV camera, the stem bending position is obtained first. For the experiments in unidirectional flow, the mean stem position was based on an image averaged over all captured frames. Based on that, it was assumed that steady-state conditions are dominating in the unidirectional flow conditions, and that flow-induced vibrations of the stem were negligible. For the oscillatory flow, the stem position was obtained through an object detection algorithm for each time frame. Details of this algorithm are described in Appendix D. The derived stem positions are in a final step phase-averaged to align with the PIV measurements.

Due to the utilization of a 2D2C PIV system, only the u and w flow components were available, representing a two dimensional (2D) flow field. Consequently, the turbulence characteristics are considered isotropic in the y -direction, a simplification that may contribute to uncertainties in the results⁶³.

Allowing for a comparison of the turbulence across different test conditions in unidirectional flow, the turbulence intensity, TI , was calculated. Here, the mean velocity $\bar{u}$ in the x direction was selected as a reference due to its dominance in the flow field, imposed by the flow straighteners, resulting in

$$TI = \frac{\sqrt{\frac{1}{2}(u'^2 + w'^2)}}{\bar{u}} \quad (4)$$

with u as the instantaneous horizontal and w as the vertical velocity component and u' and w' being the fluctuating components of the velocity field (e.g., $u' = u - \bar{u}$).

For the oscillatory flow experiments, the velocity components were phase-averaged before calculating flow characteristics. To characterize the turbulence in the flow field, the turbulent kinetic energy (TKE) for each point in time throughout the wave phase was calculated as:

$$TKE = \frac{1}{2}(u'^2 + w'^2) \quad (5)$$

Further, it was investigated if the extent of influence of the stem-induced turbulence could be characterized by the enstrophy, as seen in Saeedipour⁶⁴, which describes the intensity of rotational motion or turbulence in the fluid. The enstrophy $\mathcal{E}$ is defined as $\mathcal{E} = \frac{1}{2}\omega^2$ with ω as the vorticity, representing the local rotation in the flow field. Utilizing the scalar vorticity in 2D flow results in

$$\mathcal{E} = \frac{1}{2} \left(\frac{\partial w}{\partial x} - \frac{\partial u}{\partial z} \right)^2 \quad (6)$$

with $\partial w/\partial x$ as spatial derivative of w in the x -direction and $\partial u/\partial z$ as the spatial derivative of u in the z -direction.

For the oscillatory flow experiments, two different regions of interest (regions of interests (ROIs)) are defined to compare the undisturbed flow field and the influence of the stem. The center point of the ROIs was positioned at $z = 0.075$ m. The center point of the undisturbed ROI was positioned at -0.15 m and in the proximity of the stem in -0.025 m in x -direction. The extent of the ROIs was 0.017 m $\times$ 0.017 m. The two windows are visualized for two different stem lengths in FIG. 4. The definition of the ROIs allows for a comparison of the stem influence on the flow field across the different wave conditions and tested surrogate stems.

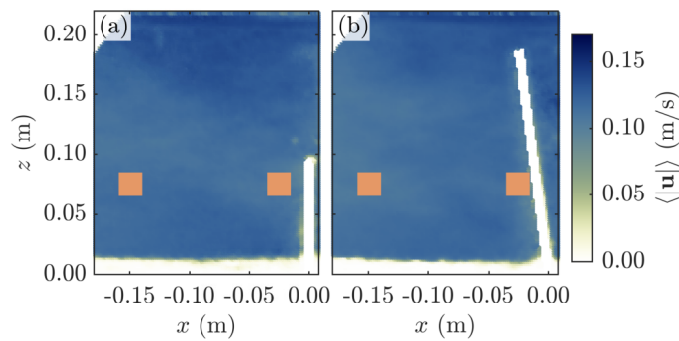


FIG. 4. Regions of interest for the oscillatory flow conditions, visualized by the velocity magnitude for (a) Flex1, $L_S = 0.10$ m, and (b) Flex2, $L_S = 0.20$ m, both with a width of 4.0 mm and wave conditions W01 and $t/T = 0.50$

The resulting PIV measurements of the oscillatory flow were decomposed into a harmonic component, $|u_h(t)|$, associated with the dominant wave frequency, and a fluctuating component $|u_f(t)|$, representing all remaining contributions. This decomposition was achieved using a fourth-order infinite impulse response (IIR) bandpass filter centered on the dominant frequencies, each with a bandwidth of 0.1 Hz. The contributions of the velocity magnitude can thus be expressed as:

$$|u(t)| = |u_h(t)| + |u_f(t)| \quad (7)$$

If a second dominant frequency is present in the flow field, Equation 7 extends to

$$|u(t)| = |u_h(t)| + |u_{h,2}(t)| + |u_f(t)| \quad (8)$$

Further on, derived phase-averaged components are referred to as $\langle |u_h| \rangle$ and $\langle |u_f| \rangle$.

III. RESULTS

A. Assessment of the influence of the stem on its surrounding flow field

In this section, the influence of the stem on its surrounding flow field is investigated based on the PIV measurements in unidirectional and oscillatory flow conditions. FIG. 5 shows the stem position and the resulting flow field for the thin, short stem (FIG. 5 (a) to (c)) in flow conditions C03 and the thick, long stem (FIG. 5 (d) to (f)) in flow conditions C02, each with three different flexibilities. It becomes apparent that the averaged relative mean horizontal flow velocity behind the stem differs for all presented cases when compared to the undisturbed flow.

Differences in the near-stem flow field can be observed depending on the stiffness of the stem. With increasing stiffness, lower mean horizontal flow velocities can be observed, especially in the proximity of the tip of the stem, for example comparing FIG. 5 (a) and FIG. 5 (c). Generally, it becomes apparent that the influence of the stem on its surrounding flow field extends further than the employed field of view (FOV) of the PIV system.

FIG. 6 shows the phase-averaged velocity magnitude and phase-averaged stem position in oscillatory flow at four selected points in time over the wave period, as indicated in (i), by example for a short, see FIG. 6 (a) to (d), and a long stem, see FIG. 6 (e) to (h). In contrast to FIG. 5, the influence of the stem on its surrounding flow field is less distinguishable for the phase-averaged

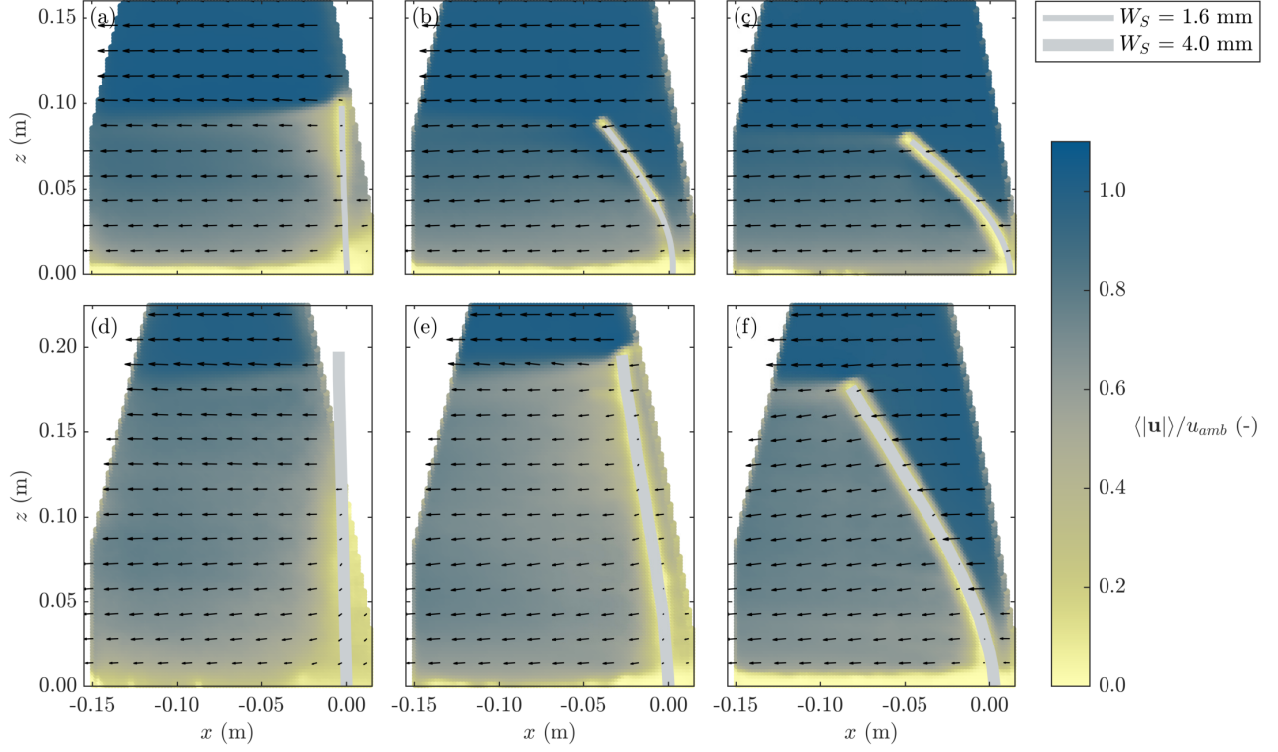


FIG. 5. Relative mean velocity magnitude, stem position and arrows indicating the mean velocity of the unidirectional flow with (a) to (c) $u_i = 0.30$ m/s, $L_S = 0.10$ m, and $W_S = 1.6$ mm and (d) to (f) $u_i = 0.20$ m/s, $L_S = 0.20$ m, and $W_S = 4.0$ mm for varying material types with (a) and (d) Stiff, (b) and (e) Flex1 and (c) and (f) Flex2

velocity magnitude in the oscillatory flow conditions. Nevertheless, the flow-induced stem motion becomes apparent for the longer stem, while the short stem remains in its initial position.

FIG. 6 highlights that further analysis is required to determine the influence of the stem on its surrounding flow field. For a deeper understanding of the FSI in oscillatory flow, the water surface elevation at WG5 and the position of the stem in x -direction are visualized in the frequency domain in FIG. 7.

In FIG. 7 (a) and (b), it becomes apparent that next to the expected initial wave frequencies, for both wave conditions W01 and W02, a second peak with a frequency twice the wave frequency occurs. Similar behavior has been observed in experimental studies by Hitzegrad *et al.*⁶⁵, suggesting the occurrence of a beat effect due to spurious harmonics generated by linear wave generation. The resulting frequencies of the stem tip positions are in alignment with both the first harmonic wave frequencies and, to a minor extent, the occurring second harmonic frequency.

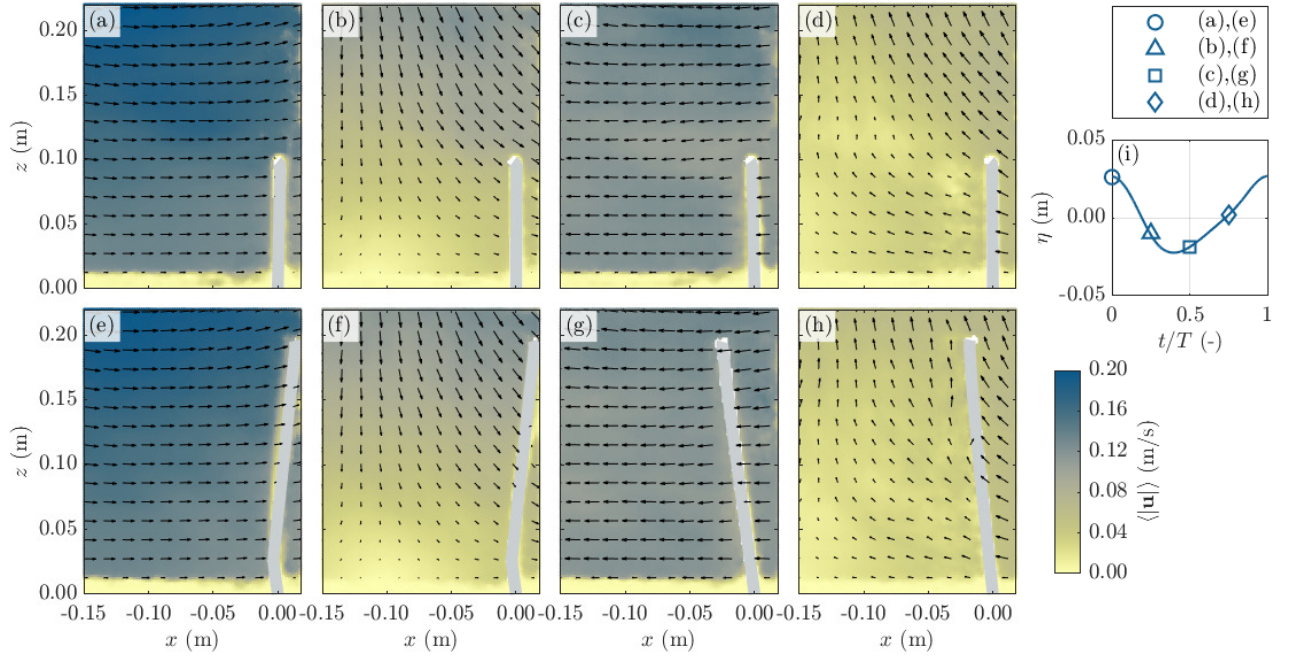


FIG. 6. Phase-averaged velocity magnitude, corresponding velocity arrows and stem position, by example for stem material Flex2, $W_S = 4$ mm and wave conditions W01 with (a) to (d) $L_S = 0.10$ m and (e) to (h) $L_S = 0.20$ m for selected points in time (a) and (e) $t/T = 0.00$, (b) and (f) $t/T = 0.25$, (c) and (g) $t/T = 0.50$, and (d) and (h) $t/T = 0.75$

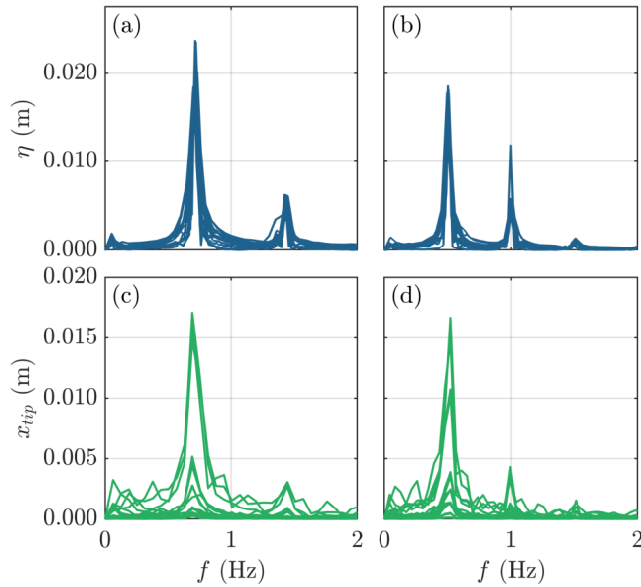


FIG. 7. Comparison of the water surface elevation (a) and (b), and the stem tip movement in x -direction (c) and (d) in the frequency domain for wave condition W01 (a) and (c) and W02 (b) and (d)

The fluctuating velocity components are expected to provide an improved visualization of the stem's influence on its surrounding flow field. The PIV measurements were decomposed based on the methodology described in Section II D. Based on the observation in FIG. 7, the decomposition is conducted for the flow fields' two dominant frequencies and the remaining components (see Equation 8). FIG. 8 (a) to (d) visualizes by example the resulting phase-averaged harmonic component of the velocity magnitude $\langle |\mathbf{u}_h| \rangle$ corresponding to the initial wave frequency (here for W01 $f_h = 0.71$ Hz). Correspondingly, the velocity magnitudes align well with the expected wave periods for each point in time of the wave phase. In contrast, FIG. 8 (e) to (h) shows the phase-averaged fluctuating component of the velocity magnitude $\langle |\mathbf{u}_f| \rangle$, excluding both dominant frequencies (0.71 Hz and 1.43 Hz).

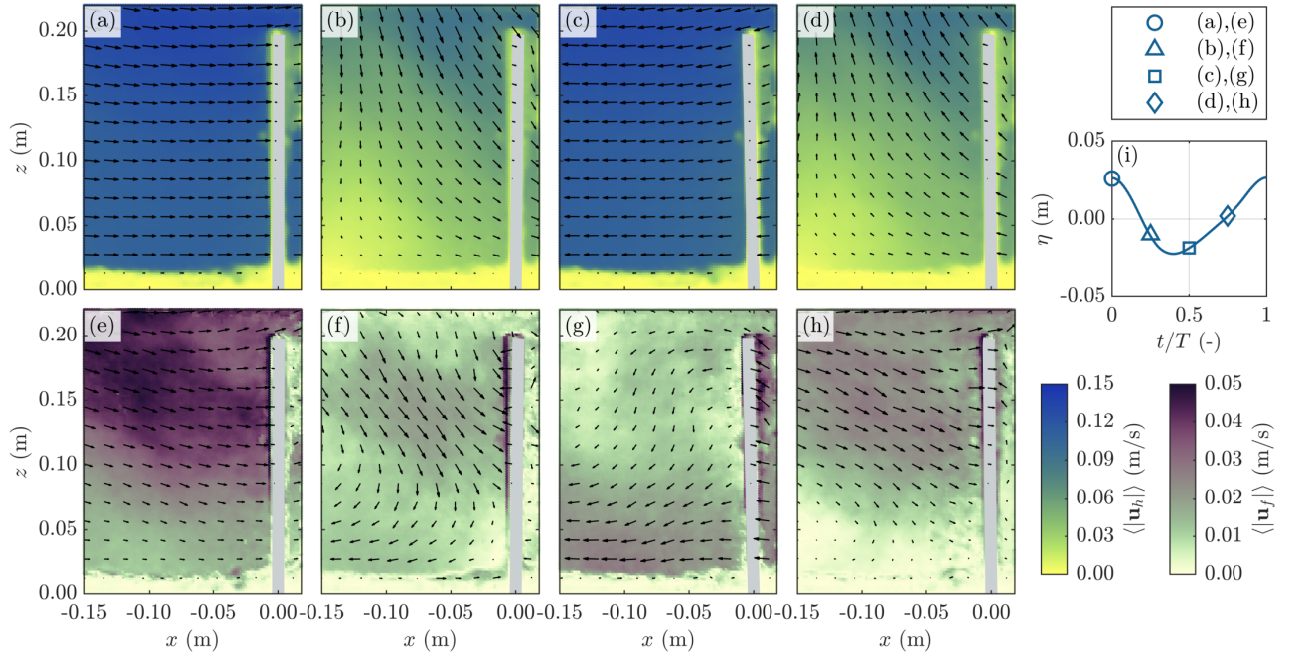


FIG. 8. Phase-averaged velocity magnitude and stem position, by example for the stiff material with $W_S = 1.6$ mm, $L_S = 0.20$ m, and wave conditions W01 for (a) to (d) the first harmonic velocity component $\langle |\mathbf{u}_h| \rangle$ and corresponding velocity arrows and (e) to (h) the fluctuating component $\langle |\mathbf{u}_f| \rangle$ and corresponding velocity arrows for selected points in time (a) and (e) $t/T = 0.00$, (b) and (f) $t/T = 0.25$, (c) and (g) $t/T = 0.50$, and (d) and (h) $t/T = 0.75$

For both components, the influence of the stem on its surrounding flow field is now distinguishable. However, it remains challenging to differentiate, especially for the fluctuating component, which processes occur solely due to the initial wave and local disturbances of the wave flume and

which are stem-induced. Therefore, the enstrophy is investigated as an alternative metric. Allowing for a distinguished comparison between wave-influenced and stem-influenced, the enstrophy is averaged over the two ROI presented in FIG. 4 and FIG. 10.

FIG. 9 compares the calculated enstrophies at the ROIs for all surrogates tested in oscillatory flow conditions. It is differentiated between wave condition W01, see FIG. 9 (a) and W02, see FIG. 9 (b). A strong contrast can be observed between the area in the proximity of the stem (solid lines) and the area that is only influenced by the incoming waves (dashed lines). Furthermore, higher peaks and earlier occurrence of the peaks within the wave phase can be observed with increasing stem flexibility. Based on the comparison of the undisturbed and stem-influenced flow field in FIG. 9, a threshold value for the enstrophy indicating the stem's influence has been selected at $5 \times 10^{-6} \text{ s}^{-2}$, emphasized by the red line in FIG. 9.

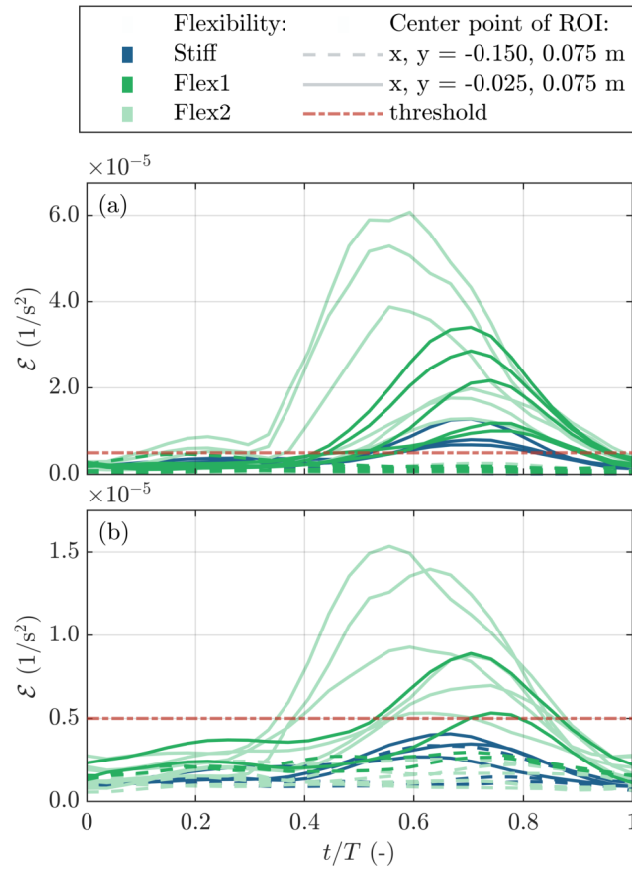


FIG. 9. Comparison of the enstrophy for the undisturbed and stem-influenced region of interest (ROI) for (a) wave conditions W01 and (b) wave conditions W02

How that threshold reflects the stem's influence in space is visualized, by example, for one stem

at two points in time in FIG. 10. FIG. 10 (a) and (c) show solely the enstrophy in the flow field, and FIG. 10 (b) and (d) highlight the influence of the stem based on the previously determined enstrophy threshold. The figure shows furthermore that the area of influence of the stem on its surrounding flow field is dependent on the wave phase, resulting in its minimum occurrence at $t/T = 0.25$ in FIG. 10 (b) and its maximum extent at $t/T = 0.75$ in FIG. 10 (d).

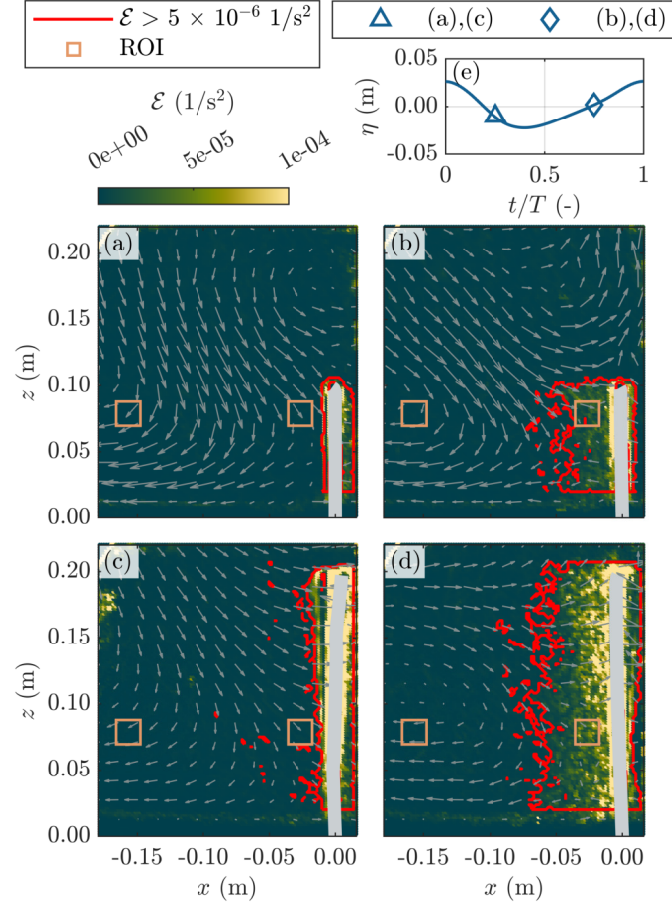


FIG. 10. Visualization of the enstrophy field, arrows showing the fluctuating velocity components, the analyzed regions of interests (ROI) and an envelope indicating the area of enstrophy threshold for (a) and (b) the Flex2 stem with $L_S = 0.10$ m, and $W_S = 4.0$ mm, and (c) and (d) the Flex1 stem with $L_S = 0.20$ m, and $W_S = 4.0$ mm and wave conditions W01 at (e) selected times of the wave period with (a) and (c) $t/T = 0.25$ and (b) and (d) $t/T = 0.75$

In summary, the influence of the stem on its surrounding flow field in unidirectional flow conditions can be straightforwardly determined based on the current velocity magnitude. For oscillatory flow conditions, the enstrophy based on the fluctuating component of the orbital velocity field appears to be a good indicator to investigate the stem-induced flow field alterations.

B. Influence of biomechanical properties on the fluid-structure interaction

After establishing means to assess the influence of the stem on the ambient flow field, it is next evaluated to what extent the biomechanical properties of the surrogate stems have an influence on the FSI for both unidirectional and oscillatory flow conditions. Focusing first on unidirectional flow, FIG. 11 visualizes the turbulence intensity for the same stems depicted in FIG. 5. Here, an enstrophy threshold of $3 \times 10^{-4} \text{ s}^{-2}$ is applied to indicate the increased area of influence in the proximity of the stem. A higher threshold value compared to the oscillatory flow conditions is utilized due to the comparably higher influence of the stem on the flow field in steady-state conditions compared to the instantaneous flow field of the oscillatory flow conditions.

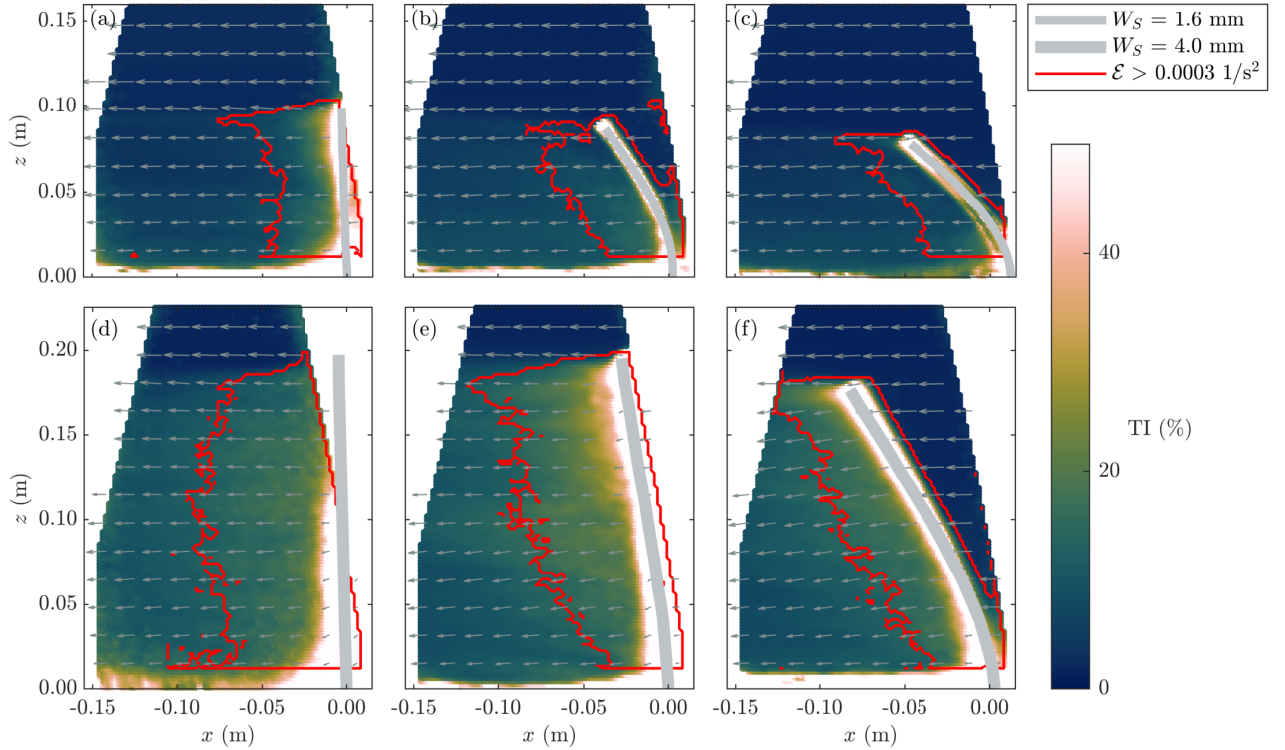


FIG. 11. Turbulence intensity and stem bending with arrows indicating the mean velocity with (a) to (c) $u_i = 0.30 \text{ m/s}$, $L_S = 0.10 \text{ m}$, and $W_S = 1.6 \text{ mm}$ and (d) to (f) $u_i = 0.20 \text{ m/s}$, $L_S = 0.20 \text{ m}$, and $W_S = 4.0 \text{ mm}$ for varying material types with (a) and (d) Stiff, (b) and (e) Flex1 and (c) and (f) Flex2

Overall, it can be observed in FIG. 5 that the highest turbulence intensities occur in the proximity of the stem, with, for example, values about 40 % for the stem depicted in FIG. 5 (e). Comparing FIG. 5 (e) and (f), it becomes apparent that the turbulence intensity in the stem's proximity

decreases with increasing flexibility. Furthermore, an alignment between the extent of the area within the enstrophy threshold and the stem bending occurs. The stiffer the stem, the larger the area within the enstrophy threshold in the proximity of the stem, independent of the stem length and thickness. In FIG. 5 (f), the applied enstrophy threshold reaches beyond the FOV of the PIV system. Based on the shape of the area within the enstrophy threshold of the other cases, further extension at the height of the stem tip is expected.

In contrast, the influence of the stem on its surrounding flow field and the corresponding wake development differ depending on the wave phase in oscillatory flow conditions. Therefore, the process of wave development (here determined between $t/T = 0.54$ and 0.75), based on the enstrophy threshold determined in FIG. 9, and its influence on the TKE in the proximity of the stem are visualized in FIG. 12 for three different selected surrogate stems.

FIG. 12 shows that the upstream wake of the stem develops within the wave period between $t/T = 0.54$ and $t/T = 0.75$ for all presented stems. At $t/T = 0.54$ and $t/T = 0.64$, it can be observed that the wake of the most flexible stem is narrower compared to the less flexible stem. However, due to its bent stem position in FIG. 12 (i), it reaches the same extent in space as the other two more stiff surrogates in comparison to FIG. 12 (c) and (f). Especially in FIG. 12 (b), (e), and (h), it can be observed that, independent of the stem's stiffness or thickness, a lower relative TKE occurs in the proximity of the stem, indicating an alteration of the flow field due to the presence of the stem.

Next, it is investigated whether a relationship between material properties and the resulting stem motion for both unidirectional and oscillatory flow can be determined. Therefore, in FIG. 13, the relationship between the relative bent stem position (h_{df}/L_S), visualized in FIG. 13 (a) and material properties EI and Ca is compared. The material parameters correlate with the resulting relative stem bending, especially for the longer stem (0.20 m). However, with the highest R^2 values being 0.62, other factors beyond the parameters EI and Ca seem to influence the resulting stem position as well. It can be concluded that for the unidirectional flow conditions, material properties such as EI and Ca are judged to be too weak to moderate indicators for the resulting relative stem height.

It remains to be evaluated if the same can be observed for the oscillatory flow conditions. FIG. 14 visualizes the phase-averaged water surface elevation for the oscillatory flow experiments and the phase-averaged motion of the stem tip for selected cases for both wave conditions. As expected, a greater excursion of the stem of the tip can be observed with increasing stem flexibility,

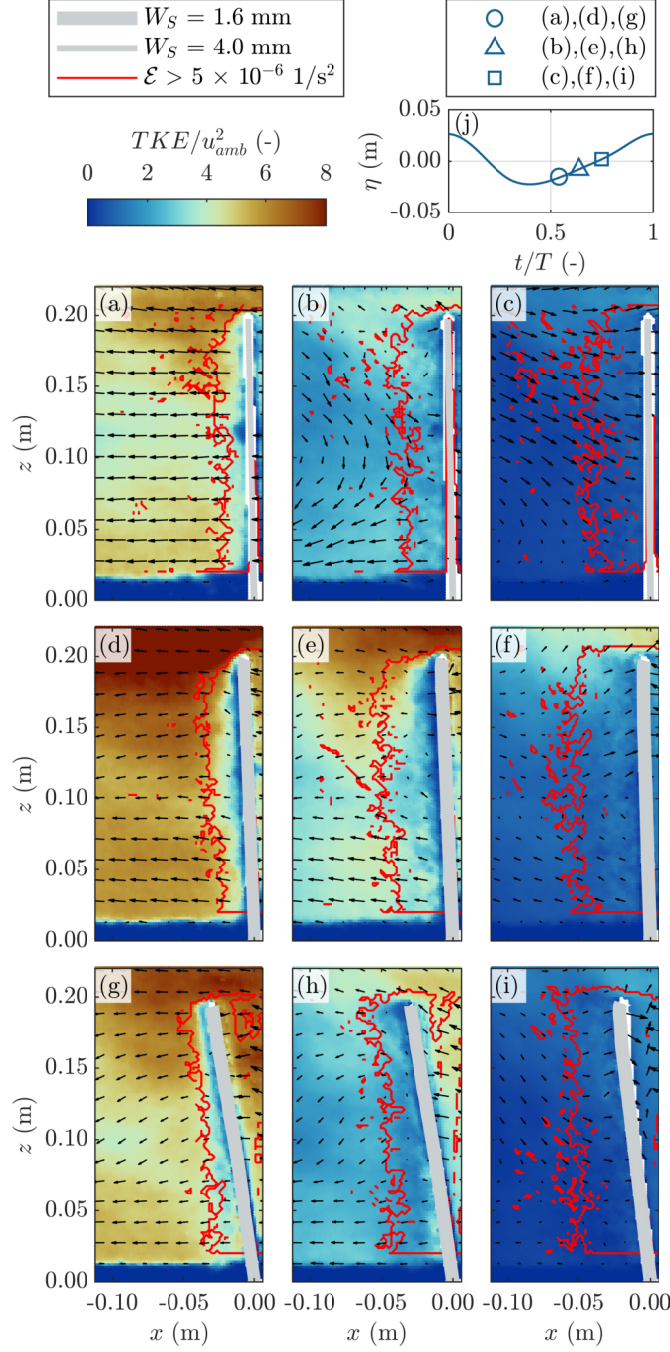


FIG. 12. Visualization of the phase-averaged relative TKE, the enstrophy mask, with the arrows indicating the fluctuating velocity components with $L_S = 0.20$ m and (a) to (c) the Stiff stem with $W_S = 1.6$ mm, (d) to (f) the Flex1 stem with $W_S = 4.0$ mm, and (g) to (i) the Flex2 stem with $W_S = 4.0$ mm for different moments of the wave phase, indicated in (j), with (a), (d) and (g) at $t/T = 0.54$, with (b), (e) and (h) at $t/T = 0.64$, and with (c), (f) and (i) at $t/T = 0.75$

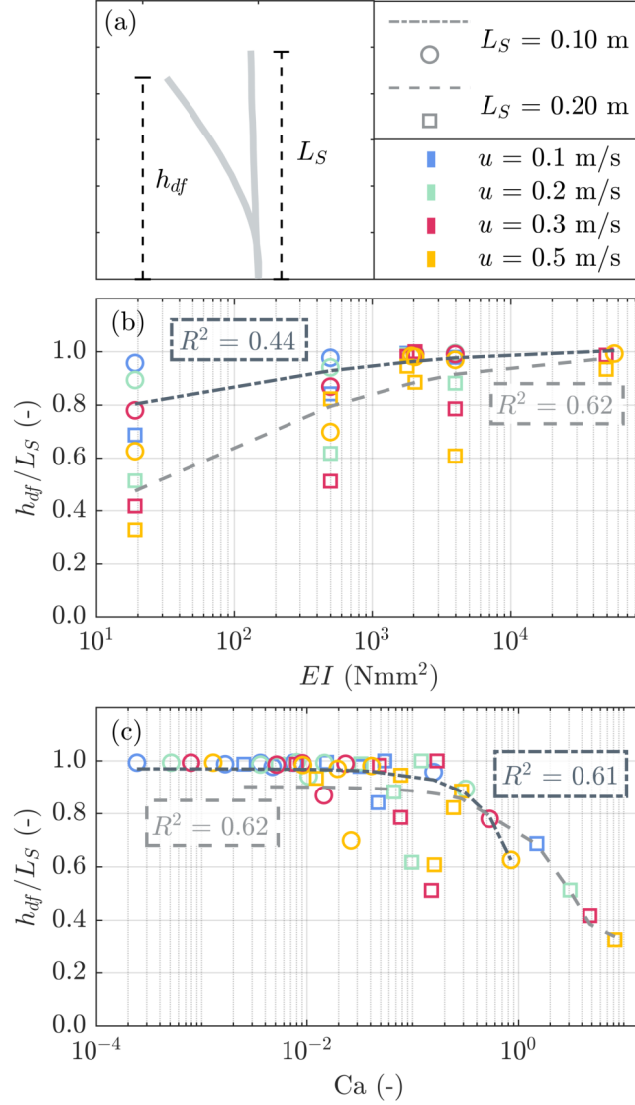


FIG. 13. Comparison of the relative bent stem tip position h_{df}/L_S , as shown for example in (a) for all test cases (C01, C02, C03, and C05) in unidirectional flow to (b) the flexural stiffness, EI , and (c) the Cauchy number, Ca , with correlations differing between the two stems lengths, L_S , and their corresponding R^2 values

comparing, for example, FIG. 14 (a), (c), and (e). Furthermore, a phase lag ΔT between the peak of the wave motion and the peak of the stem motion can be observed for all stem flexibilities. Differences in timing for the peak of the stem motion appear for different stems and wave conditions, comparing, for example, FIG. 14 (c), where the maximum tip excursion occurs around $t/T = 0.50$ and FIG. 14 (e), where the maximum tip excursion occurs around $t/T = 0.65$.

Based on the observations in FIG. 14, the distance of the minimum and maximum position

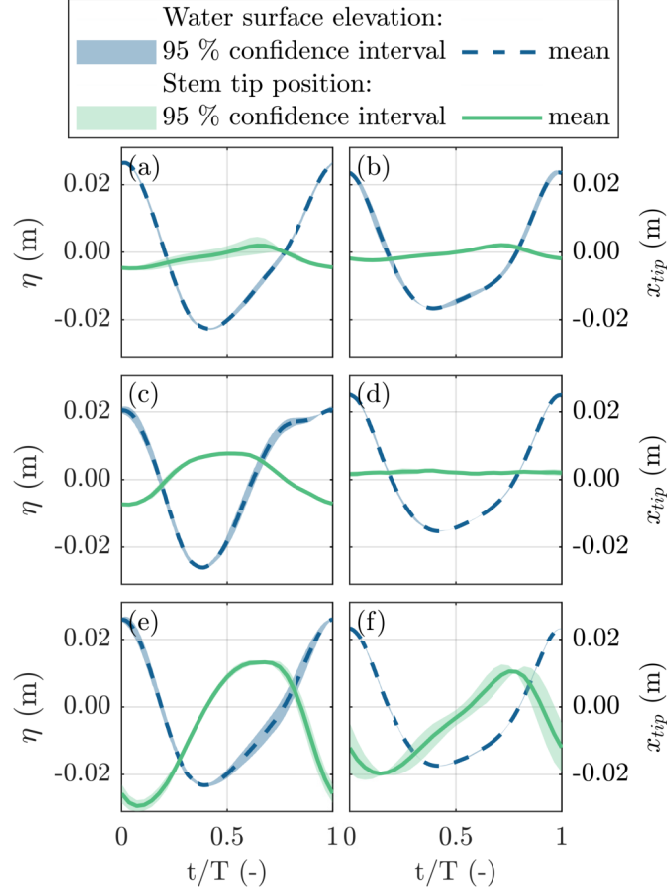


FIG. 14. Visualization of the phase-averaged water surface elevation η and the stem tip position in x -direction x_{tip} for (a) and (b) the Stiff stem with $L_S = 0.20$ m and $W_S = 1.6$ mm, for (c) and (d) the Flex1 stem with $L_S = 0.20$ m and $W_S = 4.0$ mm, and for (e) and (f) the Flex2 stem with $L_S = 0.20$ m and $W_S = 4.0$ mm with wave conditions W01 in (a), (c), and (e) and wave conditions W02 in (b), (d), and (f)

of the stem tip excursion, Δx_{tip} , relative to the stem lengths, L_S , and the phase lag ΔT between the crest of the wave and the tip motion are related to Ca in FIG. 15. In FIG. 15 (a), it becomes apparent that Ca is a good indicator for the magnitude of the relative stem excursion in x -direction. In contrast, FIG. 15 (b) shows that the phase lag ΔT does not correlate with Ca .

It can be summarized that biomechanical stem properties influence the flow field alterations. In unidirectional flow conditions, the area of influence associated with the stem increases with the stem's flexural rigidity due to higher resistance to the incoming flow, while its shape relates to the bent stem position. The relative bent stem position itself can be correlated to the non-dimensional parameter, Ca . For oscillatory flow conditions, the wake of the stem, characterized by an enstrophy threshold, develops upstream during the second half of the wave period, reaching

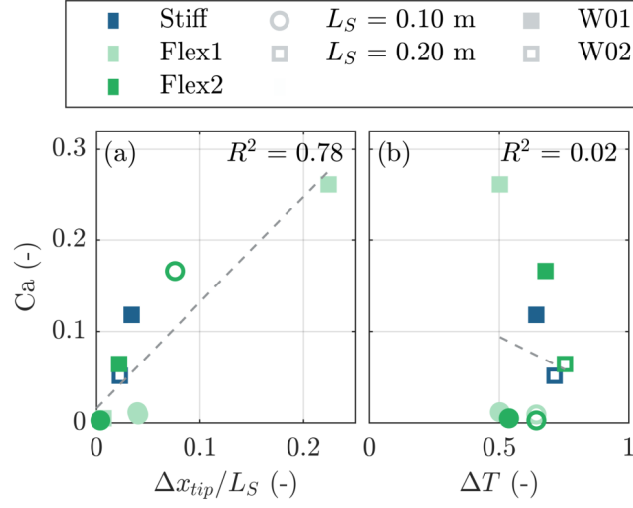


FIG. 15. Comparison of the Cauchy number Ca to (a) the excursion of the tip position in x -direction relative to the stem length $\Delta x_{tip}/L_S$ and (b) the phase lag between the peak of the water surface elevation and the stem tip position ΔT for oscillatory flow conditions

its maximum extent at $t/T = 0.75$, independent of the material properties. While the extent of the wake has been observed to be smaller for the most flexible stem, it reaches a similar point in space due to the bending movement of the stem compared to its stiffer counterparts. Furthermore, the relative excursion of the tip position in the x -direction correlates with the non-dimensional parameter Ca .

C. Replication of in situ measured live vegetation properties with flexible 3D-printed stems

FIG. 16 presents the flexural stiffnesses as a function of the stem diameter and width for the developed surrogate stems and live vegetation properties. Results do distinguish between the two salt marsh species *S. anglica* and *Elymus* spp (circles, crosses) and their seasonality (yellow, green). Data has been obtained from in situ measured live vegetation properties from selected studies^{19–22}. The 3D-printed surrogates are presented by squares in purple. Averaged values for the short and long surrogate stems are provided to facilitate the comparison.

FIG. 16 highlights that some of the surrogate stems align well with the live vegetation properties. The range of properties from the developed surrogate stems envelopes the variation of stem properties of the live vegetation. However, it becomes clear that the two selected stem widths

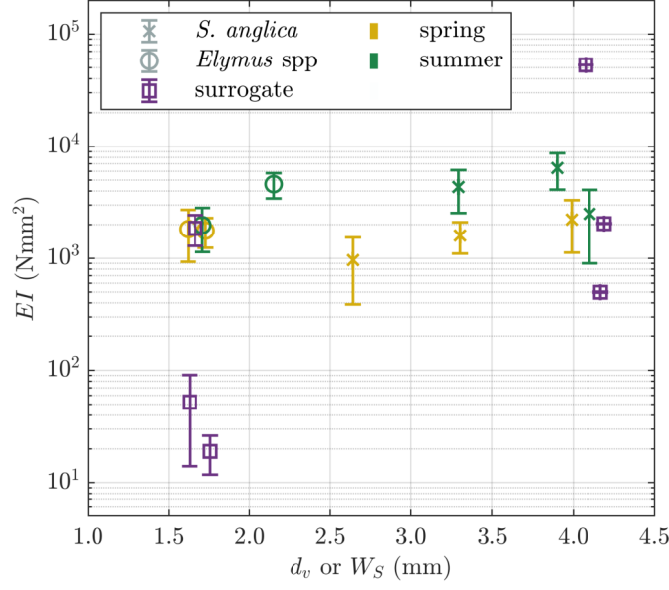


FIG. 16. Comparison of the material properties for in situ measured live vegetation stem properties^{19–22} and this study’s 3D-printed surrogate materials based on their stem diameter, d_v , and width, W_S , and the flexural stiffness, EI

cannot represent all of the various stem diameters measured in the different field campaigns. To keep the number of tested surrogates manageable, it was focused on representing the upper and lower range of the salt marsh species properties aimed to be replicated here. Furthermore, the large range of flexural stiffness based on the different utilized filaments becomes apparent in FIG. 16. Therefore, some of the surrogates may not be representative of salt marsh vegetation and should be rather treated as reference cases with increased or decreased stiffness.

After indicating similarity between surrogate and live vegetation properties based on the visual comparison in FIG. 16, the TOST approach described in Section II A is utilized for a quantitative assessment. The results of the TOST approach are summarized in TABLE IV, with 0 indicating non-similarity and 1 similarity.

The results of the TOST analysis confirm the findings of the previous visual comparison in that some of the surrogate stems replicate in situ measured live vegetation stem properties. It can then be concluded that the thin surrogate stem printed with the stiff filament is similar to the in situ measured *Elymus* spp. stem from different studies^{20,22} and that the thick surrogate printed with the Flex1 filament replicates *S. anglica* stem properties^{19,21}. However, the assessment also shows that the utilized flexible filaments cannot satisfactorily replicate the seasonal variation in

TABLE IV. Summary of the statistics comparing field^{19–22} and current laboratory vegetation properties.

Species	Study	Season	Stiff		Flex1		Flex2	
			thin	thick	thin	thick	thin	thick
<i>S. anglica</i>	Schulze et al.	Spring	0	0	0	0	0	0
<i>S. anglica</i>	Schulze et al.	Summer	0	0	0	0	0	0
<i>S. anglica</i>	Vuik et al.	Spring	0	0	0	0	0	0
<i>S. anglica</i>	Vuik et al.	Summer	0	0	0	1	0	0
<i>S. anglica</i>	Keimer et al.	Spring	0	0	0	1	0	0
<i>S. anglica</i>	Keimer et al.	Summer	0	0	0	0	0	0
<i>Elymus</i> spp.	Schulze et al.	Spring	1	0	0	0	0	0
<i>Elymus</i> spp.	Schulze et al.	Summer	0	0	0	0	0	0
<i>Elymus</i> spp.	Keimer et al.	Spring	1	0	0	0	0	0
<i>Elymus</i> spp.	Keimer et al.	Summer	1	0	0	0	0	0

biomechanical stem properties measured in the field. Such replication remains challenging due to the large variation of measured stem properties between different field studies (cf. FIG. 16).

IV. DISCUSSION

A. Applicability of 3D printing with flexible filament

Overall, the current results indicate that 3D filament printing has been proven to be a promising approach for replicating salt marsh stem properties measured in situ, confirmed by a statistical evaluation. However, the replication of seasonal variation of biomechanical stem properties was not achieved and requires fine-tuning of the printing process in future studies. The thin flexible surrogates resulted in a flexural stiffness considerably lower than the live vegetation measurements (cf. FIG. 16) and could be instead relevant to represent sea grass species^{17,66}, which are commonly more flexible than salt marsh stems. Alternatively, for future application cases, they could be utilized to represent the leaves of salt marsh vegetation. The printing set-up detailed in TABLE V in Appendix A provides guidance on how to achieve precise printing with the utilized flexible filaments. Compared to previous studies, for example²², using filament is rendered to be more suitable compared to 3D printing with flexible resin, since resin has been shown to degrade with light exposure⁴⁹ and being sensitive to hydrothermal aging⁴⁸, both altering material properties like its strength.

Although it has proven to be versatile in application, not every aspect of 3D filament printing

comes straightforward. The main challenge during the printing process is the necessity of applying a compressive force to the flexible filament, which requires slower printing speeds as the material's flexibility increases, shown in TABLE V. Using the slowest utilized printing speed with 10 and 5 mm/s depending on the component, resulted in comparably long printing durations. Furthermore, the printing process required the surrogates to have a rectangular cross-section instead of a circular one, which reduces the replication of live vegetation. The printed surrogate stems show some discrepancy in both width and thickness (cf. TABLE I), even though the input dimensions were equal in the setup. Nevertheless, for the scope of this study, this was rendered to be sufficient to replicate the materials' stiffness and the frontal area obstructing the flow, following the approach of previous studies^{38–40}.

The versatility of the 3D printing with flexible filament should be used in future studies to replicate further aspects of live vegetation. For the printing process, the influence and potential for fine-tuning of varying infill densities of the filament in the printing setup, cf. TABLE V in Appendix A should be evaluated, potentially allowing for a differentiation of seasonal variation of the biomechanical stem properties. For future field investigations, it is recommended to include the measurement of the density of live vegetation, allowing for more elaborate comparisons regarding the reproduction and influence of buoyancy for both physical experiments with surrogates and numerical studies. Future studies should also explore the opportunity for 3D printing to replicate more complex plant structures, such as including leaves, branching, hollow cross-sectional areas or varying stem diameters over the surrogate's height, which can be considered the most relevant advantage of 3D printing compared to previously used surrogate materials. The possibility to utilize 3D scans of live vegetation to serve as a model for future printing setups should be explored. Another opportunity for accurate replication would be the utilization of filaments with varying flexibilities within one surrogate, enabled by printers with multiple extrusions, for example, to print the vegetation's leaves and stem.

B. Measurement and assessment of the fluid-structure interaction

PIV measurements based on the 2D2C approach were employed in this study to assess the FSI in unidirectional and oscillatory flow. While enabling the evaluation of different flow conditions, a potential limitation of this study is the measurement of the flow field in the 2D plane. Correspondingly, the component v of the velocity field in y -direction has not been measured, leading

to an assumption of isotropic turbulence, which is not necessarily valid, as shown for example by Delafosse *et al.*⁶³ for the resulting flow field of a mixing impeller. Nevertheless, the authors consider the evaluation of the flow field resulting from the FSI within this study valuable, allowing the comparison of a great variety of material parameters and hydrodynamic conditions.

Across disciplines, enstrophy has been previously applied to assess the influence or comparison of boundary conditions of FSI^{64,67,68}. To the authors' knowledge, this is the first study to evaluate the applicability of the enstrophy to represent the influence of vegetation stems on their surrounding flow field. The extent of influence of an individual vegetation stem becomes especially relevant in sparsely vegetated zones of the salt marsh, such as the pioneer zone or lower salt marsh, where it could be utilized to determine from which vegetation density sheltering and meadow effects are occurring.

The results presented in Section III B confirmed that the influence of the stem on its surrounding flow field varies depending on biomechanical properties such as thickness and flexural rigidity. Furthermore, it was shown that the non-dimensional parameter Ca can be correlated across the different measurements for both unidirectional and oscillatory flow to the bent stem position of the stem tip movement, respectively. However, a relationship between the phase lag of the wave crest and the peak of the stem tip position to the non-dimensional parameter Ca was not confirmed, similar to the observations made by Jacobsen *et al.*⁴⁰. They suggested a relationship between phase lag occurrence and internal shear forces of the stem, which remains to be investigated in depth in future studies.

C. Further implications for ecosystem services provided by salt marshes

Based on the statistical similarity analysis presented in Section III C, implications of the FSI for the salt marsh species *Elymus* spp. and *S. anglica* can be derived from their corresponding surrogate stems. Therefore, the FSI of the two surrogate stems, for which statistical similarity has been confirmed, is shown in FIG. 17. Herein, FIG. 17 (a) and FIG. 17 (c) represent a stem of species *Elymus* spp., commonly found in the upper salt marsh, and FIG. 17 (b) and FIG. 17 (d) represent a stem of species *S. anglica*, commonly found in the lower salt marsh.

For unidirectional flow, FIG. 17 (a) and (b), it becomes apparent that the FSI with stem representing *S. anglica* results in higher turbulence intensities (up to 40 %) and a larger area of stem-induced flow field alterations compared to the stem representing *Elymus* spp. Unfortunately, the

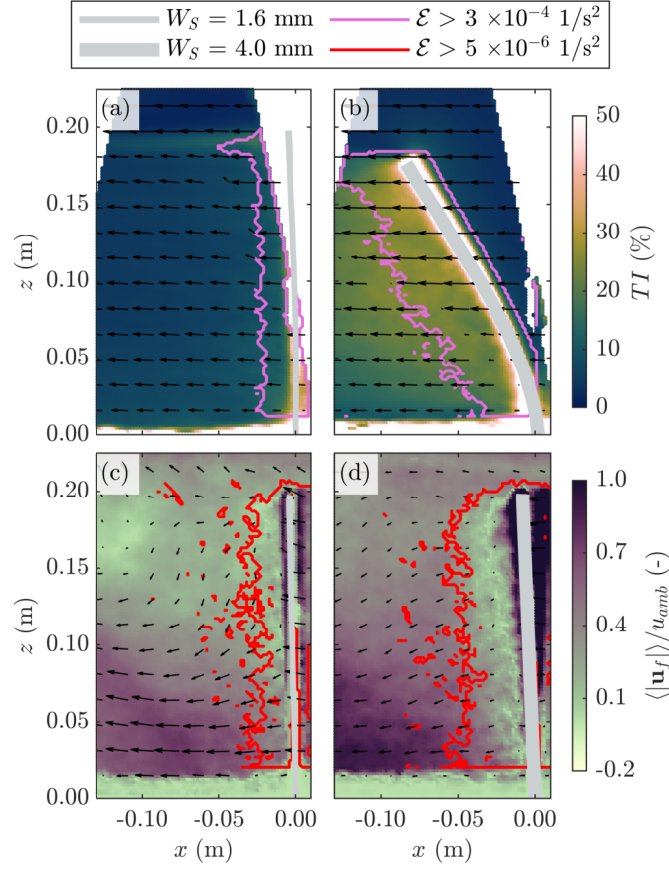


FIG. 17. Comparison of the turbulence intensity in unidirectional flow ($u_i = 0.20 \text{ m/s}$) with (a) Stiff thin stem and (b) Flex1 thick stem and the fluctuating horizontal velocity component in oscillatory flow conditions (W01) at $t/T = 0.60$ with (c) Stiff thin stem and (d) Flex1 thick stem

utilized FOV prevents the assessment of the near-stem turbulence intensity at the tip in FIG. 17 (a). The magnitude of the fluctuating component of the velocity in oscillatory flow at one point in time of the wave phase ($t/T = 0.60$), showing the largest extent of the wake for the selected test cases, is shown in FIG. 17 (c) and (d). Based on the enstrophy threshold defined in Section III A, it becomes apparent that the extent of influence of the stem representing *S. anglica*, see FIG. 17 (d), is larger compared to the stem representing *Elymus* spp. in FIG. 17 (c). For the selected point in time in the wave phase, the stem influence on its surrounding flow field corresponds to a lower magnitude of the relative fluctuating component of the velocity. The presented differences in flow field alterations for each salt marsh species confirm the necessity to accurately replicate biomechanical parameters such as the stems' thickness or flexural stiffness to investigate the fluid-structure interaction and corresponding flow field alterations.

The findings presented within this study have different implications regarding the ecosystem services of salt marsh vegetation at the stem level. First, it has been shown that the velocity gradient behind a stem in unidirectional flow conditions increases with increasing rigidity of the stem (cf. FIG. 5). However, in the same regions, an increase in turbulence intensity was observed (cf. FIG. 11). It remains to be addressed in future studies, to what extent such alterations of the flow field enhance or reduce sedimentation processes. For example, Vettori, Giordana, and Manes⁶⁹ have shown that the wave attenuation in sea grass meadows is increased through stem-induced turbulence.

Through the enstrophy threshold, the area of extent for stems representing different salt marsh species was shown. It remains to be evaluated in future studies how well it can be replicated on the meadow scale, when sheltering effects need to be considered. For the addressed salt marsh vegetation species, comparable magnitudes of the spatial density were measured in field studies throughout the seasons, ranging from 1077 m^{-2} to 1933 m^{-2} for *S. anglica*²¹ and from 1248 m^{-2} to 2108 m^{-2} for *Elymus* spp. Recently, Schoutens *et al.*⁷⁰ presented a link between the spatial density of stems in a salt marsh and their respective biomechanical properties. Subsequent studies should investigate the flow field alterations through the enstrophy threshold for vegetation patches or on the meadow scale, including the in situ measured spatial densities of the addressed salt marsh species.

V. CONCLUSION

This comprehensive study addressed the need for accurate replication of salt marsh stems by providing a first proof-of-concept for the utilization of 3D-printed stems with flexible filament to replicate in situ measured biomechanical stem properties. This allowed for the evaluation of the FSI representing field conditions in unidirectional and oscillatory flow on the stem scale. Herein, it was emphasized that alteration of the flow field on its surrounding flow field differs, depending on biomechanical material parameters like the stem width and the flexural stiffness. An enstrophy threshold was rendered useful to quantify the extent of influence of the stem, especially in the unsteady state conditions of the oscillatory flow. The development and extent of the resulting areas of influence of the stem were compared and analyzed, suggesting again an influence of biomechanical material parameters like the stem width and the flexural stiffness. Finally, it was evaluated that for both unidirectional and oscillatory flow, the non-dimensional parameter Ca correlates well with

the resulting relative bent stem position or tip excursion. In conclusion, the following observations were derived based on the research objectives posed in Section I:

- The enstrophy is a suitable indicator of near-stem influence on its surrounding flow field and differs in spatio-temporal extent, depending on biomechanical stem properties
- The non-dimensional parameter Ca correlates well with the resulting bent stem position in both unidirectional and oscillatory flow conditions
- Surrogates have been shown to accurately reproduce specific salt marsh species measured in situ, and represent the range of biomechanical parameters found in salt marshes

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DISCLOSURE STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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NOTES ON CONTRIBUTOR(S)

IP: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft. JV: Methodology, Investigation, Data Curation, Writing – review & editing, Project

administration. OL: Conceptualization, Methodology, Investigation, Writing – review & editing, Project administration. DS: Conceptualization, Writing – review & editing, Funding acquisition. IN: Conceptualization, Methodology, Writing – review & editing, Supervision. NG: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Appendix A: Printing setup

The Raise3D N2 Dual filament printer was used for the development of the 3D-printed surrogate stems. Varying printing setups were required to enable the printing with filaments with three different flexibilities, partially deviating from the producer's recommendations. The technical specifications of the utilized filaments and the printing setup from the software Ultimaker Cura are summarized in TABLE V. Parameters that are not included in TABLE V were left at the standard settings by Ultimaker Cura.

TABLE V. Summary of used filaments and the corresponding printing setup in Ultimaker Cura

Print settings	Unit	Material 1	Material 2	Material 3
Producer		Raise3D	NinjaTek®	NinjaTek®
Material Type		PLA	TPU	TPU
Product name		Premium	Cheetah	NinjaFlex
Stiffness classification		-	95A	85A
Color		black/red	fire	sapphire
<i>Quality</i>				
Layer Height	mm	0.15	0.15	0.30
<i>Infill</i>				
Infill Density	%	25	10	10
Infill Line Distance	mm	3.20	8.00	8.00
<i>Material</i>				
Printing Temperature	°C	200	255	250
Printing Temperature Initial Layer	°C	210	245	250
Initial Printing Temperature	°C	210	225	250
Final Printing Temperature	°C	185	210	235
Building Plate Temperature	°C	60	40	40
Flow	%	100	90	90
Wall Flow (and following)	%	65	90	66.5
Top/Bottom Flow (and following)	%	65	90	90
Initial Layer Flow (and following)	%	90	90	90
<i>Speed</i>				
Print Speed	mm/s	40	20	10
Infill Speed	mm/s	40	20	10
Wall Speed	mm/s	20	10	5
Outer Wall Speed	mm/s	20	10	10
Inner Wall Speed	mm/s	40	20	15
Top/Bottom Speed	mm/s	20	10	5
Initial Layer Speed	mm/s	20	20	10

Generally, higher printing temperatures and slower printing speeds were necessary with increasing material flexibility to maintain a high printing quality. For Material 3, the increase of the layer height has been observed as being crucial to avoid under-extrusion. For all material types, retraction and print cooling were enabled. A skirt type has been selected for build plate adhesion, but no additional glue was utilized.

Appendix B: Determination of similarity of the material properties

A TOST analysis was conducted to evaluate the statistical similarity between the in situ measured live vegetation properties and the surrogate stems, as shown first by Anderson and Hauck⁵⁵. Here, the model data $X_m \in R^{n_m \times p}$ represents the 3D-printed surrogates, and the prototype data $X_p \in R^{n_p \times p}$ represents in situ measured field data of live vegetation. The number of parameters p applied is two for this study (d/W and EI), but could be theoretically extended. To enable the combined evaluation of two parameters differing in scale and units, standardization was required:

$$X_{\text{scaled}} = \frac{X - \mu}{\sigma} \quad (\text{B1})$$

with μ representing the mean and σ the standard deviation vectors calculated over the combined model and prototype datasets.

For each pair of observations (i, j) of the model and prototype measurements, the squared Mahalanobis distance⁵³ was calculated utilizing the pooled diagonal covariance matrix S , assuming independence between the variables:

$$D_{ij}^2 = (x_{m,i} - x_{p,j})^\top S^{-1} (x_{m,i} - x_{p,j}) \quad \text{with } S = \frac{1}{2}(\Sigma_m + \Sigma_p) \quad (\text{B2})$$

The obtained distances were then scaled into Hotelling's T^2 statistic⁵² using:

$$T_{ij}^2 = \frac{n_{1,i} n_{2,j}}{n_{1,i} + n_{2,j}} D_{ij}^2 \quad (\text{B3})$$

where $n_{1,i}$ and $n_{2,j}$ are the sample sizes referring to each model and prototype measurement. The corresponding F -statistic is obtained utilizing the degrees of freedom $df_1 = p$ and $df_2 = n_{1,i} + n_{2,j} - p - 1$:

$$F_{ij} = \frac{n_{1,i} + n_{2,j} - p - 1}{p(n_{1,i} + n_{2,j} - 2)} T_{ij}^2 \quad (\text{B4})$$

The determination of statistical similarity is then achieved by conducting a multivariate TOST approach. An equivalence region (delta box) was defined to allow for the measurement ranges found in nature. Here, 10 % deviation relative to the average prototype value of each parameter was considered acceptable, relative to the given standard deviation:

$$\delta = \frac{\delta_{10\%}}{\sigma} \quad \text{with} \quad \delta_{10\%} = 0.1 \cdot \bar{X}_p \quad (\text{B5})$$

Then $\Delta_{ij} = x_{m,i} - x_{p,j}$ is calculated, representing the difference vector of standardized values. The 95 %-confidence ellipse, corresponding to $1 - \alpha$ for the previously determined difference vector⁵⁶, is constructed from the critical F -value:

$$A_{ij} = c^2 S, \quad c^2 = \frac{p(n_{1,i} + n_{2,j} - 2)}{n_{1,i} + n_{2,j}} F_{1-\alpha, p, n_{1,i} + n_{2,j} - p - 1} \quad (\text{B6})$$

A pair (i, j) of prototype and model measurements was considered statistically similar (equivalent) if the confidence ellipse defined by A_{ij} was fully contained within the delta box:

$$|\Delta_{ij,k}| \leq \delta_k \quad \forall k \in \{1, \dots, p\} \quad \text{and} \quad \Delta_{ij}^\top A_{ij}^{-1} \Delta_{ij} \leq 1 \quad (\text{B7})$$

This approach ensures that the observed difference lies within a region of acceptable practical equivalence, with at least 95 % confidence. As a final result of the TOST method, a binary similarity indicator matrix $S_{ij} \in \{0, 1\}^{n_m \times n_p}$ is derived. Here, a value of 1 indicates statistically significant similarity, while a value of 0 indicates that the observed difference was either too large or too uncertain to conclude similarity under the specified 95 % confidence level. Such a comparison is by example visualized in FIG. 18 (a) representing statistical similarity and FIG. 18 (b) statistical non-similarity.

Appendix C: Assessment of the ambient velocity in unidirectional flow

Due to the utilized measurement window of the PIV for the unidirectional experiments, see FIG. 2, ambient velocity for each test was determined based on the velocity profiles of reference measurements without a stem and the bulk velocity above the stem, which is considered to be not influenced by the stem. The measured velocity profile without the stem is visualized by example for a test with $u_i = 0.20$ m/s in FIG. 19 (a).

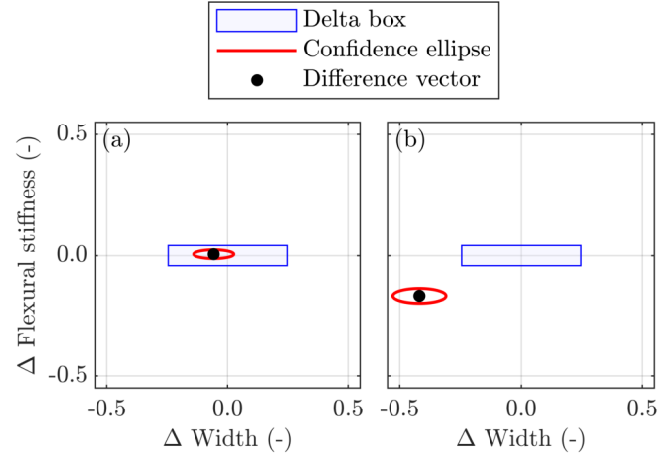


FIG. 18. Visualization of (a) statistical similarity and (b) statistical non-similarity based on the TOST method for standardized surrogate and in situ measured live vegetation properties

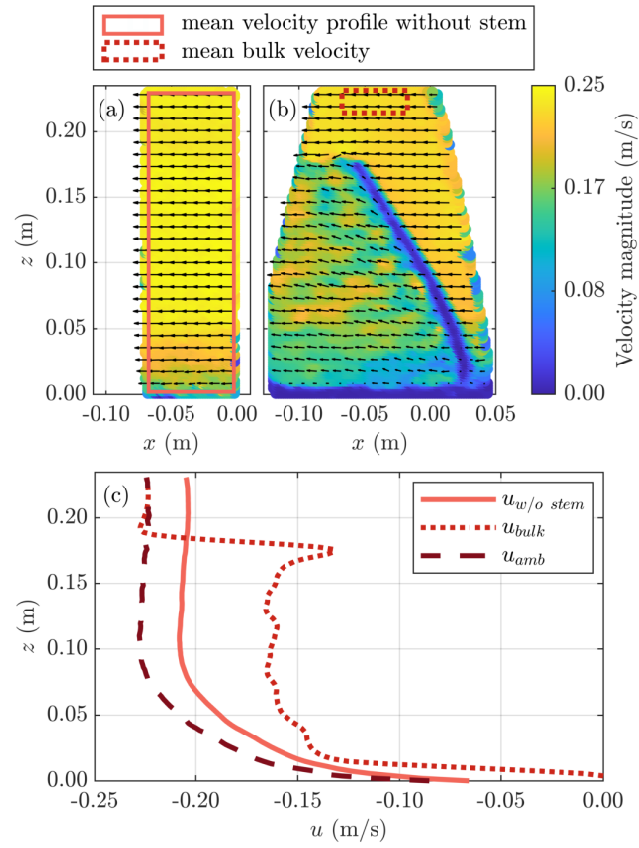


FIG. 19. Conceptual process on the determination of the ambient velocity based (a) on velocity profile without the presence of the stem and (b) the bulk velocity u_{bulk} above the stem, resulting in (c) the ambient velocity profile

As reference experiments were only available for $u_i = 0.10$ m/s and 0.20 m/s, the velocity profiles for the higher current velocities were extrapolated. The bulk velocity for each experimental test is averaged over time and space ($x_1 = -0.08$ m, $x_2 = -0.02$ m, $z_1 = 0.21$ m, $z_2 = 0.22$ m) as indicated by example in FIG. 19 (b). The comparison between the velocity profile without a stem, the measured bulk velocity, and the resulting ambient velocity profile is visualized in FIG. 19 (c).

Appendix D: Summary of test conditions and non-dimensional parameters

Here, an overview of the tested stems, the hydrodynamic conditions, and corresponding non-dimensional parameters are provided for unidirectional flow (TABLE VI) and oscillatory flow (TABLE VII) conditions.

TABLE VI. Summary of the resulting non-dimensional parameters for the tested unidirectional flow conditions and stem properties.

Type	L_S (m)	W_S (mm)	Name (-)	u_{bulk} (m/s)	$u_{amb,c}$ (m/s)	Re ($\times 10^7$)	B ($\times 10^{-2}$)	Ca ($\times 10^{-2}$)
Stiff	0.10	1.60	C01	0.11	0.09	0.92	-2.93	0.17
Stiff	0.10	1.60	C02	0.23	0.20	1.99	-2.93	0.36
Stiff	0.10	1.60	C03	0.32	0.29	2.84	-2.93	0.51
Stiff	0.10	1.60	C05	0.54	0.51	5.07	-2.93	0.91
Stiff	0.20	1.60	C01	0.11	0.10	2.05	-19.36	1.53
Stiff	0.20	1.60	C02	0.23	0.22	4.34	-19.36	3.24
Stiff	0.20	1.60	C03	0.34	0.33	6.49	-19.36	4.85
Stiff	0.20	1.60	C05	0.54	0.52	10.42	-19.36	7.78
Stiff	0.10	4.00	C01	0.11	0.09	0.88	0.24	0.02
Stiff	0.10	4.00	C02	0.22	0.19	1.86	0.24	0.05
Stiff	0.10	4.00	C03	0.32	0.29	2.88	0.24	0.08
Stiff	0.10	4.00	C05	0.50	0.47	4.69	0.24	1.13
Stiff	0.20	4.00	C01	0.11	0.10	1.99	2.11	0.25
Stiff	0.20	4.00	C02	0.23	0.21	4.20	2.11	0.53
Stiff	0.20	4.00	C03	0.33	0.32	6.32	2.11	0.80
Stiff	0.20	4.00	C05	0.51	0.49	9.74	2.11	1.23
Flex1	0.10	1.60	C01	0.11	0.09	0.91	-0.30	0.47
Flex1	0.10	1.60	C02	0.22	0.18	2.00	-0.30	1.04
Flex1	0.10	1.60	C03	0.34	0.31	2.79	-0.30	1.45
Flex1	0.10	1.60	C05	0.53	0.50	5.04	-0.30	2.62
Flex1	0.20	1.60	C01	0.11	0.10	2.01	-2.74	4.72
Flex1	0.20	1.60	C02	0.22	0.20	4.20	-2.74	9.84
Flex1	0.20	1.60	C03	0.33	0.31	6.42	-2.74	15.04
Flex1	0.20	1.60	C05	0.55	0.54	10.33	-2.74	24.20
Flex2	0.10	1.60	C01	0.11	0.09	0.92	-185.22	15.79
Flex2	0.10	1.60	C02	0.23	0.20	1.84	-185.22	31.55
Flex2	0.10	1.60	C03	0.31	0.28	3.10	-185.22	53.18
Flex2	0.10	1.60	C05	0.54	0.51	4.96	-185.22	85.05

Appendix E: Stem detection algorithm

The stem position was detected based on the raw images of the action camera. For the experiments in unidirectional flow, all images were layered on top of each other, resulting in final pictures that capture both the main stem position and the maximum and minimum bending positions. The pictures were then manually digitized.

For the experiments with oscillatory flow, a suitable stem detection algorithm was developed in

TABLE VII. Summary of the resulting non-dimensional parameters for the tested oscillatory conditions and stem properties

	L_S	W_S	Name	H_e	T_e	$u_{amb,w}$	Ca	B	KC
	(m)	(mm)	(-)	(m)	(s)	(m/s)	$(-) \times 10^{-2}$	$(-) \times 10^{-2}$	(-)
Stiff	0.20	1.60	W01	0.06	1.43	0.04	11.82	-19.36	165.97
			W02	0.05	2.01	0.03	5.17	-19.36	154.27
Flex1	0.10	4.00	W01	0.06	1.42	0.02	1.18	4.80	81.22
			W02	0.05	2.01	0.02	0.93	4.80	101.71
	0.20	4.00	W01	0.06	1.42	0.04	26.15	32.89	76.64
			W02	0.05	2.01	0.11	182.35	32.89	286.87
Flex2	0.10	4.00	W01	0.06	1.45	0.02	0.51	4.93	75.25
			W02	0.05	2.02	0.02	0.28	4.93	77.40
	0.20	4.00	W01	0.06	1.44	0.04	16.60	39.42	75.93
			W02	0.05	2.12	0.03	6.47	39.42	69.72

MATLAB to utilize the raw images of each camera frame, see for example FIG. 20 (a). First, the raw images from the camera had to be adapted to enhance the performance of the image detection process. That adaptation involved a grayscale conversion, the enhancement of the contrast to make the stem more distinguishable, and finally a Gaussian filter to reduce noise of the seedling material while preserving edges. To avoid the detection of irrelevant features such as the water surface or the flume bottom, a triangular ROI around the stem was defined, enveloping the range of stem movement for each test case. The resulting adapted image and ROI are, by example, visualized in FIG. 20 (b).

Now, the stem was detected within the ROI using the Oriented FAST and rotated BRIEF (ORB) function in MATLAB, highlighting corners or distinct texture changes along the stem. The resulting points of the ORB detection are visualized by example in FIG. 20 (c). As detection is not consistent throughout the stem length and in cases where features do not represent the stem, outlier removal is conducted afterwards. Mostly, the 10 and 90 % percentile were utilized. Due to limited light availability for the lower part of the stem, resulting in decreased feature detection, the mounting point of the stem at the bottom of the flume was added to the detected points. The

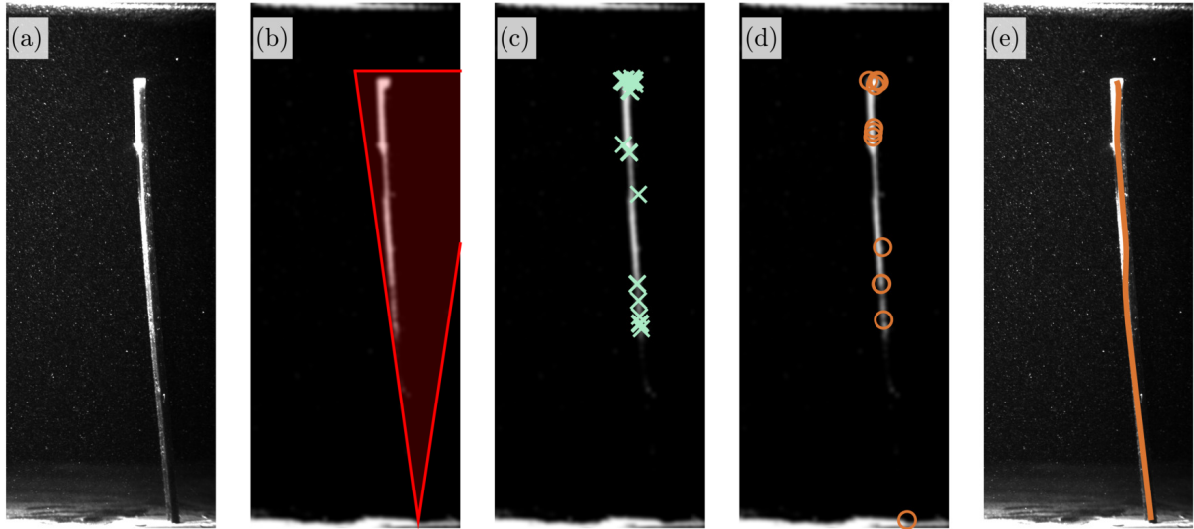


FIG. 20. Steps involved in the developed stem detection algorithm, here exemplarily shown for the 0.20 m long Flex2 stem in the wave conditions W02 with (a) raw image from the camera, (b) the improved image and the region of interest for detection, (c) the detected features, (d) the adapted features using outlier removal and adding the toe of the stem, and (e) the resulting smoothed and interpolated line in comparison to the original image

resulting feature coordinates along the stem are, for example, depicted in FIG. 20 (d).

Finally, the remaining feature coordinates are sorted and smoothed using locally weighted regression (LOESS) to form a clean centerline. The resulting line is then interpolated to a uniform vertical grid, ensuring consistent sampling and enabling comparison across images. Such a resulting line, representing the surrogate stem position, is visualized and compared by example to the original raw image in FIG. 20 (e). Then the pixel coordinates are converted to meters, enabling further analysis in the dimensions of the PIV measurements.

REFERENCES

- ¹E. B. Barbier, S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman, “The value of estuarine and coastal ecosystem services,” *Ecological Monographs* **81**, 169–193 (2011).
- ²F. Rupprecht, I. Möller, M. Paul, M. Kudella, T. Spencer, van Wesenbeeck, B. K., G. Wolters, K. Jensen, T. Bouma, M. Miranda-Lange, and S. Schimmels, “Vegetation-wave interactions in

- salt marshes under storm surge conditions,” *Ecol. Eng.* **100**, 301–315 (2017).
- ³V. Vuik, B. W. Borsje, P. W. Willemsen, and S. N. Jonkman, “Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs,” *Ocean & Coastal Management* **171**, 96–110 (2019).
- ⁴K. C. Riffe, S. M. Henderson, and J. C. Mullarney, “Wave dissipation by flexible vegetation,” *Geophysical Research Letters* **38** (2011), 10.1029/2011GL048773.
- ⁵M. S. Meixler, M. J. Kennish, and K. F. Crowley, “Assessment of plant community characteristics in natural and human-altered coastal marsh ecosystems,” *Estuaries and Coasts* **41**, 52–64 (2018).
- ⁶K. Schoutens, M. Heuner, E. Fuchs, V. Minden, T. Schulte-Ostermann, J.-P. Belliard, T. J. Bouma, and S. Temmerman, “Nature-based shoreline protection by tidal marsh plants depends on trade-offs between avoidance and attenuation of hydrodynamic forces,” *Estuarine, Coastal and Shelf Science* **236**, 106645 (2020).
- ⁷L. Cornacchia, G. Lapetoule, S. Licci, H. Basquin, and S. Puijalon, “How to build vegetation patches in hydraulic studies: a hydrodynamic-ecological perspective on a biological object,” *Journal of Ecohydraulics* **8**, 105–120 (2023).
- ⁸A. D’Ippolito, F. Calomino, S. Dey, R. Gaudio, and N. Penna, “Bedload transport through emergent vegetation: current status and its future prospect,” *Environmental Fluid Mechanics* (2023), 10.1007/s10652-023-09918-0.
- ⁹S. Puijalon, T. J. Bouma, C. J. Douady, J. van Groenendael, N. P. R. Anten, E. Martel, and G. Bornette, “Plant resistance to mechanical stress: evidence of an avoidance-tolerance trade-off,” *The New phytologist* **191** (4), 1141–1149 (2011).
- ¹⁰T. J. van Veelen, T. P. Fairchild, D. E. Reeve, and H. Karunarathna, “Experimental study on vegetation flexibility as control parameter for wave damping and velocity structure,” *Coastal Engineering* **157** (2020), 10.1016/j.coastaleng.2020.103648.
- ¹¹J. C. Mullarney and S. M. Henderson, “Wave-forced motion of submerged single-stem vegetation,” *J. Geophys. Res.* **115** (2010), 10.1029/2010JC006448.
- ¹²R. Familkhalili and N. Tahvildari, “Computational modeling of coupled waves and vegetation stem dynamics in highly flexible submerged meadows,” *Advances in Water Resources* (2022), 10.1016/j.advwatres.2022.104222.
- ¹³G. Caroppi, K. Västilä, P. Gualtieri, J. Järvelä, M. Giugni, and P. M. Rowiński, “Comparison of flexible and rigid vegetation induced shear layers in partly vegetated channels,” *Water*

Resources Research **57** (2021), 10.1029/2020WR028243.

- ¹⁴W. Yang and S.-U. Choi, “Impact of stem flexibility on mean flow and turbulence structure in depth-limited open channel flows with submerged vegetation,” *Journal of Hydraulic Research* **47**, 445–454 (2009).
- ¹⁵J. El Rahi, I. Martínez-Estévez, R. Almeida Reis, B. Tagliaferro, J. M. Domínguez, A. J. C. Crespo, V. Stratigaki, T. Suzuki, and P. Troch, “Exploring wave–vegetation interaction at stem scale: Analysis of the coupled flow–structure interactions using the sph-based dualsphysics code and the fea module of chrono,” *Journal of Marine Science and Engineering* **12**, 1120 (2024).
- ¹⁶S. Radfar, S. Mahmoudi, H. Moftakhari, T. Meckley, M. V. Bilskie, R. Collini, K. Alizad, J. A. Cherry, and H. Moradkhani, “Nature-based solutions as buffers against coastal compound flooding: Exploring potential framework for process-based modeling of hazard mitigation,” *The Science of the total environment* **938**, 173529 (2024).
- ¹⁷M. Luhar and H. M. Nepf, “Wave-induced dynamics of flexible blades,” *Journal of Fluids and Structures* **61**, 20–41 (2016).
- ¹⁸A. Markov, M. Muller, I. Nistor, S. Baker, J. Stolle, E. Murphy, and A. Cornett, “Wave interactions with spartina alterniflora on a living dyke model: New insights into the use of scaled surrogate meadows,” *Journal of Waterway, Port, Coastal, and Ocean Engineering* **151** (2025), 10.1061/JWPED5.WWENG-2182.
- ¹⁹V. Vuik, H. Y. Suh Heo, Z. Zhu, B. W. Borsje, and S. N. Jonkman, “Stem breakage of salt marsh vegetation under wave forcing: A field and model study,” *Estuarine, Coastal and Shelf Science* **200**, 41–58 (2017).
- ²⁰D. Schulze, F. Rupprecht, S. Nolte, and K. Jensen, “Seasonal and spatial within-marsh differences of biophysical plant properties: implications for wave attenuation capacity of salt marshes,” *Aquat Sci* **81** (4) (2019), 10.1007/s00027-019-0660-1.
- ²¹K. Keimer, V. Kosmalla, I. Prüter, O. Lojek, M. Prinz, D. Schürenkamp, H. Freund, and N. Goseberg, “Proposing a novel classification of growth periods based on biomechanical properties and seasonal changes of spartina anglica,” *Front. Mar. Sci.* **10** (2023), 10.3389/fmars.2023.1095200.
- ²²K. Keimer, F. Kind, I. Prüter, V. Kosmalla, O. Lojek, D. Schürenkamp, M. Prinz, S. Niewerth, J. Aberle, and N. Goseberg, “From seasonal field study to surrogate modeling: Investigating the biomechanical dynamics of elymus sp. in salt marshes,” *Limnography and Oceanography*

Methods (2024), doi.org/10.1002/lom3.10616.

- ²³T. I. Marjoribanks and M. Paul, “Modelling flow-induced reconfiguration of variable rigidity aquatic vegetation,” *Journal of Hydraulic Research* , 1–6 (2021).
- ²⁴J. el Rahi, I. Martínez-Estévez, B. Tagliafierro, J. Domínguez, A. Crespo, V. Stratigaki, T. Suzuki, and P. Troch, “Numerical investigation of wave-induced flexible vegetation dynamics in 3D using a coupling between DualSPHysics and the FEA module of Project Chrono,” *Ocean Engineering* **285** (2023), 10.1016/j.oceaneng.2023.115227.
- ²⁵K. Yin, S. Xu, W. Huang, S. Liu, and M. Li, “Numerical investigation of wave attenuation by coupled flexible vegetation dynamic model and xbeach wave model,” *Ocean Engineering* **235** (2021), 10.1016/j.oceaneng.2021.109357.
- ²⁶I. Prüter, F. Spröer, K. Keimer, O. Lojek, C. Windt, D. Schürenkamp, H. Bihs, I. Nistor, and N. Goseberg, “A comprehensive numerical study on the current-induced fluid–structure interaction of flexible submerged vegetation,” *Journal of Fluids and Structures* **133**, 104232 (2025).
- ²⁷I. Prüter, F. Spröer, O. Lojek, C. Windt, D. Schürenkamp, I. Nistor, and N. Goseberg, “Vegetation stem dynamics under wave loading: Insights from a coupled fluid–structure model,” *Applied Ocean Research* **159**, 104597 (2025).
- ²⁸F. Rupprecht, I. Möller, B. Evans, T. Spencer, and K. Jensen, “Biophysical properties of salt marsh canopies — quantifying plant stem flexibility and above ground biomass,” *Coastal Engineering* **100**, 48–57 (2015).
- ²⁹A. Markov, J. Stolle, R. Henteleff, I. Nistor, D. van Pham Bang, E. Murphy, and A. Cornett, “Deformation of spartina patens and spartina alterniflora stems under irregular wave action,” *Coastal Engineering Journal* , 1–22 (2023).
- ³⁰J. L. Lara, M. Maza, B. Ondiviela, J. Trinogga, I. J. Losada, T. J. Bouma, and N. Gordojuela, “Large-scale 3-d experiments of wave and current interaction with real vegetation. part 1: Guidelines for physical modeling,” *Coastal Engineering* **107**, 70–83 (2016).
- ³¹I. Moeller, M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B. K. van Wesenbeeck, G. Wolters, K. Jensen, T. J. Bouma, M. Miranda-Lange, and S. Schimmels, “Wave attenuation over coastal salt marshes under storm surge conditions,” *Letters Nature Geoscience* **7** (2014).
- ³²S. Baker, E. Murphy, A. Cornett, and P. Knox, “Experimental study of wave attenuation across an artificial salt marsh,” *Front. Built Environ.* **8** (2022), 10.3389/fbuil.2022.893664.
- ³³K. Keimer, D. Schürenkamp, F. Miescke, V. Kosmalla, O. Lojek, and N. Goseberg, “Ecohydraulics of surrogate salt marshes for coastal protection: Wave–vegetation interaction and

- related hydrodynamics on vegetated foreshores at sea dikes,” *J. Waterway, Port, Coastal, Ocean Eng.* **147** (6) (2021), 10.1061/(ASCE)WW.1943-5460.0000667.
- ³⁴X. Zhang, P. Lin, and H. Nepf, “A wave damping model for flexible marsh plants with leaves considering linear to weakly nonlinear wave conditions,” *Coastal Engineering* **175** (2022), 10.1016/j.coastaleng.2022.104124.
- ³⁵J. Liu, S. Kutschke, K. Keimer, V. Kosmalla, D. Schürenkamp, N. Goseberg, and M. Böhl, “Experimental characterisation and three-dimensional modelling of elymus for the assessment of ecosystem services,” *Ecological Engineering* **166** (2021), 10.1016/j.ecoleng.2021.106233.
- ³⁶P. J. Blackmar, D. T. Cox, and W.-C. Wu, “Laboratory observations and numerical simulations of wave height attenuation in heterogeneous vegetation,” *Journal of Waterway, Port, Coastal, and Ocean Engineering* **140**, 56–65 (2014).
- ³⁷M. Anderson and J. Smith, “Wave attenuation by flexible, idealized salt marsh vegetation,” *Coastal Engineering* **83**, 82–92 (2014).
- ³⁸W.-C. Wu and D. T. Cox, “Effects of vertical variation in vegetation density on wave attenuation,” *Journal of Waterway, Port, Coastal, and Ocean Engineering* **142** (2016), 10.1061/(ASCE)WW.1943-5460.0000326.
- ³⁹M. Paul, F. Rupprecht, I. Möller, T. J. Bouma, T. Spencer, M. Kudella, G. Wolters, B. K. van Wesenbeeck, K. Jensen, M. Miranda-Lange, and S. Schimmels, “Plant stiffness and biomass as drivers for drag forces under extreme wave loading: A flume study on mimics,” *Coastal Engineering* **117**, 70–78 (2016).
- ⁴⁰N. Jacobsen, W. Bakker, W. S. J. Uijttewaalt, and R. Uittenbogaard, “Experimental investigation of the wave-induced motion of and force distribution along a flexible stem,” *J. Fluid Mech.* **880**, 1036–1069 (2019).
- ⁴¹T. J. Bouma, M. B. d. Vries, E. Low, G. Peralta, I. C. Tánzos, J. van de Koppel, and P. M. J. Herman, “Trade-offs related to ecosystem engineering: A case study on stiffness of emerging macrophytes,” *Ecology* **86** (8), 2187–2199 (2005).
- ⁴²T. I. Marjoribanks, D. Lague, R. J. Hardy, R. J. Boothroyd, J. Leroux, C. Mony, and S. Puijalon, “Flexural rigidity and shoot reconfiguration determine wake length behind saltmarsh vegetation patches,” *J. Geophys. Res. Earth Surf.* **124**, 2176–2196 (2019).
- ⁴³S. F. Lima, C. F. Neves, , and N. M. L. Rosauro, “Damping of gravity waves by fields of flexible vegetation,” *Proc., 30th Int. Conf. on Coastal Engineering* (2006).
- ⁴⁴T. Koftis, P. Prinos, and V. Stratigaki, “Wave damping over artificial *posidonia oceanica*

- meadow: A large-scale experimental study,” *Coastal Engineering* **73**, 71–83 (2013).
- ⁴⁵Y. Ozeren, D. G. Wren, and W. Wu, “Experimental investigation of wave attenuation through model and live vegetation,” *Journal of Waterway, Port, Coastal, and Ocean Engineering* **140** (2014), 10.1061/(ASCE)WW.1943-5460.0000251.
- ⁴⁶T. J. van Veelen, H. Nepf, S. J. Hulscher, and B. W. Borsje, “The thresholds of sediment resuspension within emergent vegetation under combined wave-current conditions – a flume experiment,” *Coastal Engineering* , 104727 (2025).
- ⁴⁷L. N. Augustin, J. L. Irish, and P. Lynett, “Laboratory and numerical studies of wave damping by emergent and near-emergent wetland vegetation,” *Coastal Engineering* **56**, 332–340 (2009).
- ⁴⁸G. Xian, Y. Bai, X. Qi, J. Wang, J. Tian, and H. Xiao, “Hygrothermal aging on the mechanical property and degradation mechanism of carbon fiber reinforced epoxy composites modified by nylon 6,” *Journal of Materials Research and Technology* **33**, 6297–6306 (2024).
- ⁴⁹S. Ci, B. Wang, C. Di, M. Wang, B. Zhu, and K. Qiao, “Effect of ultraviolet aging on properties of epoxy resin and its pultruded fiber-reinforced composite,” *Polymers* **17** (2025), 10.3390/polym17030294.
- ⁵⁰T. M. Joseph, A. Kallingal, A. M. Suresh, D. K. Mahapatra, M. S. Hasanin, J. Haponiuk, and S. Thomas, “3d printing of polylactic acid: recent advances and opportunities,” *The International journal, advanced manufacturing technology* **125**, 1015–1035 (2023).
- ⁵¹S. M. Desai, R. Y. Sonawane, and A. P. More, “Thermoplastic polyurethane for three-dimensional printing applications: A review,” *Polymers for Advanced Technologies* **34**, 2061–2082 (2023).
- ⁵²H. Hotelling, “The generalization of student’s ratio,” *The Annals of Mathematical Statistics* **2**, 360–378 (1931).
- ⁵³P. C. Mahalanobis, “Reprint of: ’on the generalised distance in statistics.’,” *Sankhya A* **80**, 1–7 (1936).
- ⁵⁴R. de Maesschalck, D. Jouan-Rimbaud, and D. L. Massart, “The mahalanobis distance,” *Chemometrics and Intelligent Laboratory Systems* **50**, 1–18 (2000).
- ⁵⁵S. Anderson and W. W. Hauck, “A new procedure for testing equivalence in comparative bioavailability and other clinical trials,” *Communications in Statistics - Theory and Methods* **12**, 2663–2692 (1983).
- ⁵⁶D. J. Schuirmann, “A comparison of the two one-sided tests procedure and the power approach for assessing the equivalence of average bioavailability,” *Journal of pharmacokinetics and bio-*

pharmaceutics **15**, 657–680 (1987).

- ⁵⁷M. Welzel, A. Schendel, and N. Goseberg, “GWK + : Erweiterung des Großen Wellenkanals – Analyse des Einlaufbereichs,” *Bautechnik* **98**, 541–551 (2021).
- ⁵⁸N. Goseberg, *The run-up of long waves : laboratory-scaled geophysical reproduction and on-shore interaction with macro-roughness elements*, Ph.D. thesis, Gottfried Wilhelm Leibniz Universität Hannover, Hannover (2011).
- ⁵⁹O. Zielinski, D. Pieck, J. Schulz, C. Thölen, J. Wollschläger, M. Albinus, T. H. Badewien, A. Braun, B. Engelen, C. Feenders, S. Fock, C. Lehnert, K. Löhms, A. Lübken, G. Massmann, J. Meyerjürgens, H. Nicolai, T. Pollmann, K. Schwalfenberg, J. Stone, H. Waska, and H. Winkler, “The Spiekeroog Coastal Observatory: A Scientific Infrastructure at the Land-Sea Transition Zone (Southern North Sea),” *Frontiers in Marine Science* **8** (2022), 10.3389/fmars.2021.754905.
- ⁶⁰O. Zielinski, D. Meier, M. Kleyer, and H. Hillebrand, “Continuous current observations at BEFmate artificial islands in the back-barrier tidal flat, Spiekeroog, Germany, 2013-11 to 2015-10,” (2017).
- ⁶¹D. Meier, C. Thölen, H. Hillebrand, M. Kleyer, K. Löhms, and O. Zielinski, “Continuous wave and tide observations at dynacom artificial islands in the back-barrier tidal flat, spiekeroog, germany, 2019-01 to 2019-12,” (2020).
- ⁶²A. Sciacchitano, “Uncertainty quantification in particle image velocimetry,” *Measurement Science and Technology* **30**, 092001 (2019).
- ⁶³A. Delafosse, M.-L. Collignon, M. Crine, and D. Toye, “Estimation of the turbulent kinetic energy dissipation rate from 2D-PIV measurements in a vessel stirred by an axial Mixel TTP impeller,” *Chemical Engineering Science* **66**, 1728–1737 (2011).
- ⁶⁴M. Saeedipour, “An enstrophy-based analysis of the turbulence–interface interactions across the scales,” *International Journal of Multiphase Flow* **164**, 104449 (2023).
- ⁶⁵J. Hitzegrad, L. Rentsch, T. K. Hoffmann, M. Paul, C. Windt, T. Schlurmann, and N. Goseberg, “Wave-induced hydrodynamics of biogenic structures in the central wadden sea: Implications of the transformation from mussel beds to oyster reefs for wave attenuation,” *Coastal Engineering* **200**, 104763 (2025).
- ⁶⁶M. Paul, T. J. Bouma, and C. L. Amos, “Wave attenuation by submerged vegetation: combining the effect of organism traits and tidal current,” *Mar. Ecol. Prog. Ser.* **444**, 31–41 (2012).
- ⁶⁷M. Saeedipour, S. Vincent, and J.-L. Estivaleres, “Toward a fully resolved volume of fluid

- simulation of the phase inversion problem,” *Acta Mechanica* **232**, 2695–2714 (2021).
- ⁶⁸M. M. Neamtu-Halic, J.-P. Mollicone, M. van Reeuwijk, and M. Holzner, “Role of vortical structures for enstrophy and scalar transport in flows with and without stable stratification,” *Journal of Turbulence* **22**, 393–412 (2021).
- ⁶⁹D. Vettori, F. Giordana, and C. Manes, “Turbulence enhances wave attenuation of seagrass in combined wave-current flows,” *Proceedings of the National Academy of Sciences of the United States of America* **122** (2025), 10.1073/pnas.2414150122.
- ⁷⁰K. Schoutens, A. Silinski, J.-P. Belliard, T. J. Bouma, S. Temmerman, and J. Schoelynck, “Wave attenuation by intertidal vegetation is mediated by trade-offs between shoot- and canopy-scale plant traits,” *Journal of Applied Ecology* (2024), 10.1111/1365-2664.14765.
- ⁷¹Edith Cowan University, “In: <https://oceanographicmagazine.com/news/seagrass-preservation-australia/>,” (2020).
- ⁷²M. A. Abdelrhman, “Modeling coupling between eelgrass *zostera marina* and water flow,” *Mar. Ecol. Prog. Ser.* **338**, 81–96 (2007).
- ⁷³V. Agrawal, A. Kulachenko, N. Scapin, O. Tammisola, and L. Brandt, “An efficient isogeometric/finite-difference immersed boundary method for the fluid–structure interactions of slender flexible structures,” *Computer Methods in Applied Mechanics and Engineering* **418** (2024), 10.1016/j.cma.2023.116495.
- ⁷⁴C. Alessi, C. Agabiti, D. Caradonna, C. Laschi, F. Renda, and E. Falotico, “Rod models in continuum and soft robot control: a review,” *tbd* (2024).
- ⁷⁵S. Ando, M. Nishikawa, M. Kaneda, and K. Suga, “A coupled lattice boltzmann and cosserat rod model method for three-dimensional two-way fluid–structure interactions,” *AIP Advances* **11** (2021), 10.1063/5.0058694.
- ⁷⁶S. Angus and T. Dargie, “Improving the definition of a coastal habitat: Putting the salt back into saltmarsh,” *Estuarine, Coastal and Shelf Science* **309**, 108954 (2024).
- ⁷⁷N. Anjum and M. Ali, “Investigation of the flow structures through heterogeneous vegetation of varying patch configurations in an open channel,” *Environ Fluid Mech* **22** (6), 1333–1354 (2022).
- ⁷⁸H. S. Arunakumar, P. Suvarna, P. A. P. Abhijith, A. S., U. Pruthviraj, and A. Kamath, “Effect of emerged coastal vegetation on wave attenuation using open source cfd tool: Reef3d,” (2018), in: K. Murali, V. Sriram, Abdus Samad und Nilanjan Saha (Hg.): *Proceedings of the Fourth International Conference in Ocean Engineering (ICOE2018)*. Singapore: Springer Singapore

(22), S. 591–603.

- ⁷⁹T. Attili, V. Heller, and S. Triantafyllou, “Scaling approaches and scale effects in wave–flexible structure interaction,” *Journal of Fluids and Structures* **123**, 103987 (2023).
- ⁸⁰B. M. Baaij, J. Kooijman, J. Limpens, R. J. C. Marijnissen, and J. M. van Loon-Steensma, “Monitoring impact of salt-marsh vegetation characteristics on sedimentation: an outlook for nature-based flood protection,” *Wetlands* **41** (2021), 10.1007/s13157-021-01467-w.
- ⁸¹G. E. Barter, A. Robertson, and W. Musial, “A systems engineering vision for floating offshore wind cost optimization,” *Renewable Energy Focus* **34**, 1–16 (2020).
- ⁸²J. Bass, D. Granse, I. Hache, K. Jensen, V. Karius, V. Minden, M. Stock, S. Suchrow, and M. Kleyer, “Plant traits affect vertical accretion of salt marshes,” *Estuarine, Coastal and Shelf Science* **276**, 108010 (2022).
- ⁸³F.-K. Benra, H. J. Dohmen, J. Pei, S. Schuster, and B. Wan, “A comparison of one–way and two–way coupling methods for numerical analysis of fluid–structure interactions,” *Journal of Applied Mathematics* **2011** (2011), 10.1155/2011/853560.
- ⁸⁴X. Bi and Q. Zhu, “Fluid-structure investigation of a squid-inspired swimmer,” *Physics of Fluids* **31** (2019), 10.1063/1.5119243.
- ⁸⁵H. Bihs, A. Kamath, M. Alagan Chella, A. Aggarwal, and Øivind. Arntsen, “A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics,” *Computers & Fluids* **140**, 191–208 (2016).
- ⁸⁶L. Bergdahl, J. Palm, C. Eskilsson, and J. Lindahl, “Dynamically scaled model experiment of a mooring cable,” *Journal of Marine Science and Engineering* **4**, 5 (2016).
- ⁸⁷W. A. Birkemeier, “Time scales of nearshore profile changes,” *Coastal Engineering* , 1507–1521 (1984).
- ⁸⁸R. D. Blevins, *Formulas for dynamics, acoustics and vibration*, Wiley series in acoustics, noise and vibration (Wiley, Chichester, West Sussex, 2016).
- ⁸⁹T. J. Bouma, L. A. van Duren, S. Temmerman, T. Claverie, A. Blanco-Garcia, T. Ysebaert, and P. Herman, “Spatial flow and sedimentation patterns within patches of epibenthic structures: Combining field, flume and modelling experiments,” *Continental Shelf Research* **27** (8), 1020–1045 (2007).
- ⁹⁰R. H. Bush, T. S. Chyczewski, K. Duraisamy, B. Eisfeld, C. L. Rumsey, and B. R. Smith, “Recommendations for future efforts in rans modeling and simulation,” (2019), paper presented at the AIAA Scitech 2019 Forum, in San Diego, California, 7–11 January 2019.

- ⁹¹K. Bradley and C. Houser, “Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments,” *J. Geophys. Res.* **114** (F1) (2009), 10.1029/2007JF000951.
- ⁹²J. Brzenski and K. Davis, “Flexible vegetation and its implementation in the swash ocean model,” (2021), paper presented at OCEANS 2021: San Diego – Porto.
- ⁹³D. R. Cahoon, K. L. McKee, and J. T. Morris, “How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise,” *Estuaries and Coasts* **44**, 883–898 (2021).
- ⁹⁴D. Q. Cao and R. W. Tucker, “Nonlinear dynamics of elastic rods using the cosserat theory: Modelling and simulation,” *International Journal of Solids and Structures* **45** (2) (2008), 10.1016/j.ijsolstr.2007.08.016.
- ⁹⁵A. R. Carrasco, K. Kombiadou, and A. Matias, “Short-term sedimentation dynamics in mesotidal marshes,” *Scientific reports* **13**, 1921 (2023).
- ⁹⁶G. Caroppi and J. Järvelä, “Shear layer over floodplain vegetation with a view on bending and streamlining effects,” *Environ Fluid Mech* **22** (2-3), 587–618 (2022).
- ⁹⁷G. Caroppi, K. Västilä, J. Järvelä, P. M. Rowiński, and M. Giugni, “Turbulence at water-vegetation interface in open channel flow: Experiments with natural-like plants,” *Advances in Water Resources* **127**, 180–191 (2019).
- ⁹⁸F. Cassalho, A. S. de Lima, D. J. Coleman, M. Henke, T. W. Miesse, G. d. A. Coelho, and C. M. Ferreira, “Projecting future wave attenuation by vegetation from native and invasive saltmarsh species in the united states,” *Regional Studies in Marine Science* **68**, 103264 (2023).
- ⁹⁹H. Chen and Q.-P. Zou, “Eulerian–lagrangian flow-vegetation interaction model using immersed boundary method and openfoam,” *Advances in Water Resources* **126**, 176–192 (2019).
- ¹⁰⁰Y.-I. Choo and M. Casarella, “Hydrodynamic resistance of towed cables,” *J. Hydronautics Volume* **5** (4), 126–131 (1971).
- ¹⁰¹G. Chourdakis, D. Schneider, and B. Uekermann, “Openfoam-precice: Coupling openfoam with external solvers for multi-physics simulations,” *OpenFOAM J* **3**, 1–25 (2023).
- ¹⁰²E. Cosserat and F. Cosserat, “Sur la théorie de l’élasticité: Premier mémoire,” *Annales de la Faculté des sciences de Toulouse pour les sciences mathématiques et les sciences physiques 1e série* **10** (3-4) (1896).
- ¹⁰³T. Cui, G. He, M. Jiang, W. Wang, L. Yuan, D. Han, A. Kamath, and H. Bihs, “Large eddy simulation of focused breaking waves with different wave steepness,” *Ocean Modelling* **179** (2022), 10.1016/j.ocemod.2022.102122.
- ¹⁰⁴T. Cui, A. Kamath, W. Wang, D. Han, and H. Bihs, “Large-eddy simulations of gravity currents

- in the presence of waves,” *Journal of Hydraulic Research* **60:5**, 770–791 (2022).
- ¹⁰⁵H. Cui, S. Felder, and M. Kramer, “Predicting flow resistance in open-channel flows with submerged vegetation,” *Environmental Fluid Mechanics* **23**, 757–778 (2023).
- ¹⁰⁶C. Cummins, I. M. Viola, E. Mastropaolo, and N. Nakayama, “The effect of permeability on the flow past permeable disks at low reynolds numbers,” *Physics of Fluids* **29 (9)** (2017), 10.1063/1.5001342.
- ¹⁰⁷A. D’Alpaos, S. M. Mudd, and L. Carniello, “Dynamic response of marshes to perturbations in suspended sediment concentrations and rates of relative sea level rise,” *Journal of Geophysical Research* **116**, 77 (2011).
- ¹⁰⁸A. D’Alpaos, A. Finotello, G. Goodwin, and S. Mudd, “Salt marsh hydrodynamics,” in *Salt Marshes: Function, Dynamics, and Stresses*, edited by D. FitzGerald and Z. Hughes (Cambridge University Press, Cambridge, 2021) pp. 53–81.
- ¹⁰⁹J. W. Deardorff, “On the magnitude of the subgrid scale eddy coefficient,” *Journal of Computational Physics* **7 (1)**, 120–133 (1971).
- ¹¹⁰A. R. Deitrick, E. H. Hovendon, D. K. Ralston, and H. Nepf, “The influence of vegetation-generated turbulence on deposition in emergent canopies,” *Frontiers in Marine Science* **10** (2023), 10.3389/fmars.2023.1266241.
- ¹¹¹J. J. Derksen, “Bending and low-frequency vortex shedding of flexible cylinders in laminar shear flow,” *AIChE Journal* **67** (2021), 10.1002/aic.17268.
- ¹¹²S. Dietz and S. Arnold, “Atlantic provinces: Chapter 1,” in *Canada in a Changing Climate: Regional Perspectives Report*, edited by F. J. Warren, N. Lulham, and D. S. Lemmen (Government of Canada, Ottawa, ON, 2021).
- ¹¹³J. T. Dijkstra and R. E. Uittenbogaard, “Modeling the interaction between flow and highly flexible aquatic vegetation,” *Water Resour. Res.* **46** (2010), 10.1029/2010WR009246.
- ¹¹⁴M. Döllinger, Z. Zhang, S. Schoder, P. Šidlof, B. Tur, and S. Kniesburges, “Overview on state-of-the-art numerical modeling of the phonation process,” *Acta Acustica* **7**, 25 (2023).
- ¹¹⁵T. Dunlop, W. Glamore, and S. Felder, “Restoring estuarine ecosystems using nature-based solutions: Towards an integrated eco-engineering design guideline,” *The Science of the total environment* , 162362 (2023).
- ¹¹⁶P. Esselink, W. E. van Duin, J. Bunje, J. Cremer, E. O. Folmer, J. Frikkie, M. Glahn, A. V. de Groot, N. Hecker, U. Hellwig, K. Jensen, P. Körber, J. Petersen, and M. Stock, “Cwss: Salt marshes,” in *Wadden Sea Quality Status Report*, edited by S. Kloepper, M. J. Baptist,

- Bostelmann A., Busch J.A., Buschbaum C., Gutow L., Janssen G., and Jensen K. (Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany, 2017).
- ¹¹⁷J. H. Ferziger and M. Perić, *Computational Methods for Fluid Dynamics* (Springer Berlin, Heidelberg, 2002).
- ¹¹⁸D. W. Fredriksson, T. Dewhurst, A. Drach, W. Beaver, A. T. St. Gelais, K. Johndrow, and B. A. Costa-Pierce, “Hydrodynamic characteristics of a full-scale kelp model for aquaculture applications,” *Aquacultural Engineering* **90** (2020), 10.1016/j.aquaeng.2020.102086.
- ¹¹⁹J. Freund and A. Karakoç, “Shear and torsion correction factors of timoshenko beam model for generic cross sections,” *Res. Eng. Struct. Mat.* (2016), 10.17515/resm2015.19me0827.
- ¹²⁰M. S. Fonseca, J. W. Fourqurean, and M. A. R. Koehl, “Effect of seagrass on current speed: Importance of flexibility vs. shoot density,” *Frontiers in Marine Science* **6** (2019), 10.3389/fmars.2019.00376.
- ¹²¹J. L. Garzon, M. Maza, C. M. Ferreira, J. L. Lara, and I. J. Losada, “Wave attenuation by spartina saltmarshes in the chesapeake bay under storm surge conditions,” *Journal of Geophysical Research: Oceans* **124**, 5220–5243 (2019).
- ¹²²Jean-Frédéric, M. Vidrascu, and P. Frey, “Fluid–structure interaction in blood flows on geometries based on medical imaging,” *Computers & Structures* **83**, 155–165 (2005), advances in Analysis of Fluid Structure Interaction.
- ¹²³L. Gillis, M. Maza, J. Garcia-Maribona, J. L. Lara, T. Suzuki, M. Argemi Cierco, M. Paul, Folkard, and T. Balke, “Living on the edge: How traits of ecosystem engineers drive biophysical interactions at coastal wetland edges,” *Advances in Water Resources* **166**, 104257 (2022).
- ¹²⁴F. P. Gosselin, “Mechanics of a plant in fluid flow,” *Journal of experimental botany* **70** (14), 3533–3548 (2019).
- ¹²⁵G. Griggs and K. Patsch, “The protection/hardening of california’s coast: Times are changing,” *Journal of Coastal Research* **35**, 1051 (2019).
- ¹²⁶G. Guma, P. Bucher, P. Letzgus, T. Lutz, and R. Wüchner, “High-fidelity aeroelastic analyses of wind turbines in complex terrain: fluid-structure interaction and aerodynamic modeling,” *Wind Energy Science* **7**, 1421–1439 (2022).
- ¹²⁷R. Hagen, A. Plüß, R. Ihde, J. Freund, N. Dreier, E. Nehlsen, N. Schrage, P. Fröhle, and F. Kösters, “An integrated marine data collection for the german bight – part 2: Tides, salinity, and waves (1996–2015),” *Earth System Science Data* **13**, 2573–2594 (2021).

- ¹²⁸N. Hagmeyer, M. Mayr, and A. Popp, “A fully coupled regularized mortar-type finite element approach for embedding one-dimensional fibers into three-dimensional fluid flow,” *Numerical Meth Engineering* **125** (8) (2024), 10.1002/nme.7435.
- ¹²⁹E. Hairer and G. Wanner, “Stiff differential equations solved by radau methods,” *Journal of Computational and Applied Mathematics* **111** (1-2), 93–111 (1999).
- ¹³⁰M. Hassani, S. M. Laurin, N. W. Mureithi, and F. P. Gosselin, “Bending and torsional reconfiguration of chiral rods under wind and gravity,” *Extreme Mechanics Letters* **13**, 91–99 (2017).
- ¹³¹S. He, H. Liu, and L. Shen, “Simulation-based study of turbulent aquatic canopy flows with flexible stems,” *J. Fluid Mech.* **947** (2022), 10.1017/jfm.2022.655.
- ¹³²S. M. Henderson, “Motion of buoyant, flexible aquatic vegetation under waves: Simple theoretical models and parameterization of wave dissipation,” *Coastal Engineering* **152** (2019), 10.1016/j.coastaleng.2019.04.009.
- ¹³³P.-Y. Henry, D. Myrhaug, and J. Aberle, “Drag forces on aquatic plants in nonlinear random waves plus current,” *Estuarine, Coastal and Shelf Science* **165**, 10–24 (2015).
- ¹³⁴M. Heuner, A. Silinski, J. Schoelynck, T. J. Bouma, S. Puijalon, P. Troch, E. Fuchs, B. Schröder, U. Schröder, P. Meire, and S. Temmerman, “Ecosystem engineering by plants on wave-exposed intertidal flats is governed by relationships between effect and response traits,” *PloS one* **10**, e0138086 (2015).
- ¹³⁵A. Himes-Cornell, L. Pendleton, and P. Atiyah, “Valuing ecosystem services from blue forests: A systematic review of the valuation of salt marshes, sea grass beds and mangrove forests,” *Ecosystem Services* **30**, Part A, 36–48 (2018).
- ¹³⁶J. Hofstede, “Update of the schleswig-holstein state master plan for coastal flood defense and coastal protection with a focus on climate change adaptation: 22 pages,” (2022).
- ¹³⁷J. L. A. Hofstede, “Status and prospects of nature-based solutions for coastal flood and erosion risk management in the federal state of schleswig–holstein, germany,” *Journal of Coastal Conservation* **28** (2024), 10.1007/s11852-024-01042-5.
- ¹³⁸W.-x. Huai, J. Zhang, G. G. Katul, Y.-g. Cheng, X. Tang, and W.-j. Wang, “The structure of turbulent flow through submerged flexible vegetation,” *J Hydrodyn* **31** (2), 274–292 (2019).
- ¹³⁹W. Huang and H. Sung, “Three-dimensional simulation of a flapping flag in a uniform flow,” *Journal of Fluid Mechanics* **653**, 301–336 (2010).
- ¹⁴⁰Z. Huang, Y. Yao, S. Y. Sim, and Y. Yao, “Interaction of solitary waves with emergent, rigid vegetation,” *Ocean Engineering* **38** (10), 1080–1088 (2011).

- ¹⁴¹A. A. Hussain, M. A. Al-Obaidi, A. S. Mohammed, Y. M. John, and F. L. Rashid, “Distribution of the velocity profile via analytical and three-dimensional numerical vegetation modeling,” *Journal of Applied Fluid Mechanics* **17** (2024), 10.47176/jafm.17.9.2487.
- ¹⁴²N. Jacobsen, G. van Velzen, and J. Fredsøe, “Analysis of pile scour and associated hydrodynamic forces using proper orthogonal decomposition,” *Scour and Erosion: Proceedings of the 7th International Conference on Scour and Erosion*, 361–372 (2014).
- ¹⁴³N. G. Jacobsen, “Wave-averaged properties in a submerged canopy: Energy density, energy flux, radiation stresses and stokes drift,” *Coastal Engineering* **117**, 57–69 (2016).
- ¹⁴⁴C. Jin and J. Zhang, “Numerical investigation of the wave interaction with flexible vegetation: model setup and validation for a single stem study case,” *Anthropocene Coasts* **5** (2022), 10.1007/s44218-022-00003-5.
- ¹⁴⁵C. Jordan, J. Visscher, and T. Schlurmann, “Projected responses of tidal dynamics in the north sea to sea-level rise and morphological changes in the wadden sea,” *Frontiers in Marine Science* **8** (2021), 10.3389/fmars.2021.685758.
- ¹⁴⁶J. M. J. Journée and W. W. Massie, *Offshore Hydrodynamics. First Edition* (2001).
- ¹⁴⁷P. Jung, S. Leyendecker, J. Linn, and M. Ortiz, “A discrete mechanics approach to the cosserat rod theory—part 1: static equilibria,” *Numerical Meth Engineering* **85** (1), 31–60 (2011).
- ¹⁴⁸N. D. Katopodes, *Free-surface flow. Environmental fluid mechanics* (Butterworth-Heinemann, Oxford, 2019).
- ¹⁴⁹H. D. Kim, X. Yu, and D. Kaplan, “Steady flow over a finite patch of submerged flexible vegetation,” *Water Resources Research* **60** (1) (2024), 10.1029/2023WR035222.
- ¹⁵⁰S. King and J. Lester, “The value of salt marsh as a sea defence,” *Marine Pollution Bulletin* **30**, 180–189 (1995).
- ¹⁵¹S. Kloepper, M. J. Baptist, Bostelmann A., Busch J.A., Buschbaum C., Gutow L., Janssen G., and Jensen K., “Wadden sea quality status report,” (2017).
- ¹⁵²C. W. Knisely, “Strouhal numbers of rectangular cylinders at incidence: A review and new data,” *Journal of Fluids and Structures* **4**, 371–393 (1990).
- ¹⁵³V. Kosmalla, K. Keimer, D. Schürenkamp, O. Lojek, and N. Goseberg, “Erosion resistance of vegetation-covered soils: Impact of different grazing conditions in salt marshes and analysis of soil-vegetation interactions by the novel dicoastar method,” *Ecological Engineering* **181** (2022), 10.1016/j.ecoleng.2022.106657.
- ¹⁵⁴H. Lang, J. Linn, and M. Arnold, “Multi-body dynamics simulation of geometrically exact

- cosserat rods,” *MULTIBODY DYNAMICS* 2009 (2009).
- ¹⁵⁵H. Lang, J. Linn, and M. Arnold, “Multi-body dynamics simulation of geometrically exact cosserat rods,” *Multibody Syst Dyn* **25** (3), 285–312 (2011).
- ¹⁵⁶H. Lang, S. Leyendecker, and J. Linn, “Numerical experiments for viscoelastic cosserat rods with kelvin-voigt damping,” *Proceedings of the ECCOMAS Thematic Conference on Multi-body Dynamics* (2013).
- ¹⁵⁷B.-l. Li, Y.-w. Wang, B. Yin, X. Zhang, and X. Zhang, “Self-propelled swimming of a flexible filament driven by coupled plunging and pitching motions,” *Journal of Hydrodynamics* **33**, 157–169 (2021).
- ¹⁵⁸C. Le Bouteiller and J. G. Venditti, “Sediment transport and shear stress partitioning in a vegetated flow,” *Water Resources Research* **51** (4), 2901–2922 (2015).
- ¹⁵⁹K. Liao, C. Hu, and M. Sueyoshi, “Free surface flow impacting on an elastic structure: Experiment versus numerical simulation,” *Applied Ocean Research* **50**, 192–208 (2015).
- ¹⁶⁰K. E. Lilly, “On the application of the eddy viscosity concept in the inertial sub-range of turbulence,” (1966).
- ¹⁶¹W. Z. Lim and R. Y. Xiao, “Fluid-structure interaction analysis of flexible plate with partitioned coupling method,” *China Ocean Engineering* **33**, 713–722 (2019).
- ¹⁶²J. Linn and A. Lang, Holger; Tuganov, “Geometrically exact cosserat rods with kelvin-voigt type viscous damping,” *Mech. Sci.* **4** (1), 79–96 (2013).
- ¹⁶³C. Liu, C. Yan, S. Sun, J. Lei, H. Nepf, and Y. Shan, “Velocity, turbulence, and sediment deposition in a channel partially filled with a *phragmites australis* canopy,” *Water Resources Research* **58** (8) (2022), 10.1029/2022WR032381.
- ¹⁶⁴J. Liu, Q. Liu, S. Kutschke, V. Kosmalla, D. Schürenkamp, N. Goseberg, and M. Böl, “Seasonal variations in biomechanical properties of *elymus* species: Implications for assessing coastal ecosystem services,” *PAMM* **24** (2024), 10.1002/pamm.202400088.
- ¹⁶⁵Z. Liu, S. Fagherazzi, Q. He, O. Gourgue, J. Bai, X. Liu, C. Miao, Z. Hu, and B. Cui, “A global meta-analysis on the drivers of salt marsh planting success and implications for ecosystem services,” *Nature communications* **15**, 3643 (2024).
- ¹⁶⁶V. B. Lo, T. J. Bouma, J. van Belzen, C. van Colen, and L. Airolidi, “Interactive effects of vegetation and sediment properties on erosion of salt marshes in the northern adriatic sea,” *Marine environmental research* **131**, 32–42 (2017).
- ¹⁶⁷I. J. Losada, M. Maza, and J. L. Lara, “A new formulation for vegetation-induced damping

- under combined waves and currents,” *Coastal Engineering* **107**, 1–13 (2016).
- ¹⁶⁸S. Lou, H. Wang, H. Liu, G. Zhong, L. D. Radnaeva, E. Nikitina, G. Ma, and S. Liu, “Laboratory study of the effects of flexible vegetation on solute diffusion in unidirectional flow,” *Environ Sci Eur* **33** (1) (2021), 10.1186/s12302-021-00521-y.
- ¹⁶⁹A. E. H. Love, *A treatise on the mathematical theory of elasticity* (Cambridge University Press, Cambridge, England, 1906).
- ¹⁷⁰R. J. Lowe, J. L. Falter, J. R. Koseff, S. G. Monismith, and M. J. Atkinson, “Spectral wave flow attenuation within submerged canopies: Implications for wave energy dissipation,” *J. Geophys. Res.* **112** (2007), 10.1029/2006 JC003605.
- ¹⁷¹M. Luhar and H. M. Nepf, “Flow-induced reconfiguration of buoyant and flexible aquatic vegetation,” *Limnology and Oceanography* **56**, 2003–2017 (2011).
- ¹⁷²B. Marin-Diaz, D. van der Wal, L. Kaptein, P. Martinez-Garcia, C. H. Lashley, K. d. Jong, J. W. Nieuwenhuis, L. L. Govers, H. Olff, and T. J. Bouma, “Using salt marshes for coastal protection: Effective but hard to get where needed most,” *Journal of Applied Ecology* (2023), 10.1111/1365-2664.14413.
- ¹⁷³T. I. Marjoribanks, R. J. Hardy, S. N. Lane, and D. R. Parsons, “High-resolution numerical modelling of flow—vegetation interactions,” *Journal of Hydraulic Research* **52** (6), 775–793 (2014).
- ¹⁷⁴R. Marsooli and W. Wu, “Numerical investigation of wave attenuation by vegetation using a 3d rans model,” *Advances in Water Resources* **74**, 245–257 (2014).
- ¹⁷⁵T. Martin, S. Schacht, P. Riesen, and M. Paschen, “Efficient implementation of a numerical model for flexible net structures,” *Ocean Engineering* **150**, 272–279 (2018).
- ¹⁷⁶T. Martin and H. Bihs, “A numerical solution for modelling mooring dynamics, including bending and shearing effects, using a geometrically exact beam model,” *JMSE* **9** (5), 486 (2021).
- ¹⁷⁷T. Martin and H. Bihs, “A non-linear implicit approach for modelling the dynamics of porous tensile structures interacting with fluids,” *Journal of Fluids and Structures* **100** (2021), 10.1016/j.jfluidstructs.2020.103168.
- ¹⁷⁸T. Martin, G. Wang, and H. Bihs, “Numerical modeling of the interaction of moving fish nets and fluid,” *J. Offshore Mech. Arct. Eng.* **144**(1) (2022), 10.1115/1.4051088.
- ¹⁷⁹G. Matheou and D. Chung, “Large-eddy simulation of stratified turbulence. part ii: Application of the stretched-vortex model to the atmospheric boundary layer,” *Journal of the Atmospheric Sciences* **71** (12), 4439–4460 (2014).

- ¹⁸⁰S. A. Mattis, C. N. Dawson, C. E. Kees, and M. W. Farthing, “An immersed structure approach for fluid-vegetation interaction,” *Advances in Water Resources* **80** (2015), 10.1016/j.advwatres.2015.02.014.
- ¹⁸¹M. Mayr, W. A. Wall, and M. W. Gee, “Adaptive time stepping for fluid-structure interaction solvers,” *Finite Elements in Analysis and Design* **141**, 55–69 (2018).
- ¹⁸²M. Maza, J. L. Lara, and I. J. Losada, “A coupled model of submerged vegetation under oscillatory flow using navier–stokes equations,” *Coastal Engineering* **80**, 16–34 (2013).
- ¹⁸³C. J. Mcowen, L. V. Weatherdon, J.-W. van Bochove, E. Sullivan, S. Blyth, C. Zockler, D. Stanwell-Smith, N. Kingston, C. S. Martin, M. Spalding, and S. Fletcher, “A global map of saltmarshes,” *Biodiversity data journal* **5**, e11764 (2017).
- ¹⁸⁴C. Meier, A. Popp, and W. A. Wall, “Geometrically exact finite element formulations for slender beams: Kirchhoff–love theory versus simo–reissner theory,” *Archives of Computational Methods in Engineering* **26**, 163–243 (2019).
- ¹⁸⁵J. R. Morison, M. P. O’Brien, J. W. Johnson, and S. A. Schaaf, “The force exerted by surface waves on piles,” *Petroleum Transactions* **189** (1950).
- ¹⁸⁶S. G. Monismith, “Stokes drift: theory and experiments,” *Journal of Fluid Mechanics* **884** (2020), 10.1017/jfm.2019.891.
- ¹⁸⁷S. Mudhaffer, R. Althagafi, J. Haider, J. Satterthwaite, and N. Silikas, “Effects of printing orientation and artificial ageing on martens hardness and indentation modulus of 3d printed restorative resin materials,” *Dental materials: official publication of the Academy of Dental Materials* **40**, 1003–1014 (2024).
- ¹⁸⁸E. Murphy, A. Cornett, D. van Proosdij, and R. P. Mulligan, eds., *Nature-based infrastructure for coastal flood and erosion risk management: a Canadian design guide* (National Research Council of Canada, 2024).
- ¹⁸⁹M. Neumann and J. Burgner-Kahrs, “Considerations for follow-the-leader motion of extensible tendon-driven continuum robots,” *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 917–923 (2016).
- ¹⁹⁰J. Ni, C. Ji, D. Xu, X. Zhang, and D. Liang, “On monami modes and scales of a flexible vegetation array in a laminar boundary layer,” *Physics of Fluids* **35** (7) (2023), 10.1063/5.0155506.
- ¹⁹¹F. Nicoud and F. Ducros, “Subgrid-scale stress modelling based on the square of the velocity gradient tensor,” *Flow, Turbulence and Combustion* **62**, 183–200 (1999).
- ¹⁹²J. O’Connor and B. D. Rogers, “A fluid-structure interaction model for free-surface flows and

- flexible structures using smoothed particle hydrodynamics on a gpu,” *Journal of Fluids and Structures* **104** (2021), 10.1016/j.jfluidstructs.2021.103312.
- ¹⁹³T.-a. Okamoto and I. Nezu, “Large eddy simulation of 3-d flow structure and mass transport in open-channel flows with submerged vegetations,” *Journal of Hydro-environment Research* **4** (3), 185–197 (2010).
- ¹⁹⁴B. Ondiviela, I. J. Losada, M. Lara, Javier L.; Maza, C. Galván, T. J. Bouma, and J. van Belzen, “The role of seagrasses in coastal protection in a changing climate,” *Coastal Engineering* **87**, 158–168 (2014).
- ¹⁹⁵O. M. O’Reilly, *Modeling Nonlinear Problems in the Mechanics of Strings and Rods: The Role of the Balance Laws*, 1st ed., Interaction of Mechanics and Mathematics (Springer International Publishing and Imprint: Springer, Cham, 2017).
- ¹⁹⁶P. Ouro and T. Stoesser, “An immersed boundary-based large-eddy simulation approach to predict the performance of vertical axis tidal turbines,” *Computers & Fluids* **152**, 74–87 (2017).
- ¹⁹⁷K.-J. Paik and P. M. Carrica, “Fluid–structure interaction for an elastic structure interacting with free surface in a rolling tank,” *Ocean Engineering* **84**, 201–212 (2014).
- ¹⁹⁸J. Palm, C. Eskilsson, G. M. Paredes, and L. Bergdahl, “Coupled mooring analysis for floating wave energy converters using cfd: Formulation and validation,” *International Journal of Marine Energy* **16**, 83–99 (2016).
- ¹⁹⁹J. Palm, C. Eskilsson, and L. Bergdahl, “An hp -adaptive discontinuous galerkin method for modelling snap loads in mooring cables,” *Ocean Engineering* **144**, 266–276 (2017).
- ²⁰⁰J. Palm and C. Eskilsson, “Influence of bending stiffness on snap loads in marine cables: A study using a high-order discontinuous galerkin method,” *JMSE* **8** (10), 795 (2020).
- ²⁰¹D. Paprotny, P. Terefenko, A. Giza, P. Czapliński, and M. I. Vousdoukas, “Future losses of ecosystem services due to coastal erosion in europe,” *The Science of the total environment* **760**, 144310 (2021).
- ²⁰²M. Paul, C. Bischoff, and K. Koop-Jakobsen, “Biomechanical traits of salt marsh vegetation are insensitive to future climate scenarios,” *Scientific reports* **12**, 21272 (2022).
- ²⁰³C. Philippart, M. J. Baptist, C. J. Bastmeijer, T. Bregnballe, C. Buschbaum, P. Hoekstra, K. Laursen, and S. M. van Leeuwen, “Cwss: Climate change,” in *Wadden Sea Quality Status Report*, edited by S. Kloepper, M. J. Baptist, Bostelmann A., Busch J.A., Buschbaum C., Gutow L., Janssen G., and Jensen K. (Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany, 2024).

- ²⁰⁴D. Pujol, T. Serra, J. Colomer, and X. Casamitjana, “Flow structure in canopy models dominated by progressive waves,” *Journal of Hydrology* **486**, 281–292 (2013).
- ²⁰⁵S. B. Pope, *Turbulent flows* (Cambridge University Press, Cambridge, New York, 2000).
- ²⁰⁶R. Postma, “Room for sea level rise: An exploration of conceptual perspectives to keep the netherlands safe and liveable in the long term as sea levels rise,” (2024).
- ²⁰⁷T. Rabinowitz and J. Andrews, “Valuing the salt marsh ecosystem: Developing ecosystem accounts,” (2022).
- ²⁰⁸A. M. Rahimi, S. R. Lustig, J. P. Bardhan, and S. Jamali, “Drag reduction and the vogel exponent of a flexible beam in transient shear flows,” *Physics of Fluids* **34** (2022), 10.1063/5.0106700.
- ²⁰⁹F. Renda, M. Giorelli, M. Calisti, M. Cianchetti, and C. Laschi, “Dynamic model of a multi-bending soft robot arm driven by cables,” *IEEE Trans. Robot.* **30** (5), 1109–1122 (2014).
- ²¹⁰D. Rayner, W. Glamore, L. Grandquist, J. Ruprecht, K. Waddington, and D. Khojasteh, “Intertidal wetland vegetation dynamics under rising sea levels,” *Science of The Total Environment* **766**, 144237 (2021).
- ²¹¹T. Richter, *Fluid-structure Interactions*, Vol. 118 (Springer International Publishing, Cham, 2017).
- ²¹²A. Robertson, J. Jonkman, F. Vorpahl, W. Popko, J. Qvist, L. Frøyd, X. Chen, J. Azcona, E. Uzunoglu, C. Guedes Soares, C. Luan, H. Yutong, F. Pengcheng, A. Yde, T. Larsen, J. Nichols, R. Buils, L. Lei, T. A. Nygaard, D. Manolas, A. Heege, S. R. Vatne, H. Ormberg, T. Duarte, C. Godreau, H. F. Hansen, A. W. Nielsen, H. Riber, C. Le Cunff, F. Beyer, A. Yamaguchi, K. J. Jung, H. Shin, W. Shi, H. Park, M. Alves, and M. Guérinel, “Offshore code comparison collaboration continuation within iea wind task 30: Phase ii results regarding a floating semisubmersible wind system,” (2014), 10.1115/OMAE2014-24040.
- ²¹³G. Robson, E. Schoen, D. M. Chan, H. R. Ogrosky, K. Shrestha, and J. C. Zinnert, “Modeling the interaction of vegetation and sea level rise on barrier island evolution,” *PloS one* **19**, e0302395 (2024).
- ²¹⁴A. Rooijen, R. Lowe, D. P. Rijnsdorp, M. Ghisalberti, N. G. Jacobsen, and R. McCall, “Wave-driven mean flow dynamics in submerged canopies,” *Journal of Geophysical Research: Oceans* **125** (2020), 10.1029/2019JC015935.
- ²¹⁵À. Ros, J. Colomer, T. Serra, D. Pujol, M. Soler, and X. Casamitjana, “Experimental observations on sediment resuspension within submerged model canopies under oscillatory flow,”

Continental Shelf Research **91**, 220–231 (2014).

- ²¹⁶S. Roy, A. De, and E. Balaras, eds., *Immersed Boundary Method: Development and Applications*, 1st ed., Springer eBook Collection (Springer Singapore and Imprint Springer, Singapore, 2020).
- ²¹⁷D. C. Rucker and R. J. Webster III, “Statics and dynamics of continuum robots with general tendon routing and external loading,” *IEEE Trans. Robot.* **27** (6), 1033–1044 (2011).
- ²¹⁸A. Sasikumar, A. Kamath, and H. Bihs, “Modeling porous coastal structures using a level set method based vrans-solver on staggered grids,” *Coastal Engineering Journal* **62** (2), 198–216 (2020).
- ²¹⁹J.-P. Savard, D. van Proosdij, and S. O’Carroll, “Perspectives on canada’s east coast region,” in *Canada’s Marine Coasts in a Changing Climate*, edited by D.S. Lemmen, F.J. Warren, T.S. James, and C.S.L. Mercer Clarke (Government of Canada, Ottawa, ON, 2016) pp. 99–152.
- ²²⁰K. Schoppmann, B. Löhrer, S. Tschisgale, J. Fröhlich, and E. d. Langre, “An efficient solver for a cosserat rod of non-constant width applied to a problem of fluid-structure interaction,” *Proc Appl Math & Mech* **21** (1) (2021), 10.1002/pamm.202100152.
- ²²¹H. Schmucker, F. Flemming, and S. Coulson, “Two-way coupled fluid structure interaction simulation of a propeller turbine,” *International Journal of Fluid Machinery and Systems* **3**, 342–351 (2010).
- ²²²T. Schoonees, A. Gijón Mancheño, B. Scheres, T. J. Bouma, R. Silva, T. Schlurmann, and H. Schüttrumpf, “Hard structures for coastal protection, towards greener designs,” *Estuaries and Coasts* **42**, 1709–1729 (2019).
- ²²³C. C. Shepard, C. M. Crain, and M. W. Beck, “The protective role of coastal marshes: A systematic review and meta-analysis,” *PloS one* **6**, e27374 (2011).
- ²²⁴B. Simeon, “Numerical analysis of flexible multibody systems.” *Multibody Syst Dyn* **6** (4), 305–325 (2001).
- ²²⁵J. Smagorinsky, “General circulation experiments with the primitive equations,” *Mon. Wea. Rev.* **91** (3), 99–164 (1963).
- ²²⁶C. S. Steinigeweg, O. J. Siebeneicher, B. Schröder, M. Kleyer, K. Löhms, and S. Löbel, “Elevational ranges of pioneer marsh species are site specific and likely shaped by different abiotic and biotic factors,” *Ecosphere* **16** (2025), 10.1002/ecs2.70148.
- ²²⁷M. M. Stoorvogel, J. van Belzen, S. Temmerman, L. E. Wiesebron, G. S. Fivash, L. van IJzerloo, J. van de Koppel, and T. J. Bouma, “Salt marshes for nature-based flood defense: Sediment

- type, drainage, and vegetation drive the development of strong sediment beds,” *Ecological Engineering* **207**, 107335 (2024).
- ²²⁸R. Strempel, A. Bostelmann, J. Busch, and S. Klöpper, “Cwss: Introduction,” in *Wadden Sea Quality Status Report*, edited by S. Kloepper, M. J. Baptist, Bostelmann A., Busch J.A., Buschbaum C., Gutow L., Janssen G., and Jensen K. (Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany, 2017).
- ²²⁹P. Sun, D. L. Touzé, and A.-M. Zhang, “Study of a complex fluid-structure dam-breaking benchmark problem using a multi-phase sph method with apr,” *Engineering Analysis with Boundary Elements* **104**, 240–258 (2019).
- ²³⁰R. Taylor-Burns, K. Nederhoff, J. R. Lacy, and P. L. Barnard, “The influence of vegetated marshes on wave transformation in sheltered estuaries,” *Coastal Engineering* **184**, 104346 (2023).
- ²³¹S. Temmerman, E. M. Horstman, K. W. Krauss, J. C. Mullarney, I. Pelckmans, and K. Schoutens, “Marshes and mangroves as nature-based coastal storm buffers,” *Annual review of marine science* **15**, 95–118 (2023).
- ²³²J. A. Tempest, I. Möller, and T. Spencer, “A review of plant–flow interactions on salt marshes: the importance of vegetation structure and plant mechanical characteristics,” *WIREs Water* **2**, 669–681 (2015).
- ²³³F.-B. Tian, H. Dai, H. Luo, J. F. Doyle, and B. Rousseau, “Fluid-structure interaction involving large deformations: 3d simulations and applications to biological systems,” *Journal of Computational Physics* **258** (2014), 10.1016/j.jcp.2013.10.047.
- ²³⁴J. Till, V. Aloï, and C. Rucker, “Real-time dynamics of soft and continuum robots based on cosserat rod models,” *The International Journal of Robotics Research* **38** (6), 723–746 (2019).
- ²³⁵S. Timošhenko and J. Goodier, *Theory of Elasticity*, 2nd ed. (McGraw-Hill Book Company, 1951).
- ²³⁶S. Timošhenko, *History of strength of materials: With a brief account of the history of theory of elasticity and theory of structures* (Dover, New York, 1983).
- ²³⁷S. Tschisgale and J. Fröhlich, “An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid,” *Journal of Computational Physics* **423** (7) (2020), 10.1016/j.jcp.2020.109801.
- ²³⁸S. Tschisgale, B. Löhrer, R. Meller, and J. Fröhlich, “Large eddy simulation of the fluid–structure interaction in an abstracted aquatic canopy consisting of flexible blades,” *J. Fluid*

Mech. **916** (2021), 10.1017/jfm.2020.858.

- ²³⁹S. Turek and J. Hron, “Proposal for numerical benchmarking of fluid-structure interaction between an elastic object and laminar incompressible flow,” *Fluid-Structure Interaction: Modelling, Simulation, Optimisation* **53**, 371–385 (2007).
- ²⁴⁰T. S. van den Bremer and Ø. Breivik, “Stokes drift,” *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* **376** (2018), 10.1098/rsta.2017.0104.
- ²⁴¹O. D. Vinent, R. J. Johnston, M. L. Kirwan, A. D. Leroux, and V. L. Martin, “Coastal dynamics and adaptation to uncertain sea level rise: Optimal portfolios for salt marsh migration,” *Journal of Environmental Economics and Management* **98**, 102262 (2019).
- ²⁴²H. Wang, H.-w. Tang, H.-q. Zhao, X.-y. Zhao, and S.-q. Lü, “Incipient motion of sediment in presence of submerged flexible vegetation,” *Water Science and Engineering* **8**, 63–67 (2015).
- ²⁴³M. Wang, E. J. Avital, X. Bai, C. Ji, D. Xu, J. J. R. Williams, and A. Munjiza, “Fluid–structure interaction of flexible submerged vegetation stems and kinetic turbine blades,” *Comp. Part. Mech.* **7** (5) (2020), 10.1007/s40571-019-00304-6.
- ²⁴⁴J. Wang, G. He, S. Dey, and H. Fang, “Influence of submerged flexible vegetation on turbulence in an open-channel flow,” *Journal of Fluid Mechanics* **947** (2022), 10.1017/jfm.2022.598.
- ²⁴⁵G. Wang, T. Martin, L. Huang, and H. Bihs, “A numerical study of the hydrodynamics of an offshore fish farm using reef3d,” *J. Offshore Mech. Arct. Eng* **144**(2) (2022), 10.1115/1.4052865.
- ²⁴⁶J. Wang, G. He, S. Dey, and H. Fang, “Fluid–structure interaction in a flexible vegetation canopy in an open channel,” *Journal of Fluid Mechanics* **951** (2022), 10.1017/jfm.2022.899.
- ²⁴⁷L. Wang, M. Xu, C. Zhang, and W. Dai, “Numerical investigation on solitary waves traveling over rigid vegetation by a 3d-mps method,” *Applied Ocean Research* **132**, 103476 (2023).
- ²⁴⁸X. Wang and N. Rojas, “Cosserat rod modeling and validation for a soft continuum robot with self-controllable variable curvature,” *7th International Conference on Soft Robotics (RoboSoft)*, 705–710 (2024).
- ²⁴⁹W. Wei, Z. Dai, W. Pang, J. Wang, Y. Chen, and S. Gao, “Frequency-dependent wave damping by tidal wetlands under storm conditions,” *Journal of Hydrology*, 128415 (2022).
- ²⁵⁰Z. Wei, Y. Shao, T. Kristiansen, and D. Kristiansen, “An efficient numerical solver for highly compliant slender structures in waves: Application to marine vegetation,” *Journal of Fluids and Structures* **129** (2024), 10.1016/j.jfluidstructs.2024.10417.
- ²⁵¹P. Whittaker, C. A. Wilson, and J. Aberle, “An improved cauchy number approach for predicting the drag and reconfiguration of flexible vegetation,” *Advances in Water Resources* **83**,

28–35 (2015).

- ²⁵²C. Windt, J. Davidson, and J. Ringwood, “Investigation of turbulence modeling for point-absorber type wave energy converters,” *Energies* **14** (26) (2021), <https://dx.doi.org/10.3390/en14010026>.
- ²⁵³Z. Xu and C.-W. Shu, “Anti-diffusive flux corrections for high order finite difference weno schemes,” *Journal of Computational Physics* **205** (2), 458–485 (2005).
- ²⁵⁴D. Xu, J.-n. Liu, Y.-f. Wu, and C.-n. Ji, “Numerical investigation of the dynamics of flexible vegetations in turbulent open-channel flows,” *J Hydrodyn* **34** (4), 681–699 (2022).
- ²⁵⁵W. Ye and Z. Hu, “A new model for quantifying wave damping by vegetation in combined wave–current flow,” *Ocean Engineering* **288**, 116119 (2023).
- ²⁵⁶Z. Yin, Y. Wang, Y. Liu, and W. Zou, “Wave attenuation by rigid emergent vegetation under combined wave and current flows,” *Ocean Engineering* **213** (2020), 10.1016/j.oceaneng.2020.107632.
- ²⁵⁷R. B. Zeller, F. J. Zarama, J. S. Weitzman, and J. R. Koseff, “A simple and practical model for combined wave–current canopy flows,” *J. Fluid Mech.* **767**, 842–880 (2015).
- ²⁵⁸X. Zhang and H. Nepf, “Wave-induced reconfiguration of and drag on marsh plants,” *Journal of Fluids and Structures* **100**, 103192 (2021).
- ²⁵⁹C. Zhang and M. Zhang, “Numerical investigation of solitary wave attenuation and mitigation caused by vegetation using openfoam,” *Coastal Engineering Journal* , 1–19 (2023).
- ²⁶⁰C. Zhao, J. Tang, Y. Shen, and Y. Wang, “Study on wave attenuation in following and opposing currents due to rigid vegetation,” *Ocean Engineering* **236** (2021), 10.1016/j.oceaneng.2021.109574.
- ²⁶¹Y. Zhi, H. Li, S. An, L. Zhao, C. Zhou, and Z. Deng, “Inter-specific competition: *Spartina alterniflora* is replacing *spartina anglica* in coastal china,” *Estuarine, Coastal and Shelf Science* **74**, 437–448 (2007).
- ²⁶²L. Zhu, Q. Zou, K. Huguenard, and D. W. Fredriksson, “Mechanisms for the asymmetric motion of submerged aquatic vegetation in waves: A consistent-mass cable model,” *J. Geophys. Res. Oceans* **125** (2020), 10.1029/2019JC015517.
- ²⁶³Z. Zhu, Z. Yang, and T. J. Bouma, “Biomechanical properties of marsh vegetation in space and time: effects of salinity, inundation and seasonality,” *Annals of botany* **125** (2), 277–290 (2020).
- ²⁶⁴S. Zhu, W. Wei, Q. Zhu, K. Wan, F. Xing, W. Yan, J. Gao, and Y. P. Wang, “Wave attenuation

and transformation across a highly turbid muddy tidal flat-salt marsh system,” *Applied Ocean Research* **147**, 103980 (2024).

²⁶⁵R. Zijlstra, J. Hofstede, T. Piontkowitz, and F. Thorenz, “Cwss: Coastal risk management,” in *Wadden Sea Quality Status Report*, edited by S. Kloepper, M. J. Baptist, Bostelmann A., Busch J.A., Buschbaum C., Gutow L., Janssen G., and Jensen K. (Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany, 2017).

²⁶⁶Natural Resources Canada, “Growing season,” (2025).

²⁶⁷Environmental and Natural Resources Canada, “Climatology of temperature and precipitation,” (2025).

²⁶⁸Das Helmholtz-Zentrum Hereon, “Nordseeküste: Bisherige entwicklung der durchschnittlichen temperatur im jahr,” (2025).

²⁶⁹Das Helmholtz-Zentrum Hereon, “Nordseeküste: Bisherige entwicklung der vegetationsperiode im jahr,” (2025).

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A summary of this publication can be found in Section 3.2 of this thesis. The following documents show the published study as well as the answers to reviewer comments.



A comprehensive numerical study on the current-induced fluid–structure interaction of flexible submerged vegetation

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ABSTRACT

Submerged vegetation is becoming more and more relevant as a nature-based solution for coastal protection schemes, counteracting the effects of climate change and sea level rise. The numerical model REEF3D has been used to simulate the motion of and forces exerted on flexible vegetation under unidirectional currents. This study emphasizes the critical need for accurate solutions obtained by numerical models to investigate the complex ecosystem services, adopting a direct forcing approach using the immersed boundary method. The fluid–structure interaction capability within the finite difference model is comprehensively evaluated for the simulation of stem motions and forces exerted on flexible vegetation under varying unidirectional flows. Thresholds for numerical parameters, including a minimum number of 25 rigid elements composing the stem, are identified for accurate solutions. The necessity of using large eddy simulations and a Smagorinsky constant of 0.1 to simulate the turbulent flow is demonstrated. The study confirms the accuracy of the implemented fluid–structure interaction model to replicate stem bending (less than 10 % deviation relative to the stem length) and forces across varying hydrodynamic conditions.

1. Introduction

Vegetation such as seagrass or salt marsh species are flexible structures that are either permanently or temporarily submerged in coastal waters and therefore exposed to hydrodynamic forces by waves and tidal currents. Vegetation is commonly considered an ecosystem engineer along the coastal rims (Ondiviela et al., 2014; Himes-Cornell et al., 2018; Marin-Diaz et al., 2023). The ecosystem service capacity of coastal vegetation includes wave attenuation, sediment accumulation, and soil stabilization (King and Lester, 1995; Anderson and Smith, 2014; Rupprecht et al., 2017), which provides beneficial and supportive capabilities for coastal zone management to counteract the predicted sea level rise (Vuik et al., 2019). The complex ecosystem services and non-linear interactions between flexible submerged vegetation and fluids drive the need for the development of state-of-the-art numerical

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methods that accurately approximate their hydrodynamic response. The characteristics of the interaction between the fluid's velocity and pressure fields with the elastically-flexing vegetation depend on the material and geometrical properties of the vegetation (Liu et al., 2021), as well as on the magnitude of the hydrodynamic forces (Bouma et al., 2005); this interplay is commonly known as fluid–structure interaction (FSI).

Nowadays it can be considered state of the art to represent the vegetation in the FSI as a flexible body. On the process level, it is straightforward to agree that the flexibility of plant motion reduces the frontal area of the plant and the relative velocity between the plant and the water, as the flexible structure bends, resulting in a motion instigated by the hydrodynamic loading (van Veelen et al., 2020). The resulting reconfiguration of plants due to external loading can be either classified as *avoidance strategy* (minimum frontal area) or as *tolerance strategy* (maximized resistance to breakage), see Puijalon et al. (2011). Vegetation that is classified to follow the avoidance strategy has a lower flexural stiffness. The importance of including plant flexibility in studies has been shown, for example, in the analysis of the ability of vegetation to dampen incoming waves, whose wave energy reduces with increasing flexibility by 30 % to 70 % depending on the study (Mullarney and Henderson, 2010; van Veelen et al., 2020).

Two main approaches can be found in the literature to model the FSI numerically. Some methods employ semi-empirical formulations to include forces, such as drag and buoyancy, into the force balance. The specific formulations applied in the force balance of different numerical models vary, depending on the complexity of the model, e.g. by considering skin friction (Dijkstra and Uittenbogaard, 2010; Zhu et al., 2020). With the semi-empirical approach, the drag forces are calculated using the Morison equation, as performed in the works of Dijkstra and Uittenbogaard (2010), Mullarney and Henderson (2010), Maza et al. (2013) and Jin and Zhang (2022). In each of these studies, the Morison equation contains specific values of the drag coefficient (C_D). The dependency of C_D on the Reynolds number (Re) has been frequently investigated (Losada et al., 2016; van Veelen et al., 2020), but plant flexibility was usually not taken into account. While Whittaker et al. (2015) have incorporated the plant flexibility into the calculation of the drag force, values for C_D are still required. Values of C_D for specific plant species, especially regarding seasonal variation obtained from field measurements, e.g. Keimer et al. (2023, 2024), are scarce and render more accurate modeling attempts futile. A uniform drag coefficient for flexible vegetation might not exist (van Veelen et al., 2020) and is therefore of limited applicability for numerical models (van Veelen et al., 2020; Caroppi and Järvelä, 2022). The present study argues that simplistic approaches requiring coefficients like C_D cannot accurately simulate the FSI with flexible vegetation and are not further considered in this study. Accurately incorporating the variability of flexible vegetation using drag coefficients requires extensive field and laboratory investigations to generate a widely applicable dataset, considering the different vegetation species, stem-leaf configurations unaddressed so far, seasonality, and biomechanical variations within a stem.

A second, more versatile approach for numerical FSI involves direct forcing. Although this method promises higher accuracy, it does not inherently guarantee improved results, as replicating the complex geometry of live vegetation remains challenging. Direct forcing requires some form of coupling between the fluid and structural solvers. One way of achieving such coupling is to include both the fluid and the structural solver in a Lagrangian model such as the smoothed-particle hydrodynamics (SPH) approach, as shown in O'Connor and Rogers (2021) for DualSPHysics. Alternatively, el Rahi et al. (2023) proposed recently the coupling of a Lagrangian fluid approach in DualSPHysics with an external finite element method (FEM) solver. Another possibility is the coupling of an Eulerian approach for the fluid with a Lagrangian approach for the structural solver. To achieve such coupling, the Eulerian grid needs to be able to communicate with the Lagrangian grid of the structural solver and vice versa. To facilitate the communication between the two systems, a body-fitted mesh can be applied, for example, using the arbitrary Lagrangian-Eulerian (ALE) method which ensures a strong coupling. A recent implementation using a body-fitted grid was presented by Chourdakis et al. (2023). Body-fitted meshes have the drawback of mesh deformations and re-meshing when large deformations of the structural solver occur, requiring thus high computational power. Chourdakis et al. (2023) described numerical problems using OpenFOAM for simulations when the deformed mesh led to distorted cells, requiring advanced mesh motion techniques.

Alternatively, the immersed boundary method (IBM) has become increasingly popular. An Eulerian structural solver can be implemented via the IBM into the Lagrangian fluid phase, as shown by Tian et al. (2014), Tschisgale and Fröhlich (2020) Wang et al. (2020), He et al. (2022), Wang et al. (2022), Ni et al. (2023), Kim et al. (2024), Hagmeyer et al. (2024) and Agrawal et al. (2024). The IBM has the advantage of accounting for large deformations of the structural solver with an Eulerian grid and a stable fluid solver with a Lagrangian grid. The achieved accuracy of FSI studies using the IBM is promising, rendering it the favored coupling method within the context of this study. Although the previously mentioned works are all based on the IBM, they differ through their proposed coupling algorithm of the FSI, as well as the applied fluid and structural solver. He et al. (2022) applied an inextensible nonlinear Euler–Bernoulli beam, with the bending motion restricted to the streamwise–vertical direction. Similarly, Ni et al. (2023) simulated in two dimensions to focus on the monami modes of a flexible vegetation meadow. Hagmeyer et al. (2024) proposed a strongly coupled partitioned solution algorithm to model a torsion-free beam. Alternatively, Kim et al. (2024) used a finite-element structural solver with soft-body dynamics, while Wang et al. (2020) used a structural solver based on the combined finite element method–discrete element method. Both Tschisgale and Fröhlich (2020) and Agrawal et al. (2024) used the geometrically exact Cosserat rod for their structural solver, which has the advantage of capturing three-dimensional motion while using a mathematical model in one direction, thus making it computationally more efficient. Additionally, Agrawal et al. (2024) were able to simulate coarser structural meshes than the background fluid grid, highlighting the potential of such a model.

Flexible vegetation usually induces turbulent flow conditions, which can numerically either be achieved with direct numerical simulation (DNS) or via turbulence modeling. To date, DNS still comes at comparatively high computational costs when higher Reynolds numbers are concerned. The $k-\epsilon$ turbulence model in the Reynolds-averaged Navier–Stokes (RANS)-approach was often extended to include vegetation-induced turbulence to account for flexible vegetation (Dijkstra and Uittenbogaard, 2010; Maza et al., 2013; Chen and Zou, 2019). Turbulence modeling with large eddy simulations (LES) additionally resolves some of the larger scale

eddies in the flow, while the smaller portion of the energy cascade is modeled with a semi-empirical approach, known as the subgrid scale (SGS) model. Widely used SGS models are the Smagorinsky model (Tschisgale and Fröhlich, 2020; Kim et al., 2024) and the wall-adapting local eddy-viscosity (WALE) model (Ouro and Stoesser, 2017). A dynamic Smagorinsky model has been used by Mattis et al. (2015), Wang et al. (2022) and He et al. (2022) to investigate flexible vegetation. In recent years, Tschisgale and Fröhlich (2020) implemented a Cosserat rod method into a fluid solver. They chose a Smagorinsky constant $C_S = 0.15$ for their SGS, based on similar values in the literature (0.15 and 0.17) for flexible vegetation. Building on their previous study, Tschisgale et al. (2021) compared varying values of C_S (0.075, 0.15, 0.30) for a flexible meadow without finding significant differences in the velocity profile and the resolved turbulent shear stress. To the authors' knowledge, no further literature discussed which C_S would be suitable to model flexible vegetation. Further evaluation is required to quantify the extent of the contribution of the SGS constant like the Smagorinsky coefficient C_S or the WALE-coefficient C_W to accurately resolve the turbulence of the flow field around the flexible vegetation.

For an accurate representation of the complex FSI that is presented when flexible stems bend because of fluid forces, this study proposes a two-way coupling based on the IBM, along with specific turbulence modeling via RANS or LES. In line with the set requirements, this work chooses an implementation of a structural solver (Tschisgale and Fröhlich, 2020) implemented in the numerical model REEF3D::CFD, which is a finite difference (FD) incompressible, two-phase fluid solver including turbulence models common in computational fluid dynamics (CFD) codes. Another structural solver including flexibility has already been validated in REEF3D for mooring lines, which are represented in a one-way coupling fashion (Martin and Bihs, 2021). Although the structural solver calculates the forces acting on the solid directly, damping coefficients (see Section 2.1) are required to take the non-linear viscous damping of rods into account (Linn and Lang, 2013). Martin and Bihs (2021) observed that their model was not sensitive to the damping coefficients in steady-state conditions as long as they differed from zero, ensuring numerical stability. Nevertheless, these coefficients influence the transient stem motion, as observed by Martin and Bihs (2021) for the minimum and maximum tension force of a swinging elastic rod.

This study tests the FSI of stems representing aquatic vegetation under currents. Several studies in literature (Tian et al., 2014; Tschisgale and Fröhlich, 2020; Jin and Zhang, 2022) validated their model based on the current experiments of a single stem as an approximation of a plant stem by Luhar and Nepf (2011). The pertinent literature often addressed the FSI problem on either a single type of material or a single stem length. While it is important to demonstrate that numerical models can approximately govern this type of FSI problem methodically in the first place, this study aims to widen the scope of this problem to a broader range of both material properties and stem lengths; aside from these material and geometrical properties, it will be very important for further studies, i.e., on sediment transport, to better understand the effect of a wider range of hydraulic loading conditions, from very low to high exposure of the stem to the fluid motion. As this is the first study to investigate the application of the structural solver in REEF3D::CFD for flexible vegetation, the sensitivity of the model regarding parameters like the number of elements of the stem needs to be tested. From the literature, it becomes clear that different turbulence models have been applied to simulate flexible vegetation in the past. Yet, it remains open which turbulence model is suitable to accurately simulate the FSI in the FD CFD solver used for this study. Insufficient information is available regarding the application of the damping coefficient in the context of FSI with flexible vegetation and its possible relation to material properties. That relation could be crucial once field data of vegetation is implemented in the model and to accurately simulate the stem motion under waves in future studies. In summary, the following specific objectives will be addressed within this study:

- To test the model sensitivity, including its temporal and spatial resolution, to numerical parameters of the structural solver, such as the number of elements of a stem.
- To investigate the effect of different turbulence models and their model parameters on the resulting drag force exerted on single, flexible stems.
- To compare the model predictions regarding different materials, varying stem lengths, and current velocities to physical (Luhar and Nepf, 2011) and numerical (Tschisgale and Fröhlich, 2020) results.
- To evaluate the influence of the damping coefficients under uniform current loads on the resulting forces and their further implications.

2. Methodology

2.1. Numerical model

The employed numerical model is the FD solver REEF3D::CFD, characterized by the level-set method to describe the free surface and its high-order discretization schemes. The fluid solver is based on the incompressible Navier–Stokes equations, i.e., the continuity equation (1) and the incompressible momentum equation (2).

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_f} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \nu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + g_i \quad (2)$$

In Eqs. (1) and (2), u_i denotes the velocity vector in three dimensions (x, y, z), t is the time component, ρ_f is the density of the fluid, g is the gravitational acceleration, and the pressure p . Two viscosity components are included, with ν corresponding to the fluid

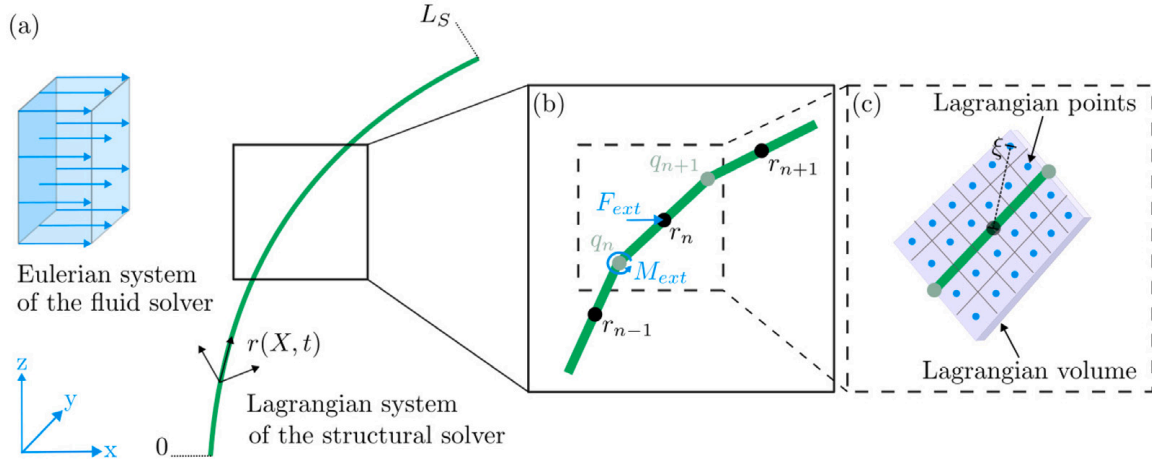


Fig. 1. Definition sketch of the coupling of the structural and the fluid solver (adapted after Tschisgale and Fröhlich (2020), Martin and Bihs (2021)) with (a) the Eulerian and Lagrangian system, (b) the external forces (F_{ext}) and moments (M_{ext}) calculated for each element center (r_n) and element edge (q_n) and (c) the Lagrangian points of an individual element, where the velocity components of the fluid are transferred, with the vector ξ representing the distance of the Lagrangian points to each element's center (r_n).

molecular kinematic viscosity. The eddy viscosity ν_t accounts for the Reynolds stress term using RANS equations and can be solved with models, e.g., the k - ω model, as described in Bihs et al. (2016). RANS formulations require particular attention when accounting for sharp velocity gradients or unsteady flow fields (Bush et al., 2019). These potential instabilities can generally be mitigated by applying limiters to the eddy viscosity across the entire fluid domain, as used in Unsteady Reynolds-averaged Navier–Stokes (URANS) methods, or by adapting the turbulence production in the proximity of the stem. The latter is here enabled by implementing a new formulation accounting for increased turbulent energy dissipation along the stem. Following the logarithmic law of the wall, the turbulent energy dissipation ω is enhanced at the surface of the stem by calculating its modification ω^* as follows

$$\omega^* = \frac{C_T D(\max(0, k))^{0.5}}{1/3(\delta x + \delta y + \delta z)\kappa C_\mu^{0.25}} \quad (3)$$

including a turbulence factor, applied here with $C_T = 50$, the kernel function D locating the grid points at the surface of the stem, the turbulent kinetic energy k , the local cell size ($\delta x, \delta y, \delta z$) and turbulence model constants κ , here equal to 0.4, and C_μ , here equal to 0.09. The implications of this first approach to account for the FSI using the k - ω model are presented in Section 3.1.

Alternatively, a spatially filtered Navier–Stokes equation can be applied to solve the subgrid-scale eddy viscosity for the LES equations. The solver can either model the subgrid-scale eddy viscosity by the Smagorinsky model or the WALE model. In the Smagorinsky model, eddies smaller than the length scale $\Delta = \sqrt[3]{\delta x \delta y \delta z}$ are not resolved but instead modeled based on the Smagorinsky subgrid-scale model:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}S_{ij} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) = 2\nu_t \bar{S}_{ij}, \quad (4)$$

including the subgrid-scale stress $\tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j$ and the sub-grid scale eddy viscosity of the large scale field $\nu_t = C_S^2 \Delta^2 |\bar{S}|$ with the strain rate $|\bar{S}| = (\bar{S}_{ij} \bar{S}_{ij})^{1/2}$. For more details on the implementation and validation, the reader is referred to Bihs et al. (2016). The WALE model, proposed by Nicoud and Ducros (1999), accounts for the rotational rate of the strain rate tensor in contrast to the Smagorinsky model, which generally reduces to zero close to walls.

The structural solver is based on the geometrically exact Cosserat rod equations (Lang et al., 2011; Tschisgale and Fröhlich, 2020). The implementation of the flexible structure in the fluid solver via IBM consists of the Eulerian coordinates of the fluid solver (x -, y -, and z -direction) and the Lagrangian coordinates (X) of the structural solver (Fig. 1a). The flexible structure itself is divided into n individual, rigid elements (see Fig. 1b). The forces and moments are calculated for each individual, rigid element. The coupling of the two coordinate systems is achieved via the Lagrangian points at the surface of the Lagrangian volume, depicted in Fig. 1c, where the velocity components of the fluid are transferred. Hereby, each marker point represents a Lagrangian volume, which must be smaller or equal to the size of the Eulerian fluid cell to ensure the impermeability of the structural solver. The distance of the Lagrangian points to each element's center is determined by the vector ξ .

The two geometrically exact Cosserat rod equations are detailed in Eqs. (5) and (6). Eq. (5) describes the translational motion $r(X, t)$ by calculating the acceleration of the rod's centerline, for each Lagrangian coordinate $X \in [0; L]$. The rotational motion $R(X, t)$ of the rod is calculated by Eq. (6).

$$\rho_s A \ddot{r} = \frac{\partial f}{\partial X} + \underline{f}_{ext} \quad (5)$$

$$\rho_s I \dot{\omega} + \omega \times \rho_s I \omega = \frac{\partial m}{\partial X} + \frac{\partial r}{\partial X} \times \underline{f} + \underline{m}_{ext} \quad (6)$$

In Eqs. (5) and (6), ρ_s , A , and I represent constant material parameters, i.e., the density of the solid, the area of the cross-section, and the second moment of area, respectively. While $\underline{f}$ and $\underline{m}$ describe the internal force and moment of the rod, $\underline{f}_{\text{ext}}$ and $\underline{m}_{\text{ext}}$ determine the external force and moment. The internal force $\underline{f}$ due to shearing and stretching and the internal moment $\underline{m}$ due to bending and twisting are determined for a linear viscoelastic material of Kelvin–Voigt type (Martin and Bihs, 2021; Tschisgale and Fröhlich, 2020):

$$\underline{f} = R \underline{f}_0 = R C_{\epsilon,0} \cdot (R^T \underline{\epsilon} - (R^T \underline{\epsilon})|_{t=0}) + R C_{\dot{\epsilon},0} \cdot (\dot{R}^T \underline{\epsilon} - (R^T \dot{\underline{\epsilon}})) \quad (7)$$

$$\underline{m} = R \underline{m}_0 = R C_{\kappa,0} \cdot (R^T \underline{\kappa} - (R^T \underline{\kappa})|_{t=0}) + R C_{\dot{\kappa},0} \cdot (\dot{R}^T \underline{\kappa} - (R^T \dot{\underline{\kappa}})) \quad (8)$$

Both equations are the sum of the linear elastic part (first addend) and the dissipative part due to internal friction (second addend) and include the strain ($\underline{\epsilon} = \frac{\partial \underline{r}}{\partial X}$) and curvature ($[\underline{\kappa}]_x = \frac{\partial \underline{R}}{\partial X}$) vector. The shearing ($C_{\epsilon,0}$) and bending ($C_{\kappa,0}$) stiffness used in Eqs. (7) and (8) depend on the material properties and are respectively determined by the following diagonals:

$$C_{\epsilon,0} = \text{diag}(EA, c_{s,Y}GA, c_{s,Z}GA) \quad (9)$$

$$C_{\kappa,0} = \text{diag}(c_t GI_X, EI_Y, EI_Z) \quad (10)$$

In both Eqs. (9) and (10), E corresponds to the Young's modulus and G to the shear modulus. I_Y and I_Z correspond to the second moment of area and $I_X = I_Y + I_Z$ to the second polar moment of area. The coefficients $c_{s,Y}$, $c_{s,Z}$, and c_t are shear and torsion correction factors to account for warping effects for shear and torsional load (Tschisgale and Fröhlich, 2020). That warping effect is not considered within this study and therefore set equal to unity. Correction factors for generic cross-sections are given in Freund and Karakoç (2016). Symbols $C_{\epsilon,0}$ and $C_{\kappa,0}$ are both diagonals that account for the structural viscosity. The first is for translational damping, the latter for rotational damping. The diagonals can be expressed as follows:

$$C_{\epsilon,0} = \text{diag}(c_{dx}, c_{dy}, c_{dz}) \quad (11)$$

$$C_{\kappa,0} = \text{diag}(c_{kx}, c_{ky}, c_{kz}) \quad (12)$$

Herein, c_{dx} accounts for the axial extension or compression, while c_{dy} and c_{dz} dampen the shear force. In the same manner, c_{kx} accounts for torsion, while c_{ky} and c_{kz} dampen the bending moment. Further information can be obtained in Lang et al. (2011) and Linn and Lang (2013).

The external force in Eq. 4 is the sum of the gravitational force ($f_g = (\rho_s - \rho_f)Ag$) and the coupling force f_r of the immersed boundary. The spatial coupling of f_r , which accounts for the difference between the three-dimensional shape of the immersed boundary to the one-dimensional Cosserat rod, is achieved by connecting the Lagrangian marker points to the Eulerian grid cells, cf. Fig. 1c, via regularized delta functions. Ensuring faster communication, the velocity field of the fluid is then replaced by the integral quantity $\bar{p}_e$ for the force and $\bar{l}_e$ for the moment, reducing the communication points to six for each rod element. The temporal coupling of f_r for the direct forcing approach is achieved through five steps, using an implicit Runge–Kutta scheme. First, a preliminary velocity is calculated for the next time level without considering the immersed boundary, which is communicated to the structural solver in the second step. In a third step, the interface velocity of the next time level is obtained using the coupling force f_r for each element

$$f_{r,e} \Delta Z = - \left[\frac{p_{r,e} - p_{r,e}^{r-1}}{t - t^{r-1}} + \frac{p_{r,e}^{r-1} - \bar{p}}{2\alpha_r \Delta t} \right]_e, \quad (13)$$

with the linear momentum of the fluid layer around an element $p_{r,e}$, the preliminary linear momentum $\bar{p}_e$ obtained in the first step and α_r as a coefficient of the Runge–Kutta scheme. Afterward, the coupling force at the current time level can be calculated based on the difference between the preliminary and calculated velocity. Finally, the velocity field of the next time level can be calculated in the fifth step, based on the resulting coupling force of step number four. Further specifications and the analog determination of the external momentum can be found in Tschisgale and Fröhlich (2020).

2.2. Model set-up

This work concerns fluid flow loading on a flexible stem resulting from uniform currents. The structural solver is first employed to test the response of a stem in currents based on the experimental work by Luhar and Nepf (2011), further referred to as the reference experiment, whereby both the bending motion and the drag force are compared. Additionally, high-resolution photos and the measured forces have been provided by Luhar and Nepf (2011). The flow field is compared to the numerical simulations of Tschisgale and Fröhlich (2020), who provided their simulation data, enabling a direct comparison of the results. Finally, measured plant properties from the field are applied to the structural solver to provide a first approximation of the capabilities of the proposed model. The plant properties from the field are taken from the study by Keimer et al. (2023), which defined different growth states of the salt marsh plant *Spartina anglica*.

Several stem lengths (0.05 m to 0.25 m) exposed to varying current velocities (0.04 m/s to 0.32 m/s) have been tested in the reference experiment. The current velocities were measured with a variation smaller than 5 % with an acoustic Doppler velocimeter placed in front of the stem. Measured average forces are available for all configurations, with the resolution of the load cell of 0.001 N and accuracy of 10 %. A stem holder was attached to the load cell, which elevated the stem by 0.04 m above the bed. Pictures of

Table 1

Summary of the investigated material properties, including the surrogate materials used by [Luhar and Nepf \(2011\)](#) and the defined growth states based on field measurements of [Keimer et al. \(2023\)](#).

	Luhar and Nepf (2011)		Field data from Keimer et al. (2023)		
v (m/s)	0.04 – 0.32		0.50	0.50	0.50
Material	Soft foam	HDPE	Flowering	Broken	Sprouting
L_S (m)	0.05 – 0.25		0.20	0.20	0.20
W_S (m)	0.01	0.01	4.11×10^{-3}	3.97×10^{-3}	4.21×10^{-3}
T_S (m)	1.9×10^{-3}	0.40×10^{-3}	4.11×10^{-3}	3.97×10^{-3}	4.21×10^{-3}
ρ (kg/m ³)	670	950	670	670	670
E (kN/m ²)	500	930 000	323 460	225 270	133 780
Ca (–)	0.55 – 5500	0.032 – 320	0.53	0.85	1.20
B (–)	2.7 – 340	0.0049 – 0.62	0.057	0.088	0.13

the stem motion were captured for the shortest (0.05 m) and longest stems (0.25 m) in combination with a medium (0.16 m/s) and the highest (0.32 m/s) current velocity using a camera. The reference experiment used two different materials, HDPE and soft foam. The stiffer HDPE material was characterized by a Young's modulus of 0.93 GPa, a density of 950 kg/m³, and a thickness of 0.0004 m. The more flexible soft foam material had a Young's modulus of 500 kPa, a density of 670 kg/m³, and a thickness of 0.0019 m. The stems were 0.01 m wide. The material properties are summarized in [Table 1](#), including the dimensionless Cauchy number (Ca) and Buoyancy parameter (B) as defined by [Luhar and Nepf \(2011\)](#). For more details of the experimental set-up, the reader is referred to [Luhar and Nepf \(2011\)](#).

The afterward applied vegetation properties from the field are additionally summarized in [Table 1](#). To mimic the cylindrical live vegetation, the width and thickness of the modeled stem were chosen equal to the measured diameter. In the field, the height of the different growth states differed as well, leading to an average stem height of the flowering plant of 0.30 m, of the broken plant to 0.22 m and of the sprouting plant to 0.07 m. For the simulations of the application case, the stem heights have been selected to be equal, ensuring a focus on the comparison of the material properties like Young's modulus and the second moment of area instead of giving the main focus to the stem height. Potentially, the difference in the resulting flow conditions would be even larger. As [Keimer et al. \(2023\)](#) did not measure the plant density, the density of the soft foam material was applied to all growth states. As a further simplification, the damping coefficients have been set to $c_d = 1$ and $c_k = 5 \times 10^{-10}$ for all growth states. The dimensionless numbers are calculated similarly to [Luhar and Nepf \(2011\)](#), showing that the Cauchy numbers of all growth states lay within the range of tested Cauchy numbers from the reference experiment. Additionally, the Buoyancy parameters are in a comparable order of magnitude as the tested soft foam material, partly due to the selected same material density.

A numerical current flume has been set up to reproduce the reference experiment, a sketch is displayed in [Fig. 2](#). For the side walls of the flume, wall functions with no-slip boundary conditions are used. As recommended by [Tschisgale and Fröhlich \(2020\)](#), a flume width of 0.16 m is chosen. The results's sensitivity in regard to flume width is analyzed in the framework of this study. For the inflow, a constant velocity profile is used, similar to the reference experiment. For both, in- and outflow boundary conditions, the water depth was kept constant at 0.30 m, with a fix level set to ensure numerical stability. For the validation with numerical results, the model set-up has been selected accordingly to [Tschisgale and Fröhlich \(2020\)](#) to ensure comparability. The cell size of the uniform grid is therefore equal to 0.5×10^{-3} m. The convergence study conducted in the [Appendix A](#) shows that the simulation converges for the applied cell size.

Following a grid convergence study in the [Appendix A](#), various simulations have been run to investigate the research objectives posed in [Section 1](#). The influence of the individual, rigid elements that the modeled stem consists of has been tested through a sensitivity analysis (see [Appendix A](#)) in order to find an independent solution and ensure accurate computability. The model performance is studied regarding its potential to accurately simulate the drag force and stem motion for varying stem lengths, material properties, and current velocities. Afterward, the influence and suitability of the turbulence model for the structural solver have been studied by comparing the performance of RANS, URANS, and LES. For the first two approaches, RANS and URANS, the $k-\omega$ model has been selected as it is widely applied by the developers of the employed numerical model – see for example [Bihs et al. \(2016\)](#), [Sasikumar et al. \(2020\)](#), and [Martin and Bihs \(2021\)](#). Finally, the time-dependent influence of the damping coefficients on the resulting forces and stem motion has been investigated and the capabilities of the model have been emphasized by applying field data from live vegetation to the proposed model.

The simulations were run on the Phoenix-Cluster of the TU Braunschweig, Germany, which provides 304 nodes in total, each equipped with dual CPU INTEL Xeon E5-2640v4@3.4 GHz and 64 GB RAM. The simulations were run on two nodes, resulting in 40 processor cores per simulation. The grid was generated with a mesh generator, DIVEMesh, and the simulations used REEF3D::CFD, both version v230614.

The results of the convergence study are summarized in [Table A.3](#) in the appendix, and confirm the assumption that a fine grid close to the flexible stem is crucial for the resulting forces. The resulting non-uniform grid for the current simulations can be seen in [Fig. 3](#). Note that the refined area around the stem in the x- and z-direction is adapted proportionally to the stem lengths to ensure comparable conditions for the different stems. Considering the available computational resources in the case of the longest stem, the refined length was set to $F = 1.2L_S$, while the refined length in y-direction was 0.04 m for all tested cases. With a stretching factor of 1.1, the cell size varied from 1.5×10^{-3} m in the refined area to 0.03 m in the coarser area. That setup results in ~ 1.1 M cells for the 0.05 m stem and ~ 4.5 M cells for the 0.25 m stem.

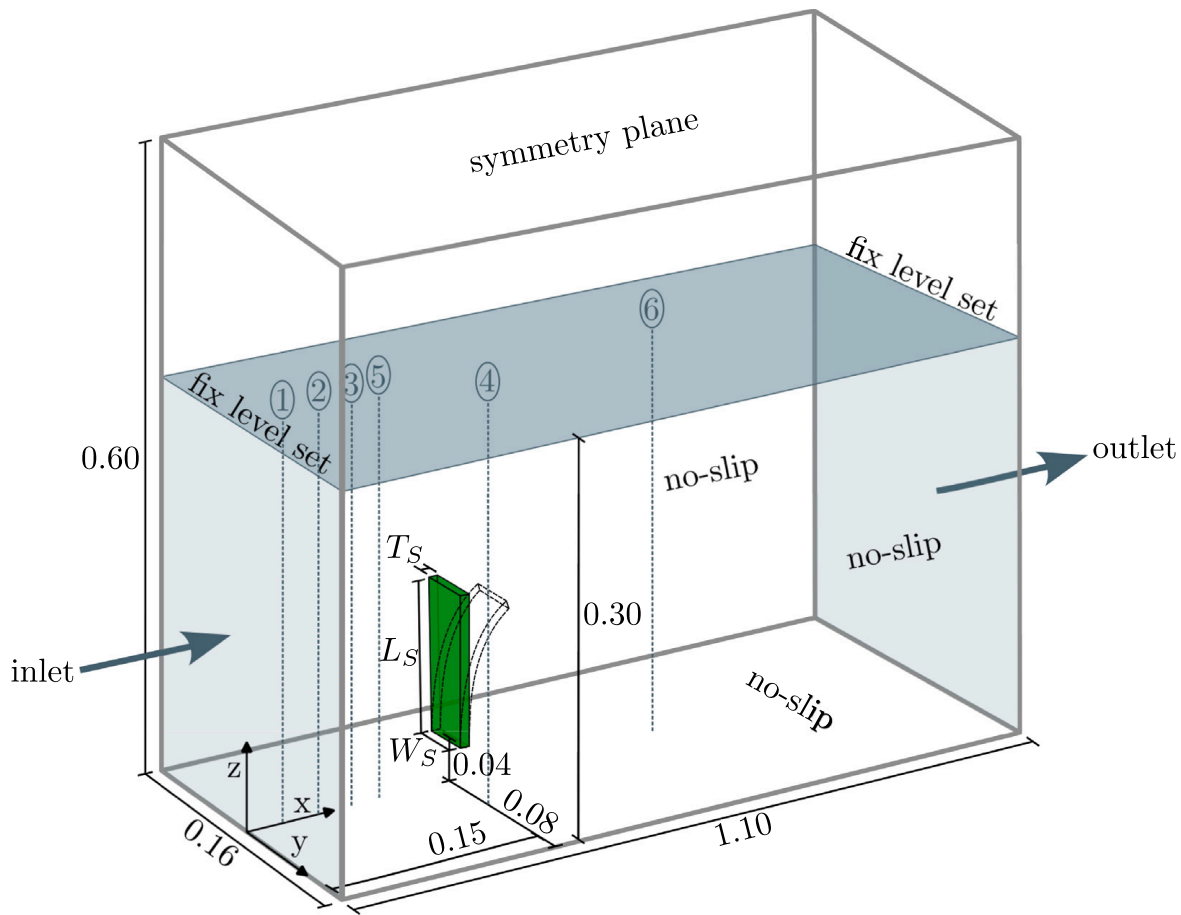


Fig. 2. Sketch of the numerical model set-up for the current simulations, including the thickness of the stem (T_s), the length of the stem (L_s), the width of the stem (W_s), and the positions of the applied line probes 1–6, dimensions in m (not to scale).

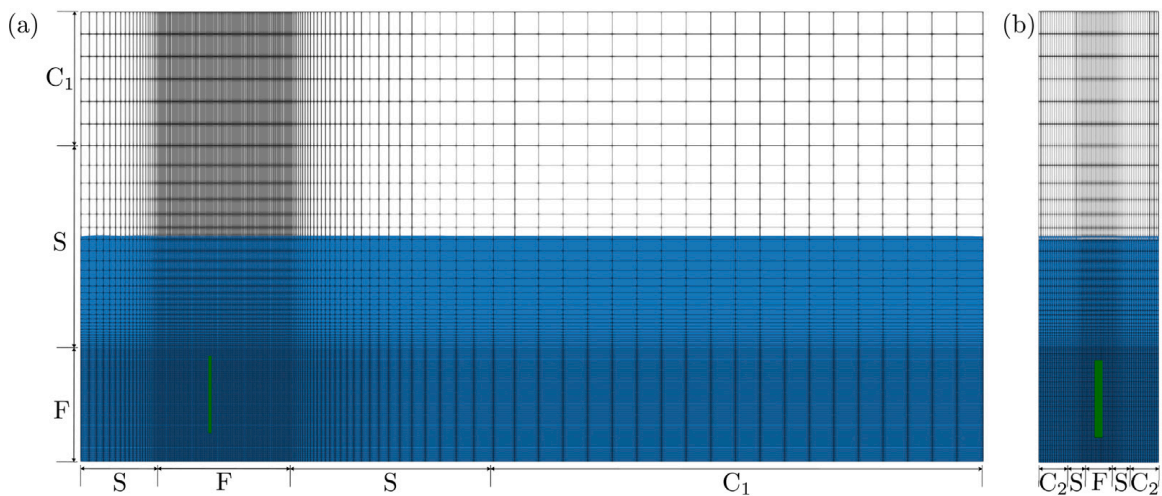


Fig. 3. Non-uniform grid in (a) side view and (b) front view, distances shown for the 0.1 m long stem. The fine grid (F) cell size is 1.5×10^{-3} m, followed by a stretching zone (S) with a factor of 1.1, and a coarse grid ($C_1 = 0.03$ m and $C_2 = 3.0 \times 10^{-3}$ m).

3. Results

3.1. Velocity field and influence of turbulence modeling

Before a detailed investigation of the complex FSI, it is paramount to test and select a model family on the fluid part that governs the process of eddy production and detachment in the vicinity of the dynamic stem motion. In terms of model families, RANS, URANS, and LES fluid solvers have been tested with a variety of parameter settings; the accuracy that could be obtained

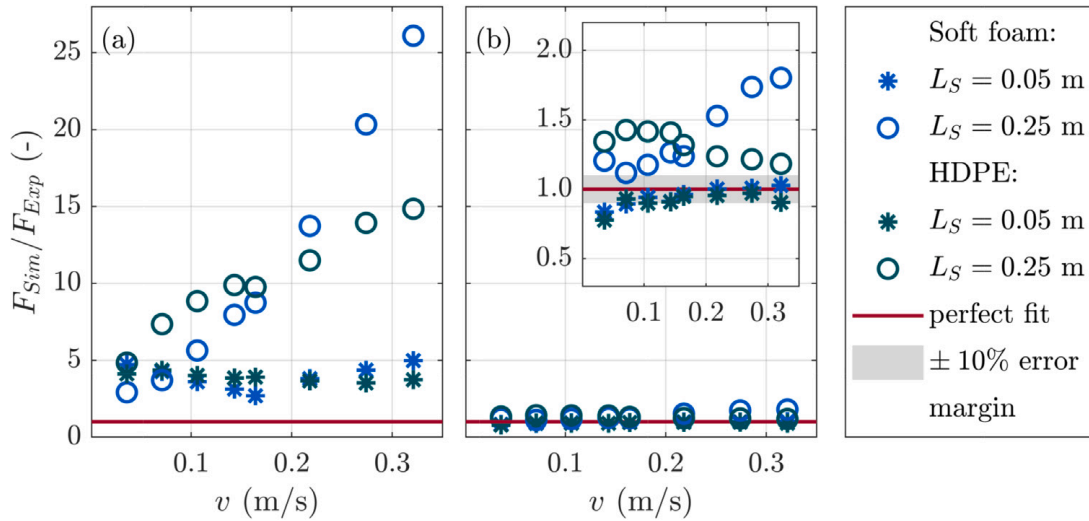


Fig. 4. Comparison of simulated vs. experimentally-derived forces (Luhar and Nepf, 2011), for both the soft foam and HDPE Material and two stem lengths $L_S = 0.05$ m and $L_S = 0.25$ m with (a) RANS and (b) wall-adapted RANS turbulence modeling; inset shows the same data but with adjusted y-axis scale.

by the FSI has then been compared to an experimental dataset (Luhar and Nepf, 2011), and against results of a recently published numerical study (Tschisgale and Fröhlich, 2020).

First, the influence of the wall-adapted RANS approach on the FSI is presented and compared to the RANS approach without modification. The resulting forces for a variation of tested material types, stem lengths, and current velocities are compared between RANS and the wall-adapted RANS approach in Fig. 4. The resulting stem bending between the two approaches is compared for a selected test case in Fig. 5. It can be observed that the RANS simulations, using the $k-\omega$ turbulence model without wall-adaption, overestimate the forces measured in the reference experiment. While the overestimation of the forces for the 0.05 m long stem remains the same order of magnitude independent of the current velocity, the overestimation by the numerical model increases for the 0.25 m long stem with higher current velocities (Fig. 4a). In contrast, the resulting forces with the wall-adapted RANS approach are in the same order of magnitude as the experimental results, see Fig. 4b. Nevertheless, the forces for the 0.25 m long stem are overestimated by 20 % to 40 % for the HDPE material and by 10 % to 80 % for the soft foam material.

The large observed deviations between the resulting forces for the RANS compared to the wall-adapted RANS approach render an evaluation of the occurring processes essential. Fig. 5 compares the resulting flow field around the stem for the 0.25 m long HDPE stem with a current velocity of 0.16 m/s for the RANS and the wall-adapted RANS approach, providing further insights and possible explanations for occurring differences. It can be seen that the simulation using the RANS turbulence model also overestimates the bending position compared to the resulting bending of the wall-adapted RANS approach, even though the incoming flow field does not vary. The overestimation of the bending and forces in the RANS simulations without wall-adaption is likely due to the turbulent kinetic energy generated near the stem being dispersed across a broader area within the flow field by the RANS turbulence model, which appears to inhibit the recirculation of the flow field beneath the stem, resulting in its excessive bending. This effect can be prevented by enhancing the turbulent energy dissipation in the proximity of the stem, as introduced in Section 2, utilizing the wall-adapted RANS approach. The resulting stem bending and surrounding flow field of the wall-adapted RANS approach provide a more reasonable FSI, depicted in Fig. 5b. In conclusion, the wall-adapted RANS is considered more suitable for simulating the FSI within the FD CFD model compared to the non-adapted RANS approach. Consequently, the wall-adapted approach is employed for further comparison with results from other turbulence models, including URANS and LES.

Fig. 6 compares the simulated results for the wall-adapted RANS, URANS, and LES simulations for both the HDPE and soft foam material. Independent of the selected turbulence model and the tested material type, the resulting forces of the 0.05 m stem are in high agreement with the experimental forces, with the majority being within the estimated error margin of $\pm 10\%$ of the experimental force sensor. In contrast, the forces of the 0.25 m long stem are generally overestimated. In Fig. 6b the numerical results using URANS with the $k-\omega$ turbulence model have the tendency of being higher compared to those obtained with the wall-adapted RANS turbulence model (Fig. 6a). The force computed for the 0.25 m long stem overestimates the experimental results by a factor of 1.5 for the HDPE material and over 2 for the fastest current velocity for the case of the soft foam material. Smaller deviations to the experimental data could be observed using LES in Fig. 6c. Especially for the 0.05 m long stem, the deviations of the simulated to the experimental forces are for seven out of eight investigated velocities within a $\pm 10\%$ error margin. Larger deviations can be seen for the 0.25 m long stem, pointing out that accurate modeling of the turbulence is especially crucial with longer stem lengths.

Concluding the comparison between the resulting FSI for different turbulence models, Fig. 7 depicts the flow fields and resulting bending positions of the stem for the wall-adapted RANS, URANS, and LES. It becomes apparent that utilizing the wall-adapted RANS and URANS results in a similar flow field and stem bending position (Fig. 7a and Fig. 7b). As anticipated, the LES results differ in the flow field due to its ability to resolve larger eddies (Fig. 7c). Nevertheless, the stem bending results are in the same position for all herein compared to the turbulence models.

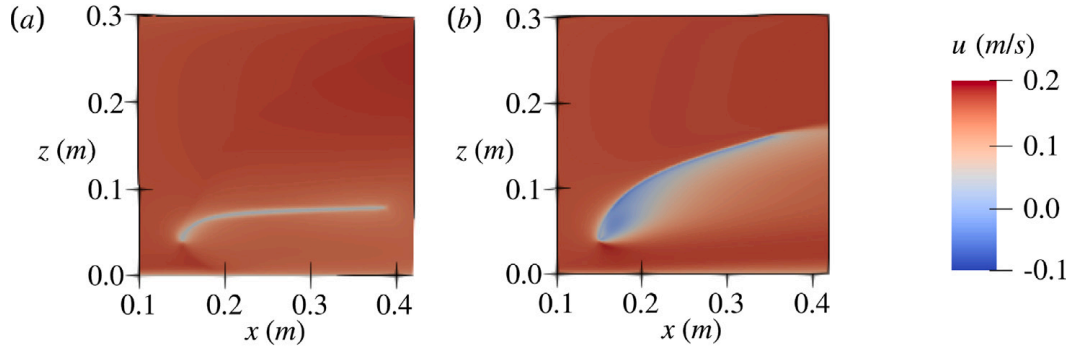


Fig. 5. Simulated flow field for the 0.25 m long stem with HDPE Material and a current velocity of 0.16 m/s, comparing the simulations results of (a) RANS and (b) wall-adapted RANS approach.

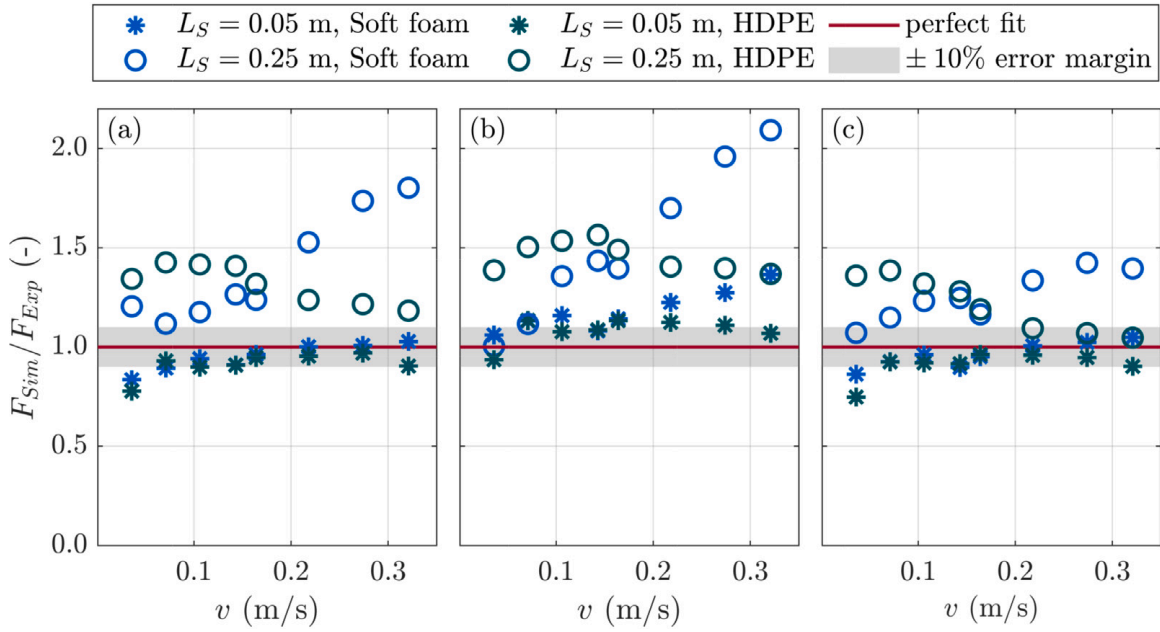


Fig. 6. Comparison of simulated vs. experimentally-derived forces (Luhar and Nepf, 2011), for both the soft foam and HDPE Material and two stem lengths $L_S = 0.05$ m and $L_S = 0.25$ m with (a) wall-adapted RANS, (b) URANS and (c) LES turbulence modeling.

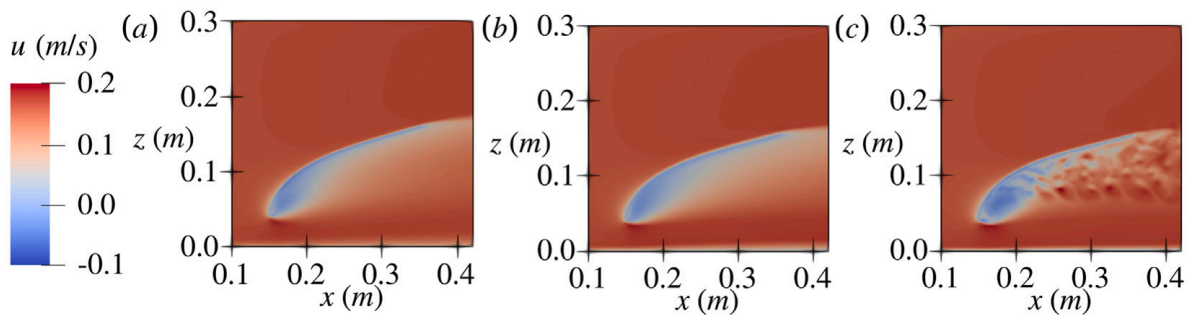


Fig. 7. Simulated flow field for the 0.25 m long stem with HDPE Material and a current velocity of 0.16 m/s comparing (a) wall-adapted RANS, (b) URANS and (c) LES turbulence modeling.

In summary, the wall-adapted RANS approach enhances the FSI in the FD CFD solver, confirmed by the resulting reasonable forces and stem bending. Similar stem bending can be observed when comparing different turbulence model families, including wall-adapted RANS, URANS, and LES. However, LES demonstrated the closest alignment with experimental results in terms of force deviations, making it the preferred turbulence modeling approach for this study.

As the resulting forces are sensitive to the chosen turbulence model, the sensitivity regarding the SGS model and their corresponding coefficients was also tested. Fig. 8a visualizes the resulting force deviations for the WALE and Fig. 8b for the Smagorinsky SGS model. The constant C_W applied in the WALE model has been varied between 0.30 and 0.60, and the Smagorinsky

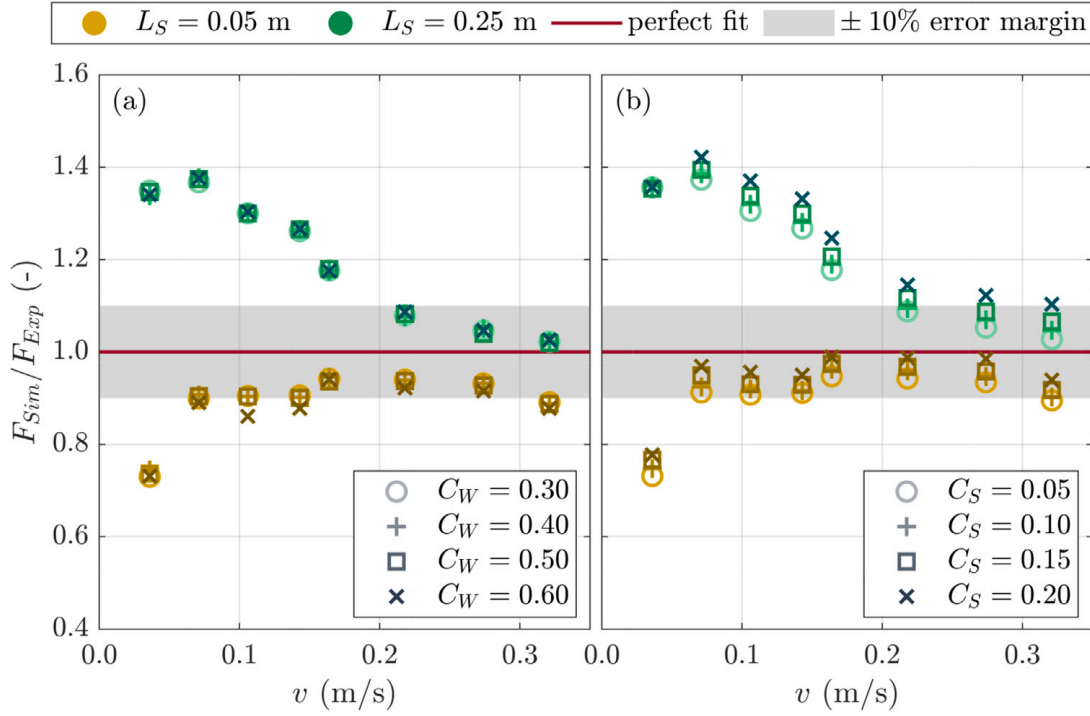


Fig. 8. Simulated forces in relation to experimental forces (Luhar and Nepf, 2011) for both the HDPE Material and two stem lengths $L_S = 0.05$ m and $L_S = 0.25$ m with (a) using the WALE SGS-model and a variation of WALE-coefficients and (b) Smagorinsky SGS-model and variation of Smagorinsky coefficients.

constant C_S has been varied between 0.05 and 0.20, covering a wide range, to enable a general comparison of its influence. Fig. 8a shows that the variation of C_W has, for most simulations, no influence on the resulting forces. Correspondingly, the mean difference between the resulting forces for the smallest and largest C_W is 1.87 % for $L_S = 0.05$ m and 0.52 % for a stem length of 0.25 m. On average, using a C_W of 0.40 leads to an underestimation of 10.50 % for the 0.05 m long stem and to an overestimation of 20.09 % for the 0.25 m long stem. By contrast, it can be observed in Fig. 8b that, with larger C_S , the resulting numerical forces increase and thus the deviation from the experimental results increases. The comparably larger influence of the chosen C_S is outlined by the mean difference between the resulting forces of the smallest and largest C_S , being 4.70 % for $L_S = 0.05$ m and 3.31 % for $L_S = 0.25$ m. The deviations to the experimental forces using a C_S of 0.10 are in a similar range to $C_W = 0.40$, resulting in an underestimation of 9.00 % for the 0.05 m long stem and an overestimation of the 0.25 m long stem by 21.84 %.

The value of C_S has been chosen equally to 0.10, as it leads to less overestimation of the simulated forces for the 0.25 m long stem compared to the results using $C_S = 0.15$ and 0.25 and less underestimation of the simulated forces for the 0.05 m long stem compared to the results with $C_S = 0.05$. Additionally, the recommended range of values for C_S , depending on the source, lies between 0.10 and 0.20. Ferziger and Perić (2002), Katopodes (2019) and previous studies using the same numerical model (Cui et al., 2022a,b) have successfully applied a C_S value of 0.10 for their LES studies.

Further validation of the accuracy of the numerical simulation of the FSI was achieved using published numerical results by Tschisgale and Fröhlich (2020). Their spatial velocity information of the FSI was compared to the results of the FD CFD solver in the x -direction (u), as shown in Fig. 9, for an inflow velocity (v) of 0.16 m/s. Overall, the qualitative comparison of the flow fields in Fig. 9 leads to the conclusion that the results of the simulation are comparable to the output of the solver used by Tschisgale and Fröhlich (2020). The minimum and maximum velocities are in a comparable order of magnitude for the selected time step, ranging from -0.60 m/s to 1.47 m/s for the results of Tschisgale and Fröhlich (2020) and from -0.56 m/s to 1.33 m/s for the results of this study. Overall, the turbulence of the wake distributes over a similar area behind the stem for both simulated flow fields. At the base of the stem, the wake extends over a larger area and small eddies are less visible in the FD CFD solver compared to the results of Tschisgale and Fröhlich (2020). The latter is likely due to the use of different spatial discretization methods. Tschisgale and Fröhlich (2020) used a second-order central differences method, while the FD CFD solver in this study was developed for the fifth-order weighted essentially nonoscillatory (WENO) method, which is known to be more diffusive but provides more stability (Xu and Shu, 2005; Bihs et al., 2016).

The tip position of the two simulations deviates by 4 % of the stem length. While the simulated tip position of Tschisgale and Fröhlich (2020) shows good agreement with the reference experiment with a deviation of 2 % relative to the stem length, this study shows a slightly better agreement with a relative deviation of the tip position of 1.8 % compared to the experimental tip position. The resulting forces are in the same order of magnitude ($F_{sim} = 0.0074$ N and $F_{simT} = 0.0076$ N) and in agreement with the measured experimental force ($F_{exp} = 0.0077$ N).

Fig. 10 additionally compares the normalized horizontal velocity for four different locations behind the stem for one time step. Overall, it can be seen that the influence of the stem on the flow is in similar areas in z -direction for all locations. The deviation of

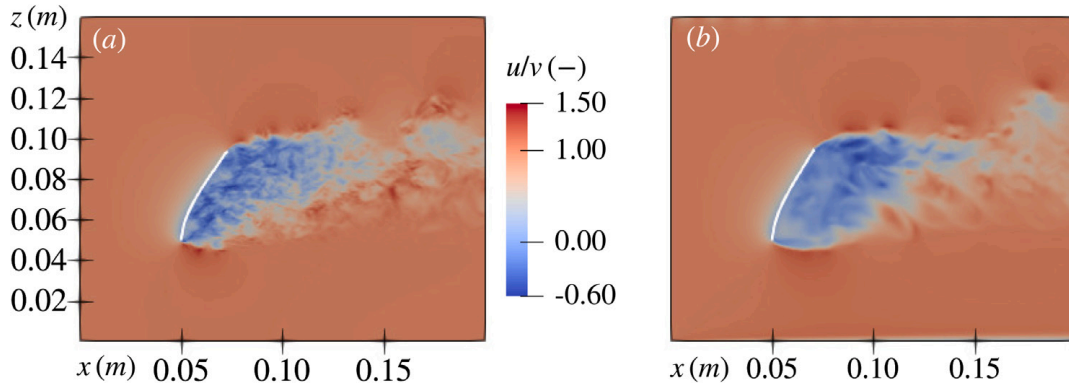


Fig. 9. Comparison of the normalized horizontal velocity (u/v) with $L_s = 0.05$ m, $v = 0.16$ m/s and the soft foam material with (a) the simulated results of Tschisgale and Fröhlich (2020) and (b) the simulated results of this study.

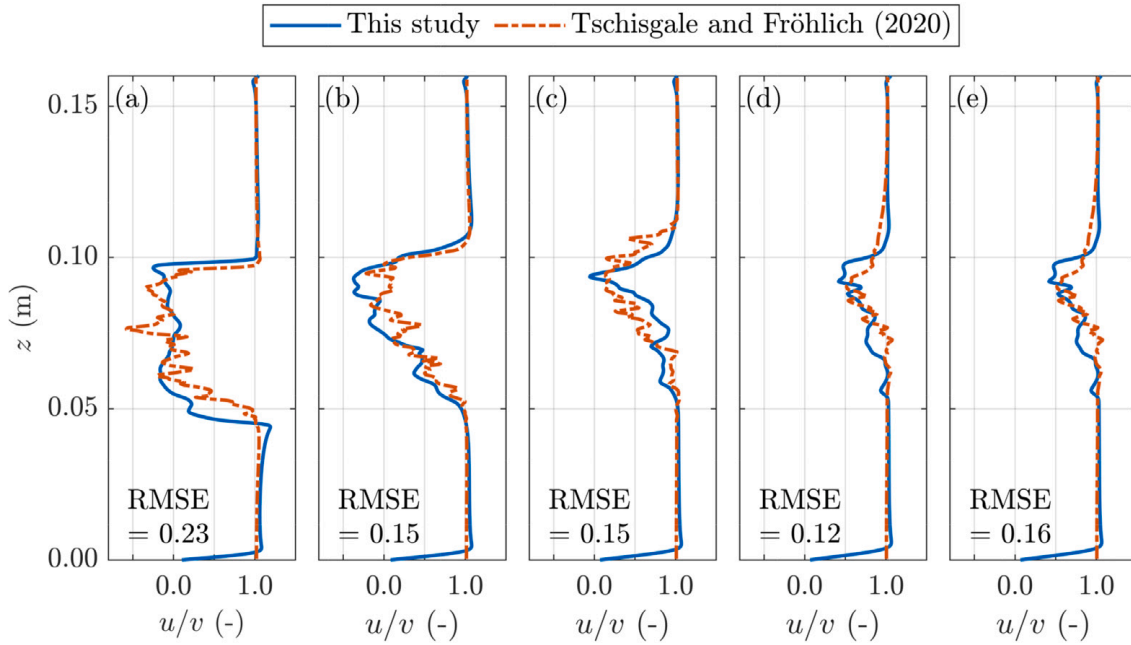


Fig. 10. Comparison of the normalized horizontal velocity over the flume height for this study and the results of Tschisgale and Fröhlich (2020) at different positions behind the stem with $y = 0.00$ m and $x =$ (a) 0.075 m, (b) 0.10 m, (c) 0.125 m, (d) 0.15 m and (e) 0.175 m.

the normalized horizontal velocity is largest close to the stem (Fig. 10a) with the RMSE equal to 0.23 and in a similar magnitude for the other locations (RMSE = 0.12 - 0.16). The minimum and maximum normalized velocities are in the same range for both simulations, even though the negative peak is slightly higher for the simulations of this study in locations b to e. Additionally, the before observed enhanced diffusivity of the FD CFD solver can be seen as well due to the larger fluctuations of the horizontal velocity over the flume height for the simulations of Tschisgale and Fröhlich (2020).

A thorough calibration and validation approach has provided confidence that the chosen LES approach is resulting in good agreement of simulated drag forces, bending motion and the resulting velocity profile of flexible vegetation in the FD CFD solver compared to both results of physical experiments and numerical simulations. In the next sections, further parameters, such as the fluctuations of the stem in the current-induced flow and the resulting turbulence intensity are evaluated.

3.2. Variation of material properties and hydrodynamic conditions

Within this section, the simulated results for several stem lengths, current velocities, and material properties are presented. The comparison of the simulated forces to the forces measured in the reference experiments for all tested stem lengths and current velocities for the HDPE material is shown in Fig. 11. It can be observed that independent of stem length and current velocities, most simulated forces are within a range of $\pm 10\%$ around the measured forces of the reference experiment. A single case (0.05 m stem in combination with the lowest current velocity) showed a slightly higher deviation, underestimating the experimental force by more than 10%. In contrast, the experimental forces are overestimated for the 0.25 m stem with current velocities lower than 0.16 m/s. In general, it appears that the deviation between the simulated and experimental forces is larger for lower current velocities. In

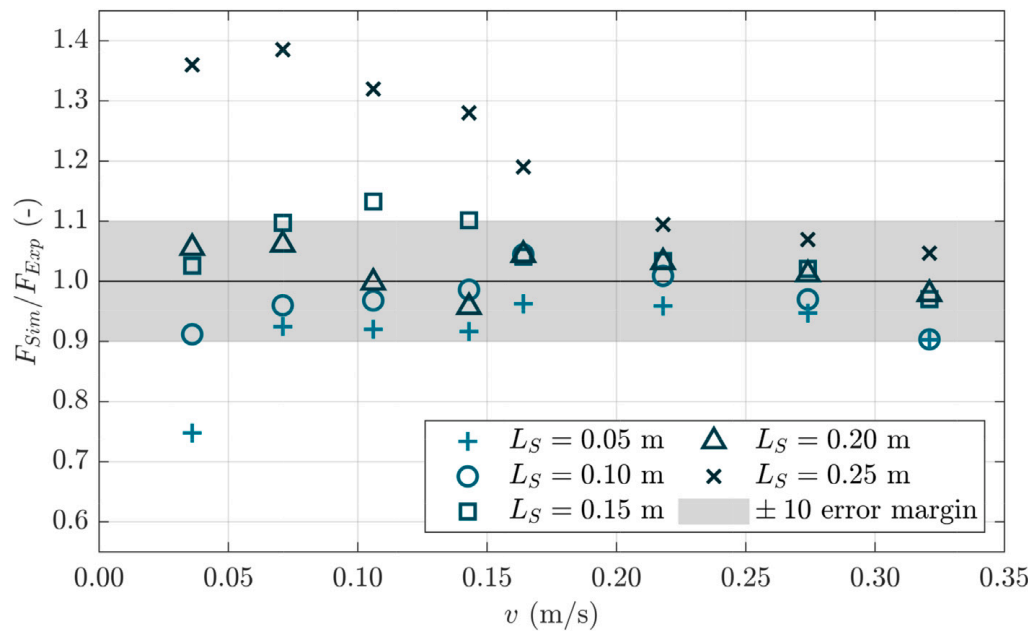


Fig. 11. Resulting normalized forces of the HDPE material for all current velocities and stem lengths.

contrast, the absolute error ($|F_{Exp} - F_{Sim}|$) is highest for the faster current velocity, with up to 0.0049 N compared to a maximum of 0.00061 N for the lowest current velocity. This can be explained, as the overall magnitudes decrease, and even minor absolute errors resulting from inaccurate process representation become accentuated.

While drag forces are one important indicator proxy for the accuracy of a numerical model, it remains important to note that the deflection of the stem is a second important measure to judge the performance of the model. In addition, an analysis of the deflection may help to better interpret why an overestimated force for the lower current velocities for the HDPE material and the higher current velocities for the soft foam material (see Fig. 6c) occurs. Hence, the bending behavior of the two simulated materials is compared next (see Figs. 12 and 13). It should be noted that different positions of the longer stems have been observed throughout the reference experiments, as the flexible stems generally do not take a steady-state position while interacting with the flow field, and the turbulent motion of the flow leads to continuous stem movement. Luhar and Nepf (2011) selected therefore individual snapshots showing the observed variation in the stem position of the reference experiment, displayed in Fig. 12 and Fig. 13. The same can be observed in the numerical simulations, which is visualized as the gray area next to the average stem position for each simulation in Fig. 12 and Fig. 13. The gray area spans over the maximum and minimum positions of the stem. For the longer stems, it can be observed that the fluctuation is larger for both materials with faster current velocity. In addition, the fluctuations are higher for the more flexible soft foam material.

The relation between the tip deviation and the stem length is stated (Δ_{tip}/L_S) and displayed in Fig. 14. As for the forces, the bending of the smaller stem ($L_S = 0.05$ m) provides better agreement for both materials and velocities, with less than 3 % deviation in relation to the stem length. For the longer stem ($L_S = 0.25$ m), the bending provides good agreement for $v = 0.32$ m/s for the soft foam material (Fig. 12d) and for $v = 0.16$ m/s for the HDPE material (Fig. 13b) with 2.76 and 4.32 % deviation to the stem length, respectively. The bending of the simulated 0.25 m soft foam stem for the current velocity with 0.16 m/s is larger compared to that measured in reference experiment (Fig. 12b), with 9.44 % deviation in relation to the stem length. The same can be observed for the HDPE material with the faster current velocity (0.32 m/s, Fig. 13d), resulting in 9.52 % deviation in relation to the stem length. While having some variation within the simulated and experimental stem position, all resulting deviations in relation to the stem length are smaller than 10 % (see Fig. 14).

Together with the observations regarding the deviations of the simulated forces, the analysis of the deflection leads to the conclusion that the forces exerted onto the long stem are overestimated when the long stem is in the same spatial position as the stem in the experiment. The simulated forces are in accordance with the results of the reference experiment for the 0.25 m stem when the bending is larger than expected, for both types of material. Since the results of the stem bending have been only published for the 0.05 m, and 0.25 m long stems, it cannot be assessed if the deviation also occurs for the other stem lengths (0.10 m to 0.20 m).

3.3. Influence of the damping coefficients

The structural solver in the FD CFD solver necessitates the use of damping coefficients to take the non-linear viscous damping of rods into account, see also Eqs. (11) and (12). While this part of the FSI simulation seems straightforward, it has never been subject to an in-depth investigation, as to how these parameters influence the structural motion and, as a consequence, how it would then feed back into the flow field downstream of the FSI. This is, however, a rather important factor for follow-up studies, e.g., on sediment transport problems of soil around coastal vegetation.

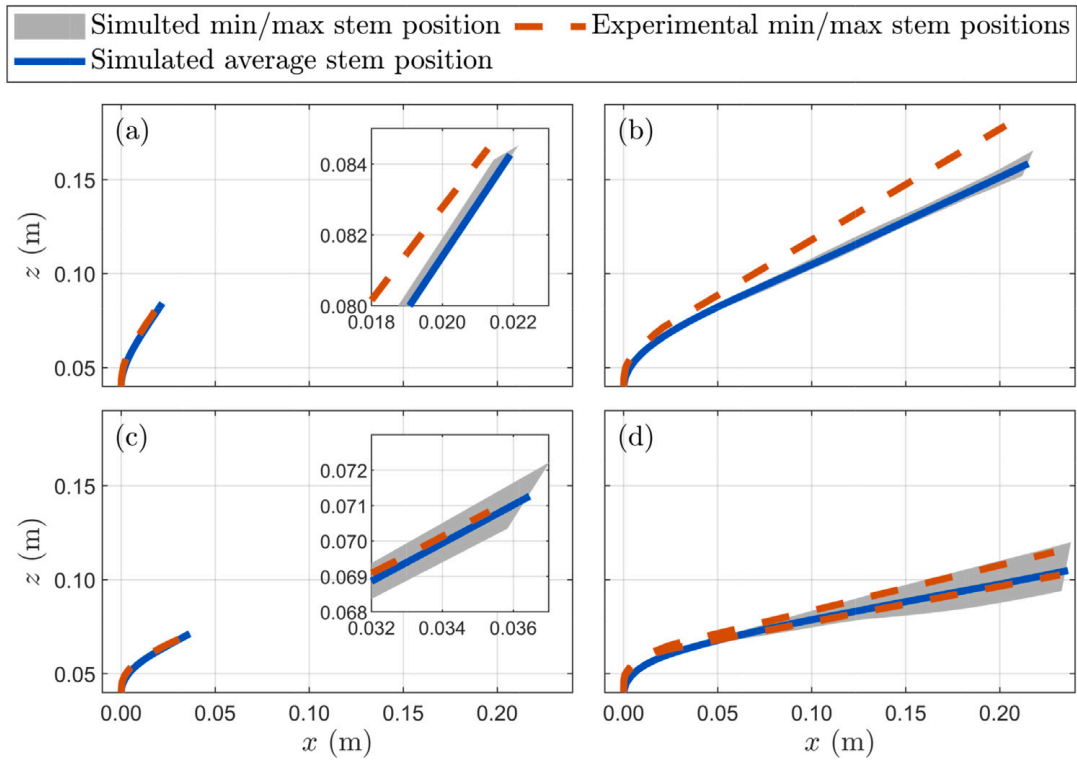


Fig. 12. Bending of the simulated and experimental stem (Luhar and Nepf, 2011) for the soft foam material with (a) $L_S = 0.05$ m and $v = 0.16$ m/s, (b) $L_S = 0.25$ m and $v = 0.16$ m/s (c) $L_S = 0.05$ m and $v = 0.32$ m/s and (d) $L_S = 0.25$ m and $v = 0.32$ m/s.

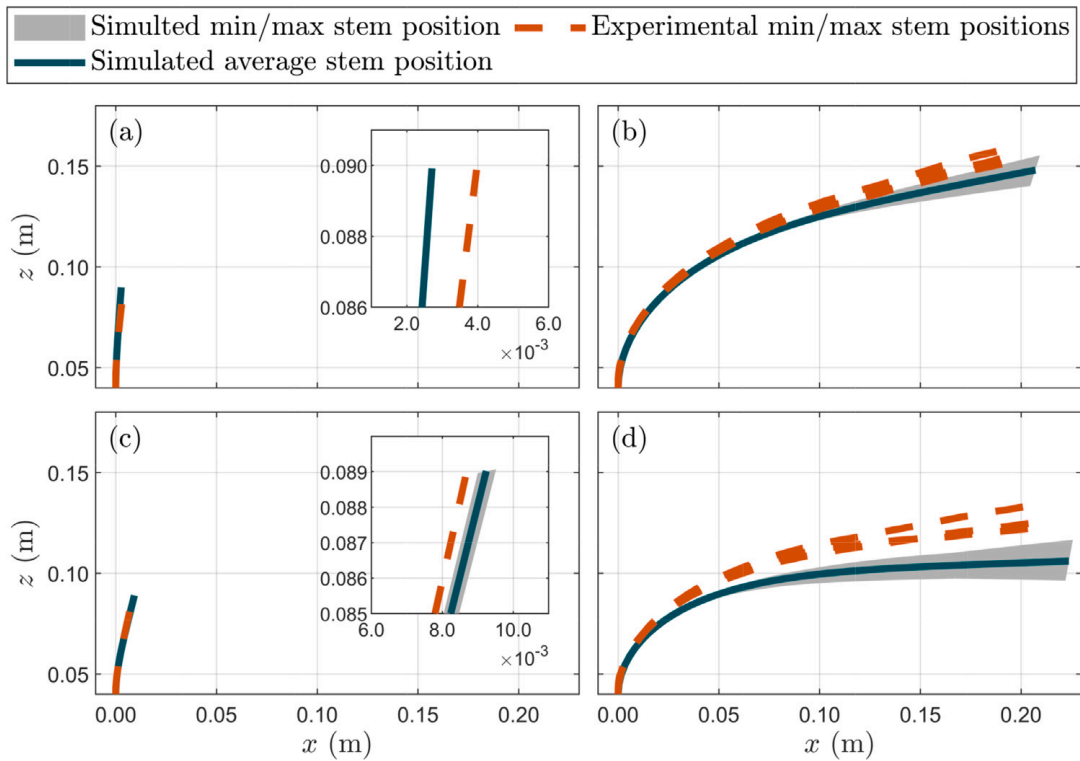


Fig. 13. Bending of the simulated and experimental stem (Luhar and Nepf, 2011) for the HDPE material with (a) $L_S = 0.05$ m and $v = 0.16$ m/s, (b) $L_S = 0.25$ m and $v = 0.16$ m/s (c) $L_S = 0.05$ m and $v = 0.32$ m/s and (d) $L_S = 0.25$ m and $v = 0.32$ m/s.

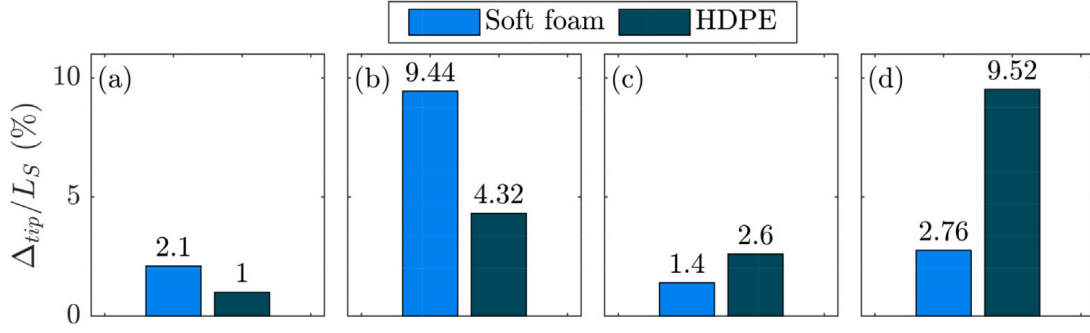


Fig. 14. Comparison of the tip position for the soft foam and the HDPE material with (a) $L_S = 0.05$ m and $v = 0.16$ m/s, (b) $L_S = 0.25$ m and $v = 0.16$ m/s (c) $L_S = 0.05$ m and $v = 0.32$ m/s and (d) $L_S = 0.25$ m and $v = 0.32$ m/s.

For the shorter and more rigid stems, the damping coefficients only influence the time between the initial position and the steady-state bending, as their movement is minimal. In contrast, Fig. 12b and d as well as Fig. 13b and d show that the 0.25 m-stem continuously undergoes a movement with a magnitude of centimeters in z -direction, most visible for the 0.25 m long soft foam stem with the fastest current velocity ($v = 0.32$ m/s) with a movement of 0.03 m in z -direction.

To investigate the potential influence of the damping coefficients on the dynamic stem movement of the longest soft foam stem, the setup with a current velocity of 0.32 m/s is tested for a variation of the damping coefficients. Hereby, only c_k is varied, as c_d was examined to not influence the bending behavior of the stem and is therefore kept constant ($c_d = 1$). It should be noted that the damping coefficients only have a minor influence on the average forces (e.g. $c_k = 1 \times 10^{-4}$, $F_{sim} = 0.023$ N, for $c_k = 1 \times 10^{-5}$, $F_{sim} = 0.022$ N and for $c_k = 1 \times 10^{-7}$, $F_{sim} = 0.021$ N).

The time history of the drag force, representative of the influence of the damping coefficient on the stem movement, is plotted in Fig. 15a-c. A low-pass filter and a Tukey window have been applied to the simulated drag forces to reduce the effect of leakage for the fast Fourier transform (FFT). A filter width of 150 Hz has been selected for the low-pass filter, ensuring that only the smallest fluctuations are filtered without discarding effects in the range of 0 Hz to 1 Hz, which has been shown relevant in the further analysis. To provide a broader comparison, the natural frequency of the blade has been calculated with the constant $C_n = 0.56$ and the assumption of C_M being equal to 1 (Luhar and Nepf, 2016):

$$f_n = C_n \sqrt{\frac{EI}{L_S^4(\rho_S W_S T_S + \rho C_M (\pi T_S^2/4))}} \quad (14)$$

The force amplitude spectrum for the three cases with varied damping coefficients in the frequency domain are compared in Fig. 15d. The highest damping coefficient shown here ($c_k = 1 \times 10^{-4}$) appears to dampen the larger force fluctuations that occur for the two other damping coefficients, which is also apparent due to the peak at a much smaller frequency (0.01 Hz) compared to the other two peaks (0.20 and 0.22 Hz). The results for the other two damping coefficients are similar, suggesting that a threshold value appears from which the force variation is limited. The reduced variation of the resulting forces can suggest a restricted movement of the flexible structure.

To evaluate the influence of variation of damping coefficients applied to the stems on the flow field, the turbulence intensity TI has been calculated using the time-averaged velocity $\bar{u}$ and u_{rms} :

$$TI = \frac{u_{rms}}{\bar{u}} \quad \text{with} \quad u_{rms} = \sqrt{\overline{(u(t) - \bar{u})^2}} \quad (15)$$

Here, the TI is used as an indicator of the impact of the stem to the flow field for two locations, one in front of the stem ($x = 0.10$ m, $y = 0.00$ m), representing the undisturbed flow field and a second one in the wake of the stem ($x = 0.40$ m, $y = 0.00$ m), depicted in Fig. 2 as line probe 5 and 6. Fig. 16 displays the resulting normalized mean horizontal velocity, the RMS of the time track of the horizontal velocity, and the resulting TI for both locations. The results show that the stem influences the flow field behind by reducing the horizontal velocity (Fig. 16a). The extent of reduction differs depending on the applied damping coefficient. The fluctuations of the horizontal velocity, expressed by its RMS, have a varying extent for different damping coefficients (Fig. 16b), whereby the results for $c_k = 1 \times 10^{-7}$ differ the most. The resulting TI has similar trends (Fig. 16c), showing that the use of a smaller damping coefficient leads to less turbulence in the flow field for the selected position. While the turbulence conditions in front of the blade can be classified as low turbulence ($< 1\%$), the results with $c_k = 1 \times 10^{-7}$ fall into the category of mid turbulence and with $c_k = 1 \times 10^{-4}$ and $c_k = 1 \times 10^{-5}$ as high turbulence with $TI > 10\%$ (Windt et al., 2021).

3.4. Application of field data

Providing further insights of the capability of the proposed model, different vegetation parameters from field measurements, see Table 1, are applied to the numerical model and its outcomes compared. For the same horizontal current velocity of 0.50 m/s, the resulting drag force, bending angle, and drag coefficient are provided in Table 2. The applied bending angle follows the definition of Luhar and Nepf (2011) and is accordingly given relative to the initial stem position. The angle is determined at mid of the stem

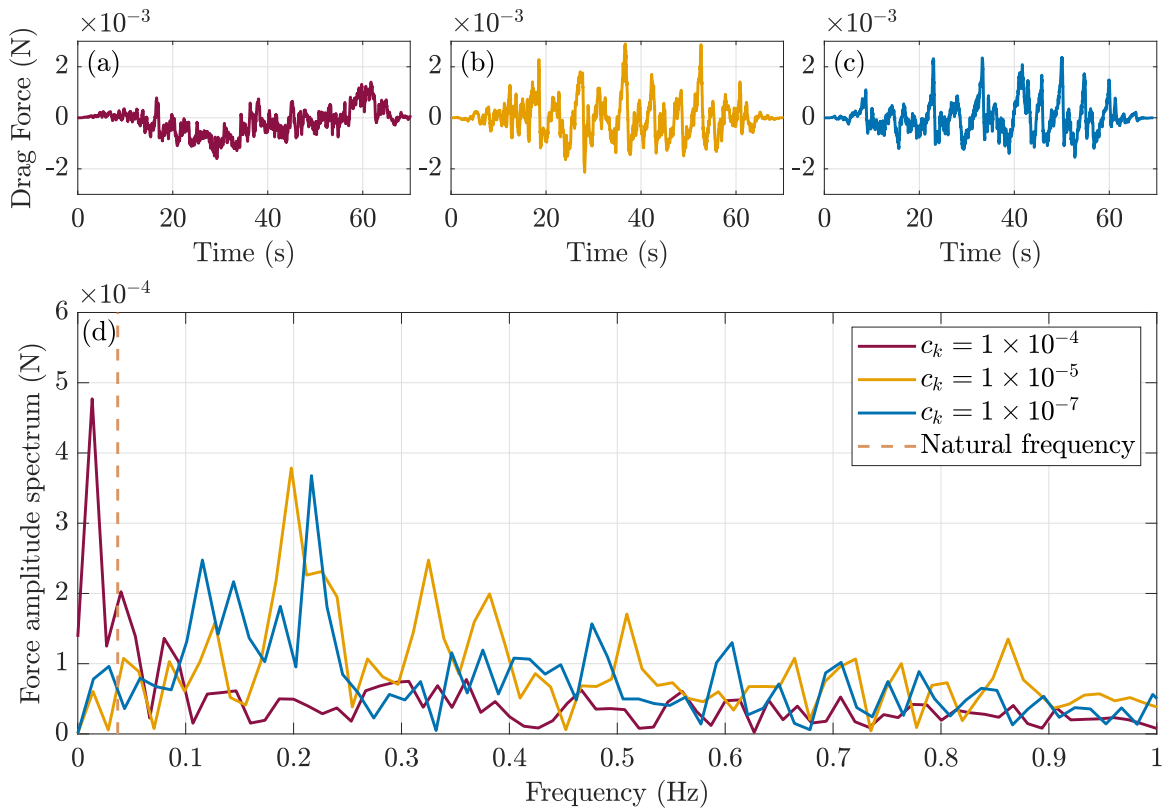


Fig. 15. Filtered simulated drag force for varying damping coefficients in the (a-c) time histories and (d) force amplitude spectra, including the natural frequency of the stem.

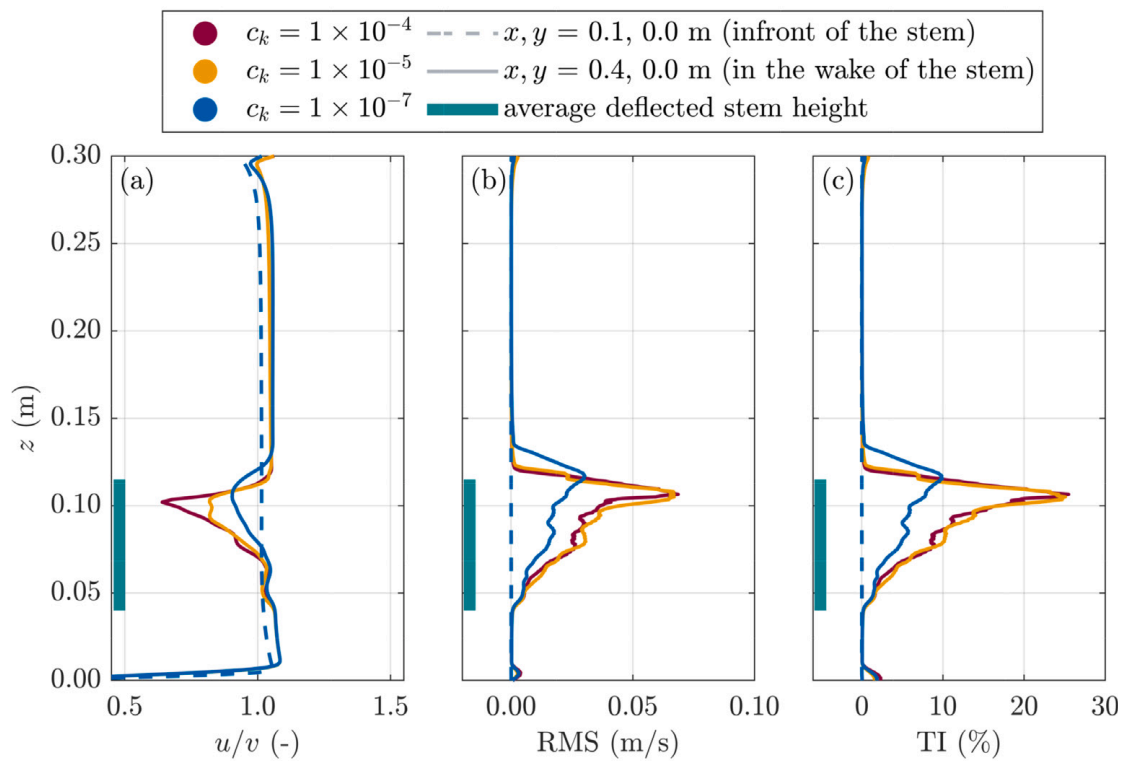


Fig. 16. (a) Normalized horizontal flow velocity, (b) RMS of the horizontal velocity, and (c) resulting turbulence intensity compared for three different damping coefficients in front of (probe line 5) and behind (probe line 6) the stem. The results for probe line 5 are identical, independent of the applied damping coefficient.

Table 2

Resulting parameters from simulations with different growth states and a current velocity of 0.50 m/s.

Growth state		Flowering	Broken	Sprouting
Drag Force	F_D (N)	0.19	0.18	0.18
Bending angle	ϕ (°)	8.65	13.32	18.18
Drag coefficient	C_D (-)	0.73	0.67	0.58

and calculated by $\phi = 90^\circ - \tan^{-1}((z_{tip} - z_{mid})/(x_{tip} - x_{mid}))180/\pi$, with z_{tip} and x_{tip} describing the bent position at the tip of the stem and z_{mid} and x_{mid} the bent stem position at half of the stem length. The drag coefficient was calculated with the equation from [Luhar and Nepf \(2011\)](#), resulting in $C_D = F_D/(0.5\rho W_S v^2 \cos(\phi)^2)$.

The results show that the same plant species in different growth states have comparable drag forces (0.19, 0.18, and 0.18 N) while differing in their resulting stem bending, here expressed by bending angles (8.65°, 13.32°, and 18.18°). Consequently, the calculated drag coefficients differ, even though their average forces are of similar magnitude, with the flowering plant having the highest drag coefficient (0.73), followed by the broken plant (0.67) and the sprouting state (0.58). The variation of resulting drag coefficients emphasizes the need for advanced numerical models that do not require the use of drag coefficients to be able to simulate live vegetation, as long as drag coefficients for individual plant species including seasonality are not available.

Further on, the results are compared and confirmed by an approach based on non-dimensional parameters and empirical relations. [Luhar and Nepf \(2011\)](#) proposed to use the effective length l_e to calculate the drag force ($F_D = 0.5\rho C_D b l_e U^2$). The effective length is determined by an empirical relation between Ca and B :

$$\frac{l_e}{l} = 1 - \frac{1 - 0.9Ca^{-1/3}}{1 + Ca^{-3/2}(8 + B^{3/2})} \quad (16)$$

The calculated effective length for the flowering stem is 0.20 m, for the broken stem 0.19 m, and for the sprouting stem 0.18 m. When using a C_D of 1.95 (following [Luhar and Nepf \(2011\)](#)), the calculated drag force is 0.20 N for the flowering stem and 0.18 N for both the broken and sprouting stem, which are in high agreement with the simulated forces (cf. [Table 2](#)). The high agreement underlines both the capability of the proposed model to simulate the resulting forces and the empirical model of [Luhar and Nepf \(2011\)](#) to determine the resulting forces based on the dimensionless parameters Ca and B .

Overall, relatively stiff vegetation has been chosen for this application study, underlined by the calculated effective length being almost equal to the initial stem length, resulting in a limited influence of the stem reconfiguration on the resulting forces. Future investigations should include more flexible live vegetation to confirm the general applicability of that approach and the proposed model.

Providing further insights into the resulting flow field behind the stems, the stem position, the normalized horizontal velocity, and the turbulence intensity for the three growth states are illustrated in [Fig. 17c](#). This analysis follows the methodology previously described for the variation of damping coefficients presented in [Section 3.3](#). The normalized horizontal flow velocity varies with height across different growth states ([Fig. 17b](#)), induced by the varying positions of the bent stems ([Fig. 17a](#)). The resulting turbulence intensity for each growth state is depicted in [Fig. 17c](#). While the comparison reveals similar maximum values of the turbulence intensity at around 25 % for all growth states, large differences regarding their profile in z -direction become apparent.

The comparison indicates that the turbulence dynamics in the wake of the stem vary depending on the growth state, which can, for example, become relevant when looking at the sediment transport behavior in the proximity of the stem.

4. Discussion

4.1. Applicability of the model

The importance of choosing a suitable turbulence model to accurately simulate the flexible stem motion and the corresponding forces of the FSI has been highlighted in [Section 3.1](#). The approach of a wall-adapted RANS turbulence model to improve the FSI shows promising results compared to the RANS approach without adaption. Its application should be the subject of future investigations, such as evaluating the influence when varying the incorporated turbulence factor, which enhances the turbulent energy dissipation. Based on that, the wall-adapted RANS approach can be a viable option for test setups including FSI when LES is not the favorable turbulence model. However, [Fig. 6](#) shows that the resulting forces are in the highest agreement with the experimental results when utilizing the LES turbulence model. As a potential explanation, the resolved eddies close to the surface of the structure could be crucial to simulate the motion and forces correctly, and they can be simulated using the LES approach. A variation of the Smagorinsky coefficient C_S has been studied, revealing that lower values of C_S result in smaller forces applied on the stem. In contrast, [Tschisgale et al. \(2021\)](#) varied C_S (0.075, 0.15, 0.30) and observed no differences in the resulting mean velocity and the resolved turbulent shear stress of a flexible vegetation meadow. Those differing findings imply that parameter choices regarding the SGS model are not relevant when looking at the flow field of a vegetation meadow but certainly for the coupled forces of individual stems.

Previous studies ([Tian et al., 2014](#); [Tschisgale and Fröhlich, 2020](#)), focused on simulating a rather short stem (i.e., 0.05 m), replicating the reference experiments. The FSI for such a short stem is dominated by compression flow and the stem only responds with minimal deflection (cf. [Fig. 18](#)), which is well represented by the structural solver used in this study. Moreover, it also produces accurate results for the longer stem lengths, especially stem lengths up to 0.20 m, see [Fig. 11](#). In general, the numerical model shows

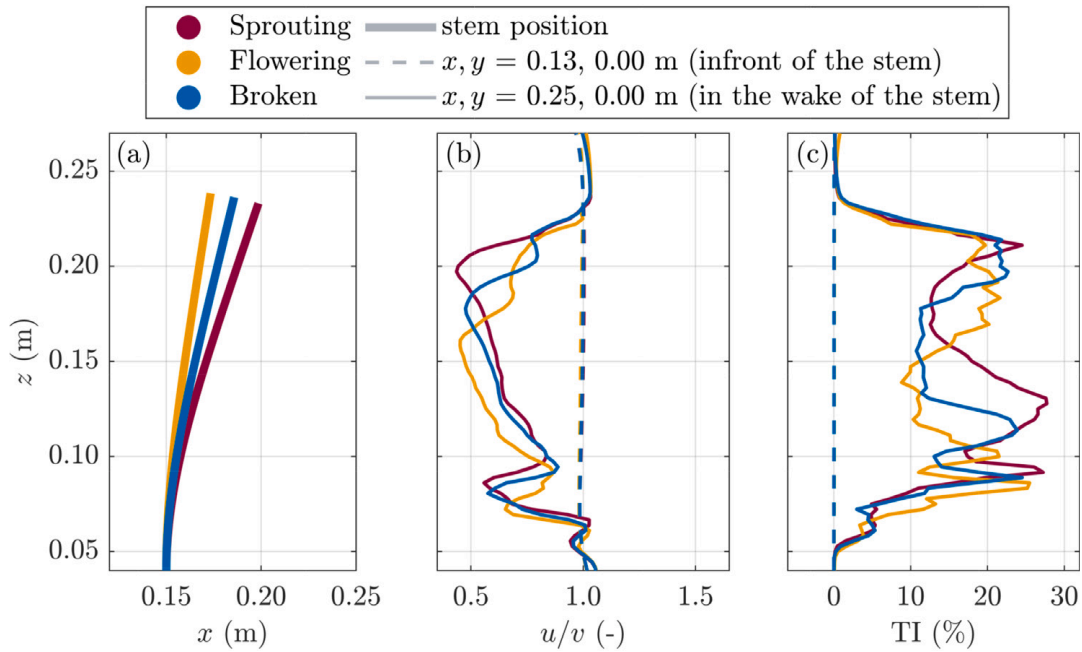


Fig. 17. (a) Stem position in steady state, (b) normalized horizontal flow velocity, and (c) resulting turbulence intensity, compared for three different growing states in front of and behind the stem.

consistent results independent of the stem length regarding the relationship between stem curvature and resulting drag forces. To evaluate that relationship, the deflected stem height (H_{df}) has been defined in this study as the highest point (in the z -direction) the stem reaches on average in its bent position. In Fig. 18, H_{df} is displayed with the simulated forces for the HDPE material. While H_{df} has a deviation of less than 2% to L_S for the shorter stems for all current velocities ($H_{df} \approx L_S$), it differs highly for the longer stems ($H_{df} < L_S$). The latter case has been highlighted in Fig. 18 and a fitted curve was added. As expected, smaller H_{df} correlate with higher simulated forces independent of the initial stem length. Fig. 18 shows that the FSI in this study is consistent in simulating forces respective to the resulting deflected stem heights H_{df} for all simulated current velocities and stem lengths.

In Section 3.3, the importance of studying the damping coefficients for the flexible stem motion has been shown. The accurate simulation of the stem motion under currents has potential implications for future studies. In particular, when investigating the flow through a vegetation patch is considered in combination with sediment transport. There, the feedback of the vegetation-influenced flow field is crucial to the sediment mobility solution, see Le Bouteiller and Venditti (2015), Huai et al. (2019), Lou et al. (2021), Liu et al. (2022). The difference of the time-dependent variation for selected damping coefficients could not be validated through the reference experiments in this study, since transient behavior is often not recorded or published for current investigations. Therefore, to gain an improved understanding, time-dependent measurements of the forces for current experiments are required to enable a comparison of the resulting stem motion in the frequency domain. Even though the damping coefficients do not influence the average forces under currents, suitable damping coefficients are required to simulate the resulting forces for stem motion under waves (Martin and Bihs, 2021). As the damping coefficients are specific for the geometrically exact Cosserat rod, damping coefficients for other beam theories from the literature are challenging to apply, and their material dependency requires further investigation.

4.2. Model limitations and improvements

Deviations have been observed regarding both, the stem bending and resulting forces, compared to the reference experiment for the longest stem ($L_S = 0.25$ m) for both material types. One explanation could be the comparably high grid uncertainty (cf. Appendix A.2) that was calculated for the 0.25 m stem (on average 10.42%) in contrast to the 0.05 m stem (on average 2.39%) for the intermediate cell size of 1.5×10^{-3} m (see Table A.3). Therefore, a refined cell size would be more accurate for modeling the flow close to the surface of the structure and lead potentially to less deviation in the solution but comes with a high computational cost.

Another explanation could be related to a limitation of the coupled numerical model, which is neglecting any wall shear or skin friction of the stem. With longer stem lengths and corresponding larger surface areas that limitation would be increasingly relevant, in agreement with the presented results of this study, as displayed in Fig. 12 and Fig. 13. For the short stem, the bending is minimal, and compression flow dominates, while the deflected curvature of the long stem results in a much longer stem surface exposed to shear stresses. Correspondingly, the current acting on the upper part of the stem changes from a compression towards a longitudinal shear flow. Wall or skin friction, while increasing the resulting force in one-way coupled approaches, could affect the surrounding hydrodynamics, dissipate energy, and reduce flow velocities, by inducing small-scale turbulence along the surface of the stem. The absence of this process within the presented model is a potential source of error. Gosselin (2019) discussed that the influence of the skin friction for flexible vegetation could be larger for smaller values of Re , which corresponds to the deviations displayed

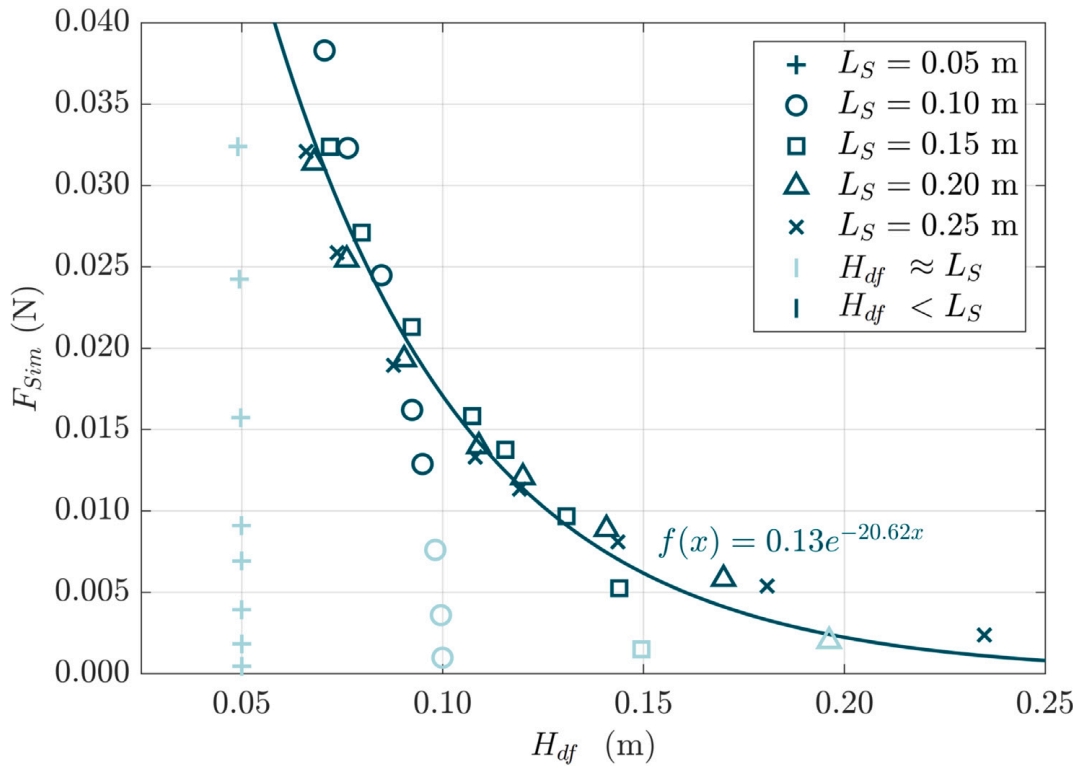


Fig. 18. Relation between simulated forces of the HDPE material to the deflected stem height, including a fitted curve for $H_{df} < L_S$, with the sum of squared errors (SSE) = 0.0002 and $R^2 = 0.93$.

in Fig. 11. Then again, the skin friction might become relevant when the stem is bent parallel to the flow, which is expected for higher current velocities, corresponding to higher values of Re . Future work should therefore integrate skin friction and investigate its influence along the stem. A possible solution to include the vegetation is the application of wall-adapted velocity functions for the coupling of the FSI. Another possibility could be the application of skin friction coefficients to the coupling of the FSI. In the literature (Abdelrhman, 2007; Zhu et al., 2020), a relationship between Re and the skin friction coefficient (C_f) has been applied ($C_f = 0.074Re^{-1/5}$) to simulate flexible vegetation, leading to skin friction coefficients of 0.02, 0.07, and 0.10 (Abdelrhman, 2007; Zeller et al., 2015; Luhar and Nepf, 2016).

The structural solver currently approximates vegetation by a uniform beam of square cross-section; this could be an oversimplification of live vegetation. Field investigations on vegetation have reported a variation of material properties over the plant height, i.e., the diameter or Young's modulus (Keimer et al., 2023). Previous numerical simulations have shown that using uniform properties instead of a variation of material properties over the vegetation height leads to errors predicting the drag coefficient of up to 26% (Marjoribanks and Paul, 2021). Recently, an approach to include a varying width over the stem height for a Cosserat rod solver has been proposed (Schoppmann et al., 2021); however, the integration of further geometrical properties of plants, like leaves, would require additional modifications currently unaccounted for. More accurately modeled plant configurations, including nodes and leaves, could be of importance, as wave attenuation in field conditions is correlated to leaf properties (Zhang et al., 2022); however, the same correlation could not be observed for the leaf lengths, potentially due to the reconfiguration of longer leaves. Nevertheless, as observed by Keimer et al. (2023), vegetation species in dormancy often lose their leaves, wherefore a beam seems to be a suitable simplification to simulate conditions during storm surge season.

5. Conclusion

When quantitatively assessing the ecosystem services provided by coastal vegetation, such as salt marsh or seagrass, the use of accurate numerical models that adopt a direct forcing approach without reliance on coefficients like C_D enable further evaluation of the involved dynamic processes. Parameters such as the dynamic fluctuation of the current-induced stem motion and the resulting turbulence intensity provide insights regarding the sediment mobility solution around flexible stems. Already recognized as a promising approach, the FSI within the model REEF3D::CFD was evaluated towards its ability to accurately simulate the motion and resulting forces of flexible vegetation under varying current conditions. The specific objectives posed at the beginning of this work could now be addressed as follows:

- The convergence analysis of the structural solver underscores the importance of a fine grid resolution in the proximity of the vegetation stem. In the context of the currents examined in this study, no discernible sensitivity to temporal resolution was observed. For the simulated stem with a length of 0.25 m, an optimal number of individual rigid elements has been determined, totaling 200 elements per meter.

- A comparative assessment of simulated forces employing three turbulence models, namely RANS, URANS and LES, highlighted that the wall-adapted RANS approach represents a more reasonable FSI compared to the non-adapted approach, while the utilization of LES shows the smallest deviations of simulated to experimental forces.
- The outcomes of this investigation demonstrate that the FSI implemented in REEF3D::CFD can accurately replicate both stem bending and associated forces across diverse stem lengths, current velocities, and material compositions.
- The influence of the damping coefficients on the flexible motion of the longer stems under current load was highlighted with a force amplitude spectrum.

Subsequent investigations should prioritize the incorporation of wave conditions and evaluate potential material dependencies of damping coefficients. Addressing the current limitations of the structural solver may involve the inclusion of vegetation skin friction and the variation of material properties along the stem height.

CRediT authorship contribution statement

Inga Prüter: Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Felix Spröer:** Writing – review & editing, Visualization, Validation, Methodology. **Kara Keimer:** Writing – review & editing, Methodology, Conceptualization. **Oliver Lojek:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Christian Windt:** Writing – review & editing, Validation, Methodology, Conceptualization. **David Schürenkamp:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Hans Bihs:** Methodology, Software, Writing – review & editing. **Ioan Nistor:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Nils Goseberg:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Model sensitivity

This appendix focuses on the sensitivity analysis of the model regarding the temporal and spatial discretization as well as the number of individual rigid elements, of which the stem consists of.

A.1. Influence of the flume width

First, the influence of the wall on the horizontal flow velocity is investigated. Ensuring computability required a reduction of the experimental flume width of 0.38 m (for the lower current velocities) and 0.76 m (for the higher current velocities). Therefore the time-averaged horizontal velocity of approximately the last six seconds of the simulation in seven flume widths, ranging from 0.08 m to 0.32 m, are compared at four different locations in the flume. Additionally, the influence of using a slip boundary condition for the walls has been tested for the flume width of 0.16 m. Three probes are located in between the inflow and the stem to evaluate the flow conditions acting on the stem and determine the influence of the wall in x - and z -direction. A fourth probe is located in between the stem and the wall to evaluate the wall influence in y -direction, an overview of the positioning of the line probes is given in Fig. 2. The results are visualized in Fig. A.19, where Fig. A.19a displays the inflow boundary condition, which is not yet influenced by the flume width. In Fig. A.19b, c, and d, the influence of the walls is apparent for two flume widths of 0.08 m and 0.12 m.

To quantify the wall influence, the deviation of the depth-averaged horizontal velocity to the widest simulated flume is calculated and displayed in Fig. A.20a. In Fig. A.20b, the deviation of the average simulated force compared to the average simulated force of the widest tested flume is displayed. Additionally, the simulation time for each flume width is visualized. As the deviation of the horizontal velocity for the flume width of 0.16 m is at about 2 % and of about 3 % for the average force, while simulating twice as fast as the 0.32 m wide flume, it is a reasonable compromise between results' accuracy and simulation time. The slip BC was not chosen, as it can be seen in Fig. A.19 in that the flow profile deviates from the other no-slip boundary conditions cases still at the lower height of the tip, thus leading to potentially different results compared to those from the physical experiments. The ideal combination could be in conclusion a no-slip BC for the bottom of the flume and a slip BC for the flume walls. However, this possibility is currently not implemented in the used finite-differences solver.

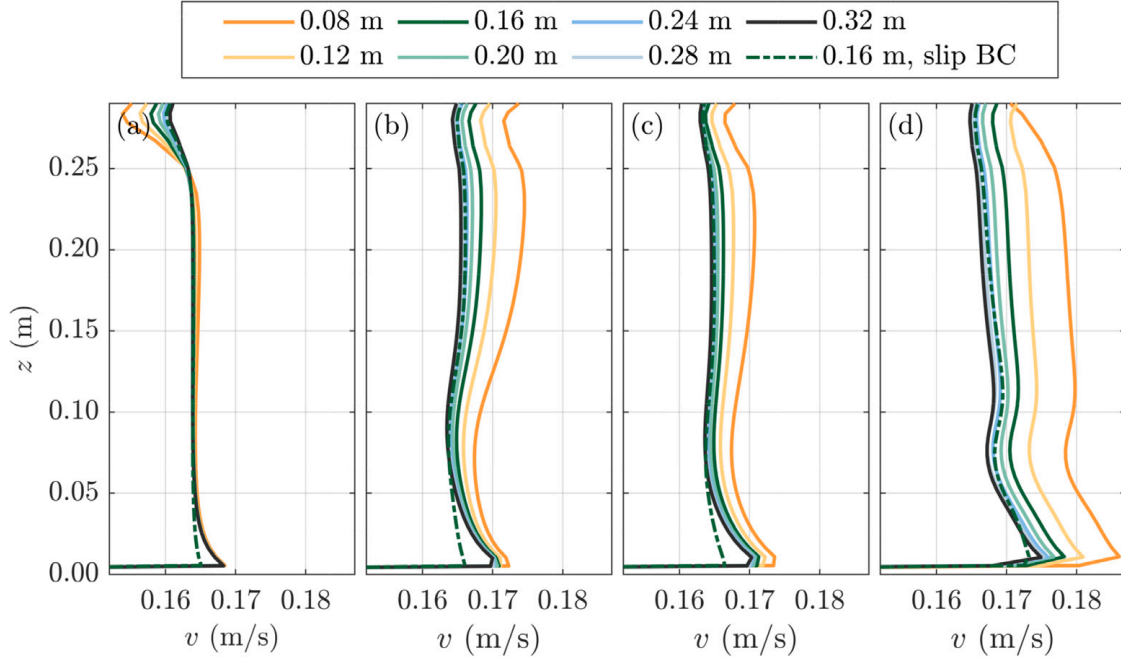


Fig. A.19. Comparison of the time-averaged horizontal velocity for a variation of flume widths, for (a) Probe 1 at $x = 0.025$, $y = 0.00$, (b) Probe 2 at $x = 0.05$, $y = 0.00$, (c) Probe 3 at $x = 0.075$, $y = 0.00$ and (d) Probe (4) at $x = 0.15$, $y = 0.03$.

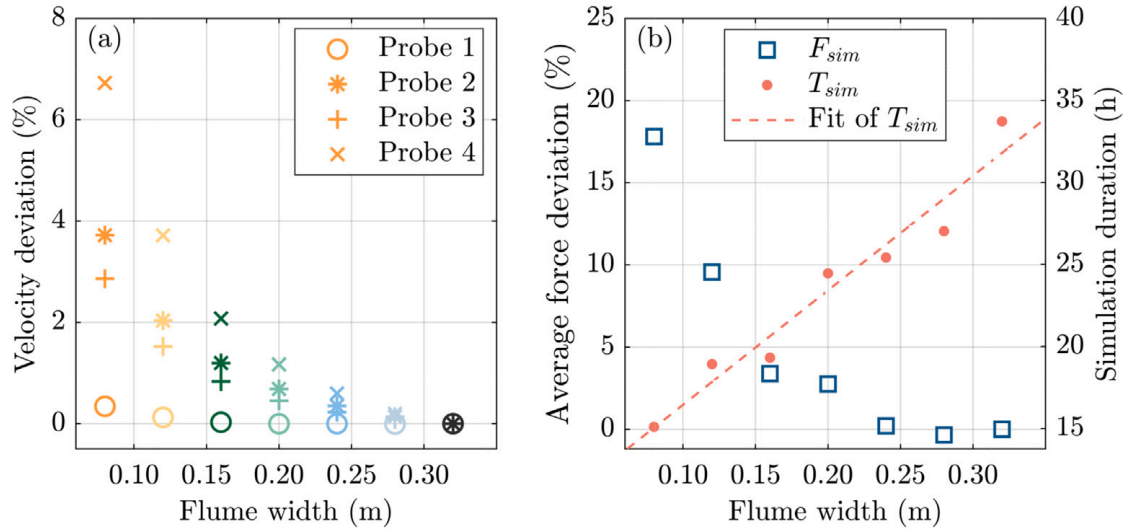


Fig. A.20. Comparison of (a) the deviation of the horizontal velocity to the horizontal velocity of the widest simulated flume and (b) the deviation of the simulated force to the simulated force of the widest simulated flume, including the simulation duration for a variation of flume widths.

A.2. Grid convergence study

A grid convergence study has been carried out for both materials used in the experiments to be able to determine the necessary grid resolution to reproduce the forces acting on the stem, following Cummins et al. (2017), based on the assumption:

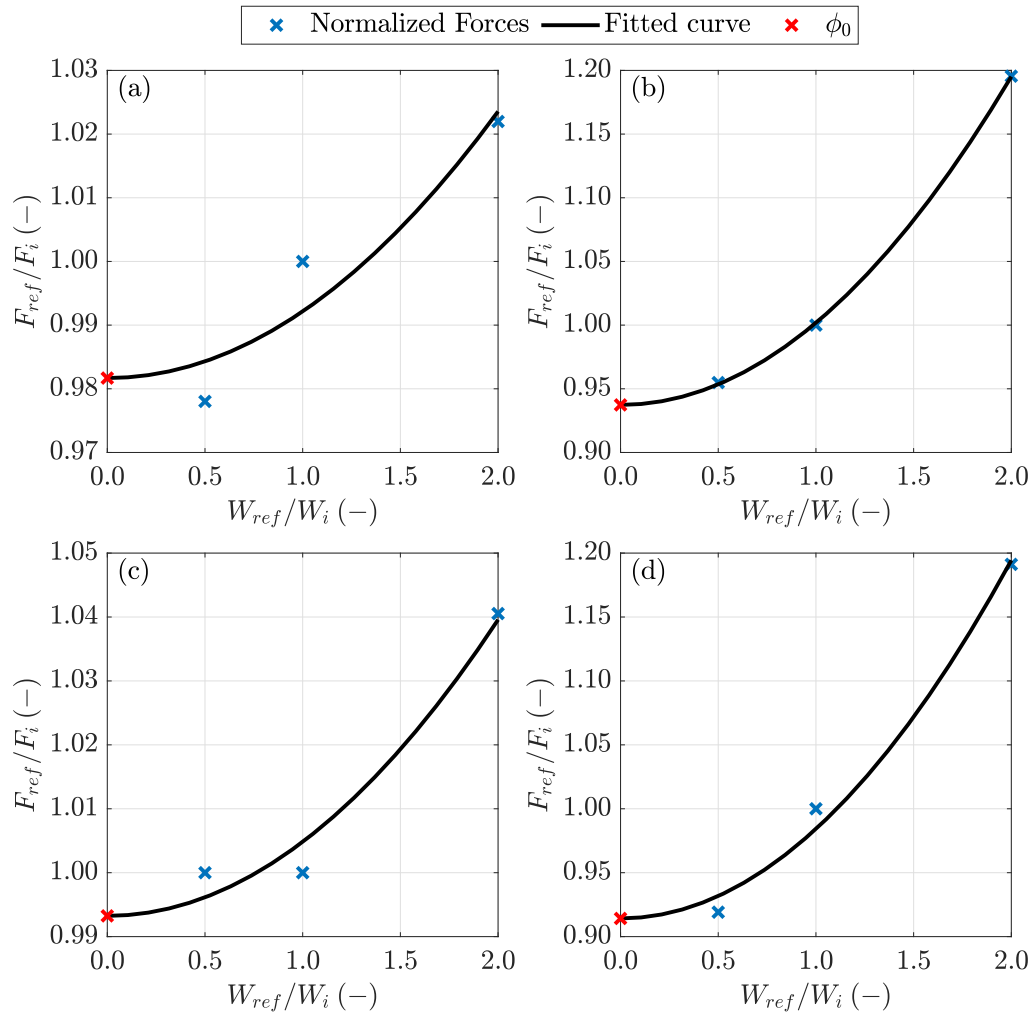
$$\phi(h) = \phi_0 + \alpha h^p \quad (\text{A.1})$$

Here, h_i corresponds to the ratio of the cell sizes of the i th grid to that of the reference grid and ϕ_i to the ratio of simulated forces to the force of the reference grid. For each material type and stem length, quadratic convergence is assumed, making p equal to two. Correspondingly, a parabola is applied for the curve fit to evaluate ϕ_0 , which describes the estimated normalized force in the limit of infinite resolution. The parameters ϕ_0 and α are then obtained by the least squares method. Afterwards, the standard error of the fit is calculated by

$$\sigma_{fit} = \sqrt{\frac{\sum_{i=1}^{n_g} (\phi_i - \phi(h_i))^2}{n}}, \quad (\text{A.2})$$

Table A.3Grid convergence after (Cummins et al., 2017) for the HDPE and soft foam material with $v = 0.16$ m/s.

Material	Refined cell size	$L_S = 0.05$ m		$L_S = 0.25$ m	
		Drag force (N)	Grid uncertainty %	Drag forces (N)	Grid uncertainty %
HDPE	0.75×10^{-3}	0.0089	1.48	0.0127	2.43
	1.5×10^{-3}	0.0091	3.31	0.0133	8.06
	3.0×10^{-3}	0.0093	6.05	0.0159	32.50
Soft foam	0.75×10^{-3}	0.0074	1.47	0.0125	2.65
	1.5×10^{-3}	0.0074	1.47	0.0136	12.77
	3.0×10^{-3}	0.0077	6.53	0.0162	36.66

**Fig. A.21.** Grid convergence study after Cummins et al. (2017) for grid sizes in the refined area of 0.75×10^{-3} m, 1.5×10^{-3} m and 3.0×10^{-3} m for (a) the 0.05 m and (b) the 0.25 m-long HDPE stem as well as (c) the 0.05 m and (d) the 0.25 m-long soft foam stem.

including $n = n_g - 3$ as the number of degrees of freedom of the fit. Additionally, the error of the reference grid is estimated by $\delta = |1 - \phi_0|$. The grid uncertainty is then calculated including a safety factor of 1.25 and the standard error of the fit.

$$U_g = 1.25\delta + \sigma_{fit} \quad (\text{A.3})$$

The calculated grid uncertainties are summarized in Table A.3. The resulting regressions for two material types and stem lengths are visualized in Fig. A.21.

Table A.4

Simulated drag force (F_{sim}) for two different test cases with varying CFL-criteria (0.2 - 1.0) and the time in hours required to simulate 20.0 s.

CFL-criterion (-)	HDPE, $v = 0.16$ m/s, $L_S = 0.05$ m		SF, $v = 0.32$ m/s, $L_S = 0.25$ m	
	F_{sim} (N)	Time (h)	F_{sim} (N)	Time (h)
0.2	0.0093	216	0.0220	329
0.4	0.0091	106	0.0224	171
0.6	0.0091	72	0.0222	122
0.8	0.0092	53	0.0222	88
1.0	0.0091	47	0.0224	70

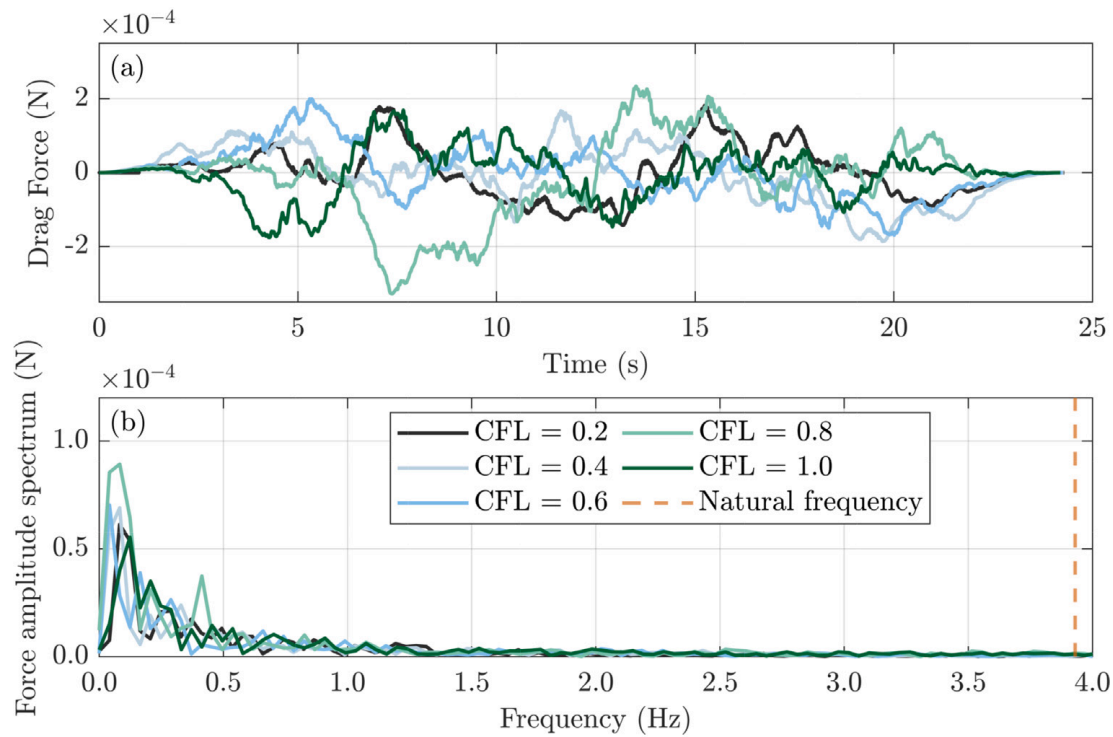


Fig. A.22. Comparison of the simulated forces for a variation of CFL-criteria by transferring the data from (a) the time series to (b) the frequency domain for the HDPE stem with $v = 0.16$ m/s, $L_S = 0.05$ m, including the natural frequency of the stem.

A.3. Influence of the CFL-criterion

In the fluid solver, the time step size is calculated based on the Courant–Friedrichs–Lewy (CFL)-criterion. To test the model sensitivity, the CFL-criterion has been varied for the 0.05 m long HDPE stem with a medium current velocity (0.16 m/s) and the 0.25 m long soft foam stem with a high current velocity (0.32 m/s). The resulting forces are shown in Table A.4, with results differing by a maximum of 2.12 % for the HDPE material relative to the simulated results with the lowest CFL-criterion.

In addition, the time series of the forces has been evaluated, corresponding to the evaluation of the damping coefficients, and compared in the frequency spectrum. Additionally, the natural frequency of the stem has been calculated based on Eq. (14). The results, shown in Fig. A.22, suggest that the CFL-criterion has a minor influence on the fluctuations of the simulated forces. For the satisfactory convergence of drag forces involving uniform current conditions, the CFL-criterion is set equal to unity, which additionally reduces the simulation duration.

A.4. Choice of number of elements

The stem movement and resulting forces exerted on the 0.25 m stem have been tested for varying numbers of elements ($n = 5$ to 100), the results are shown in Fig. A.23. Depending on the degree of curvature, more elements are required to reproduce the bending of the physical stem correctly, as shown in Fig. A.23a and b. The sharpest curvature appears for the 0.25 m long soft foam stem with the highest current velocity of 0.32 m/s. To quantify the accuracy of the stem bending in relation to the physical results, the RMSE is additionally calculated. With a lower number of elements ($n = 5$ to 20), large differences in the resulting bending of the stem can be seen (cf. Fig. A.23d). In contrast, the results remain similar for the larger number of elements ($n = 25, 50, 100$). Correspondingly, the largest variation of the resulting forces is observed for element numbers smaller than 25 and stays relatively constant afterward, for both tested materials (cf. Fig. A.23c).

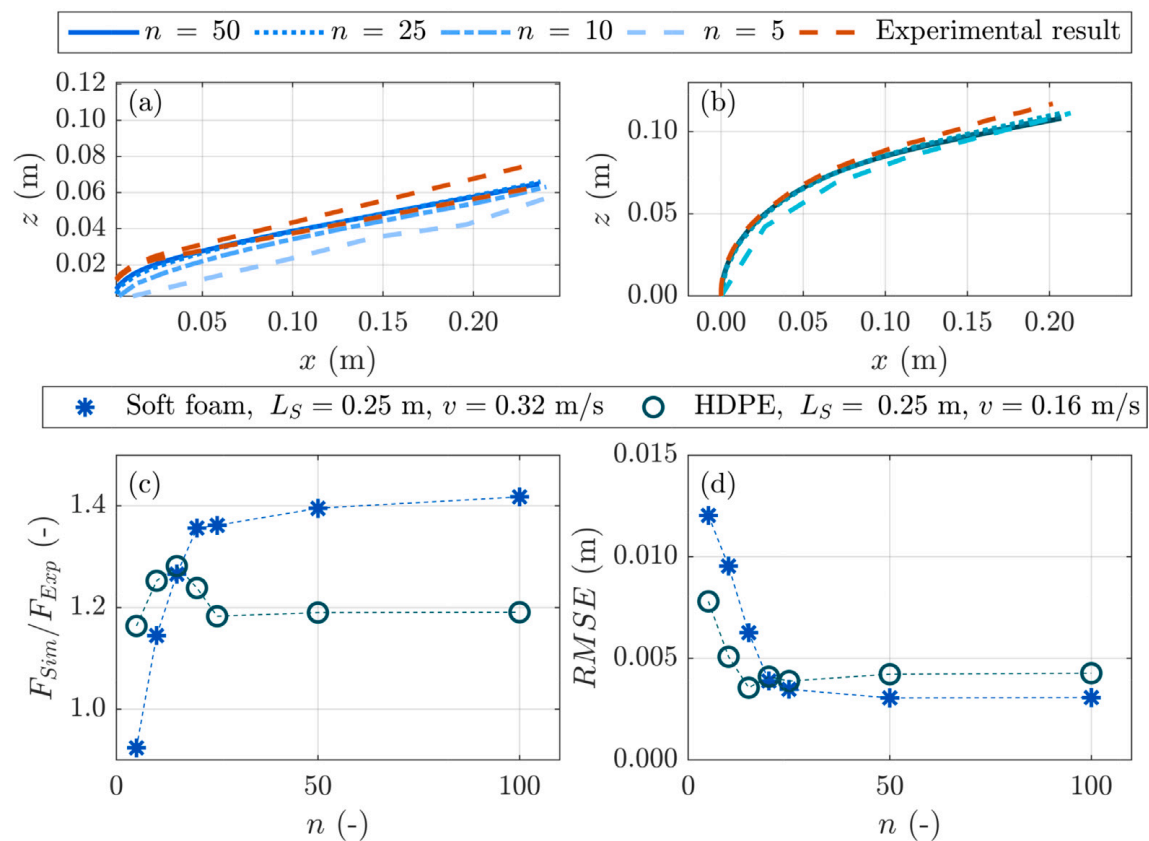


Fig. A.23. Variation of the number of elements for the simulated stem and comparison to the experimental data of [Luhar and Nepf \(2011\)](#) with (a) visualization of the bending behavior for soft foam material and $v = 0.32$ m/s for a selected number of elements, (b) visualization of the bending behavior for the HDPE material and $v = 0.16$ m/s for a selected number of elements, (c) visualization of the normalized forces and (d) the root-mean-square error (RMSE) for the bending behavior for both materials.

Table A.5
Number of elements for the different stem lengths.

Stem length L_S (m)	No. of elements n –	No. of elements per meter (n/m)	Length per element (m/n)
0.05	20	400	2.5×10^{-3}
0.10	32	320	3.6×10^{-3}
0.15	40	267	4.3×10^{-3}
0.20	46	230	4.7×10^{-3}
0.25	50	200	5.0×10^{-3}

Therefore, 50 elements, equivalent to 200 n/m, are chosen for the 0.25 m stem, given that the computational time also increases with increasing number of elements. For the 0.05 m stem, it has been observed that the solver diverges when using 200 n/m, leading to unstable simulations for faster current velocities. Increasing the number of elements to 20 (400 n/m) stabilized the simulations for the shortest stem. With the number of elements set to 400 n/m for the 0.05 m long stem and 200 n/m for the 0.25 m long stem, the number of elements for the remaining stem lengths have been selected accordingly, with a linear increase in the length per element, as detailed in [Table A.5](#) in the appendix.

Data availability

Data will be made available on request.

References

Abdelrhman, M.A., 2007. Modeling coupling between eelgrass *zostera marina* and water flow. *Mar. Ecol. Prog. Ser.* 338, 81–96. <http://dx.doi.org/10.3354/meps338081>.

Agrawal, V., Kulachenko, A., Scapin, N., Tammissola, O., Brandt, L., 2024. An efficient isogeometric/finite-difference immersed boundary method for the fluid–structure interactions of slender flexible structures. *Comput. Methods Appl. Mech. Engrg.* 418, <http://dx.doi.org/10.1016/j.cma.2023.116495>.

- Anderson, M., Smith, J., 2014. Wave attenuation by flexible, idealized salt marsh vegetation. *Coast. Eng.* 83, 82–92. <http://dx.doi.org/10.1016/j.coastaleng.2013.10.004>.
- Bihs, H., Kamath, A., Alagan Chella, M., Aggarwal, A., Arntsen, Ø., 2016. A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. *Comput. & Fluids* 140, 191–208. <http://dx.doi.org/10.1016/j.compfluid.2016.09.012>.
- Bouma, T.J., Vries, M.B.d., Low, E., Peralta, G., Tanczos, I.C., van de Koppel, J., Herman, P.M.J., 2005. Trade-offs related to ecosystem engineering: A case study on stiffness of emerging macrophytes. *Ecology* 86 (8), 2187–2199. <http://dx.doi.org/10.1890/04-1588>.
- Bush, R.H., Chyczewski, T.S., Duraisamy, K., Eisfeld, B., Rumsey, C.L., Smith, B.R., 2019. Recommendations for future efforts in RANS modeling and simulation. Paper presented at the AIAA Scitech 2019 Forum, in San Diego, California, 7–11 January 2019.
- Caroppi, G., Järvelä, J., 2022. Shear layer over floodplain vegetation with a view on bending and streamlining effects. *Environ. Fluid. Mech.* 22 (2-3), 587–618. <http://dx.doi.org/10.1007/s10652-022-09841-w>.
- Chen, H., Zou, Q.-P., 2019. Eulerian–Lagrangian flow-vegetation interaction model using immersed boundary method and OpenFOAM. *Adv. Water Resour.* 126, 176–192. <http://dx.doi.org/10.1016/j.advwatres.2019.02.006>.
- Chourdakis, G., Schneider, D., Uekermann, B., 2023. Openfoam-precice: Coupling openfoam with external solvers for multi-physics simulations. *OpenFOAM J.* 3, 1–25. <http://dx.doi.org/10.51560/ofj.v3.88>.
- Cui, T., He, G., Jiang, M., Wang, W., Yuan, L., Han, D., Kamath, A., Bihs, H., 2022a. Large eddy simulation of focused breaking waves with different wave steepness. *Ocean Model.* 179, <http://dx.doi.org/10.1016/j.ocemod.2022.102122>.
- Cui, T., Kamath, A., Wang, W., Han, D., Bihs, H., 2022b. Large-eddy simulations of gravity currents in the presence of waves. *J. Hydraul. Res.* 60:5, 770–791. <http://dx.doi.org/10.1080/00221686.2022.2064345>.
- Cummins, C., Viola, I.M., Mastropaolo, E., Nakayama, N., 2017. The effect of permeability on the flow past permeable disks at low Reynolds numbers. *Phys. Fluids* 29 (9), <http://dx.doi.org/10.1063/1.5001342>.
- Dijkstra, J.T., Uittenbogaard, R.E., 2010. Modeling the interaction between flow and highly flexible aquatic vegetation. *Water Resour. Res.* 46, <http://dx.doi.org/10.1029/2010WR009246>.
- el Rahi, J., Martínez-Estévez, I., Tagliafierro, B., Domínguez, J., Crespo, A., Stratigaki, V., Suzuki, T., Troch, P., 2023. Numerical investigation of wave-induced flexible vegetation dynamics in 3D using a coupling between DualSPHysics and the FEA module of project chrono. *Ocean Eng.* 285, <http://dx.doi.org/10.1016/j.oceaneng.2023.115227>.
- Ferziger, J.H., Perić, M., 2002. *Computational Methods for Fluid Dynamics*. Springer Berlin, Heidelberg.
- Freund, J., Karakoç, A., 2016. Shear and torsion correction factors of timoshenko beam model for generic cross sections. *Res. Eng. Struct. Mat.* <http://dx.doi.org/10.17515/resm2015.19me0827>.
- Gosselin, F.P., 2019. Mechanics of a plant in fluid flow. *J. Exper. Botany* 70 (14), 3533–3548. <http://dx.doi.org/10.1093/jxb/erz288>.
- Hagmeyer, N., Mayr, M., Popp, A., 2024. A fully coupled regularized mortar-type finite element approach for embedding one-dimensional fibers into three-dimensional fluid flow. *Numer. Meth Eng.* 125 (8), <http://dx.doi.org/10.1002/nme.7435>.
- He, S., Liu, H., Shen, L., 2022. Simulation-based study of turbulent aquatic canopy flows with flexible stems. *J. Fluid Mech.* 947, <http://dx.doi.org/10.1017/jfm.2022.655>.
- Himes-Cornell, A., Pendleton, L., Atiyah, P., 2018. Valuing ecosystem services from blue forests: A systematic review of the valuation of salt marshes, sea grass beds and mangrove forests. *Ecosyst. Serv.* 30, Part A, 36–48. <http://dx.doi.org/10.1016/j.ecoser.2018.01.006>.
- Huai, W.-x., Zhang, J., Katul, G.G., Cheng, Y.-g., Tang, X., Wang, W.-j., 2019. The structure of turbulent flow through submerged flexible vegetation. *J. Hydrodyn.* 31 (2), 274–292. <http://dx.doi.org/10.1007/s42241-019-0023-38>.
- Jin, C., Zhang, J., 2022. Numerical investigation of the wave interaction with flexible vegetation: model setup and validation for a single stem study case. *Anthropocene Coast.* 5, <http://dx.doi.org/10.1007/s44218-022-00003-5>.
- Katopodes, N.D., 2019. *Free-surface flow*. Environmental fluid mechanics. Butterworth-Heinemann, Oxford.
- Keimer, K., Kind, F., Prüter, I., Kosmalla, V., Lojek, O., Schürenkamp, D., Prinz, M., Niewerth, S., Aberle, J., Goseberg, N., 2024. From seasonal field study to surrogate modeling: Investigating the biomechanical dynamics of elymus sp. in salt marshes. *Limnograph. Oceanograph. Methods* <http://dx.doi.org/10.1002/lom3.10616>.
- Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Prinz, M., Schürenkamp, D., Freund, H., Goseberg, N., 2023. Proposing a novel classification of growth periods based on biomechanical properties and seasonal changes of spartina anglica. *Front. Mar. Sci.* 10, <http://dx.doi.org/10.3389/fmars.2023.1095200>.
- Kim, H.D., Yu, X., Kaplan, D., 2024. Steady flow over a finite patch of submerged flexible vegetation. *Water Resour. Res.* 60 (1), <http://dx.doi.org/10.1029/2023WR035222>.
- King, S., Lester, J., 1995. The value of salt marsh as a sea defence. *Marine Poll. Bull.* 30, 180–189.
- Lang, H., Linn, J., Arnold, M., 2011. Multi-body dynamics simulation of geometrically exact cosserat rods. *Multibody Syst. Dyn.* 25 (3), 285–312. <http://dx.doi.org/10.1007/s11044-010-9223-x>.
- Le Bouteiller, C., Venditti, J.G., 2015. Sediment transport and shear stress partitioning in a vegetated flow. *Water Resour. Res.* 51 (4), 2901–2922. <http://dx.doi.org/10.1002/2014WR015825>.
- Linn, J., Lang, A., 2013. Geometrically exact cosserat rods with Kelvin–Voigt type viscous damping. *Mech. Sci.* 4 (1), 79–96. <http://dx.doi.org/10.5194/ms-4-79-2013>.
- Liu, J., Kutschke, S., Keimer, K., Kosmalla, V., Schürenkamp, D., Goseberg, N., Böhl, M., 2021. Experimental characterisation and three-dimensional modelling of elymus for the assessment of ecosystem services. *Ecol. Eng.* 166, <http://dx.doi.org/10.1016/j.ecoleng.2021.106233>.
- Liu, C., Yan, C., Sun, S., Lei, J., Nepf, H., Shan, Y., 2022. Velocity, turbulence, and sediment deposition in a channel partially filled with a phragmites australis canopy. *Water Resour. Res.* 58 (8), <http://dx.doi.org/10.1029/2022WR032381>.
- Losada, I.n.J., Maza, M., Lara, J.L., 2016. A new formulation for vegetation-induced damping under combined waves and currents. *Coast. Eng.* 107, 1–13. <http://dx.doi.org/10.1016/j.coastaleng.2015.09.011>.
- Lou, S., Wang, H., Liu, H., Zhong, G., Radnaeva, L.D., Nikitina, E., Ma, G., Liu, S., 2021. Laboratory study of the effects of flexible vegetation on solute diffusion in unidirectional flow. *Environ. Sci. Eur.* 33 (1), <http://dx.doi.org/10.1186/s12302-021-00521-y>.
- Luhar, M., Nepf, H.M., 2011. Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. *Limnol. Oceanogr.* 56, 2003–2017. <http://dx.doi.org/10.4319/lo.2011.56.6.2003>.
- Luhar, M., Nepf, H.M., 2016. Wave-induced dynamics of flexible blades. *J. Fluids Struct.* 61, 20–41. <http://dx.doi.org/10.1016/j.jfluidstructs.2015.11.007>.
- Marin-Diaz, B., van der Wal, D., Kaptein, L., Martinez-Garcia, P., Lashley, C.H., Jong, K.d., Nieuwenhuis, J.W., Govers, L.L., Olf, H., Bouma, T.J., 2023. Using salt marshes for coastal protection: Effective but hard to get where needed most. *J. Appl. Ecol.* <http://dx.doi.org/10.1111/1365-2664.14413>.
- Marjoribanks, T.I., Paul, M., 2021. Modelling flow-induced reconfiguration of variable rigidity aquatic vegetation. *J. Hydraul. Res.* 1–6. <http://dx.doi.org/10.1080/00221686.2020.1866693>.
- Martin, T., Bihs, H., 2021. A numerical solution for modelling mooring dynamics, including bending and shearing effects, using a geometrically exact beam model. *JMSE* 9 (5), 486. <http://dx.doi.org/10.3390/jmse9050486>.
- Mattis, S.A., Dawson, C.N., Kees, C.E., Farthing, M.W., 2015. An immersed structure approach for fluid-vegetation interaction. *Adv. Water Resour.* 80, <http://dx.doi.org/10.1016/j.advwatres.2015.02.014>.

- Maza, M., Lara, J.L., Losada, I.J., 2013. A coupled model of submerged vegetation under oscillatory flow using Navier–Stokes equations. *Coast. Eng.* 80, 16–34. <http://dx.doi.org/10.1016/j.coastaleng.2013.04.009>.
- Mullarney, J.C., Henderson, S.M., 2010. Wave-forced motion of submerged single-stem vegetation. *J. Geophys. Res.* 115, <http://dx.doi.org/10.1029/2010JC006448>.
- Ni, J., Ji, C., Xu, D., Zhang, X., Liang, D., 2023. On monami modes and scales of a flexible vegetation array in a laminar boundary layer. *Phys. Fluids* 35 (7), <http://dx.doi.org/10.1063/5.0155506>.
- Nicoud, F., Ducros, F., 1999. Subgrid-scale stress modelling based on the square of the velocity gradient tensor. *Flow Turbul. Combust.* 62, 183–200.
- O'Connor, J., Rogers, B.D., 2021. A fluid-structure interaction model for free-surface flows and flexible structures using smoothed particle hydrodynamics on a GPU. *J. Fluids Struct.* 104, <http://dx.doi.org/10.1016/j.jfluidstructs.2021.103312>.
- Ondiviela, B., Losada, I.J., Lara, J.L., Maza, M., Galván, C., Bouma, T.J., van Belzen, J., 2014. The role of seagrasses in coastal protection in a changing climate. *Coast. Eng.* 87, 158–168. <http://dx.doi.org/10.1016/j.coastaleng.2013.11.005>.
- Ouro, P., Stoesser, T., 2017. An immersed boundary-based large-eddy simulation approach to predict the performance of vertical axis tidal turbines. *Comput. Fluids* 152, 74–87. <http://dx.doi.org/10.1016/j.compfluid.2017.04.003>.
- Puijalon, S., Bouma, T.J., Douady, C.J., van Groenendael, J., Anten, N.P.R., Martel, E., Bornette, G., 2011. Plant resistance to mechanical stress: evidence of an avoidance-tolerance trade-off. *New Phytol.* 191 (4), 1141–1149. <http://dx.doi.org/10.1111/j.1469-8137.2011.03763.x>.
- Rupprecht, F., Möller, I., Paul, M., Kudella, M., Spencer, T., van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T., Miranda-Lange, M., Schimmels, S., 2017. Vegetation-wave interactions in salt marshes under storm surge conditions. *Ecol. Eng.* 100, 301–315. <http://dx.doi.org/10.1016/j.ecoleng.2016.12.030>.
- Sasikumar, A., Kamath, A., Bihs, H., 2020. Modeling porous coastal structures using a level set method based VRANS-solver on staggered grids. *Coastal Eng. J.* 62 (2), 198–216. <http://dx.doi.org/10.1080/21664250.2020.1734412>.
- Schoppmann, K., Löhrer, B., Tschigale, S., Fröhlich, J., Langre, E.d., 2021. An efficient solver for a cosserat rod of non-constant width applied to a problem of fluid-structure interaction. *Proc. Appl. Math. Mech.* 21 (1), <http://dx.doi.org/10.1002/pamm.202100152>.
- Tian, F.-B., Dai, H., Luo, H., Doyle, J.F., Rousseau, B., 2014. Fluid-structure interaction involving large deformations: 3D simulations and applications to biological systems. *J. Comput. Phys.* 258, <http://dx.doi.org/10.1016/j.jcp.2013.10.047>.
- Tschigale, S., Fröhlich, J., 2020. An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid. *J. Comput. Phys.* 423 (7), <http://dx.doi.org/10.1016/j.jcp.2020.109801>.
- Tschigale, S., Löhrer, B., Meller, R., Fröhlich, J., 2021. Large eddy simulation of the fluid–structure interaction in an abstracted aquatic canopy consisting of flexible blades. *J. Fluid Mech.* 916, <http://dx.doi.org/10.1017/jfm.2020.858>.
- van Veelen, T.J., Fairchild, T.P., Reeve, D.E., Karunaratna, H., 2020. Experimental study on vegetation flexibility as control parameter for wave damping and velocity structure. *Coast. Eng.* 157, <http://dx.doi.org/10.1016/j.coastaleng.2020.103648>.
- Vuik, V., Borsje, B.W., Willemsen, P.W., Jonkman, S.N., 2019. Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. *Ocean Coastal Manag.* 171, 96–110. <http://dx.doi.org/10.1016/j.ocecoaman.2019.01.010>.
- Wang, M., Avital, E.J., Bai, X., Ji, C., Xu, D., Williams, J.J.R., Munjiza, A., 2020. Fluid–structure interaction of flexible submerged vegetation stems and kinetic turbine blades. *Comp. Part. Mech.* 7 (5), <http://dx.doi.org/10.1007/s40571-019-00304-6>.
- Wang, J., He, G., Dey, S., Fang, H., 2022. Influence of submerged flexible vegetation on turbulence in an open-channel flow. *J. Fluid Mech.* 947, <http://dx.doi.org/10.1017/jfm.2022.598>.
- Whittaker, P., Wilson, C.A., Aberle, J., 2015. An improved Cauchy number approach for predicting the drag and reconfiguration of flexible vegetation. *Adv. Water Resour.* 83, 28–35. <http://dx.doi.org/10.1016/j.advwatres.2015.05.005>.
- Windt, C., Davidson, J., Ringwood, J., 2021. Investigation of turbulence modeling for point-absorber type wave energy converters. *Energies* 14 (26), <http://dx.doi.org/10.3390/en14010026>.
- Xu, Z., Shu, C.-W., 2005. Anti-diffusive flux corrections for high order finite difference WENO schemes. *J. Comput. Phys.* 205 (2), 458–485. <http://dx.doi.org/10.1016/j.jcp.2004.11.014>.
- Zeller, R.B., Zarama, F.J., Weitzman, J.S., Koseff, J.R., 2015. A simple and practical model for combined wave–current canopy flows. *J. Fluid Mech.* 767, 842–880. <http://dx.doi.org/10.1017/jfm.2015.59>.
- Zhang, X., Lin, P., Nepf, H., 2022. A wave damping model for flexible marsh plants with leaves considering linear to weakly nonlinear wave conditions. *Coast. Eng.* 175, <http://dx.doi.org/10.1016/j.coastaleng.2022.104124>.
- Zhu, L., Zou, Q.-P., Huguenard, K., Fredriksson, D.W., 2020. Mechanisms for the asymmetric motion of submerged aquatic vegetation in waves: A consistent-mass cable model. *J. Geophys. Res. Oceans* 125, <http://dx.doi.org/10.1029/2019JC015517>.

Response to the reviewers

Dear Editor and Reviewers,

The authors would like to express their appreciation for the time taken and effort made to help improve the present manuscript. The authors believe that addressing the raised comments increased the overall quality of the revised manuscript.

Please find attached a marked version of the manuscript, indicating the amendments the authors performed along with a clean manuscript. Detailed answers to the reviewers' comments are provided in this rebuttal letter. A line count has been added to the revised version of the manuscript to enable clear references to specific sentences in the future.

Answers to the individual comments can be found below. The convention is as follows:

- Refers to the reviewer's comments
- *Refers to our responses to the comments*
- Refers to new text added to the manuscript
- ~~Refers to text deleted from the manuscript~~

Reviewer 1

This manuscript presents a numerical study on the current induced fluid-structure interaction of flexible submerged vegetation. The role of aquatic vegetations is becoming an emerging hotspot issue of river management and coastal engineering following the growing concerns on water environment and ecology. There are numerous studies on this topic using experiments, numerical simulations and field observations targeting a variety of aspects in recent years. The authors present an implementation of a two-way coupled model based on the open source CFD package REEF3D, targeting at a better understanding of fluid-structural interactions between turbulent flow and flexible vegetation as solids. The methodology is described and verified via a series of tests against experimental data. The influence of the damping coefficients is also discussed based on the results. Apparently, this work will add up to the capability of REEF3D, however, the discussions is not sufficiently "comprehensive" as pointed out in the title in my opinion and can be improved in different aspect.

Comment 1 Although FSI simulations for vegetations are quite challenging, there are indeed some recently published works regarding the two-way coupled simulation of flexible vegetations using immersed boundary methods and Large Eddy Simulations, which are very similar to this study. Such works had better be carefully examined and discussed in the introduction part to highlight the innovation of this study by addressing their differences.

Response: *Thank you for this comment. The authors agree that some of the recent literature had not been incorporated and the emphasis on similar studies should be enhanced. The Introduction section was therefore revised as outlined in the following.*

Actions taken: Further literature has been reviewed and the following section of the Introduction regarding the application of the IBM has been adapted as follows.

[Line 98 - 123] "Alternatively, the IBM has become increasingly popular. An Eulerian structural solver can be implemented via the IBM into the Lagrangian fluid phase, as shown by Tian et al. (2014), Tschisgale and Fröhlich (2020) Wang et al. (2020), He et al. (2022), and Wang et al. (2022), Ni et al. (2023), Kim et al. (2024), Hagmeyer et al. (2024) and Agrawal et al. (2024). The IBM has the advantage of accounting for large deformations of the structural solver with an Eulerian grid and a stable fluid solver with a Lagrangian grid. The achieved accuracy of FSI studies using the IBM is promising, rendering it the favored coupling method within the context of this study. Although the previously mentioned works are all based on the IBM, they differ through their proposed coupling algorithm of the FSI, as well as the applied fluid and structural solver. He et al. (2022) applied an inextensible nonlinear Euler–Bernoulli beam, with the bending motion restricted to the streamwise–vertical direction. Similarly, Ni et al. (2023) simulated in two dimensions to focus on the monami modes of a flexible vegetation meadow. Hagmeyer et al. (2024) proposed a strongly coupled partitioned solution algorithm to model a torsion-free beam. Alternatively, Kim et al. (2024) used a finite-element structural solver with soft-body dynamics, while Wang et al. (2020) used a structural solver based on the combined finite element method–discrete element method. Both Tschisgale and Fröhlich (2020) and Agrawal et al. (2024) used the geometrically exact Cosserat rod for their structural solver, which has the advantage of capturing three-dimensional

motion while using a mathematical model in one direction, thus making it computationally more efficient. Additionally, Agrawal et al. (2024) were able to simulate coarser structural meshes than the background fluid grid, highlighting the potential of such a model.”

Comment 2 The authors highlight the advantage of LES over traditional RANS turbulent models. However, only one cases are tested and only one RANS turbulent model is adopted. One may wonder whether the conclusion is general or case-specific.

Response: *Thank you for addressing the topic of comparing different turbulence models. The authors agree with the reviewer that the application of more test cases and turbulence models would help to underline the statement. Therefore, both materials have been now included in the turbulence comparison and additionally, the performance of the URANS turbulence approach has been investigated, in order to amend the present work. The results suggest that LES is the preferable choice for both tested material types, stem lengths, and current velocities. As expected, the use of URANS leads to better results compared to RANS, but is, especially for the longer stems, less accurate than the LES approach. The results are visualized in Figure 4.*

Actions taken: More simulations have been performed for the HDPE material using RANS and URANS and for the soft foam material using URANS. These new results have been displayed in a new figure which replaces previous Fig. 5 in the old manuscript.

[Line 406 - 436] ”In terms of model families, RANS, URANS, and LES fluid solvers have been tested with a variety of parameter settings; the accuracy that could be obtained by the FSI has then been compared to an experimental dataset (Luhar and Nepf, 2011), and against results of a recently published numerical study (Tschisgale and Fröhlich, 2020). Fig. 4 compares the simulated results for RANS, URANS, and LES simulations for ~~the soft foam material stem both the HDPE and soft foam material~~. It can be observed that the RANS simulations, using the $k-\omega$ turbulence model, overestimate the forces measured in the reference experiment. While the overestimation of the forces for the 0.05 m long stem remains in the same magnitude independent of the current velocity, the overestimation by the numerical model increases for the 0.25 m long stem with higher current velocities (Fig. 4a). In Fig. 4b the numerical results using ~~LES URANS with the $k-\omega$ turbulence model~~ are much closer to the experimental forces of the reference experiment compared to those obtained with the RANS turbulence model. Nevertheless, the force computed for the 0.25 m long stem is still overestimated by a factor of 1.5 for the HDPE material and over 2 for the fastest current velocity for the case of the soft foam material. Smaller deviations to the experimental data could be observed using LES in Fig. 4c. Especially for the 0.05 m long stem, the deviations of the simulated to the experimental forces are for seven out of eight investigated velocities within a $\pm 10\%$ error margin. Larger deviations can be seen for the 0.25 m long stem, pointing out that accurate modeling of the turbulence is especially crucial with longer stem lengths. Accordingly, LES has been selected as the more suitable turbulence modeling approach.”

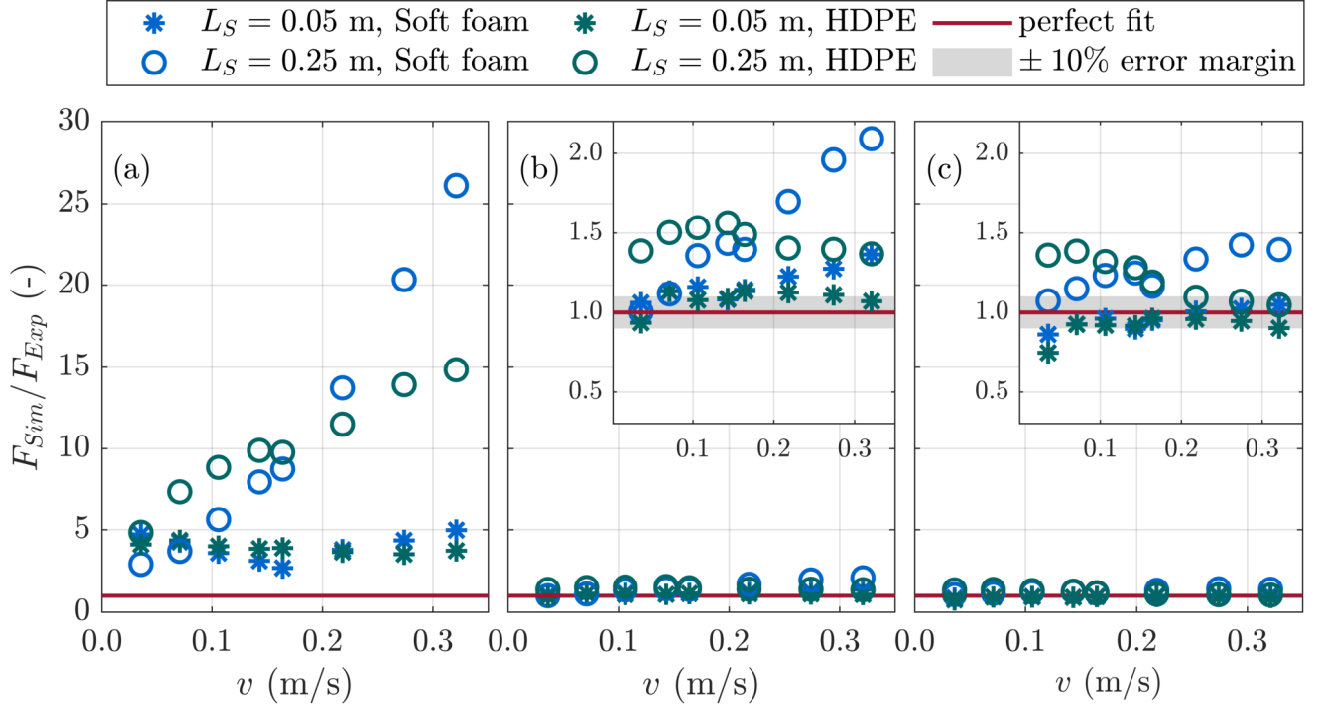


Figure 4: Comparison of simulated vs. experimentally-derived forces (Luhar and Nepf, 2011), for both the soft foam and HDPE Material and two stem lengths $L_S = 0.05$ m and $L_S = 0.25$ m with (a) RANS, (b) URANS and (c) LES turbulence modeling

Comment 3 The coupling between fluid and solid shall be presented in a more detailed way. For example, how the body forces are computed and distributed? There is only body force due to the gravitational force in governing equation (2), where is the influence of the immersed boundary? How the interpolation on the immersed boundary point is implemented?

Response: *Thank you for asking for more details regarding the coupling of the fluid and structural solver. As the coupling is a very important aspect of the fluid-structure interaction, we will address this topic in more depth in the manuscript. The authors hope that the proposed modifications better describe the influence of the immersed boundary and its interpolation.*

Actions taken: The section of the text has been adapted to clarify the coupling between the fluid and structural solver.

[Line 279 - 300] "The external force in Eq. 4 is the sum of the gravitational force ($f_g = (\rho_s - \rho_f)Ag$) and the coupling force f_Γ of the immersed boundary. The spatial coupling of f_Γ , which accounts for the difference between the three-dimensional shape of the immersed boundary to the one-dimensional Cosserat rod, is achieved by connecting the Lagrangian marker points to the Eulerian grid cells, cf. Fig. 1c, via regularized delta functions. Ensuring faster communication, the velocity field of the fluid is then replaced by the integral quantity $\tilde{p}_e$ for the force and $\tilde{l}_e$ for the moment, reducing the communication points to six for each rod element. The temporal coupling of f_Γ for the direct forcing approach is achieved through five steps, using an implicit Runge-Kutta scheme. First, a preliminary velocity is calculated for the next time level without considering the immersed boundary, which is communicated to the structural solver in the second step. The surface-specific force is hereby replaced by its volumetric

~~component (Tschisgale and Fröhlich, 2020). Therefore, it can be calculated with the following equation:~~ In a third step, the interface velocity of the next time level is obtained using the coupling force f_Γ for each element

$$f_{\Gamma,e}\Delta Z = - \left[\frac{p_\Gamma - p_\Gamma^{r-1}}{t - t^{r-1}} + \frac{p_\Gamma^{r-1} - \tilde{p}}{2\alpha_r\Delta t} \right]_e, \quad (1)$$

with the linear momentum of the fluid layer around an element $p_{\Gamma,e}$, the preliminary linear momentum $\tilde{p}_e$ ~~obtained in the first step~~ and α_r as a coefficient of the Runge-Kutta scheme. ~~Afterward, the coupling force at the current time level can be calculated based on the difference between the preliminary and calculated velocity. Finally, the velocity field of the next time level can be calculated in a fifth step, based on the resulting coupling force of step number 4. Further specifications and the analog determination of the external momentum can be found in Tschisgale and Fröhlich (2020)."~~

Comment 4 The coupling force presented in Equation (12) shows influence from the pressure only, what's the influence of the velocity differences between fluid and solid?

Response: *The authors agree with the reviewer that the context of Equation (12) is not sufficient. The equation does not entail the pressure, but the integral quantity p_Γ of the velocity field and serves as a replacement of the latter.*

Actions taken: Thank you: the text has been adapted to clarify the context, see the added section in **Comment 3**.

Comment 5 Is the vegetation shape-resolved or not? If yes, what's the resolution for the immersed boundary points over structural surface?

Response: *The authors would like to clarify the shape and resolution of the immersed boundary. The vegetation is indeed shape-resolved regarding the coupling of the velocity field of the fluid. Ensuring faster communication, the velocity field of the fluid is replaced by the integral quantity $\tilde{p}_e$, reducing the communication points to six for each rod element.*

Actions taken: The text has been revised based on the reviewer's comment. For additional clarification see the added section in **Comment 3**.

[Line 237 - 244] "[...] The coupling of the two coordinate systems is achieved via the Lagrangian points at the surface of the Lagrangian volume, depicted in Fig. 1c, where the velocity components of the fluid are transferred. ~~Hereby, each marker point represents a Lagrangian volume, which must be smaller or equal to the size of the Eulerian fluid cell to ensure the impermeability of the structural solver.~~ The distance of the Lagrangian points to each element's center is determined by the vector ξ ."

Comment 6 Why the k-w turbulent model is selected for comparison against LES?

Response: *Thank you for asking about the reasoning for choosing the k-w turbulence model. The k-w turbulence model has been used as the standard RANS turbulence model in the previous publications of the REEF3D developers, see Bihs et al. (2016), Sasikumar et al. (2020), and Martin and Bihs (2021). An additional comparison against the URANS turbulence model has been added to provide a broader perspective, as explained in **Comment 2**.*

Actions taken: The text in the manuscript has been adapted to clarify the reviewer's question.

[Line 373 - 379] "Afterward, the influence and suitability of the turbulence model for the structural solver have been studied by comparing the performance of RANS (~~$k-\omega$ model~~), URANS and LES. For the first two approaches, RANS and URANS, the $k-\omega$ model has been selected as it is widely applied by the developers of the employed numerical model – see for example Bihs et al. (2016), Sasikumar et al. (2020), and Martin and Bihs (2021)."

Comment 7 There is only one simulation case for a flexible plate in flow, is this sufficient to represent vegetation in river or coastal environment?

Response: *Thank you for asking about the representability of the selected test cases. The application of current-induced fluid-structure interaction has been selected here for a first evaluation of the solver and its capabilities. The authors would like to emphasize the selected test cases extend in terms of current velocity, stem length, and material parameters. The selection of tested conditions has been careful, ensuring comparability to the validation of other solvers, as the experiments of Luhar and Nepf (2011) can be considered standard validation cases. Additionally, novel information could be obtained by studying the fluctuation motion of the vegetation. To show the possibilities of the proposed FSI, an application case using parameters from field data is presented and evaluated to conclude the manuscript. However, to keep the paper's scope and overall length manageable, further test cases have not been included. The authors agree with the reviewer that additional work is required to evaluate the solver's capability to represent coastal vegetation.*

Actions taken: An additional application case has been added to emphasize the possibilities of the herein proposed model to simulate vegetation including plant properties from field data, the results are given in Section 3.4 in the manuscript.

Reviewer 2

This paper compares the LES and RANS simulations of the interaction between a flexible stem and unidirectional flow. It explores various numerical configuration parameters to ensure accurate simulation results for stem deflection and drag force. Additionally, the study investigates the impact of the damping coefficient on drag force fluctuations. These explorations are crucial for obtaining credible results in simulating canopy flow, which holds significance in real-world scenarios such as salt marshes, coral reefs, and seagrasses. Consequently, I believe that this paper aligns with the scope of the Journal of Fluids and Structures. However, several issues in the paper require addressing before its potential publication in the journal.

Comment 1 It is recommended to introduce dimensionless numbers, such as the Cauchy number for stem flexibility and buoyancy number, in the case setup. This would generalize the paper's contribution to cases with parameters beyond the explored range but with similar dimensionless numbers.

Response: *Thank you for suggesting the use of dimensionless parameters, which the authors agree that would add to the general contributions of this study. Based on your and the other reviewers' suggestions, the authors included additionally an application case based on plant properties from field measurements, which are additionally described by the Cauchy number and Buoyancy parameter; these modifications bridge between dimensional parameters and their dimensionless counterparts while showing the range of dimensionless numbers considered in this study.*

Actions taken: The Cauchy number and Boayancy parameter are provided in the new Table 1 in the revised Section 2.2, summarizing all applied material parameters within this study.

Table 1: Summary of the investigated material properties, including the surrogate materials used by Luhar and Nepf (2011) and the defined growth states based on field measurements of Keimer et al. (2023).

	Luhar and Nepf (2011)		Field data from Keimer et al. (2023)		
v (m/s)	0.04 - 0.32		0.50	0.50	0.50
Material	Soft foam	HDPE	Flowering	Broken	Sprouting
L_S (m)	0.05 - 0.25		0.20	0.20	0.20
W_S (m)	0.01	0.01	4.11×10^{-3}	3.97×10^{-3}	4.21×10^{-3}
T_S (m)	1.9×10^{-3}	0.40×10^{-3}	4.11×10^{-3}	3.97×10^{-3}	4.21×10^{-3}
ρ (kg/m ³)	670	950	670	670	670
E (kN)	93000	5000	323460	225270	133780
Ca (-)	0.032 - 320	0.55 - 5500	10.38	1.66	2.34
B (-)	0.0049 - 0.62	2.7 - 340	0.057	0.088	0.13

Comment 2 (Page 11, Lines 38-42) Although stems are not considered walls, the no-slip boundary condition is applied to the flume wall as shown in Figure 2. Is there any effect of omitting the wall effect in the turbulence model regarding this condition?

Response: *The authors gladly clarify the influence of the walls, the chosen turbulence model, and its relevance. The effect of the wall using a flume width of 0.16 m is about 2 % compared to a flume twice the size and corresponding to twice the simulation time, using a no-slip boundary condition. As the water level has the same height as in the experiments, a no-slip boundary condition ensures a similar flow field in z -direction and is therefore applied to all walls. A more detailed*

discussion is stated in the answer to **Comment 15** of reviewer 3 and included in the appendix of the manuscript. Whether the influence of the walls is relevant for the turbulence model has been investigated by comparing the resulting forces for a Smagorinsky and WALE subgrid-scale turbulence model in Fig. 6. A more in-depth description of the evaluation is given in the answer to **Comment 10** of reviewer 3. As the results differ on average by 1.62 % the effect of turbulence close to the walls can be considered negligible.

Actions taken: A additional sensitivity analysis regarding the flume width and selected boundary condition has been added to the appendix of the manuscript. The investigation of the turbulence model has been expanded by the WALE model, the results are discussed in Section 3.1 in the manuscript.

Comment 3 (Page 18, Line 41) Explicitly providing the definition of grid uncertainty, rather than merely citing Cummins et al. (2017), would enhance clarity. Alternatively, placing the definition in the appendix, similar to Cummins et al. (2017) citing Viola et al. (2013), is another suitable option.

Response: *Thank you for asking about the method of grid convergence, which has indeed not been explained in detail. The authors agree that it is an important aspect of the work and have therefore adapted the explanation of the grid convergence accordingly. To ensure a suitable extent of the manuscript, the whole sensitivity analysis has been moved to the appendix.*

Actions taken: An explanation of the grid convergence methodology has been added to the appendix. The adapted text is given in response to your comment 14.

[Line 869 - 872] "A grid convergence study has been carried out for both materials used in the experiments to be able to determine the necessary grid resolution to reproduce the forces acting on the stem, following Cummins et al. (2017), [...]"

Comment 4 (Page 23, Lines 51-55) While $C_s = 0.05$ can also result in deviations smaller than 20%, what is the rationale for requiring C_s to be 0.1?

Response: *Thank you for asking for further explanation regarding the choice of the Smagorinsky coefficient. A Smagorinsky coefficient of 0.10 has been chosen, as it led to both less overestimation of the simulated forces for the 0.25 m long stem, compared to the results with $C_S = 0.15$ and 0.25, and less underestimation of the simulated forces for the 0.05 m long stem, compared to the results with $C_S = 0.05$. Additionally, the range of recommended values for C_S usually varies between 0.1 and 0.2 (e.g. Ferziger and Perić (2002) or Katopodes (2019)) and previous studies based on the same numerical model have successfully applied a C_S value of 0.1 for their LES (Cui et al., 2022a,b).*

Actions taken: A clarification regarding the choice of C_S has been added to the text based on the reviewer's comment.

[Line 458 - 465] "The value of C_S has been chosen equally to 0.10, as it leads to ~~deviations smaller than 20 % for all stem lengths using the HDPE material and current velocity of 0.16 m/s (cf. Fig. 6a)~~ less overestimation of the simulated forces for the 0.25 m long stem compared to the results using $C_S = 0.15$ and 0.25 and less underestimation of the simulated forces for the 0.05 m long stem compared to the results with $C_S = 0.05$. Additionally, the recommended range of values for C_S , depending on the source, lies between 0.10 and 0.20. (e.g. Ferziger and Perić (2002) or Katopodes (2019)) and previous studies using the

same numerical model (Cui et al., 2022a,b) have successfully applied a C_s value of 0.10 for their LES studies.”

Comment 5 (Page 24, Lines 26-29) Could you incorporate the reason why small eddies are less visible compared to Tschisgale and Fröhlich (2020) into the text?

Response: *Thank you, based on your comment the authors examined the difference between the two numerical models in more detail. Based on the results of further simulations, the authors assume now that the main reason for the different resolutions of the smallest eddies lies within the deviating choice of spatial discretization scheme. While Tschisgale and Fröhlich (2020) use a second-order central difference scheme, REEF3D uses the fifth-order weighted essentially non-oscillatory (WENO) method as a standard, which is known to be more diffusive, see for example Xu and Shu (2005). When also using second-order central differences, the resulting eddies seem more similar to the results of Tschisgale and Fröhlich (2020), see the Figure below. However, due to the higher numerical stability when using a 5th-order WENO method, it is the preferred scheme in the context of this study (Bihs et al., 2016).*

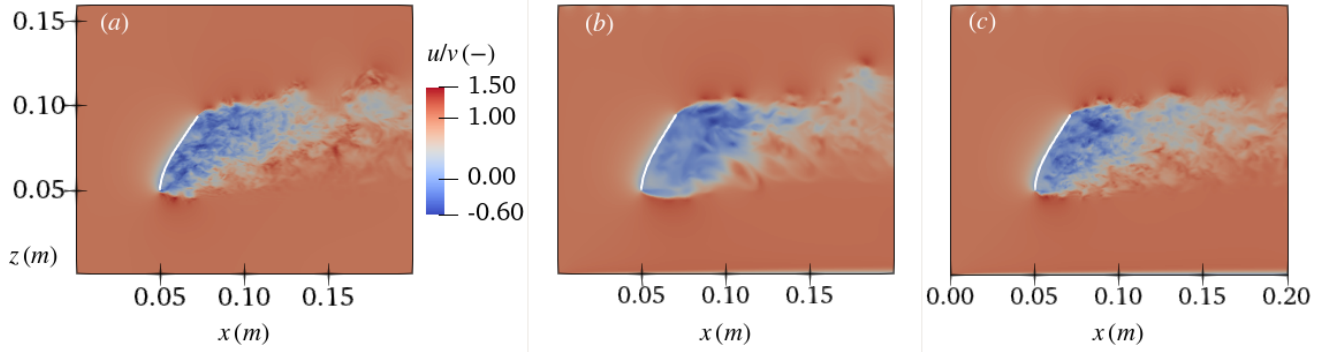


Figure 7: Comparison of the normalized horizontal velocity (u/v) with $L_s = 0.05\text{ m}$, $v = 0.16\text{ m/s}$ and the soft foam material with (a) the simulated results of Tschisgale and Fröhlich (2020) and the simulated results of this study using (b) the fifth-order weighted essentially non-oscillatory method and (c) second-order central difference scheme for the spatial discretization

Actions taken: The authors ran additional simulations comparing the results for different spatial discretization schemes, the results are presented in the previous Figure. The text has been adapted to clarify the reasoning for the increased diffusivity.

[Line 478 - 485] ”At the base of the stem, the wake extends over a larger area and small eddies are less visible in the FD CFD solver compared to the results of Tschisgale and Fröhlich (2020). The latter is likely due to the use of different spatial discretization methods. Tschisgale and Fröhlich (2020) uses a second-order central differences method, while the FD CFD solver in this study was developed for the fifth-order weighted essentially nonoscillatory (WENO) method, which is known to be more diffusive but provides more stability (Xu and Shu, 2005; Bihs et al., 2016).”

Comment 6 (Page 29, Line 50 - Page 30, Line 11) The observed phenomena of overestimated force for the same spatial position and the same force for overestimated bending

both suggest that the simulation tends to overestimate force. However, Section 4.2 states that the present model neglects skin friction. If skin friction is added, the force on the stem may be even more overestimated. How can this be explained?

Response: *Thank you for pointing out this inaccuracy in our statement, on which the authors would like to elaborate further. Indeed, in the semi-empirical force balances, as mentioned in the Discussion, skin friction was added, resulting in a higher force. However, the authors argue that in a two-way coupled model, the interaction of the skin friction and the fluid is be also in a two-way manner. Accordingly, the skin friction would also lead to a reduction of flow velocity and potentially turbulence regime in the flow field near the stem, which would be especially relevant for the longer stems. However, the extent of that influence remains unknown and should be further investigated.*

Actions taken: The aspect of a two-way manner regarding the influence of the skin friction has been added to the Discussion section.

[Line 729 - 733] "Wall or skin friction, while increasing the resulting force in one-way coupled approaches, ~~inducing small-scale turbulence along the surface~~, could affect the surrounding hydrodynamics, dissipate energy, and reduce flow velocities, by inducing small-scale turbulence along the surface of the stem."

Comment 7 (Page 30, Lines 11-17) It seems that Luhar and Nepf (2011) do not provide photos for 0.10 m and 0.20 m stems. It is advisable to clarify this point to demonstrate that these values are not omitted intentionally.

Response: *Thank you for suggesting the clarification of that topic. Indeed Luhar and Nepf (2011) did not provide further photos and they have not been omitted intentionally.*

Actions taken: The suggested point has been clarified in the manuscript.

[Line 572 - 574] "Since the ~~results of the stem bending comparison of the bending movement have been only published is only available~~ for the 0.05 m, and 0.25 m long stems, it cannot be assessed if the deviation also occurs for the other stem lengths (0.10 m to 0.20 m)."

Comment 8 (Page 31, Lines 18-23) Could you provide details about the low-pass filter? How do you ensure that the important physical component of the fluctuation is not filtered?

Response: *The authors agree that a more detailed description of the applied low-pass filter would enhance the clarity of the applied approach. A filter width of 150 Hz has been selected ensuring that only the smallest the smallest fluctuations of the time track of the force data are filtered. After the filter has been applied, initially simulated forces have been displayed together with the resulting filtered forces to compare the difference. By that, it has been ensured that none of the larger fluctuations, which are of interest for further investigations, have been filtered. Additionally, it can be seen in Figure 13 in the manuscript that the range of interest regarding the differences in the frequency spectrum lay in the range of 0 to 1 Hz and differ by a large extent from the filtered frequency.*

Actions taken: A description of the application of the low-pass filter has been added to the manuscript based on the reviewer's suggestion.

[Line 600 - 605] "A low-pass filter and a Tukey window have been applied to the simulated drag forces to reduce the effect of leakage for the FFT. A filter width of 150 Hz has been selected for the low-pass filter, ensuring that only the smallest fluctuations are filtered without discarding effects in the range of 0 Hz to 1 Hz, which has been shown relevant in the further analysis."

Comment 9 (Page 37, Lines 30-31) The singular form of "leaves" is "leaf," not "leave."

Response: *We thank the reviewer for recognizing the spelling mistake.*

Actions taken: Thank you for pointing out this spelling mistake which has been corrected accordingly.

[Line 761 - 763] "[...]; however, the same correlation could not be observed for the ~~leave~~leaf lengths, potentially due to the reconfiguration of longer leaves."

Comment 10 (Page 41, Line 9) The title of Appendix A, "Section title of first appendix," appears unclear. It would be better to have a title that succinctly summarizes all the figures and tables in this section.

Response: *The authors agree with the unclear naming of the appendix and thank the reviewer for pointing that out.*

Actions taken: The title of the appendix has been changed and now addresses more appropriately the topic of that section. To further enhance the clarity of the appendix, subsections have been added, too.

[Line 831] "Appendix A. ~~Model sensitivity Section title of first appendix~~"

Comment 11 (Page 41) The purpose of Appendix A is unclear. If it focuses on the convergence study of temporal and spatial discretizations, why is Figure 4 not included? Additionally, Figure A.14, which compares different Smagorinsky coefficients, is a major contribution and may warrant inclusion in the main part.

Response: *Thank you for noting the unclear purpose of the appendix, which the authors agree on. To clarify the structure, the main parts of the sensitivity analysis have been bundled and moved to the appendix.*

Actions taken: The content of the appendix has been re-ordered in agreement with the reviewer's suggestions. Appendix A is now solely focused on evaluating the model sensitivity. The remaining figures about the variation of the Smagorinsky coefficients and the table regarding the tip position have been moved to the main part of the manuscript.

[Line 832 - 834] "This appendix focuses on the sensitivity analysis of the model regarding the temporal and spatial discretization as well as the number of individual rigid elements, of which the stem consists of."

Comment 12 (Pages 41 and 43) The figure indices should restart from 1 for the appendix section.

Response: *Thank you for this comment, but the continuous indices for the appendix section follow the journal layout and will need to be kept accordingly.*

Comment 13 (Page 41) The meaning of each subfigure is unclear. Do they correspond to different grid resolutions, stem configurations, or something else?

Response: *The authors agree that the meaning of the subfigures has not been specified. They correspond to different stem lengths and material types, providing a broad overview of the grid uncertainty.*

Actions taken: The meaning of the subfigures has been clarified in the caption of the figure.

”Figure A.18: Grid convergence study after Cummins et al. (2017) for ~~the HDPE material and the 0.05 and 0.25 m long stem for grid sizes in the refined area of $0.75 \times 10^{-3} \text{ m}$, $1.5 \times 10^{-3} \text{ m}$ and $3.0 \times 10^{-3} \text{ m}$~~ grid sizes in the refined area of $0.75 \times 10^{-3} \text{ m}$, $1.5 \times 10^{-3} \text{ m}$ and $3.0 \times 10^{-3} \text{ m}$ for (a) the 0.05 m and (b) the 0.25 m-long HDPE stem as well as (c) the 0.05 m and (d) the 0.25 m-long soft foam stem.”

Comment 14 (Page 41) Why does the curve fit perfectly only for Subfigure (b)? Additionally, are the fitted order p the same for all cases? If the numerical scheme is uniform, p should also be consistent according to Cummins et al. (2017).

Response: *Thank you for addressing the topic of the grid convergence study. The authors are happy to clarify the approach used in this study further. For each material type and stem length, quadratic convergence is assumed. Correspondingly a parabola is applied for the curve fit to evaluate ϕ_0 , which describes the estimated normalized force in the limit of infinite resolution. As a result of the constant p -value, the curve fit of the resulting normalized forces suits differently well. The authors also would like to point out the different ranges of the y -axis, leading to the impression that subplots (b) and (d) are a more accurate fit.*

Actions taken: The methodology of the grid convergence after Cummins et al. (2017) is further clarified in the appendix of the manuscript and the reviewer’s questions are addressed.

[Line 869 - 888] ”A grid convergence study has been carried out for both materials used in the experiments to be able to determine the necessary grid resolution to reproduce the forces acting on the stem, following Cummins et al. (2017), based on the assumption:

$$\phi(h) = \phi_0 + \alpha h^p \quad (2)$$

Here, h_i corresponds to the ratio of the cell sizes of the i th grid to that of the reference grid and ϕ_i to the ratio of simulated forces to the force of the reference grid. For each material type and stem length, quadratic convergence is assumed, making p equal to two. Correspondingly, a parabola is applied for the curve fit to evaluate ϕ_0 , which describes the estimated normalized force in the limit of infinite resolution. The parameters ϕ_0 and α are then obtained by the least squares method. Afterwards, the standard error of the fit is calculated by

$$\sigma_{fit} = \sqrt{\frac{\sum_{i=1}^{n_g} (\phi_i - \phi(h_i))^2}{n}}, \quad (3)$$

including $n = n_g - 3$ as the number of degrees of freedom of the fit. Additionally, the error of the reference grid is estimated by $\delta = |1 - \phi_0|$. The grid uncertainty is then calculated including a safety factor of 1.25 and the standard error of the fit.

$$U_g = 1.25\delta + \sigma_{fit} \quad (4)$$

The calculated grid uncertainties are summarized in Table A.3 The resulting regressions for two material types and stem lengths are visualized in Fig. A.18.”

Reviewer 3

This paper presents results from the application of a coupled fluid-structure model to simulate flow around individual vegetation stems. The study is the first to implement such a model within this particular software (REEF3D-CFD), however the fluid and structural models are not novel in themselves. Instead, the work represents a parametric study, which investigates the influence of different flow (turbulence model, velocity, grid size) and structural (length, resolution, damping) parameters on the predicted flow and structural dynamics.

The model seems state-of-the-art in terms of capability for modelling flow-vegetation interactions which I am sure could be applied to provide new process understanding and I share the authors' enthusiasm regarding the importance of models such as theirs for investigating this topic. However, given the complexity and capability of their model I find the metrics and analyses presented in the paper surprising.

The case for such models is not well made through this paper, as many of the results presented can be achieved through the application of much simpler semi-empirical methods. The work of Luhar and Nepf (<https://doi.org/10.4319/lo.2011.56.6.2003>) and others has demonstrated that for single blades/stems, we can predict with accuracy stem posture and bulk drag forces using a Cauchy number or Reconfiguration number approach. I understand that even a complex FSI model must first demonstrate that it can reproduce the basic properties, but the paper does not then go beyond these bulk or time-averaged measures to really emphasise the added value of the CFD model for predicting either fluid or structural dynamics. The damping coefficient analysis is the only part that really begins to look at dynamics.

A parametric study by itself could be of great value, but the results shown are fairly brief (some only appearing in the appendix) and only the impact on the bulk time-averaged properties is considered. Given the use of LES, it would be interesting to see for example the impact of stem discretisation and CFL number on motion dynamics.

While I commend the authors for the development of their model, which seems to have good potential in this area of application, at present I do not believe the paper provides new insight into the underlying physics or presents novel methodologies and therefore I do not believe it is suitable for publication in its present form. Below are some specific comments that support the comments above and add further minor points for consideration/clarification.

Response: Thank you for such a detailed discussion of the submitted manuscript. The authors would like to summarize here the four main findings of the revised manuscript which contribute new insights in our opinion, before addressing your specific comments. First, including the recent addition to the manuscript, this work is the first to show the capability of the proposed fluid-structure interaction model to simulate time-averaged parameters, like the bending position and resulting forces, as well as analyzing time-resolved properties of the flow field like the turbulence intensity. Second, the implications of using different turbulence models for the implementation of the fluid-structure interaction on both the resulting forces and flow field are discussed in detail. Third, this work is the first to show the influence of the required different damping coefficients on both the stem motion and the corresponding flow field and turbulence intensity for unidirectional flow. Finally, it is shown that the application of measured vegetation properties from the field leads to different drag coefficients depending on seasonality, highlighting the necessity of the proposed model compared to semi-empirical solutions. The authors believe that the current form of the manuscript gives an enhanced perspective of the possibilities and advantages of the proposed fluid-structure interaction model.

Comment 1 Pg 3 Ln 23: It is true that early studies did assume rigid cylinders, but there are also a substantial number of papers since 2010 onwards that have now dealt with flexible vegetation that are not mentioned, or only mentioned in passing

later. I recommend the authors focus less on rigid vegetation in providing an overview of the state of the science.

Response: *Thank you, the authors agree with the reviewer in that the broad introduction to studies regarding rigid cylinders is not necessary. More similar recent publications are available which should be addressed instead. The text is therefore adapted to address the scope of the manuscript.*

Actions taken: The text has been adapted based on the reviewer's suggestion. Additionally, state-of-the-art papers are discussed in more depth in the Introduction section.

[Line 41 - 43] ~~"Nowadays it can be considered state-of-the-art to represent the vegetation in the FSI as a flexible body. Earlier studies on vegetation FSI, both by physical (Lowe et al., 2007; Huang et al., 2011; Zhao et al., 2021; Keimer et al., 2021) and numerical models (Okamoto and Nezu, 2010; Zhang and Zhang, 2023) or combinations thereof (Bouma et al., 2007; Yin et al., 2020), often chose to represent the vegetation with rigid cylinders to simplify the constraints on the FSI problem.~~ On the process level, it is straightforward to agree that [...]

[Line 98 - 123] Alternatively, the IBM has become increasingly popular. An Eulerian structural solver can be implemented via the IBM into the Lagrangian fluid phase, as shown by Tian et al. (2014), Tschisgale and Fröhlich (2020) Wang et al. (2020), He et al. (2022), and Wang et al. (2022), Ni et al. (2023), Kim et al. (2024), Hagemeyer et al. (2024) and Agrawal et al. (2024). The IBM has the advantage of accounting for large deformations of the structural solver with an Eulerian grid and a stable fluid solver with a Lagrangian grid. The achieved accuracy of FSI studies using the IBM is promising, rendering it the favored coupling method within the context of this study. ~~Although the previously mentioned works are all based on the IBM, they differ by their proposed coupling algorithm of the FSI and the applied fluid and structural solver. He et al. (2022) applied an inextensible nonlinear Euler–Bernoulli beam, with the bending motion restricted to the streamwise–vertical direction. Similarly, Ni et al. (2023) simulated in two dimensions to focus on the monami modes of a flexible vegetation meadow. Hagemeyer et al. (2024) proposed a strongly coupled partitioned solution algorithm to model a torsion-free beam. Alternatively, Kim et al. (2024) used a finite-element structural solver with soft-body dynamics, while Wang et al. (2020) used a structural solver based on the combined finite element method–discrete element method. Both Tschisgale and Fröhlich (2020) and Agrawal et al. (2024) use the geometrically exact Cosserat rod for their structural solver, which has the advantage of capturing three-dimensional motion while using a mathematical model in one direction, thus making it computationally more efficient. Additionally, Agrawal et al. (2024) were able to simulate coarser structural meshes than the background fluid grid, highlighting the potential of such a model."~~

Comment 2 Pg 3 Ln 44-47: "Vegetation that is classified to follow the avoidance strategy has a higher flexural stiffness." Please check. It seems that plants with tolerance strategy would be the ones with higher rigidity?

Response: *Thank you for pointing us at this imprecision. The reviewer is correct that vegetation classified to follow the avoidance strategy has a lower flexural stiffness.*

Actions taken: The text has been corrected accordingly.

[Line 49 - 50] "Vegetation that is classified to follow the avoidance strategy has a ~~higher~~~~lower~~ flexural stiffness."

Comment 3 Pg 4: This general discussion of FSI feels out of place. It mentions other non-vegetation examples, and in some cases compares characteristics, but it is not clear for what purpose.

Response: *Thank you for pointing out the unclear purpose of that discussion point. Its aim was to provide a broader perspective on the challenges of FSI problems and how fluid vegetation interaction faces its unique challenges. The authors agree with the reviewer that this paragraph is not relevant to the overall content of this manuscript.*

Actions taken: The paragraph was removed to ensure that the Introduction section is consistent and of appropriate length.

~~"The general implementation of FSI in numerical models including structural flexibility is a promising means to the application of flexible vegetation, but usually cannot be straightforwardly transferred to model vegetation, as the simulation challenges like the magnitude of exerted forces or structural properties are rather specific to each application. A standard test case for FSI is a flapping flag in the wind application, first proposed by Turek and Hron (2007). It became a benchmark test for FSI including structure flexibility and is used to validate numerical models (Tian et al., 2014; Tian et al., 2010) dealing with a complex three-dimensional flow field. The induced movement parallel to the flow leads to less deformation and a rather uniform motion of the structure compared to what is expected from the motion of flexible vegetation. In contrast, the impact forces of dam-break-induced flow onto a flexible structure (Liao et al., 2015; Liao et al., 2019), are usually higher and these structures, tested for ship and ocean engineering, have a higher stiffness than coastal vegetation. Unlike vegetation in this study, in the dam-break scenario, the structure is initially not submerged, leading to the challenge of correctly simulating air entrapment. Mooring cables are also simulated as flexible FSI problems with dimensions differing largely from vegetation, as they are, in reality, very long compared to their thickness. The ratio of the diameter relative to the lengths of the cable ranges from 0.0024 (Palm et al., 2016) to 0.014 (Martin and Bihs, 2021) compared to approximately 0.024 for vegetation studies (Luhar and Nepf, 2011). Another FSI problem is the simulation of a rolling tank to simulate flexible ship appendages (Paik and Carica, 2014), which poses additional challenges as both the fluid and the structure are simultaneously in motion. The coupling of two moving grids can lead to grid distortions and requires specific grid treatment. This study focuses on investigating the two-way coupling between a fluid and structural solver, explicitly focusing on the interaction of flexible vegetation and hydrodynamics. As previously described, this presents unique challenges that are not comparable to other common FSI problems found in related disciplines. Vegetation has a comparable low stiffness, leading to large deformations of a thin structure, while comparably small forces are coupling the fluid and the structure. A comprehensive study, involving various stem lengths, material properties, and associated numerical discretization parameters is currently missing, despite a large need for a more complete understanding of the FSI process."~~

Comment 4 Pg 4 Ln 49: Does the diameter/length ratio of 0024 correspond to thickness here? Worth noting that diameter will often be different to thickness for aquatic

vegetation.

Response: *Thank you for asking about this detail. For rectangular structures, an equivalent diameter has been estimated for this broad comparison. The authors agree with the reviewer that these differences should have been stated more clearly. Based on the previous comment, this paragraph is removed from the manuscript including the addressed comparison.*

Comment 5 Pg 5 Ln 22-28: This sentence describes the gap before really describing what has been done in this space (see earlier comment). It should be placed after the following paragraph on Pg 5.

Response: *Thank you for suggesting that change of structure. Unfortunately, the count of lines seems to differ for our version of the manuscript, so the authors could not follow which sentence which specifically you are referring to with the reviewer's comment. The authors would gladly address it if the reviewer could point out that sentence again with the updated line count.*

Actions taken: A line count has been added to the revised version of the manuscript to enable clear references to specific sentences in the future.

Comment 6 Pg 5 Ln 53-55: Authors such as Whittaker et al (<https://doi.org/10.1016/j.advwatres.2015.05.005>), and Luhar and Nepf (see earlier) have addressed the dependence of drag coefficients on plant flexibility (even if not through drag coefficients)

Response: *Thank you for referencing us to the work of Whittaker et al. (2015). Even though their findings regarding the incorporation of plant flexibility are promising, the authors consider that it does not invalidate the author's statement regarding the availability of plant-specific drag coefficients and the corresponding limited application of semi-empirical approaches.*

Actions taken: The addressed reference has been incorporated into the text and the corresponding statement has been clarified.

[Line 65 - 77] "The dependency of C_D on the Reynolds number (Re) ~~and Keulegan-Carpenter number (KC)~~ has been frequently investigated (Losada et al., 2016; van Veelen et al., 2020), but plant flexibility was usually not taken into account. ~~While Whittaker et al. (2015) have incorporated the plant flexibility into the calculation of the drag force, values for C_D are still required.~~ Values of C_D for specific plant species, especially regarding seasonal variation obtained from field measurements, e.g. Keimer et al. (2023), are scarce and render more accurate modeling attempts futile. A uniform drag coefficient for flexible vegetation might not exist (van Veelen et al., 2020) and is therefore of limited applicability for numerical models (van Veelen et al., 2020; Caroppi and Järvelä, 2022). The present study argues that simplistic approaches that require coefficients like C_D cannot accurately simulate the FSI with flexible vegetation and are not further considered in this study."

Comment 7 Pg 6 Ln 9-23: The authors state the limitations of drag coefficients due to the lack of species-specific drag coefficients and seasonal variations. I agree with this point, however it should be noted that more explicit representation of the forcing does not necessarily address the issue. There are still issues of how one represents the geometry effectively (most vegetation is not simply a single flexible blade/cylinder) as well as the mechanical properties (e.g. flexural

rigidity, buoyancy). These limitations arguably mean that direct forcing methods retain many of the uncertainties of the semi-explicit methods. These issues are discussed a little later in the discussion, but I think the argument of the benefit of FSI could be made more convincingly.

Response: *The authors agree with the point raised by the reviewer that some limitations from semi-empirical models remain with the use of a direct forcing approach, as the simplified geometry. However, the authors think that direct forcing approaches can reproduce the mechanical behavior of the stem motion in much more detail as it takes complex motions, such as torsion, into account. To underline the advantages of such models, an application case has been added to the manuscript, showing the implementation of stem properties from the field, their resulting drag coefficients, and their effects on the flow field.*

Actions taken: An application case highlighting the advantages of the direct forcing approach has been added to the manuscript. The results are provided in section 3.4.

Comment 8 Pg 6 Ln 55: Suggest rewording 'requiring thus' to 'thus requiring'

Response: *Thank you for suggesting this rewording, which we agree on.*

Actions taken: The text has been changed following the reviewer's suggestions.

[Line 78 - 79] "A second, more versatile approach for numerical FSI uses direct forcing, **thus** requiring ~~thus~~ some form of coupling of the fluid and the structural solver."

Comment 9 Pg 7 Ln 49: Suggest rewording 'Other widely used. . .' as this is the first mention of SGS models. Or if the 'other' is referring to the k-e model then the text should be re-ordered.

Response: *Thank you for pointing out this imprecision; indeed no other SGS models have been addressed before.*

Actions taken: The text has been changed following the reviewer's suggestions.

[Line 134 - 135] "~~Other-w~~ Widely used SGS models are the Smagorinsky model and the WALE model."

Comment 10 Pg 8 Ln 23: As well as variation in Cs value, also the impact of constant/dynamic/ WALE for vegetated flows is important to evaluate.

Response: *Thank you for suggesting further evaluation of the sub-grid scale models. Although the authors agree that the results would be of interest, a dynamic sub-grid scale model cannot be investigated as it is unfortunately not yet available in the fluid solver. However, an evaluation of different WALE coefficients was conducted and compared to the results of different Smagorinsky coefficients. The simulated forces when using WALE are in a similar relation to the experimental forces as using a Smagorinsky sub-grid scale model. Nevertheless, the authors think it is an interesting addition to the evaluation of the choice of turbulence model and in contrast clarifies the impact of the Smagorinsky coefficient.*

Actions taken: Additional simulations have been done to evaluate the effect of the WALE sub-grid scale model and the variation of different WALE coefficients. The results are then compared to the variation of different Smagorinsky coefficients and their implications are evaluated in Section 3.1 in the manuscript.

[Line 437 - 465] "As the resulting forces are sensitive to the chosen turbulence model, the sensitivity regarding the SGS model and their corresponding coefficients was also tested. a variation of C_S has been conducted, see Fig. X in the appendix. Fig. 7a visualizes the resulting force deviations for the WALE and Fig. 7b for the Smagorinsky SGS model. The constant C_W applied in the WALE model has been varied between 0.30 and 0.60, and the Smagorinsky constant C_S has been varied between 0.05 and 0.20, covering a wide range, to enable a general comparison of its influence.

Fig. 7a shows that the variation of C_W has, for most simulations, no influence on the resulting forces. Correspondingly, the mean difference between the resulting forces for the smallest and largest C_W is 1.87% for $L_S = 0.05$ m and 0.52% for a stem length of 0.25 m. On average, using a C_W of 0.40 leads to an underestimation of 10.50% for the 0.05 m long stem and to an overestimation of 20.09% for the 0.25 m long stem. By contrast, it can be observed in Fig. 7b that, with larger C_S , the resulting numerical forces increase and thus the deviation from the experimental results increases. Fig. 6 indicates that the deviation regarding C_S increases with larger stem lengths and higher current velocities. The comparably larger influence of the chosen C_S is outlined by the mean difference between the resulting forces of the smallest and largest C_S , being 4.70% for $L_S = 0.05$ m and 3.31% for $L_S = 0.25$ m. The deviations to the experimental forces using a C_S of 0.10 are in a similar range to $C_W = 0.40$, resulting in an underestimation of 9.00% for the 0.05 m long stem and an overestimation of the 0.25 m long stem by 21.84%.

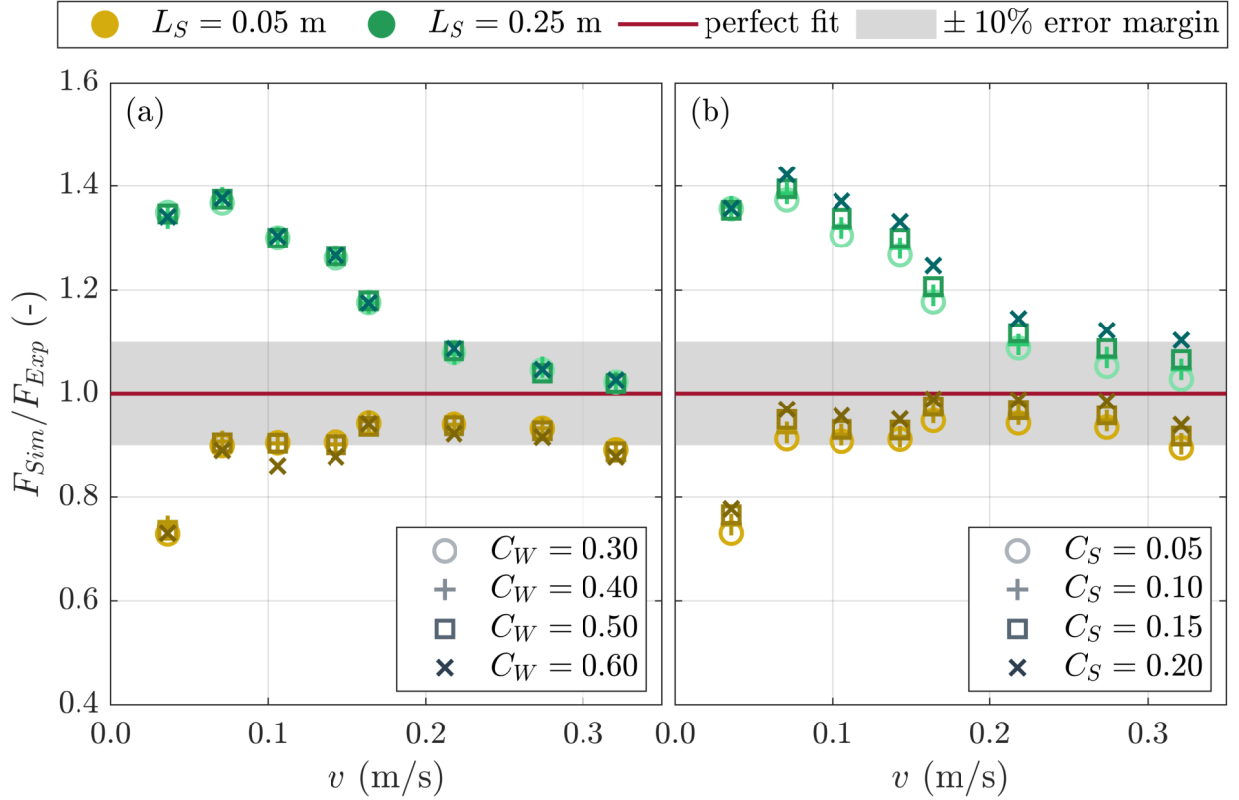


Figure 7: Simulated forces in relation to experimental forces (Luhar and Nepf, 2011) for both the HDPE Material and two stem lengths $L_S = 0.05$ m and $L_S = 0.25$ m with (a) using the WALE SGS-model and a variation of WALE-coefficients and (b) Smagorinsky SGS-model and variation of Smagorinsky coefficients.

The value of C_S has been chosen equally to 0.10, as it leads to ~~deviations smaller than 20 % for all stem lengths using the HDPE material and current velocity of 0.16 m/s (cf. Fig. 6a)~~ less overestimation of the simulated forces for the 0.25 m long stem compared to the results with $C_S = 0.15$ and 0.25 and less underestimation of the simulated forces for the 0.05 m long stem compared to the results with $C_S = 0.05$. Additionally, the recommended range of values for C_S , depending on the source, lies between 0.10 and 0.20. (e.g. Ferziger and Perić (2002) or Katopodes (2019)) and previous studies using the same numerical model (Cui et al., 2022a,b) have successfully applied a C_S value of 0.10 for their LES studies.”

Comment 11 Pg 8 Ln 30-34: ”This study hypothesizes that a two-way coupling based on the IBM, as well as specific turbulence modeling via RANS or LES, is an inevitable requirement”. Is this specific hypothesis tested though? I would argue it is not, because all or nearly all of the results presented can also be obtained from semi-empirical methods.

Response: *The authors agree with the reviewer’s point of view that the hypothesis has not been specifically tested. However, the authors do think that the two-way coupling based on the IBM can provide more detailed results compared to the semi-empirical models, for example, the investigation of turbulence production that is caused by the resolved tip motion in a two-way manner. The statement has been revised accordingly.*

Actions taken: The sentence has been reformulated based on the reviewer’s suggestion.

[Line 151 - 154] ”For an accurate representation of the complex FSI that is presented when flexible stems bend because of fluid forces, this study ~~hypothesizes thatproposes~~ a two-way coupling based on the IBM, ~~as well as along with~~ specific turbulence modeling via RANS or LES, ~~is an inevitable requirement.~~”

Comment 12 Pg 8 Ln 53-55: ”Martin and Bihs (2021) observed that their model was not sensitive to the damping coefficients as long as they differed from zero” This is unclear. Was there really no sensitivity for non-zero values?

Response: *Thank you for asking about the details of this statement. The authors agree that the statement does not fully reproduce the findings of Martin and Bihs (2021) and the paragraph has been revised accordingly.*

Actions taken: The text has been clarified based on the reviewer’s question.

[Line 163 - 168] ”Martin and Bihs (2021) observed that their model was not sensitive to the damping coefficients ~~in steady-state conditions~~ as long as they differed from zero, ~~ensuring numerical stability~~. Nevertheless, these coefficients influence the ~~transienttime-dependent~~ stem motion, as observed by Martin and Bihs (2021) for the minimum and maximum tension force of a swinging elastic rod~~which is dominant for the structural solver under wave load.~~”

Comment 13 Pg 9 Ln 17-19: The paper has so far focussed in several places on waves. It is therefore surprising at this point that the focus is purely on currents. I suggest removing or reducing reference to waves earlier (e.g. KC number, wave load).

Response: *The reviewer is correct that the authors address waves in the introduction without further investigation that specific hydrodynamic regime. The reference to waves has been reduced for clarification purposes. Nevertheless, the role*

of flexible submerged vegetation has not been fully removed as it is an important aspect of future work.

Actions taken: The text has been adapted based on the reviewer's suggestion.

[Line 166 - 168] "Nevertheless, these coefficients influence the ~~transienttime-dependent~~ stem motion, as observed by Martin and Bihs (2021) for the minimum and maximum tension force of a swinging elastic rod~~which is dominant for the structural solver under wave load.~~

[...]

[Line 65 - 67] The dependency of C_D on the Reynolds number (Re) ~~and Keulegan-Carpenter number (KC)~~ has been frequently investigated (Losada et al., 2016; van Veelen et al., 2020), but plant flexibility was usually not taken into account."

Comment 14 Pg 11 Ln 38-42: I am not entirely clear as to the justification for not considering WALE further? WALE has been successfully applied to LES using IBM (e.g. <https://doi.org/10.1016/j.compfluid.2017.04.003>). Could you clarify?

*Response: Thank you for addressing the use of WALE for the proposed model. The authors of your referred paper provided an interesting example of an application of WALE with IBM. Based on the reviewer's **Comment 10**, the results for different Smagorinsky and WALE coefficients have been compared and evaluated. The results show that the use of WALE does not provide better agreement of the simulated with the experimental forces compared to the results of the Smagorinsky model.*

Actions taken: Simulations of a variation of WALE coefficients have been compared to the results of different Smagorinsky coefficients. The changes in the text based on the results are displayed in the answer to **Comment 10**.

Comment 15 Pg 16 Ln 30: What was the rationale for choosing a flume width (0.16 m) which was less than Luhar and Nepf's flume and yet using no-slip conditions for the side walls? Wouldn't frictionless symmetry boundaries be a better approximation?

Response: Thank you for raising the topic of the chosen flume width, which the authors would like to evaluate in more depth. The initial reason for choosing a width of 0.16 m was the statement of Tschisgale and Fröhlich (2020) seeing no influence of the walls on the results with that chosen width. However, as they used a free-slip boundary condition for the walls and additional evaluation of the influence of the flume width on the flow has been conducted. The results show a deviation of less than 2 % for the horizontal velocity and of about 3 % for the average force compared to a flume width of 0.32 m, while keeping the simulation time at a reasonable level.

Actions taken: Additional simulations with a variation of the flume width have been evaluated and the results are presented in the appendix of the manuscript.

[Line 836 - 866] "~~First, the influence of the wall on the horizontal flow velocity is investigated. Ensuring computability required a reduction of the experimental flume width of 0.38 m (for the lower current velocities) and 0.76 m (for the higher current velocities). Therefore, the time-averaged horizontal velocity of approximately the last six seconds of the simulation in seven flume widths, ranging from 0.08 m to 0.32 m, are compared at four different locations in the flume. Additionally, the influence of using a slip boundary condition for the walls has been tested for the flume width of 0.16 m. Three probes are located in between the~~

inflow and the stem to evaluate the flow conditions acting on the stem and determine the influence of the wall in x - and z -direction. A fourth probe is located in between the stem and the wall to evaluate the wall influence in y -direction an overview of the positioning of the line probes is given in Fig. 2. The results are visualized in Fig. A.16, where (a) displays the inflow boundary condition, which is not yet influenced by the flume width. In (b), (c), and (d), the influence of the walls is apparent for two flume widths of 0.08 and 0.12 m.

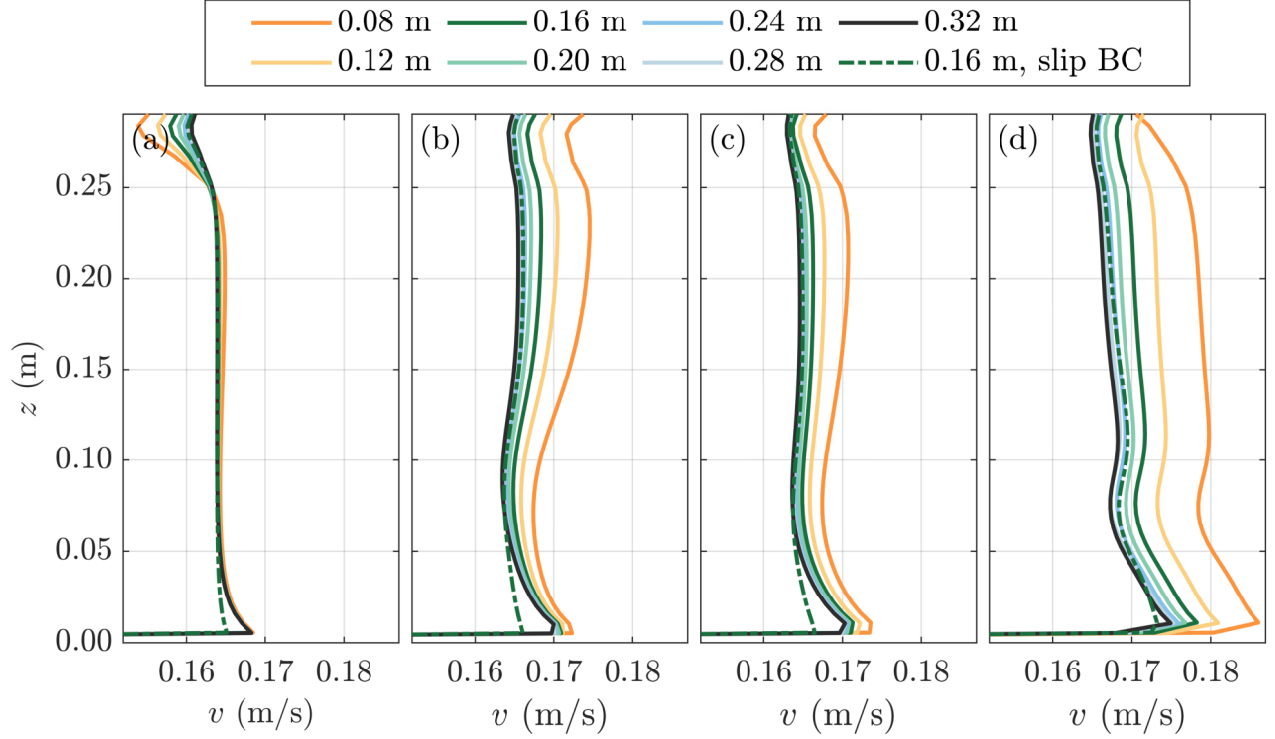


Figure A.16: Comparison of the time-averaged horizontal velocity for a variation of flume widths, for (a) Probe 1 at $x = 0.025$, $y = 0.00$, (b) Probe 2 at $x = 0.05$, $y = 0.00$, (c) Probe 3 at $x = 0.075$, $y = 0.00$ and (d) Probe (4) at $x = 0.15$, $y = 0.03$

To quantify the wall influence, the deviation of the depth-averaged horizontal velocity to the widest simulated flume is calculated and displayed in Fig. A.17. In Figure Fig. A.17b the deviation of the average simulated force compared to the average simulated force of the widest tested flume is displayed. Additionally, the simulation time for each flume width is visualized. As the deviation of the horizontal velocity for the flume width of 0.16 m is at about 2 % and of about 3 % for the average force, while simulating twice as fast as the 0.32 m wide flume, it is a reasonable compromise between results' accuracy and simulation time. The slip BC was not chosen, as it can be seen in A.16 in that the flow profile deviates from the other no-slip boundary conditions cases still at the lower height of the tip, thus leading to potentially different results compared to those from the physical experiments. The ideal combination could be in conclusion a no-slip BC for the bottom of the flume and a slip BC for the flume walls. However, this possibility is currently not implemented in the used finite-differences solver.

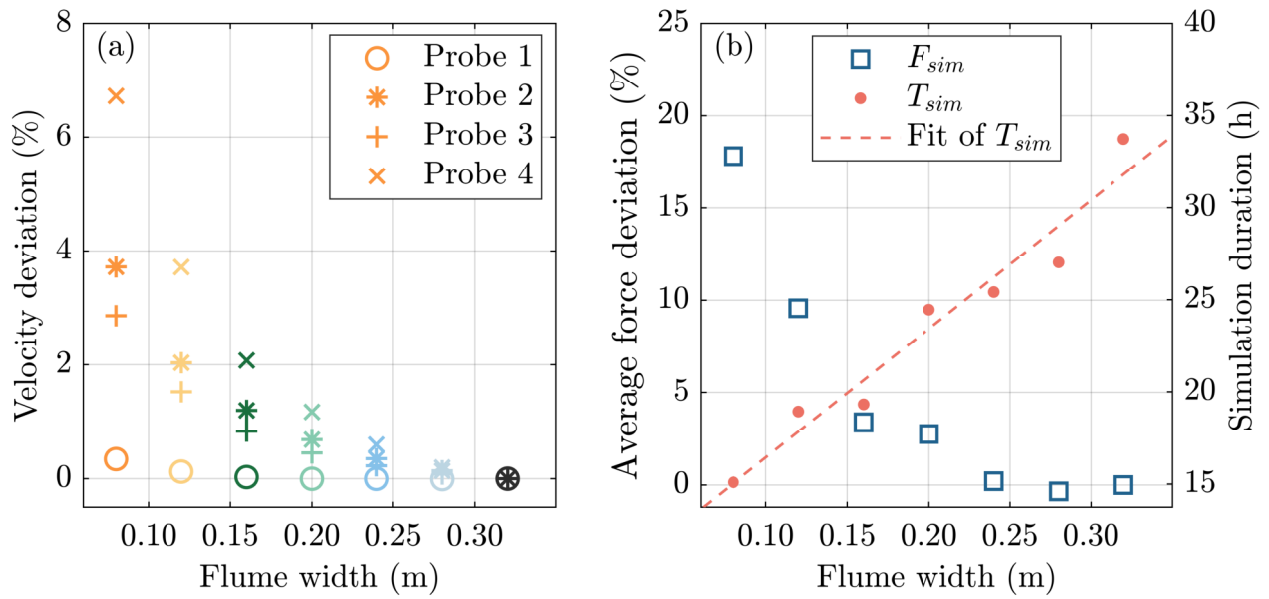


Figure A.17: Comparison of (a) the deviation of the horizontal velocity to the horizontal velocity of the widest simulated flume and (b) the deviation of the simulated force to the simulated force of the widest simulated flume, including the simulation duration for a variation of flume widths

”

Comment 16 Pg 16 Ln 44: Should this read 1.5×10^{-3} ?

Response: *Thank you for reading the numbers carefully. For the comparison of the two numerical simulations, the cell size was indeed 0.5×10^{-3} m in accordance to the simulations of Tschisgale and Fröhlich (2020).*

Actions taken: The text has been adapted for clarification based on the reviewer’s suggestion.

[Line 363 - 365] ”~~The cell size of the uniform grid is therefore equal to 0.5×10^{-3} m. The convergence study conducted in Section 2.3~~the Appendix A shows that the simulation converges for the applied grid size(~~0.5×10^{-3} m~~).”

Comment 17 Pg 16 Ln 47-53: This description of the stem is repetitive from the previous section.

Response: *The authors agree with the reviewer’s impression that the description is repetitive.*

Actions taken: The wording has been shortened accordingly.

[Line 368 - 371] ”~~Each stem in the model consists of a set number of individual, rigid elements, as visualized in Fig. 1b, for which the moments and forces are calculated separately. Their~~ The influence of the individual, rigid elements that the modeled stem consists of has been tested through a sensitivity analysis (see Section 2.3Appendix A) in order to find an independent solution and ensure accurate computability.”

Comment 18 Section 2.3: The results in Section 2.3 seem to be split across the main figures and appendix. I wonder if it would be clearer to include all figures within the main paper? Also some of the appendix figures are not adequately explained.

Response: *Thank you for noting this unclear structure of Section 2.3 and appendix, which the authors agree to. To clarify the structure, the main parts of*

the sensitivity analysis have been bundled and moved to the appendix, and previously missing explanations have been added.

Actions taken: The content of the appendix has been re-ordered. Appendix A is now solely focused on evaluating the model sensitivity. The remaining figure about the variation of the sub-grid scale coefficients has been moved to the main part of the manuscript.

[Line 832 - 834] "This appendix focuses on the sensitivity analysis of the model regarding the temporal and spatial discretization as well as the number of individual rigid elements, of which the stem consists of."

Comment 19 Pg 18 Ln 41: "The calculated grid uncertainty includes a safety factor of 1.25 and the standard error of the fit" Unclear what this means, please clarify if it is a key part of the analysis (and also explain Figure A.13 in more detail).

Response: The authors acknowledge that the methodology of evaluating the grid uncertainty has not been thoroughly explained. As the grid convergence is now part of the appendix, space limitations are no longer a reason to keep this explanation short.

Actions taken: An explanation of the grid convergence methodology has been added to the appendix, see subsection A.2. The explanation has been additionally stated in the response to **Comment 14** of reviewer 2.

Comment 20 Pg 19 Ln 55: I wonder if time-averaged forces are the best metric to test the CFL criterion? Also, presumably the maximum CFL was set to 1? With a lower mean value due to changes in grid resolution across the domain?

Response: Thank you for asking about the evaluation of the CFL-criterion, the authors agree that the average force should not be the only tested parameter to quantify its influence. Accordingly, the time series of the forces has been evaluated, corresponding to the evaluation of the damping coefficients, and compared in the frequency spectrum. The results suggest that the CFL-criterion has a minor influence on the fluctuations of the simulated forces. To ensure numerical stability, a CFL-criterion larger than 1 has not been tested within this study.

Actions taken: The time track of the simulated drag force for a variation of CFL-criterion (0.2 - 1.0) has been transferred to and compared in the frequency domain.

[Line 895 - 905] "The resulting forces are shown in Table A.4 ~~in the appendix~~, with results differing by a maximum of 2.12 % for the HDPE material relative to the simulated results with the lowest CFL-criterion.

In addition, the time series of the forces has been evaluated, corresponding to the evaluation of the damping coefficients, and compared in the frequency spectrum. Additionally, the natural frequency of the stem has been calculated based on Eq. 13. The results, shown in Fig. A.19, suggest that the CFL-criterion has a minor influence on the fluctuations of the simulated forces. For the satisfactory convergence of drag forces involving uniform current conditions, the CFL-criterion is set equal to unity, which additionally reduces the simulation duration.

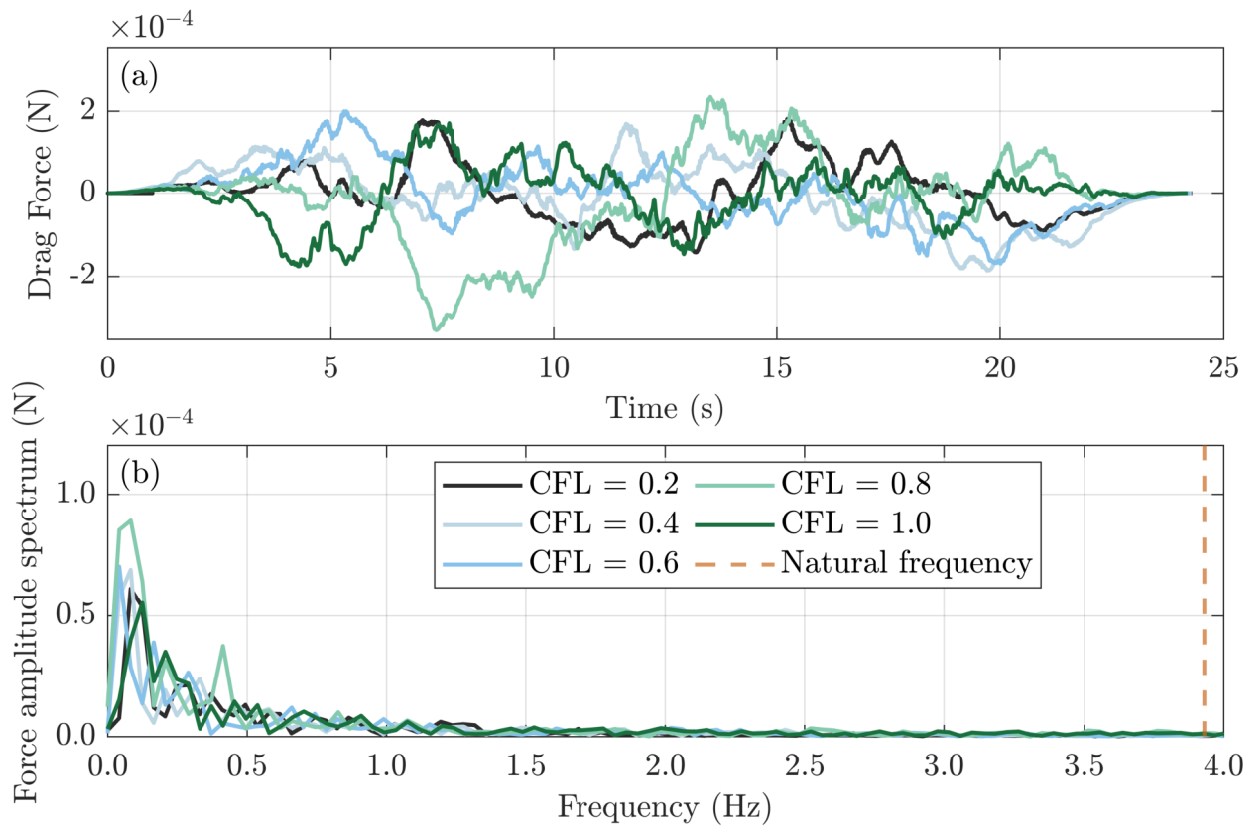


Figure A.19: Comparison of the simulated forces for a variation of CFL-criteria by transferring the data from (a) the time series to (b) the frequency domain for the HDPE stem with $v = 0.16$ m/s, $L_S = 0.05$ m, including the natural frequency of the stem

”

Comment 21 Figure 5a: The RANS errors seem particularly high. Can you explain in more detail the reason for this? Was the plant posture incorrect? Or just the flow structure around the plant? Showing some other output from the simulation may be helpful.

Response: *Thank you for asking for further details regarding the error resulting from using a RANS turbulence mode. To provide further insights, the authors visualized the resulting bending for the 0.25 m long stem with the HDPE material and for a medium flow velocity ($v = 0.16$ m/s), see the Figure below, which is also representative of the results for the soft foam material and other current velocities. While the incoming flow conditions for the different turbulence models are similar, the resulting stem positions clarify that both the forces as well as the bending are highly overestimated when using a RANS turbulence model. In contrast, the resulting stem positions for URANS and LES are by far more comparable.*

Actions taken: An additional visual comparison to provide an estimation of the flow field and bending of the stem for the different tested turbulence models has been added to the revised manuscript.

[Line 414 - 424] ”While the overestimation of the forces for the 0.05 m long stem remains in the same magnitude independent of the current velocity, the overestimation by the numerical model increases for the 0.25 m long stem with higher current velocities (Fig. 4a). Fig. 5 compares the different flow fields and

resulting bending positions for the different tested turbulence models. It can be seen that the simulations using the RANS turbulence model also overestimate the bending position compared to the resulting bending of URANS and LES, even though the incoming flow field does not vary.

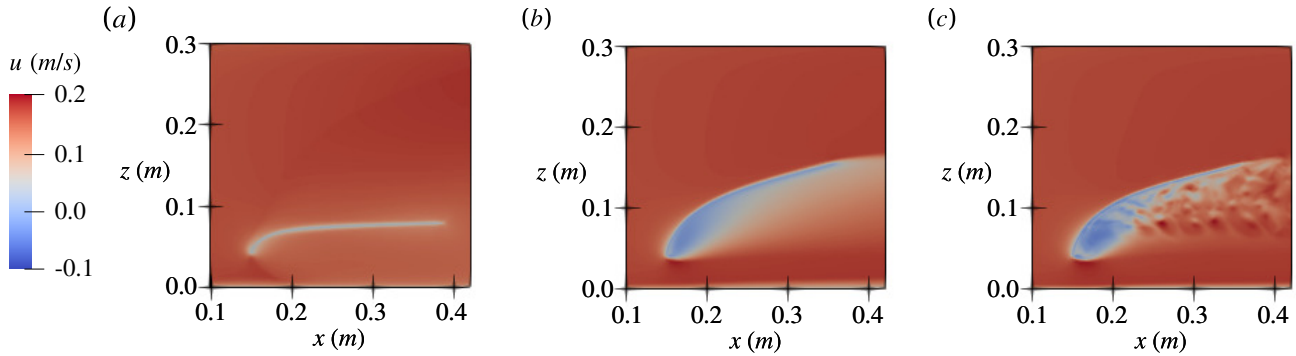


Figure 5: Simulated flow field for the 0.25 m long stem with HDPE Material and a current velocity of 0.16 m/s comparing (a) RANS, (b) URANS and (c) LES turbulence modeling

Comment 22 Figure 6: This is a nice figure that goes beyond the bulk properties to demonstrate the capability of the model. The analysis is quite qualitative and could be improved to start to quantify some of the differences observed, particularly in the flow.

Response: *Thank you for suggesting a more quantitative comparison between the two numerical models. Based on your suggestions, the authors incorporated further comparison of the difference in the resulting flow fields to the manuscript. As only one time step was available for the reference case, time-dependent parameters, like the turbulence intensity, could not be quantified for this comparison. Additionally, an explanation for the observed differences between the two flow fields has been added.*

Actions taken: The paragraph has been revised based on the reviewer's suggestions. An additional figure has been added, comparing the normalized horizontal velocity in different positions behind the stem for the two simulations.

[Line 470 - 485] "Overall, the qualitative comparison of the flow fields in Fig. 7 leads to the conclusion that the results of the simulation are comparable to the output of the solver used by Tschisgale and Fröhlich (2020). The minimum and maximum velocities are in a comparable order of magnitude for the selected time step, ranging from -0.60 m/s to 1.47 m/s for the results of Tschisgale and Fröhlich (2020) and from -0.56 m/s to 1.33 m/s for the results of this study. Overall, and the turbulence of the wake distributes over a similar area behind the stem for both simulated flow fields. At the base of the stem, the wake extends over a larger area and small eddies are less visible in the FD CFD solver compared to the results of Tschisgale and Fröhlich (2020). The latter is likely due to the use of different spatial discretization methods. Tschisgale and Fröhlich (2020) used a second-order central differences method, while the FD CFD solver in this study was developed for the fifth-order weighted essentially nonoscillatory (WENO) method, which is known to be more diffusive but provides more stability (Xu and Shu, 2005; Bihs et al., 2016).

[...]

[Line 494 - 505] Fig. 8 additionally compares the normalized horizontal velocity for four different locations behind the stem for one time step. Overall, it can be seen that the influence of the stem on the flow is in similar areas in z -direction for all locations. The minimum and maximum normalized velocities are in the same range for both simulations, even though the negative peak is slightly higher for the simulations of this study in the locations (b) to (e). Additionally, the before observed enhanced diffusivity of the FD CFD solver can be seen as well due to the larger fluctuations of the horizontal velocity over the flume height for the simulations of Tschisgale and Fröhlich (2020).

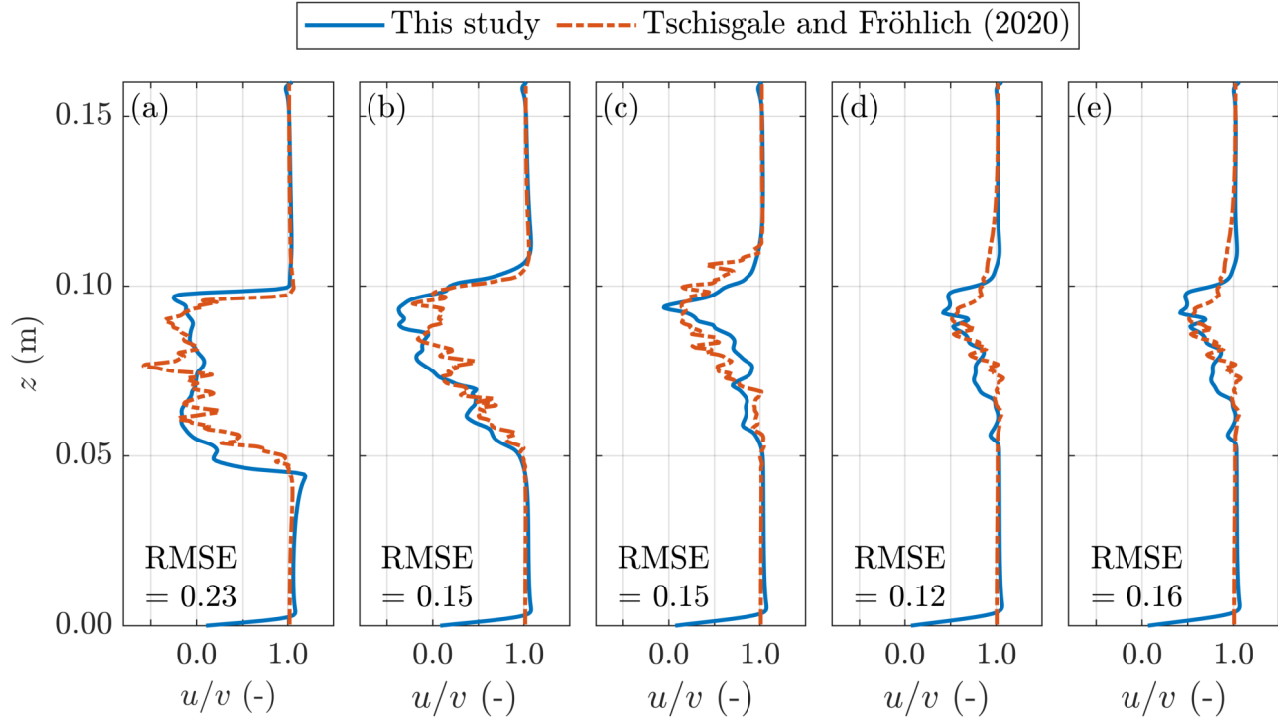


Figure 8: Comparison of the normalized horizontal velocity over the flume height for this study and the results of Tschisgale and Fröhlich (2020) at different positions behind the stem with $y = 0.00$ m and $x =$ (a) 0.075 m, (b) 0.10 m, (c) 0.125 m, (d) 0.15 m and (e) 0.175 m.

”

Comment 23 Pg 25 Ln 47-49: This seems logical for relative errors, as the overall magnitudes are lower and therefore small absolute errors due to incomplete process representation are magnified.

Response: *Thank you for pointing out the logic behind that statement, which the authors agree on. To provide an additional perspective on the magnitude of deviation for the different current velocities, the maximum absolute error is now stated in addition and the argument has been incorporated into the paragraph.*

Actions taken: The text has been revised to clarify the statement based on the reviewer’s suggestions.

[Line 524 - 530] ”In general, it appears that the deviation between the simulated and experimental forces is larger for lower current velocities. In contrast, the absolute error ($|F_{Exp} - F_{Sim}|$) is highest for the faster current velocity, with up to 0.0049 N compared to a maximum of 0.00061 N for the lowest current

velocity. This can be explained, as the overall magnitudes decrease, and even minor absolute errors resulting from inaccurate process representation become accentuated.”

Comment 24 Pg 25 Ln 53-56: It could be argued that drag force and mean stem reconfiguration can both be resolved by semi-explicit models. Surely the real strength of proper FSI comes when considering dynamic deflection in response to the unsteady, turbulent velocity field?

Response: *Thank you for referring to the real strength of the proposed FSI solver, which the authors agree to. Nevertheless, they think it is inevitable to first evaluate necessary model parameters with more straightforward properties like the average drag force or mean stem position. Further evaluation has been included in the following to extend the evaluation to metrics like the fluctuating motion and the turbulence intensity.*

Actions taken: The paragraph has been revised based on the reviewer’s suggestion.

[Line 506 - 512] ”A thorough calibration and validation approach has provided confidence that the chosen LES approach is resulting in good agreement of simulated drag forces, ~~and~~ bending motion **and the resulting velocity profile** of flexible vegetation in the FD CFD solver compared to both results of physical experiments and numerical simulations. **In the next sections, further parameters, such as the fluctuations of the stem in the current-induced flow and the resulting turbulence intensity are evaluated.**”

Comment 25 Section 3.3: This section begins to consider dynamics and identifies that simulations producing the same time-averaged properties (e.g. drag forces) may have very different dynamic behaviour. It would be interesting to consider the effects of these dynamics on flow (e.g., vortex shedding).

Response: *Thank you for suggesting further evaluation of the dynamic behavior on the flow, which is indeed interesting. The authors have therefore extended the analysis by selecting a line probe in front and behind the stem. For both positions, the normalized mean horizontal velocity, the RMS of the horizontal velocity, and the resulting turbulence intensity have been calculated. This allows the authors to evaluate both the effect of the stem in general on the flow field as well as the impact of the variation of the damping coefficients.*

Actions taken: Two line probes of the simulations with different damping coefficients have been evaluated regarding the normalized horizontal velocity, the RMS of the horizontal velocity, and the resulting turbulence intensity. The results are visualized in the Figure below.

[Line 618 - 638] ”**To evaluate the influence of variation of damping coefficients applied to the stems on the flow field, the turbulence intensity TI has been calculated using the time-averaged velocity $\bar{u}$ and u_{rms} :**

$$TI = \frac{u_{rms}}{\bar{u}} \text{ with } u_{rms} = \sqrt{\overline{(u(t) - \bar{u})^2}} \quad (5)$$

Here, the TI is used as an indicator of the impact of the stem to the flow field for two locations, one in front of the stem ($x = 0.10$ m, $y = 0.00$ m), representing the undisturbed flow field and a second one in the wake of the stem ($x = 0.40$ m,

$y = 0.00\text{ m}$), depicted in Fig. 2 as line probe 5 and 6. Fig. 14 displays the resulting normalized mean horizontal velocity, the RMS of the time track of the horizontal velocity, and the resulting TI for both locations. The results show that the stem influences the flow field behind by reducing the horizontal velocity (Fig. 14a). The extent of reduction differs depending on the applied damping coefficient. The fluctuations of the horizontal velocity, expressed by its RMS, have a varying extent for different damping coefficients (Fig. 14b), whereby the results for $c_k = 1 \times 10^{-7}$ differ the most. The resulting TI has similar trends (Fig. 14c), showing that the use of a smaller damping coefficient leads to less turbulence in the flow field for the selected position. While the turbulence conditions in front of the blade can be classified as low turbulence ($< 1\%$), the results with $c_k = 1 \times 10^{-7}$ fall into the category of mid turbulence and with $c_k = 1 \times 10^{-4}$ and $c_k = 1 \times 10^{-5}$ as high turbulence with $TI > 10\%$ (Windt et al., 2021).

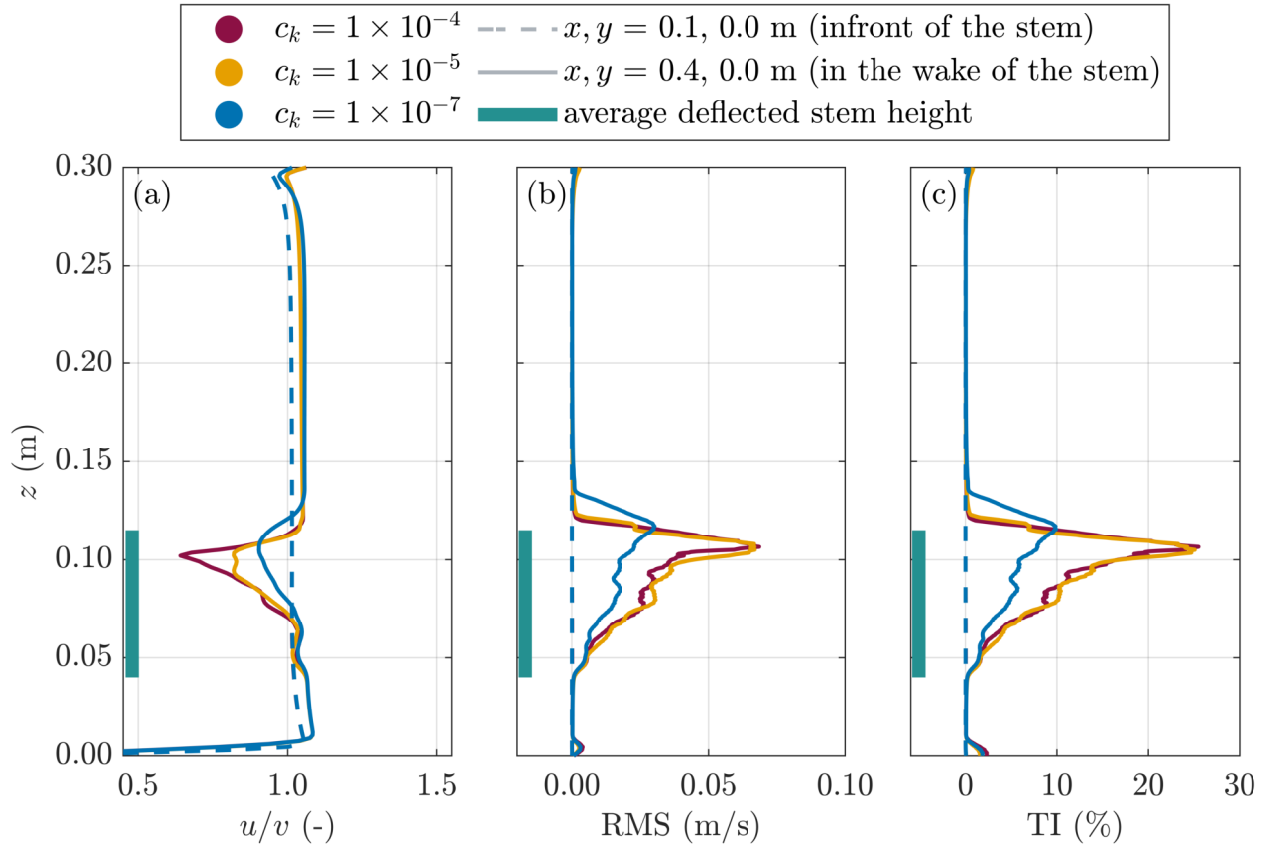


Figure 14: (a) Normalized horizontal flow velocity, (b) RMS of the horizontal velocity, and (c) resulting turbulence intensity compared for three different damping coefficients in front of (probe line 5) and behind (probe line 6) the stem. The results for probe line 5 are identical, independent of the applied damping coefficient

”

Comment 26 Pg 33: Ln 9-13: Related to previous comment. Please could the authors explain this statement in more detail.

Response: *Thank you for asking about further clarification. Similar to the answer to your **Comment 5**, the authors are here not exactly sure which statement the*

reviewer is referring to due to different line counts. The authors gladly address it if the reviewer could point out that sentence again in the updated manuscript line count.

Actions taken: A line count has been added to the revised version of the manuscript to enable clear references to specific sentences in the future.

Comment 27 Pg 33 Ln 46: Would be useful to compare to Luhar and Nepf effective length instead of this, which appears to be the deflected height(?) and also Cauchy number as this is a standard method used for considering drag on flexible structures. Framing the analysis in terms of existing metrics could enhance the significance of the results.

Response: *Thank you for suggesting the use of existing metrics. Indeed, the applied plant height should be referred to as the deflected stem height (H_{df}), which has been adapted accordingly. The authors agree that the use of dimensionless and frequently used parameters generally enhances the compatibility and therefore relevance of a study. Therefore, non-dimensional parameters like the Chauchy number and the buoyancy parameter are now provided with the material parameters – see Table 1 in the manuscript. However, the authors think that the used metrics in Fig. 15 are suitable, as its aim in the first place was not to compare the results to other flexible structures, but, instead, to show the capabilities of the proposed FSI application.*

Actions taken: The wording in the manuscript has been changed from effective length to the deflected stem height.

Comment 28 Pg 36 Ln 32: Lower Re may make skin friction more important, but greater deflection (which may mean higher velocity and Re) will also make it more important due to plant posture as mentioned above.

Response: *Thank you for addressing this important point when it comes to the relevance of the skin friction for different values of Re . The authors think this argument is important and should be included into the Discussion section.*

Actions taken: The argument of the reviewer has been added to the revised manuscript.

[Line 734 - 739] "Gosselin (2019) discussed that the influence of the skin friction for flexible vegetation could be larger for smaller values of Re , which corresponds to the deviations displayed in Fig. 9~~7~~. Then again, the skin friction might become relevant when the stem is bent parallel to the flow, which is expected for higher current velocities, corresponding to higher values of Re . Ffuture work should therefore [...]"

Comment 29 Pg 37 Ln 44-50: This conclusion feels unsupported by the data presented. Existing semi-empirical methods could replicate the majority of the results reported (and have done).

Response: *Thank you for addressing that conclusion. The authors agree that the bending motion and drag forces itself can be simulated by semi-empirical models as well. However, they think the additional evaluation provided throughout this manuscript shows the possibilities of the model going beyond time-averaged properties. Both the turbulence-inducing motion of the stem, including the variation due to different applied damping coefficients, and the implementation of seasonal vegetation properties based on field measurements could not have been simulated*

and evaluated in the same manner using semi-empirical models. The content of the conclusion is revised to emphasize these possibilities.

Actions taken: The paragraph has been revised to address the reviewer's comment.

[Line 768 - 777] "~~To~~When quantitatively assessing the ecosystem services provided by coastal vegetation, such as salt marsh or seagrass, ~~it is imperative to employ~~the use of accurate numerical models that adopt a direct forcing approach without reliance on coefficients like C_D enable further evaluation of the involved dynamic processes. Parameters such as the dynamic fluctuation of the current-induced stem motion and the resulting turbulence intensity provide insights regarding the sediment mobility solution around flexible stems. Already recognized as a promising approach, the FSI within the model REEF3D::CFD was evaluated towards its ability to accurately simulate the motion and resulting forces of flexible vegetation under varying current conditions."

Comment 30 Figure A.13: The method behind this figure is not well explained. The reference is included, but if it is an important aspect of the work, then the method should be recapped and all terms defined (e.g. ϕ_0).

Response: *Thank you for asking about the method of grid convergence, which has indeed not been explained in detail. The authors agree that it is an important aspect of the work and have therefore adapted the explanation of the grid convergence accordingly.*

Actions taken: Already based on your and the other reviewer's concerns raised in the earlier comments, the methodology of the grid convergence study has been explained in the appendix in more detail. The adapted paragraph is stated in the appendix of the manuscript and displayed in the response to **Comment 14** of reviewer 2.

References

- Agrawal, V., Kulachenko, A., Scapin, N., Tammisola, O., Brandt, L., 2024. An efficient isogeometric/finite-difference immersed boundary method for the fluid–structure interactions of slender flexible structures. *Computer Methods in Applied Mechanics and Engineering* 418. doi:doi: 10.1016/j.cma.2023.116495.
- Bihs, H., Kamath, A., Alagan Chella, M., Aggarwal, A., Arntsen, Øivind., 2016. A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. *Computers & Fluids* 140, 191–208. doi:doi: 10.1016/j.compfluid.2016.09.012.
- Caroppi, G., Järvelä, J., 2022. Shear layer over floodplain vegetation with a view on bending and streamlining effects. *Environ Fluid Mech* 22 (2-3), 587–618. doi:doi: 10.1007/s10652-022-09841-w.
- Cui, T., He, G., Jiang, M., Wang, W., Yuan, L., Han, D., Kamath, A., Bihs, H., 2022a. Large eddy simulation of focused breaking waves with different wave steepness. *Ocean Modelling* 179. doi:doi: 10.1016/j.ocemod.2022.102122.
- Cui, T., Kamath, A., Wang, W., Han, D., Bihs, H., 2022b. Large-eddy simulations of gravity currents in the presence of waves. *Journal of Hydraulic Research* 60:5, 770–791. doi:doi: 10.1080/00221686.2022.2064345.

- Cummins, C., Viola, I.M., Mastropaolo, E., Nakayama, N., 2017. The effect of permeability on the flow past permeable disks at low reynolds numbers. *Physics of Fluids* 29 (9). doi:doi: 10.1063/1.5001342.
- Ferziger, J.H., Perić, M., 2002. *Computational Methods for Fluid Dynamics*. Springer Berlin, Heidelberg.
- Gosselin, F.P., 2019. Mechanics of a plant in fluid flow. *Journal of experimental botany* 70 (14), 3533–3548. doi:doi: 10.1093/jxb/erz288.
- Hagmeyer, N., Mayr, M., Popp, A., 2024. A fully coupled regularized mortar-type finite element approach for embedding one-dimensional fibers into three-dimensional fluid flow. *Numerical Meth Engineering* 125 (8). doi:doi: 10.1002/nme.7435.
- He, S., Liu, H., Shen, L., 2022. Simulation-based study of turbulent aquatic canopy flows with flexible stems. *J. Fluid Mech.* 947. doi:doi: 10.1017/jfm.2022.655.
- Katopodes, N.D., 2019. *Free-surface flow. Environmental fluid mechanics*. Butterworth-Heinemann, Oxford.
- Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Prinz, M., Schürenkamp, D., Freund, H., Goseberg, N., 2023. Proposing a novel classification of growth periods based on biomechanical properties and seasonal changes of *spartina anglica*. *Front. Mar. Sci.* 10. doi:doi: 10.3389/fmars.2023.1095200.
- Kim, H.D., Yu, X., Kaplan, D., 2024. Steady flow over a finite patch of submerged flexible vegetation. *Water Resources Research* 60 (1). doi:doi: 10.1029/2023WR035222.
- Losada, I.J., Maza, M., Lara, J.L., 2016. A new formulation for vegetation-induced damping under combined waves and currents. *Coastal Engineering* 107, 1–13. doi:doi: 10.1016/j.coastaleng.2015.09.011.
- Luhar, M., Nepf, H.M., 2011. Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. *Limnology and Oceanography* 56, 2003–2017. doi:doi: 10.4319/lo.2011.56.6.2003.
- Martin, T., Bihs, H., 2021. A numerical solution for modelling mooring dynamics, including bending and shearing effects, using a geometrically exact beam model. *JMSE* 9 (5), 486. doi:doi: 10.3390/jmse9050486.
- Ni, J., Ji, C., Xu, D., Zhang, X., Liang, D., 2023. On monami modes and scales of a flexible vegetation array in a laminar boundary layer. *Physics of Fluids* 35 (7). doi:doi: 10.1063/5.0155506.
- Sasikumar, A., Kamath, A., Bihs, H., 2020. Modeling porous coastal structures using a level set method based vrans-solver on staggered grids. *Coastal Engineering Journal* 62 (2), 198–216. doi:doi: 10.1080/21664250.2020.1734412.
- Tian, F.B., Dai, H., Luo, H., Doyle, J.F., Rousseau, B., 2014. Fluid-structure interaction involving large deformations: 3d simulations and applications to biological systems. *Journal of Computational Physics* 258. doi:doi: 10.1016/j.jcp.2013.10.047.
- Tschisgale, S., Fröhlich, J., 2020. An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid. *Journal of Computational Physics* 423 (7). doi:doi: 10.1016/j.jcp.2020.109801.

- van Veelen, T.J., Fairchild, T.P., Reeve, D.E., Karunarathna, H., 2020. Experimental study on vegetation flexibility as control parameter for wave damping and velocity structure. *Coastal Engineering* 157. doi:doi: 10.1016/j.coastaleng.2020.103648.
- Wang, J., He, G., Dey, S., Fang, H., 2022. Influence of submerged flexible vegetation on turbulence in an open-channel flow. *Journal of Fluid Mechanics* 947. doi:doi: 10.1017/jfm.2022.598.
- Wang, M., Avital, E.J., Bai, X., Ji, C., Xu, D., Williams, J.J.R., Munjiza, A., 2020. Fluid–structure interaction of flexible submerged vegetation stems and kinetic turbine blades. *Comp. Part. Mech.* 7 (5). doi:doi: 10.1007/s40571-019-00304-6.
- Whittaker, P., Wilson, C.A., Aberle, J., 2015. An improved cauchy number approach for predicting the drag and reconfiguration of flexible vegetation. *Advances in Water Resources* 83, 28–35. doi:doi: 10.1016/j.advwatres.2015.05.005.
- Windt, C., Davidson, J., Ringwood, J., 2021. Investigation of turbulence modeling for point-absorber type wave energy converters. *Energies* 14 (26). doi:doi: <https://dx.doi.org/10.3390/en14010026>.
- Xu, Z., Shu, C.W., 2005. Anti-diffusive flux corrections for high order finite difference weno schemes. *Journal of Computational Physics* 205 (2), 458–485. doi:doi: 10.1016/j.jcp.2004.11.014.

Response to the reviewers

Dear Editor and Reviewers,

The authors would like to express their appreciation for the time taken and effort made to evaluate the reversed version of the manuscript. The authors believe that by addressing the raised comments increased the overall quality of the revised manuscript.

Please find attached a marked version of the manuscript, indicating the amendments the authors performed along with a clean manuscript. Detailed answers to the reviewers' comments are provided in this rebuttal letter. The line numbers refer to the revised clean version of the manuscript.

Answers to the individual comments can be found below. The convention is as follows:

- Refers to the reviewer's comments
- *Refers to our responses to the comments*
- Refers to new text added to the manuscript
- ~~Refers to text deleted from the manuscript~~

Reviewer 1

The authors have well answered all my questions and made corresponding revisions accordingly. The quality of the manuscript has been improved. I have no further comments.

Reviewer 2

No comment.

Reviewer 3

The authors have thoroughly addressed the reviewer comments and provided detailed responses. I commend them for their clarity and detail in doing so. As a result, the paper is substantially improved. In particular, the results are much better organised across the main paper and the Appendix and several methodological aspects/choices are much clearer. However, there are still a few issues and queries which I believe should be addressed before the paper is suitable for publication.

Response: *Thank you for acknowledging the improvements in the revised version of the manuscript. The authors addressed your remaining comments in detail below.*

Comment 1 Lines 74-79: My previous query on this topic has been partly addressed but I think would still benefit from further clarification. I agree with the authors that "simplistic approaches that require coefficients like C_D cannot accurately simulate the FSI with flexible vegetation" and removing the need for C_D estimates within predictive models is usually beneficial. However, while direct forcing has the potential to improve accuracy it is not a given and a couple of different roles of the drag coefficient are lumped together here. First, there is the change in drag forcing purely due to reconfiguration. Methods such as Luhar and Nepf's (2011) aim to address this and would claim that one does not need varying drag coefficients, as you can calculate the drag force of a reconfigured stem using the effective length and Cauchy number approach (see later comments on results). Second, species-specific drag coefficients can represent complex shapes (deviations from a simple cylindrical or rectangular cross-section). In this case, direct forcing is only beneficial if the additional complexity in form is adequately represented. Finally, species-specific or seasonal drag coefficients may represent complexity in biomechanics (e.g. within-stem variation, seasonal change in biomechanics, non-linearity). This final case is mentioned in the discussion. While the text does not need this level of detail, it would benefit from mentioning the caveat that while direct forcing has the potential for greater accuracy through improved physical coupling, there remain challenges here too (e.g. very few studies have considered anything beyond a single homogenous cylindrical/rectangular stem).

Response: *The authors appreciate the reviewer's comments and acknowledge the multifaceted roles of the drag coefficient in FSI modeling with flexible vegetation. The authors agree that it is important to clarify that direct forcing, while potentially more accurate, does not inherently guarantee improved results. Overall drag coefficients have a variety of application cases, such as the mentioned species-specific drag coefficients to capture complex shapes, and biomechanical variations within species or across seasons. While the discussion touches upon these aspects, the authors acknowledge that direct forcing still faces challenges*

despite its promise for enhanced physical coupling, particularly with limited studies addressing heterogeneous or non-cylindrical stems. The authors would like to emphasize that the current study is the first to explore the capabilities of the proposed model, providing the potential for applying more complex studies for future work. However, the advantages as mentioned earlier of the drag coefficients are limited by the available datasets, as extensive field and laboratory studies are necessary to obtain drag coefficients that represent both the species-specific, biomechanical, and seasonal variations.

Actions taken: The paragraph has been adapted to address the reviewer's concerns and emphasize the weighing-up between approaches based on drag coefficients and direct forcing.

[Line 75 - 87] The present study argues that simplistic approaches requiring coefficients like C_D cannot accurately simulate the FSI with flexible vegetation and are not further considered in this study. *Accurately incorporating the variability of flexible vegetation using drag coefficients requires extensive field and laboratory investigations to generate a widely applicable dataset, considering the different vegetation species, stem-leaf configurations unaddressed so far, seasonality, and biomechanical variations within a stem.*

A second, more versatile approach for numerical FSI ~~uses~~*involves* direct forcing. *Although this method promises higher accuracy, it does not inherently guarantee improved results, as replicating the complex geometry of live vegetation remains challenging. Direct forcing requires,*~~thus requiring~~ some form of coupling between the fluid and structural solvers. One way to achieve such coupling is [...]

Comment 2 Figures 4 and 5: The improved figures help explain this trend, but I still have questions about how this result was achieved. I would not expect such great differences between RANS and URANS and have never seen such a poor relative comparison. There seems to be little to no wake development within the RANS model, and the vegetation form suggests it is substantially over-deflected, as if based only on the initial forcing from the upright position. Can you confirm how the vegetation solver was run in the RANS model? Was it allowed to iterate to a converged steady state? Why is there no wake formation behind the stem? At present I have little confidence in this result as it seems so different, when ultimately the main model physics is the same.

Response: *Thank you for your comment. The achieved converged steady-state condition is demonstrated in Fig. 1. This figure illustrates that both RANS and URANS simulations reach a steady state after approximately two seconds, as evidenced by the drag force, which corresponds with the stem bending. The Figure shows as well that the resulting force at the beginning of the simulation is in a similar order of magnitude for both cases, but the force based on the RANS simulation gradually increases shortly afterward until reaching a steady state.*

During each iteration of solving the equations within the vegetation solver, REEF3D evaluates conditions such as whether the iterative solution's time step size has diminished excessively or if the number of iterations has exceeded a threshold. In such cases, an error notification is generated, but these conditions did not occur in the simulations under discussion.

The authors agree with the reviewer that the differing outcomes observed in the simulation utilizing the RANS turbulence model are rather unexpected. The com-

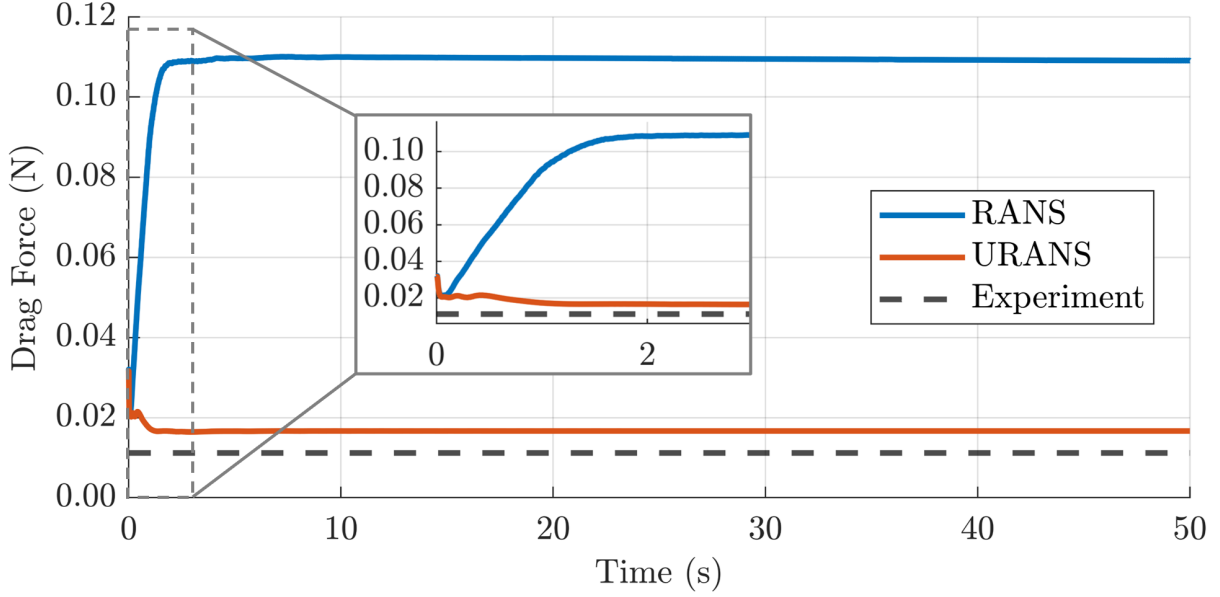


Figure 1: Comparison of the drag force over time for the RANS and URANS simulations, with the experimental average force given as a reference.

combination of overestimated forces and bending suggests a possible issue in the resulting flow field of the FSI. The RANS model is routinely used within the REEF3D::CFD framework and is generally expected to be correctly implemented. To provide further insights regarding the comparison of RANS and URANS, a comparison of different quantities of the flow field for three different time steps of the simulation is provided in a new Appendix B in the manuscript.

The selected variables are the residual pressure (Fig. B22), the kinematic turbulent energy (Fig. B23), and the eddy viscosity (Fig. B24). The selected time steps represent the three different stages of the bending process: first the initial condition, second during the stem bending, and third the steady state bent position. The first selected time step, before the FSI begins, shows that the initial conditions of the RANS and URANS simulations are the same for all presented quantities.

Based on the provided analysis, it can be assumed that the overestimation of the bending and forces in the RANS simulations is due to the turbulent kinetic energy generated near the stem being dispersed across a broader area within the flow field by the RANS turbulence model. Consequently, the model overestimates the eddy viscosity around the stem, which the authors assume prevents the recirculation of the flow field beneath the stem, thereby resulting in an overbent position of the stem.

Differences in the residual pressure, kinematic turbulent energy, and eddy viscosity are observed when comparing the results of the RANS and URANS simulations. The resulting flow field from the RANS turbulence model is influenced by a combination of factors, including the general characteristics of the RANS model, its implementation in REEF3D::CFD, the inherent parameters of the models, and the specific limiter functions applied within REEF3D::CFD. In case the application of RANS in combination with the FSI solver is desired, future studies should investigate which of these contributors can be adapted to reproduce physically accurate behavior to improve the suitability of the RANS turbulence model

in REEF3D::CFD when used with the FSI solver. Otherwise, it could be studied if further enhancements in performance using URANS would potentially achieve comparable accuracy to the results obtained using the LES turbulence model.

Yet, adapting the RANS turbulence model's implementation to enhance its performance with the vegetation solver is beyond the scope of this manuscript. Instead, the authors' aim is to provide researchers with insights into the outcomes of different turbulence models within the REEF3D::CFD framework and emphasize the significance of selecting an appropriate turbulence model when using the vegetation solver. The variation in results is not confined to the RANS solver alone, as evidenced by the differing forces observed in the URANS and LES simulations, as well as the coefficients of the LES subgrid-scale model.

Actions taken: Based on the reviewer's question, a comparison of the simulation results between the RANS and URANS cases has been included as a new Appendix B to the manuscript.

[Line 429 - 439] It can be seen that the simulations using the RANS turbulence model also overestimate the bending position compared to the resulting bending of URANS and LES, even though the incoming flow field does not vary. The overestimation of the bending and forces in the RANS simulations is likely due to the turbulent kinetic energy generated near the stem being dispersed across a broader area within the flow field by the RANS turbulence model, see Fig. B23 in Appendix B. Consequently, the model overestimates the eddy viscosity around the stem (Fig. B24), which appears to inhibit the recirculation of the flow field beneath the stem, resulting in its excessive bending. A more detailed analysis of the phenomenon is provided in Appendix B.

[...]

[Line 982 - 1030]

Appendix B. Comparison of results between the RANS and URANS turbulence model

The combination of overestimated forces and bending of the RANS simulations suggests a possible issue in the simulation dynamics. To provide further insights, the results of RANS and URANS are compared for different quantities. Three different time steps of the simulation are provided in Fig. B22, B23 and B24. These time steps represent the three different stages of the bending process: first the initial condition, second during the stem bending, and third the steady state bent position. The first selected time step, before the FSI begins, shows that the initial conditions of the RANS and URANS simulations are the same for all presented quantities.

Fig. B22 displays the residual pressure, calculated by $p_{res} = p - (\rho g(h - z))$, around the stem to provide an impression of the flow field. As expected, positive pressure can be observed above the stem and negative pressure below it for both turbulence models. The stem using RANS shows locally (at the bottom and at the tip of the stem) lower negative pressures compared to the URANS simulation. An indicator of the unexpected behavior of the RANS simulation could be negative pressure above the stem, which appears slightly in Fig. B22b and is more pronounced in Fig. B22c. To determine possible explanations for

the unexpected pressure above the stem using RANS, parameters describing the turbulence model are compared in the following.

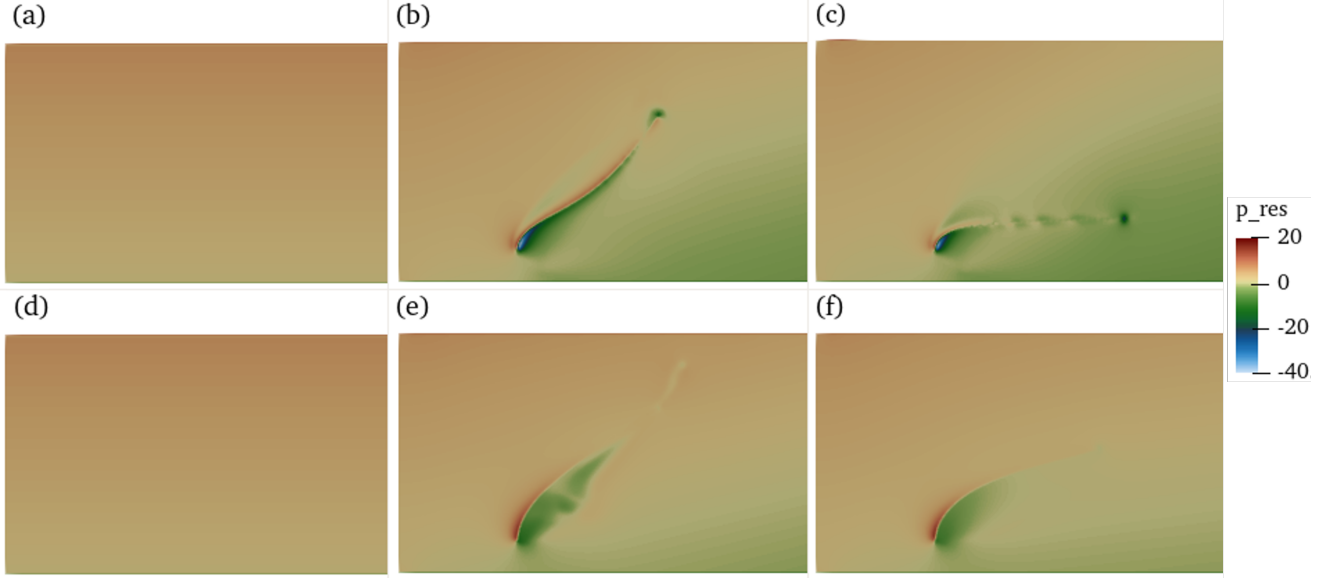


Figure B22: Comparison of the residual pressure for the (a-c) RANS and (d-f) URANS simulations at (a,d) the initial condition ($t = 0$ s), (b,e) the bending phase ($t = 1$ s) and (c,f) the final bending position ($t = 50$ s)

The turbulent kinetic energy is displayed for the RANS and URANS simulation in Fig. B23. Overall, a larger turbulent kinetic energy can be observed at the area of the stem for the RANS simulation compared to URANS. It is apparent that only the URANS stem develops a wake. Furthermore, the same area, which showed a negative residual pressure in Fig. B22c, shows the presence of turbulent kinetic energy in Fig. B23c for the RANS simulation. Possibly, the turbulence produced at the proximity of the stem is transported by the RANS turbulence model to a wider area in the flow field.

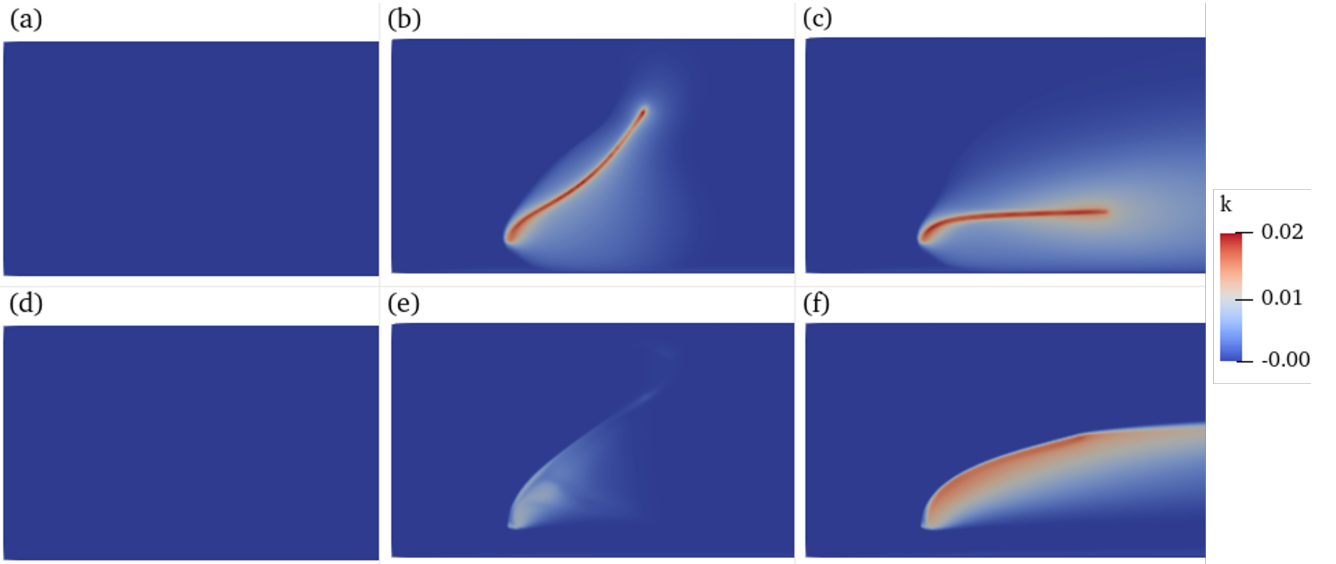


Figure B23: Comparison of the kinematic turbulent energy for the (a-c) RANS and (d-f) URANS simulations at (a,d) the initial condition ($t = 0$ s), (b,e) the bending phase ($t = 1$ s) and (c,f) the final bending position ($t = 50$ s).

Depending on the kinematic turbulent energy, the differences in the eddy vis-

cosity between the two turbulence models can be seen in Fig. B24. A logarithmic scale has been applied to the results in Fig. B24 to visualize the spread of magnitude of the eddy viscosity around the stem between the two turbulence models. For the stem of the URANS simulation, an increased eddy viscosity can be observed below and in the wake of the stem, where turbulence is expected (Fig. B24e and f). For the RANS simulation, the area of the increased eddy viscosity in Fig. B24c resembles, logically, the area of increased kinematic turbulent energy in Fig. B23c. The overestimation of the eddy viscosity based on the RANS turbulence model possibly prevents the recirculation of the flow field below the stem, leading it to be overbent.

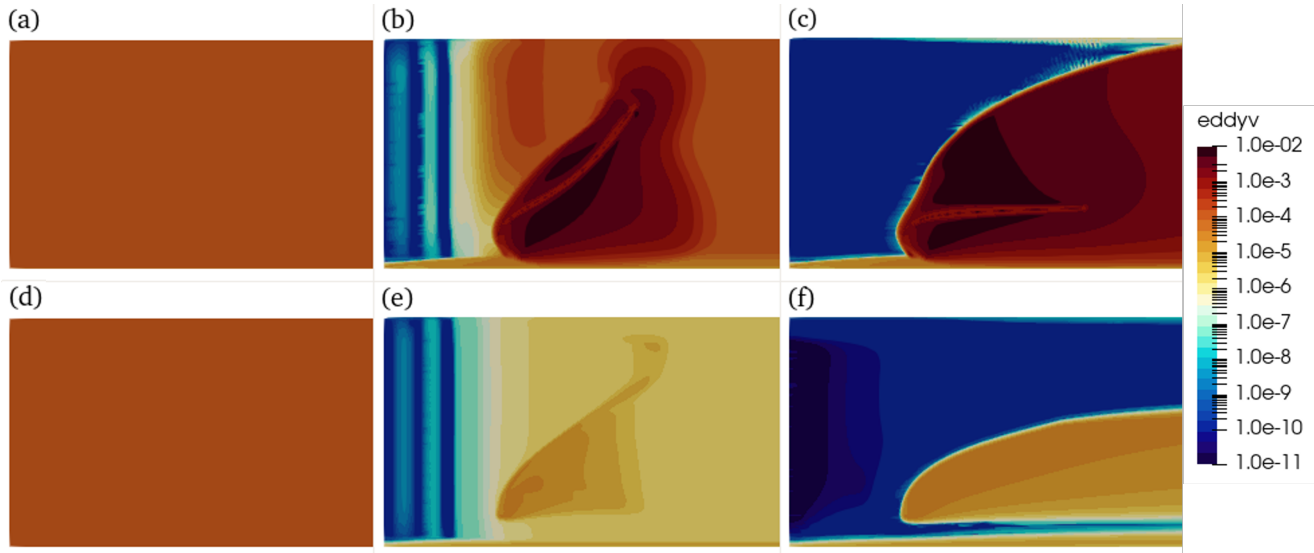


Figure B24: Comparison of the eddy viscosity for the (a-c) RANS and (d-f) URANS simulations at (a,d) the initial condition ($t = 0$ s), (b,e) the bending phase ($t = 1$ s) and (c,f) the final bending position ($t = 50$ s)

Overall, differences in the residual pressure, kinematic turbulent energy, and eddy viscosity can be observed when comparing the results of the RANS and URANS simulations. The resulting flow field based on the RANS turbulence model is a combination of the RANS model in general, its implementation in REEF3D::CFD, the model's inherent parameters, and specific limiter functions applied in REEF3D::CFD. Future studies should investigate which of the contributors can be adapted, while reproducing physical correct behavior, to achieve suitability of the RANS turbulence model in REEF3D::CFD in combination with the FSI solver.

Comment 3 Table 2: Contrary to what the text says, the Table doesn't contain turbulence intensity

Response: *Thank you for reading the text carefully and pointing out that inaccuracy. Throughout the review process, the idea was first to compare the turbulence intensity at one specific point behind the stem. During the analysis, it became obvious that a comparison of the turbulence intensity based on the point probes is not suitable, but the text has not been updated accordingly. Now, a comparison based on line probes has been added to the analysis, see the answer to your Comment 5.*

Actions taken: The turbulence intensity has been removed from the description of the table in the text.

[Line 657 - 659] For the same horizontal current velocity of 0.50 m/s, the resulting drag force, bending angle, ~~and drag coefficient, and turbulence intensity at a specific point behind the stem~~ are ~~given~~provided in Table 2.

Comment 4 Line 643: Please define how the bending angle is measured (i.e. relative to the initial upright position, or to the bed)

Response: *Thank you for the comment: the authors agree that the definition of the bending angle is important information and should be included in the text. As the drag coefficient has been calculated based on the equation of Luhar and Nepf (2011), the bending angle follows their definition as well.*

Actions taken: The calculation of the bending angle has been added to the text.

[Line 677 - 711] ~~The applied bending angle follows the definition of Luhar and Nepf (2011) and is accordingly given relative to the initial stem position. The angle is determined at mid of the stem and calculated by $\phi = 90^\circ - \tan^{-1}((z_{tip} - z_{mid})/(x_{tip} - x_{mid}))180/\pi$, with z_{tip} and x_{tip} describing the bent position at the tip of the stem and z_{mid} and x_{mid} the bent stem position at half of the stem length.~~

Comment 5 Line 645-646: This comparison with field data is helpful. However, in theory the Luhar and Nepf (2011) paper claims to be able to deal with these biomechanical differences through the effective length and Cauchy number approach. If you use the Luhar and Nepf method to calculate F_D based on Ca, are the results accurate? This would be a useful comparison to demonstrate that the direct-forcing approach offers a substantial advantage over other simplified approaches. As I stated in my previous review, I do agree that direct forcing methods are a huge improvement on drag-based approaches, so I agree with your overall conclusion. However, I am not so sure their strength lies in prediction of mean forces and positions, so it would be good to demonstrate whether that is the case or not here.

Response: *The authors thank the reviewer for the suggestion to compare the simulated application case to the proposed formulation of Luhar and Nepf (2011). The obtained results suggest that the proposed approach of Luhar and Nepf (2011) is in agreement with the simulated results, although it should be noted that the live vegetation is rather stiff, so the effect of stem reconfiguration is not specifically tested with this example. Overall, the authors agree with the reviewer that non-dimensional parameter empirical relationships are suitable for predicting average forces. However, the authors would prefer to include the comparison, as it provides further insight into the applicability of the proposed model.*

Additionally, the comparison of the resulting turbulence intensity of the three different growth states is included, to provide further insights into the resulting flow field behind the stem. The authors agree with the reviewer's opinion that the advantage of the direct forcing simulations compared to empirical approaches is to provide properties beyond average stem position and forces.

Actions taken: The effective length and drag forces have been calculated for the applied field data following the definition of Luhar and Nepf (2011) and afterward the results are evaluated and discussed. A comparison between the different growth states regarding the flow field has been included and evaluated.

[Line 669 - 702] Further on, the results are compared and confirmed by an approach based on non-dimensional parameters and empirical relations. Luhar and Nepf (2011) proposed to use the effective length l_e to calculate the drag force ($F_D = 0.5\rho C_D b l_e U^2$). The effective length is determined by an empirical relation between Ca and B :

$$\frac{l_e}{l} = 1 - \frac{1 - 0.9Ca^{-1/3}}{1 + Ca^{-3/2}(8 + B^{3/2})} \quad (1)$$

The calculated effective length for the flowering stem is 0.20 m, for the broken stem 0.19 m, and for the sprouting stem 0.18 m. When using a C_D of 1.95 (following Luhar and Nepf (2011)), the calculated drag force is 0.20 N for the flowering stem and 0.18 N for both the broken and sprouting stem, which are in high agreement with the simulated forces (cf. Table 2). The agreement underlines both the capability of the proposed model to simulate the resulting forces and the empirical model of Luhar and Nepf (2011) to determine the resulting forces based on the dimensionless parameters Ca and B .

Overall, relatively stiff vegetation has been chosen for this application study, underlined by the calculated effective length being almost equal to the initial stem length, resulting in a limited influence of the stem reconfiguration on the resulting forces. Future investigations should include more flexible live vegetation to confirm the general applicability of that approach and the proposed model.

Providing further insights into the resulting flow field behind the stems, the stem position, the normalized horizontal velocity, and the turbulence intensity for the three growth states are illustrated in Fig. 15c. This analysis follows the methodology previously described for the variation of damping coefficients presented in Section 3.3. The normalized horizontal flow velocity varies with height across different growth states (Fig. 15b), induced by the varying positions of the bent stems (Fig. 15a). The resulting turbulence intensity for each growth state is depicted in Fig. 15c. While the comparison reveals similar maximum values of the turbulence intensity at around 25 % for all growth states, large differences regarding their profile in z -direction become apparent.

The comparison indicates that the turbulence dynamics in the wake of the stem vary depending on the growth state, which can, for example, become relevant when looking at the sediment transport behavior in the proximity of the stem.

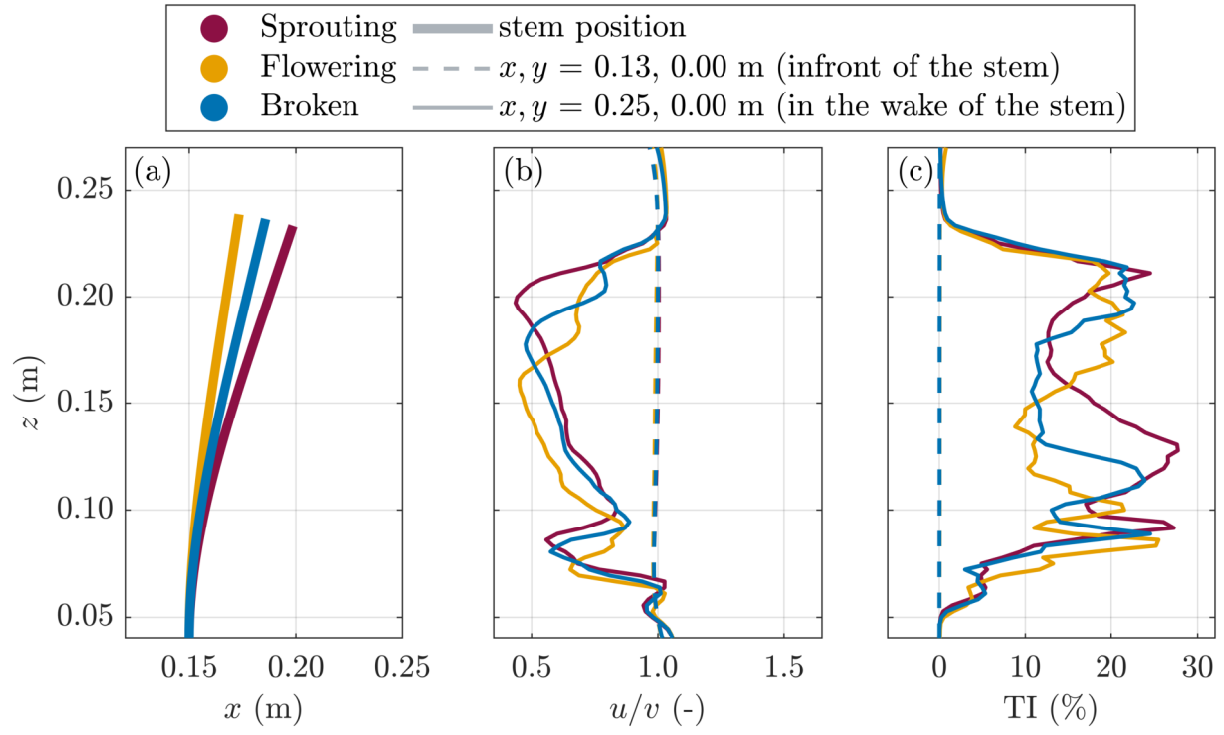


Figure 15: (a) Stem position in steady state, (b) normalized horizontal flow velocity, and (c) resulting turbulence intensity, compared for three different growing states in front of and behind the stem.

References

Luhar, M., Nepf, H.M., 2011. Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. *Limnology and Oceanography* 56, 2003–2017. doi:doi: 10.4319/lo.2011.56.6.2003.

Response to the reviewers

Dear Editor and Reviewers,

The authors would like to express their appreciation for the time taken and effort made to evaluate the reversed version of the manuscript. The authors believe that by addressing the raised comments increased the overall quality of the revised manuscript.

Please find attached a marked version of the manuscript, indicating the amendments the authors performed, along with a clean manuscript. Detailed answers to the reviewers' comments are provided in this rebuttal letter. The line numbers refer to the revised, clean version of the manuscript.

Answers to the individual comments can be found below. The convention is as follows:

- Refers to the reviewer's comments
- *Refers to our responses to the comments*
- Refers to new text added to the manuscript
- ~~Refers to text deleted from the manuscript~~

Reviewer 1

No comment.

Reviewer 2

No comment.

Reviewer 3

The authors have comprehensively addressed my comments, providing additional clarification in the text and through the additional figures which have improved the manuscript and satisfactorily addressed all but one of my comments.

Response: *Thank you for acknowledging the improvements in the revised version of the manuscript. The authors addressed your remaining concern in the following.*

Comment 1 Regarding Comment 2, the authors provide three new figures which help to illustrate the difference between the RANS and URANS cases. However, looking at these figures reinforces my initial concerns regarding the validity of the RANS model outputs. The pressure field does not look like it is in equilibrium with the structure (low pressure above the stem, very little net pressure gradient to drive stem reconfiguration above the stem base), the TKE plots have some strange effects persisting above the stem and the eddy viscosity plot exhibits a sharp, unexplained boundary in viscosity values far above the stem. In contrast, the URANS results seem reasonable and well-converged, exhibiting the expected behavior.

The authors partly acknowledge these errors and the need to adapt the RANS model to reproduce correct behavior in the Appendix. However, if the results are demonstrably incorrect due to modelling error (rather than the limitations of RANS) then I would question their inclusion within the paper. Possible options would be to either investigate the RANS simulations further and resolve the issue, remove the RANS simulations for the paper, or to retain the RANS simulations and clearly state that they are erroneous. As I say, I believe this last option is the least ideal as I do not think the results present a fair comparison with the capability of a working RANS model.

Response: *The authors agree with the reviewer that the results of the RANS simulations are not representative of physical behavior or the overall capabilities of RANS turbulence models. However, it can be argued that the results rather highlight the necessity for adapting the RANS turbulence model and its application in this study, to incorporate the fluid-structure interaction correctly than a modeling error.*

Therefore, the authors have decided to follow the reviewers' suggestion to improve the fluid-structure interaction within the model framework for the application of RANS turbulence models by adapting the local turbulence dissipation at the wall of the stem; this immersed boundary had not been given explicit treatment for the turbulence model, and the authors deem this being the main issue that the reviewer correctly had criticized. The introduction to the improved RANS application and its evaluation are elaborated in the following. The authors believe that including the wall-adapted RANS approach provides now a comprehensive

comparison of the utilization of different turbulence models with the proposed FSI solver.

Actions taken: The authors have implemented a new wall boundary condition along the stem to increase the turbulence dissipation rate in its proximity. This first approach prevents the overproduction of the kinematic turbulent energy and the eddy viscosity within the flow field. The results suggest that the flow field around the stem with the wall-adapted RANS approach appears similar to the results utilizing URANS. The resulting forces of the stem when using the wall-adapted RANS are in comparable order of magnitude to the results of the other tested turbulence models and overall in much-improved agreement when compared to the experimental results.

In the manuscript, the wall-adapted RANS approach is introduced in the methodology (Section 2.1), followed by a comparison in the results (Section 3.1) between the two RANS approaches regarding the resulting forces and stem bending and flow field. Afterward, the results of the wall-adapted RANS approach are compared to the results based on URANS and LES turbulence models. The implications of the new wall-adapted RANS approach are briefly elaborated in the discussion (Section 4.1). The previously added evaluation of the limitations of the RANS approach in Appendix B has been removed from the manuscript. The adaptations to the manuscript can be found in the following.

Methodology section: [Line 221 - 244]

Two viscosity components are included, with ν corresponding to the fluid molecular kinematic viscosity. The eddy viscosity ν_t accounts for the Reynolds stress term using RANS equations and can be solved with models, e.g., the k - ω model, as described in Bihs et al. (2016). **RANS formulations require particular attention when accounting for sharp velocity gradients or unsteady flow fields (Bush et al., 2019).** These potential instabilities can generally be mitigated by applying limiters to the eddy viscosity across the entire fluid domain, as used in URANS methods, or by adapting the turbulence production in the proximity of the stem. The latter is here enabled by implementing a new formulation accounting for increased turbulent energy dissipation along the stem. Following the logarithmic law of the wall, the turbulent energy dissipation ω is enhanced at the surface of the stem by calculating its modification ω^* as follows

$$\omega^* = \frac{C_T D (\max(0, k))^{0.5}}{1/3(\delta x + \delta y + \delta z) \kappa C_\mu^{0.25}} \quad (3)$$

including a turbulence factor, applied here with $C_T = 50$, the kernel function D locating the grid points at the surface of the stem, the turbulent kinetic energy k , the local cell size $(\delta x, \delta y, \delta z)$ and turbulence model constants κ , here equal to 0.4, and C_μ , here equal to 0.09. The implications of this first approach to account for the FSI using the k - ω model are presented in Section 3.1.

Alternatively, a spatially filtered Navier-Stokes equation can be applied to solve the subgrid-scale eddy viscosity for the LES equations. [...]

Result section: [Line 427 - 510]

3.1 Velocity field and influence of turbulence modeling

Before a detailed investigation of the complex FSI, it is paramount to test and select a model family on the fluid part that governs the process of eddy production and detachment in the vicinity of the dynamic stem motion. In terms of model families, RANS, URANS, and LES fluid solvers have been tested with a variety of parameter settings; the accuracy that could be obtained by the FSI has then been compared to an experimental dataset (Luhar and Nepf, 2011), and against results of a recently published numerical study (Tschisgale and Fröhlich, 2020).

First, the influence of the wall-adapted RANS approach on the FSI is presented and compared to the RANS approach without modification. The resulting forces for a variation of tested material types, stem lengths, and current velocities are compared between RANS and the wall-adapted RANS approach in Fig. 4. The resulting stem bending between the two approaches is compared for a selected test case in Fig. 5. It can be observed that the RANS simulations, using the $k-\omega$ turbulence model **without wall-adaption**, overestimate the forces measured in the reference experiment. While the overestimation of the forces for the 0.05 m long stem remains the same order of magnitude independent of the current velocity, the overestimation by the numerical model increases for the 0.25 m long stem with higher current velocities (Fig. 4a). **In contrast, the resulting forces with the wall-adapted RANS approach are in the same order of magnitude as the experimental results, see Fig. 4b. Nevertheless, the forces for the 0.25 m long stem are overestimated by 20 % to 40 % for the HDPE material and by 10 % to 80 % for the soft foam material.**

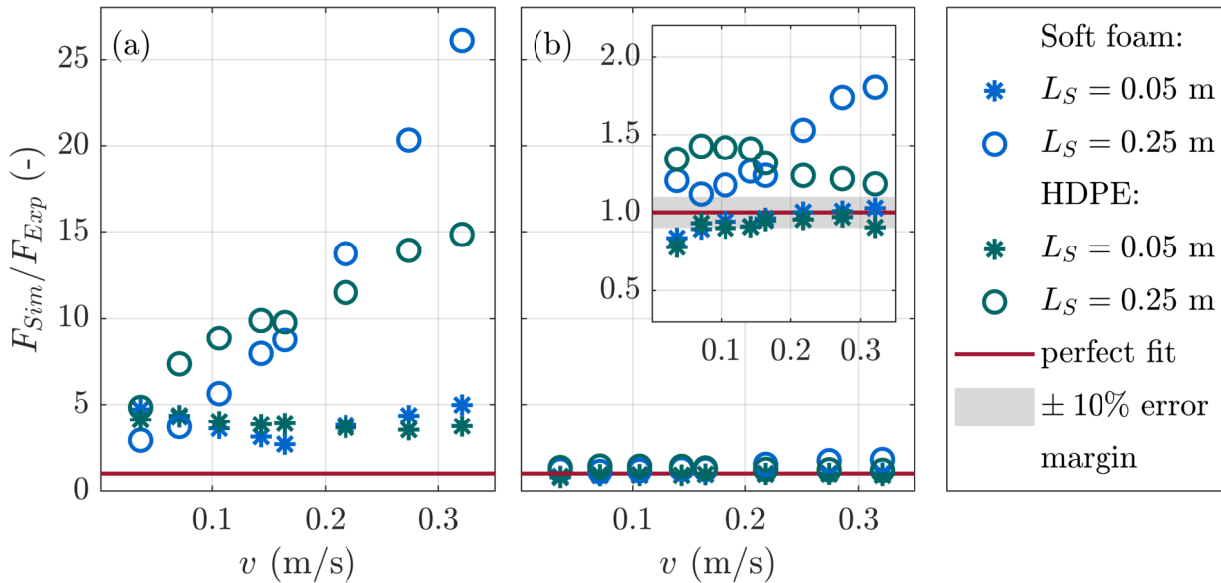


Figure 4: Comparison of simulated vs. experimentally-derived forces (Luhar and Nepf, 2011), for both the soft foam and HDPE Material and two stem lengths $L_S = 0.05$ m and $L_S = 0.25$ m with (a) RANS and (b) wall-adapted RANS turbulence modeling; inset shows the same data but with adjusted y-axis scale

The large observed deviations between the resulting forces for the RANS compared to the wall-adapted RANS approach render an evaluation of the occurring processes essential. Fig. 5 compares the resulting flow field around the stem for

the 0.25 m long HDPE stem with a current velocity of 0.16 m/s for the RANS and the wall-adapted RANS approach, providing further insights and possible explanations for occurring differences. It can be seen that the simulations using the RANS turbulence model also overestimates the bending position ~~compared to the resulting bending of URANS and LES~~ compared to the resulting bending of the wall-adapted RANS approach, even though the incoming flow field does not vary. The overestimation of the bending and forces in the RANS simulations ~~without wall-adaption~~ is likely due to the turbulent kinetic energy generated near the stem being dispersed across a broader area within the flow field by the RANS turbulence model, ~~see Fig. B.23 in Appendix B. Consequently, the model overestimates the eddy viscosity around the stem (Fig. B.24),~~ which appears to inhibit the recirculation of the flow field beneath the stem, resulting in its excessive bending. ~~A more detailed analysis of the phenomenon is provided in Appendix B.~~ This effect can be prevented by enhancing the turbulent energy dissipation in the proximity of the stem, as introduced in Section 2, utilizing the wall-adapted RANS approach. The resulting stem bending and surrounding flow field of the wall-adapted RANS approach provide a more reasonable FSI, depicted in Fig. 5b. In conclusion, the wall-adapted RANS is considered more suitable for simulating the FSI within the FD CFD model compared to the non-adapted RANS approach. Consequently, the wall-adapted approach is employed for further comparison with results from other turbulence models, including URANS and LES.

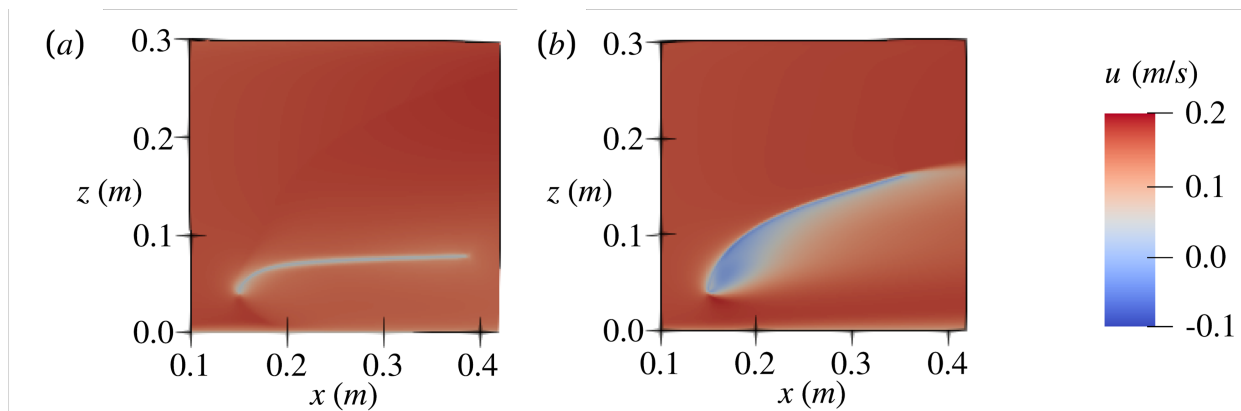


Figure 5: Simulated flow field for the 0.25 m long stem with HDPE Material and a current velocity of 0.16 m/s, comparing the simulations results of (a) RANS and (b) wall-adapted RANS approach

Fig. 6 compares the simulated results for the wall-adapted RANS, URANS, and LES simulations for both the HDPE and soft foam material. Independent of the selected turbulence model and the tested material type, the resulting forces of the 0.05 m stem are in high agreement with the experimental forces, with the majority being within the estimated error margin of $\pm 10\%$ of the experimental force sensor. In contrast, the forces of the 0.25 m long stem are generally overestimated. In Fig. 6b the numerical results using URANS with the $k-\omega$ turbulence model are much closer to the experimental forces of the reference experiment have the tendency of being higher compared to those obtained with the wall-adapted RANS turbulence model (Fig. 6a). Nevertheless, the force computed for the 0.25 m long stem is still overestimated overestimates the experimental results by a factor of 1.5 for the HDPE material and over 2 for the fastest current velocity for the case of the soft foam material. Smaller deviations to the experimental

data could be observed using LES in Fig. 6c. Especially for the 0.05 m long stem, the deviations of the simulated to the experimental forces are for seven out of eight investigated velocities within a $\pm 10\%$ error margin. Larger deviations can be seen for the 0.25 m long stem, pointing out that accurate modeling of the turbulence is especially crucial with longer stem lengths.

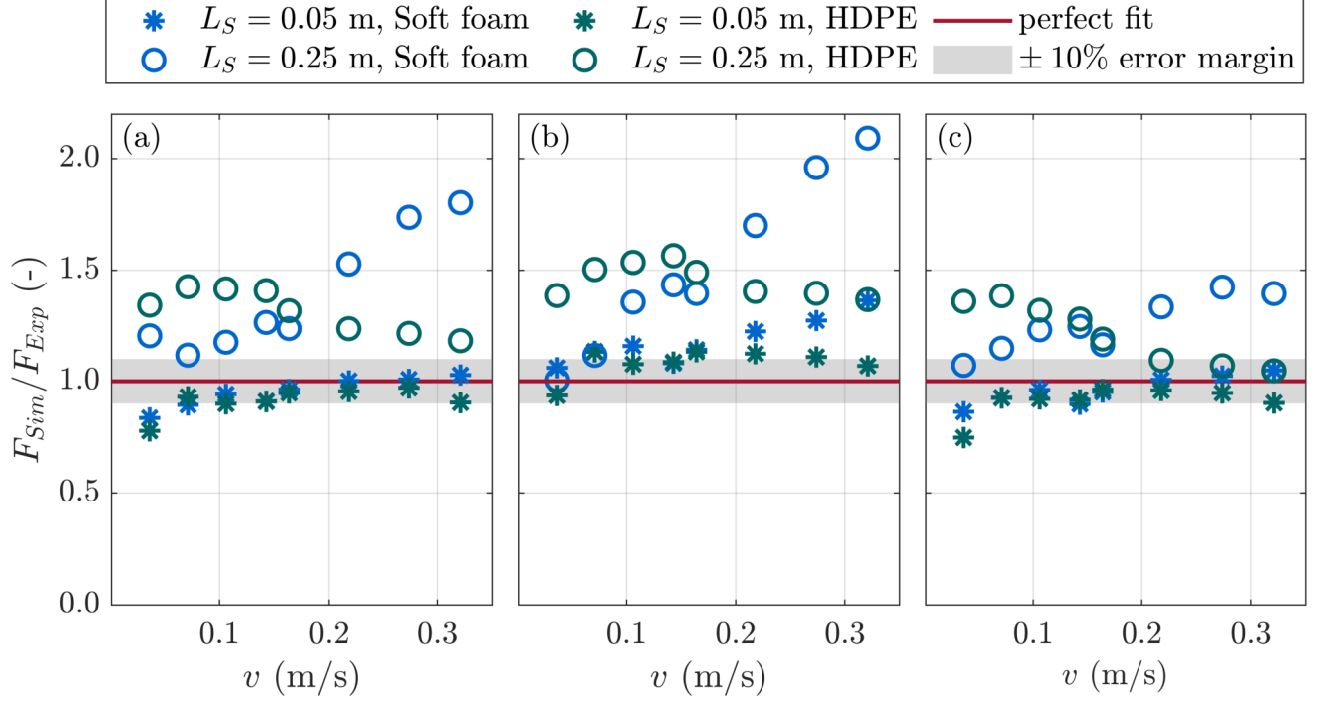


Figure 6: Comparison of simulated vs. experimentally-derived forces (Luhar and Nepf, 2011), for both the soft foam and HDPE Material and two stem lengths $L_S = 0.05$ m and $L_S = 0.25$ m with (a) wall-adapted RANS, (b) URANS and (c) LES turbulence modeling

Concluding the comparison between the resulting FSI for different turbulence models, Fig. 7 depicts the flow fields and resulting bending positions of the stem for the wall-adapted RANS, URANS, and LES. It becomes apparent that utilizing the wall-adapted RANS and URANS results in a similar flow field and stem bending position (Fig. 7a and Fig. 7b). As anticipated, the LES results differ in the flow field due to its ability to resolve larger eddies (Fig. 7c). Nevertheless, the stem bending results are in the same position for all herein compared to the turbulence models.

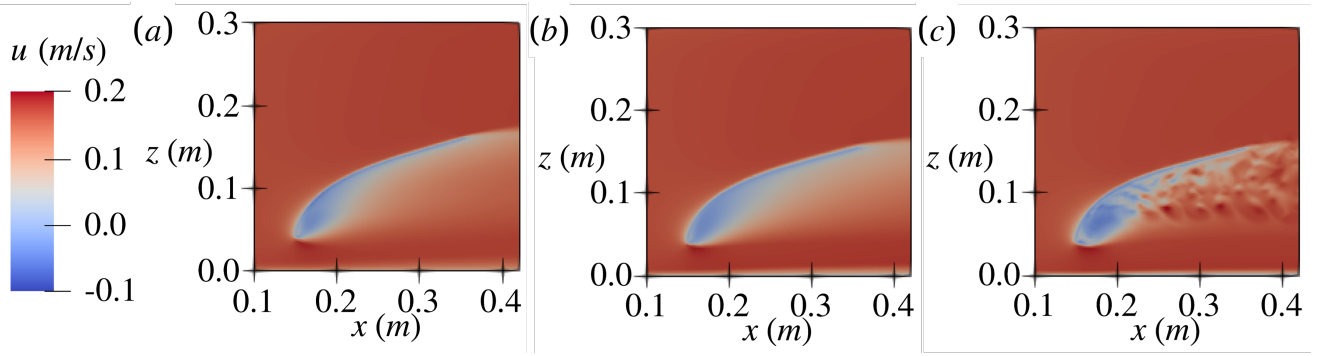


Figure 7: Simulated flow field for the 0.25 m long stem with HDPE Material and a current velocity of 0.16 m/s comparing (a) wall-adapted RANS, (b) URANS and (c) LES turbulence modeling

In summary, the wall-adapted RANS approach enhances the FSI in the FD CFD solver, confirmed by the resulting reasonable forces and stem bending. Similar stem bending can be observed when comparing different turbulence model families, including wall-adapted RANS, URANS, and LES. However, LES demonstrated the closest alignment with experimental results in terms of force deviations, making it the preferred turbulence modeling approach for this study.

As the resulting forces are sensitive to the chosen turbulence model, the sensitivity regarding the SGS model and their corresponding coefficients was also tested. [...]

Discussion section: [Line 769 - 785]

4.1 Applicability of the model

The importance of choosing a suitable turbulence model to accurately simulate the flexible stem motion and the corresponding forces of the FSI has been highlighted in Section 3.1. The approach of a wall-adapted RANS turbulence model to improve the FSI shows promising results compared to the RANS approach without adaption. Its application should be the subject of future investigations, such as evaluating the influence when varying the incorporated turbulence factor, which enhances the turbulent energy dissipation. Based on that, the wall-adapted RANS approach can be a viable option for test setups including FSI when LES is not the favorable turbulence model. However, Fig. 6 shows that the resulting forces are in the highest agreement with the experimental results when utilizing the LES turbulence model. As a potential explanation, the resolved eddies close to the surface of the structure could be crucial to simulate the motion and forces correctly, and they can be simulated using the LES approach. A variation of the Smagorinsky coefficient C_S has been studied, revealing that lower values of C_S result in smaller forces applied on the stem. [...]

Appendix: [After Line 1046]

~~Appendix B. Comparison of results between the RANS and URANS turbulence model~~

~~The combination of overestimated forces and bending of the RANS simulations suggests a possible issue in the simulation dynamics. To provide further insights, the results of RANS and URANS are compared for different quantities. Three~~

different time steps of the simulation are provided in Fig. B22, B23 and B24. These time steps represent the three different stages of the bending process: first the initial condition, second during the stem bending, and third the steady state bent position. The first selected time step, before the FSI begins, shows that the initial conditions of the RANS and URANS simulations are the same for all presented quantities.

Fig. B22 displays the residual pressure, calculated by $p_{res} = p - (\rho g(h - z))$, around the stem to provide an impression of the flow field. As expected, positive pressure can be observed above the stem and negative pressure below it for both turbulence models. The stem using RANS shows locally (at the bottom and at the tip of the stem) lower negative pressures compared to the URANS simulation. An indicator of the unexpected behavior of the RANS simulation could be negative pressure above the stem, which appears slightly in Fig. B22b and is more pronounced in Fig. B22e. To determine possible explanations for the unexpected pressure above the stem using RANS, parameters describing the turbulence model are compared in the following.

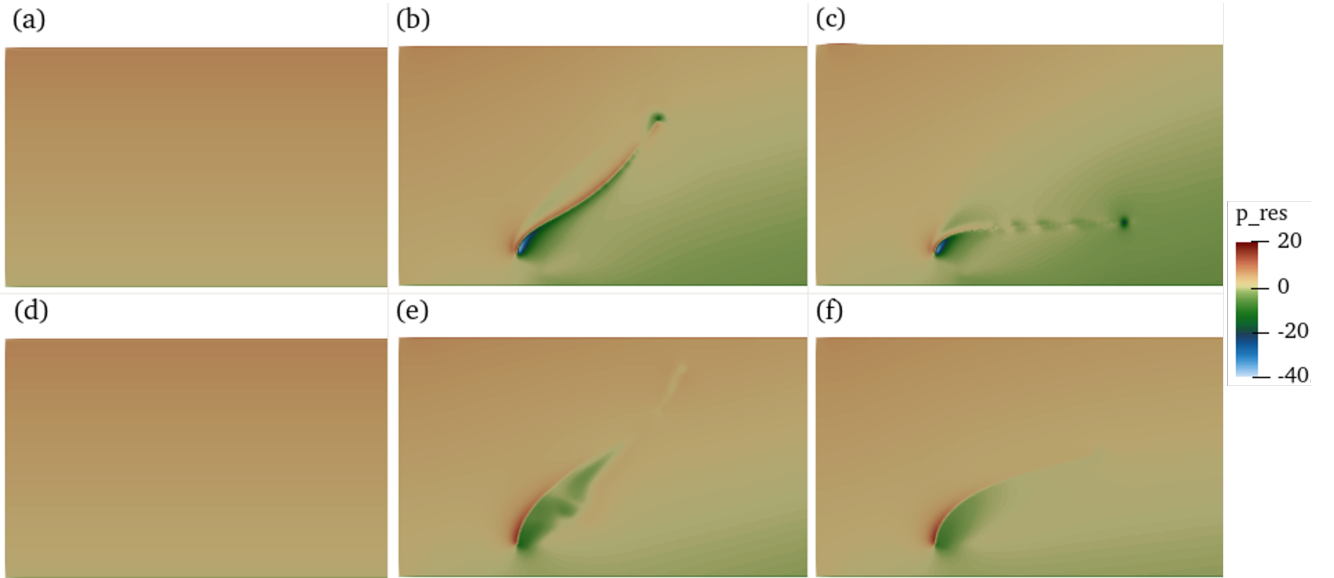


Figure B22: Comparison of the residual pressure for the (a-c) RANS and (d-f) URANS simulations at (a,d) the initial condition ($t = 0$ s), (b,e) the bending phase ($t = 1$ s) and (c,f) the final bending position ($t = 50$ s)

The turbulent kinetic energy is displayed for the RANS and URANS simulation in Fig. B23. Overall, a larger turbulent kinetic energy can be observed at the area of the stem for the RANS simulation compared to URANS. It is apparent that only the URANS stem develops a wake. Furthermore, the same area, which showed a negative residual pressure in Fig. B22e, shows the presence of turbulent kinetic energy in Fig. B23e for the RANS simulation. Possibly, the turbulence produced at the proximity of the stem is transported by the RANS turbulence model to a wider area in the flow field.

Depending on the kinematic turbulent energy, the differences in the eddy viscosity between the two turbulence models can be seen in Fig. B24. A logarithmic scale has been applied to the results in Fig. B24 to visualize the spread of magnitude of the eddy viscosity around the stem between the two turbulence models. For the stem of the URANS simulation, an increased eddy viscosity can be observed

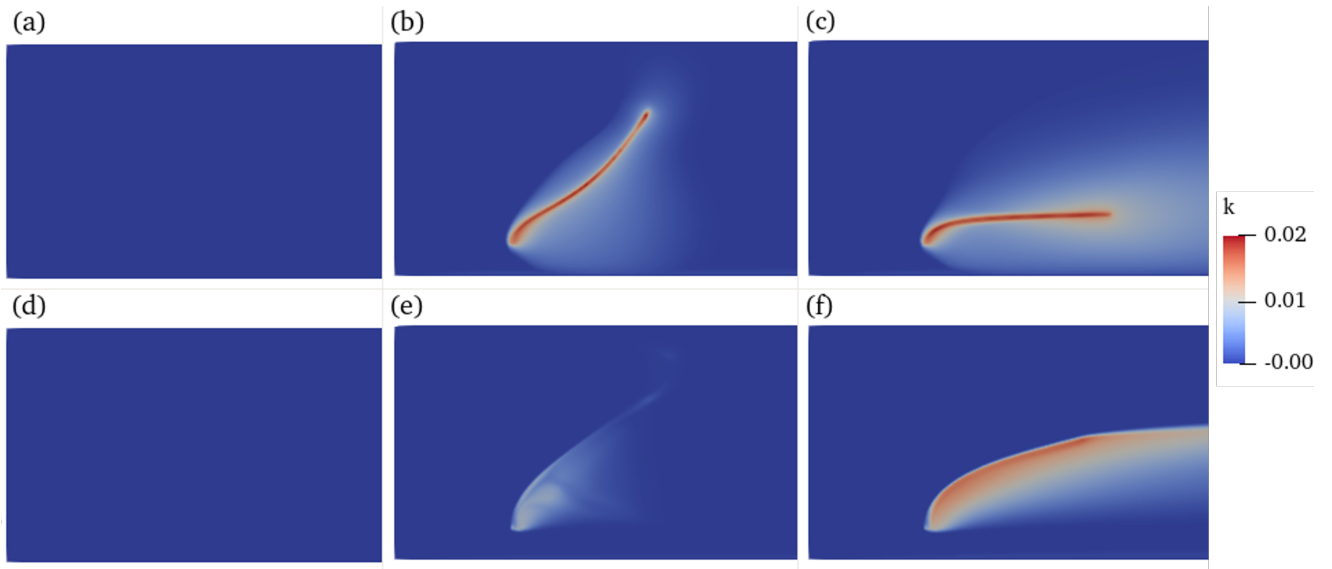


Figure B23: Comparison of the kinematic turbulent energy for the (a-c) RANS and (d-f) URANS simulations at (a,d) the initial condition ($t = 0$ s), (b,e) the bending phase ($t = 1$ s) and (c,f) the final bending position ($t = 50$ s).

below and in the wake of the stem, where turbulence is expected (Fig. B24e and f). For the RANS simulation, the area of the increased eddy viscosity in Fig. B24e resembles, logically, the area of increased kinematic turbulent energy in Fig. B23c. The overestimation of the eddy viscosity based on the RANS turbulence model possibly prevents the recirculation of the flow field below the stem, leading it to be overbent.

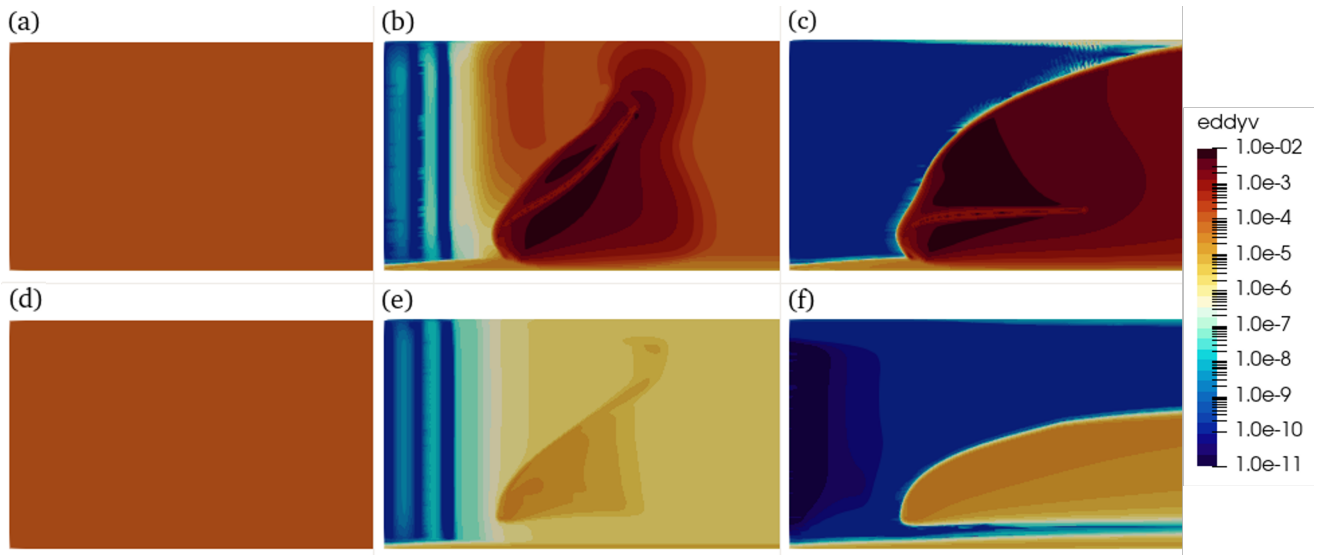


Figure B24: Comparison of the eddy viscosity for the (a-c) RANS and (d-f) URANS simulations at (a,d) the initial condition ($t = 0$ s), (b,e) the bending phase ($t = 1$ s) and (c,f) the final bending position ($t = 50$ s)

Overall, differences in the residual pressure, kinematic turbulent energy, and eddy viscosity can be observed when comparing the results of the RANS and URANS simulations. The resulting flow field based on the RANS turbulence model is a combination of the RANS model in general, its implementation in REEF3D::CFD, the model's inherent parameters, and specific limiter functions

~~applied in REEF3D::CFD. Future studies should investigate which of the contributors can be adapted, while reproducing physical correct behavior, to achieve suitability of the RANS turbulence model in REEF3D::CFD in combination with the FSI solver.~~

References

- Bihs, H., Kamath, A., Alagan Chella, M., Aggarwal, A., Arntsen, Øivind., 2016. A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. *Computers & Fluids* 140, 191–208. doi:doi: 10.1016/j.compfluid.2016.09.012.
- Bush, R.H., Chyczewski, T.S., Duraisamy, K., Eisfeld, B., Rumsey, C.L., Smith, B.R., 2019. Recommendations for future efforts in rans modeling and simulation. Paper presented at the AIAA Scitech 2019 Forum, in San Diego, California, 7–11 January 2019.
- Luhar, M., Nepf, H.M., 2011. Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. *Limnology and Oceanography* 56, 2003–2017. doi:doi: 10.4319/lo.2011.56.6.2003.
- Tschisgale, S., Fröhlich, J., 2020. An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid. *Journal of Computational Physics* 423 (7). doi:doi: 10.1016/j.jcp.2020.109801.

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A summary of this publication can be found in Section 3.3 of this thesis. The following documents show the published study as well as the answers to reviewer comments.



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Research paper

Vegetation stem dynamics under wave loading: Insights from a coupled fluid–structure model

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ABSTRACT

Accurate replication of the stem motion of submerged aquatic vegetation is crucial to gain insights into its capacity for coastal protection and adaptability, such as the wave attenuation capacity and local sediment mobilization. The fluid–structure interaction solver within the numerical model REEF3D::CFD is validated, and then further employed to analyze vegetation stem motion and resulting drag forces, under wave loads using reference experiments, and covering a wide range of material properties and hydrodynamic conditions found in natural aquatic vegetation. Good agreement between simulated and experimental results is achieved for most test cases. This is expressed by less than 10% deviation of the simulated to the experimental forces and the stem positions relative to the stem length. To investigate possible sources of discrepancies between the numerical and experimental results, the flow field in front of the stem is compared with that measured during the reference experiments. Bending modes of stem movements provide further insights into the complex dynamic behavior of stems. Additionally, the study demonstrates the influence of the model's built-in damping coefficients on the time-dependent stem movement under wave load for different material types. For all tested material types, the findings suggest that the use of damping coefficients ranging between 1×10^{-8} and 1×10^{-6} led to the successful replication of the stem dynamics and the resulting drag forces. Accurate predictions of vegetation response to wave loading require careful selection of the governing parameters in the structural model replicating the stem. Considering this, the proposed fluid–structure interaction solver proves highly effective for simulating a wide range of flexible, submerged vegetation stems.

1. Introduction

Submerged aquatic vegetation can be found in various environments and among different species, such as seagrass meadows, kelp forests, or salt marshes. Each offers vital ecosystem services, such as increased wave attenuation (Paul et al., 2012; Keimer et al., 2021), sedimentation rates (Bouma et al., 2005) and erosion resistance (Lo et al., 2017; Kosmalla et al., 2022). Numerical simulations allow for projections of such ecosystem services submerged aquatic vegetation provides (Henderson, 2019; Marjoribanks et al., 2019). Nevertheless, replicating the diverse properties of live vegetation, including the flexibility of its components, remains challenging to date (Wang et al., 2023; Cui et al., 2023). While the wave attenuation capacity is directly related to the vegetation's flexibility (van Veelen et al., 2020; Lou

et al., 2021; Schoutens et al., 2024), the sedimentation rate and erosion resistance are indirectly influenced by the plant's flexibility through the altered turbulence of the surrounding flow field and correspondingly the sediment motion in the water column (Ros et al., 2014; Heuner et al., 2015; Cahoon et al., 2021). However, submerged aquatic vegetation exhibits a wide range of flexural stiffness, varying with both plant species and their local environment (Keimer et al., 2024), necessitating models capable of accounting for this variability.

The highest flexibility can be observed in plants that are permanently submerged, such as eelgrass, e.g., *Thalassia testudinum* with $EI = 1.10 \times 10^{-8} \text{ Nm}^2$ (Bradley and Houser, 2009), and kelp, e.g., *Saccharina latissima* with $EI = 7.86 \times 10^{-5} \text{ Nm}^2$ (Fredriksson et al., 2020). Salt marsh

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vegetation, which is only inundated during high tides, such as the upper salt marsh species *Elymus athericus* with $EI = 8.00 \times 10^8 \text{ Nm}^2$ (Zhu et al., 2020a) and the lower salt marsh species *Spartina anglica* with $EI = 2.10 \times 10^9 \text{ Nm}^2$ (Vuik et al., 2017) have comparably high flexural stiffness. The flexural stiffness of the salt marsh species is additionally influenced by seasonal variation (Schulze et al., 2019; Liu et al., 2024), ranging, for example, for *S. anglica* from $1.45 \times 10^9 \text{ Nm}^2$ in May and June to $3.98 \times 10^9 \text{ Nm}^2$ in December and January (Keimer et al., 2023). Accurately replicating the flexibility properties of such vegetation in a model is essential when modeling their stem dynamics. Not only does the flexibility of the vegetation differ between species, but also their phenology and geometry. This study simplifies, as a first approach, natural vegetation to its stem, neglecting hence its roots, branches, and leaves. However, some vegetation, for example *S. anglica* in its winter state (Keimer et al., 2023), consists of only a stem and can be therefore fully characterized by the presence of only the stem.

Numerical models replicating flexible vegetation stems in different hydrodynamic conditions can be either one-way coupled, simulating the impact of the fluid on the vegetation solely, e.g., Luhar and Nepf (2016), or two-way coupled, resulting in alterations of the surrounding flow field due to reaction of the stems, e.g., Chen and Zou (2019) or Derksen (2021). Aiming for future investigations regarding the vegetation's ecosystem services in a coastal environment, this study focuses on two-way coupled fluid–structure interaction (FSI), replicating the motion of flexible stems under wave loading. To date, such coupling remains complex also due to the differences in geometry of the considered domains: wave height and water depth are usually in the order of several centimeters to meters, while stem width and thickness usually have a millimeter range (e.g., Moeller et al. (2014), Garzon et al. (2019), Markov et al. (2023), Keimer et al. (2023)). Additionally, such delicate structures undergo large deformations depending on the impacting wave conditions. Meanwhile, the vegetation dynamics under wave loading are time-dependent, involving rapid stem movement (Mullarney and Henderson, 2010; Rupprecht et al., 2017). Therefore, replicating the conditions of wave-induced FSI observed in nature requires a high-resolution flow field combined with robust coupling.

In the literature, several studies report on the simulation of individual, flexible stems under wave load (Maza et al., 2013; Chen and Zou, 2019; Henderson, 2019; Hagmeyer et al., 2024), yet without a thorough analysis of the time-dependent stem motion and resulting forces, due to the overall aim of investigating parameters such as the wave attenuation on a canopy scale. For example, Maza et al. (2013) calibrated drag coefficients based on decreasing wave heights over a vegetation meadow from physical experiments for their numerical model of individual, flexible stems. Afterward, they validated their model of a swaying vegetation meadow through a model comparison, using wave attenuation and vertical velocity profiles. The physical experiments of Maza et al. (2013) have been used to validate the models' minimum and maximum stem deflection by Chen and Zou (2019), without considering the time-dependent components, followed by an investigation of the wave attenuation by a vegetation patch under wave load and the turbulence characteristics within the meadow. Henderson (2019) utilized a model including individual stems under wave loading while emphasizing the influence of stem buoyancy and flexibility on wave attenuation including life vegetation properties. Its replication of natural conditions remains uncertain, given a constant drag coefficient was applied for all evaluated plant species without validating the resulting forces. Hagmeyer et al. (2024) studied configuration parameters of their numerical model for an individual stem with an inflow velocity profile similar to waves but did not validate the resulting forces exerted on the stem, before focusing their investigation on the monami phenomenon, which describes the synchronized movement of vegetation meadows in unidirectional flow. None of the previously referenced studies examined the time-dependent motion of vegetation stems under wave load in detail, despite its significance, as downstream velocity and

vorticity fields are directly influenced by upstream vegetation dynamics (Caroppi et al., 2019; Hussain et al., 2024). Moreover, accurately replicating stem movement is crucial for understanding sediment dynamics, as it affects the incipient sediment motion (Wang et al., 2015). It is also important to accurately replicate stem motion to ensure that studies of meadow-scale phenomena, such as monami and large-scale vortices (Tschisgale et al., 2021; Wang et al., 2022; Xu et al., 2022), reflect the behavior of live vegetation, as well as to correctly replicate plant reconfiguration at the meadow scale, where reconfiguration can lead to the closure of gaps between individual plants (Fonseca et al., 2019). Last, accurately replicating and understanding individual stem dynamics is essential before utilizing parameterization in large-scale engineering models, particularly for flexible stems, where it remains unclear whether nonlinear wave kinematics or Lagrangian motion predominantly governs the forces acting on the stems (Jacobsen et al., 2019).

Other studies have specifically focused on the motion and forces of individual, flexible stems under wave loading. The experiments by Luhar and Nepf (2016), conducted in the framework of the study specifically for validation purposes, serve as a benchmark test case for numerous other studies (Zhu et al., 2020b; Yin et al., 2021; Jin and Zhang, 2022; el Rahi et al., 2023). Some of these studies applied a variation of the Morison equation to calculate the wave loads acting on the stem (Zhu et al., 2020b; Yin et al., 2021; Jin and Zhang, 2022), leading to overall good agreements between experimental and numerical stem motion. The required drag coefficient has been either based on the proposed value by Luhar and Nepf (2016) with $C_D = 1.95$ (Jin and Zhang, 2022), extended by a relationship to the KC number (Zhu et al., 2020b) with $C_D = \max(10KC^{-1/3}, 1.95)$, or estimated based on model calibration (Yin et al., 2021). Famikhilili and Tahvildari (2022) used a drag coefficient dependent on the local curvature of the stem and validated their model's stem movement with the experiments of Maza et al. (2013) and their resulting forces with experiments from Jacobsen et al. (2019). Nevertheless, it remains uncertain to which extent such models can replicate the stem movement and resulting forces exerted on live vegetation, as they rely on drag coefficients calibrated with surrogate models.

Allowing for further insights into the vegetation's ecosystem services of specific locations of interest requires in-situ measured vegetation properties to be incorporated into numerical models. However, applying in-situ data to such models remains challenging due to the limited availability of drag coefficients for specific vegetation species, especially including seasonality (Riffe et al., 2011; Caroppi and Järvelä, 2022). As an alternative to approaches relying on drag coefficients, el Rahi et al. (2023) proposed the coupling of a Lagrangian fluid solver with an external finite element method (FEM) solver utilizing smoothed-particle hydrodynamics (SPH), yielding promising results with a mean absolute error of -0.002 N based on a variation of stem lengths. To date, the simulation with fine resolutions and thin stems remains challenging for SPH approaches. Successfully applied two-way couplings of a flexible structural solver based on a Lagrangian approach to its surrounding Eulerian fluid can be found in various application cases, such as bio-inspired swimmers (Bi and Zhu, 2019; Li et al., 2021), flexible plates for structural applications (Lim and Xiao, 2019; Ando et al., 2021) or turbomachinery (Schmucker et al., 2010; Benra et al., 2011). Even though providing a strong coupling approach, replicating the range of motion resulting from the previously introduced range of stiffness found in submerged flexible vegetation remains challenging. Studies like those of Jin and Zhang (2022) and el Rahi et al. (2023), validated their models based only on the stiffer material, as used by Luhar and Nepf (2016). Wei et al. (2024) recently introduced a FSI solver that can undergo relatively large deformations and thus mimic highly flexible vegetation by incorporating a truss-spring model to represent the vegetation stem. The critical time step size of the structural solver applied by Wei et al. (2024) is related to the Young's modulus of the stem, leading to a decreased efficiency for more

stiff vegetation species, such as salt marsh vegetation. To date, two-way coupled FSI solvers utilizing direct forcing are limited to some extent by their range of applicability, rendering the evaluation of further FSI solvers, their validity, and application range useful.

Aiming to replicate the large and rapid deformation dynamics of a stem's motion under wave load for a broad range of flexural stiffness, this study investigates the capabilities and requirements of such a two-way coupled FSI solver. Therefore, a structural solver based on the direct-forcing approach, described by Tschisgale and Fröhlich (2020), is used within the numerical model REEF3D::CFD. The model entails a finite difference (FD), incompressible, two-phase fluid solver. The FSI tool within the FD-models framework uses a two-way coupling between the structural and fluid solver. It has been successfully validated by Prüter et al. (2025) for unidirectional flow. The authors demonstrated the model's ability to simulate both the motion and resulting forces of a flexible vegetation stem, including the dependency of the force spectrum with respect to the damping coefficients. The model's capacity to evaluate parameters beyond phase-averaged properties such as turbulence intensities was shown. The model's ability to include vegetation properties measured in the field was particularly emphasized.

The structural model applied in this work solves the two Cosserat rod equations (see Section 2.1). The Cosserat rod theory, see O'Reilly (2017) for a general introduction, has been studied in theoretical mechanics (Cao and Tucker, 2008; Lang et al., 2011; Jung et al., 2011) and was employed for various applications to simulate the movement of slender bodies. One example is the area of robotics, where it is used to model cables or actuators (Rucker and Webster III, 2011; Renda et al., 2014; Till et al., 2019). Solving FSI problems comparable to the case at hand, both Tschisgale and Fröhlich (2020) and Agrawal et al. (2024) deploy the geometrically exact Cosserat rod for their structural solver, with the advantage of capturing three-dimensional motion while using a one-dimensional mathematical model for their stem, thus making it computationally more efficient.

The FSI tool used in this study can be characterized by its ability to directly calculate the forces acting on the solid, without requiring empirical parameters, such as the drag coefficient. However, the structural solver incorporates damping coefficients (see Section 2.1), which are essential to account for the internal non-linear viscous damping of rods (Lang et al., 2011; Linn and Lang, 2013) and to reduce the transient bending modes (Palm and Eskilsson, 2020). Martin and Bihs (2021) mentioned that the structural solver's inherent damping coefficients influence the time-dependent stem motion and are crucial for ensuring the numerical stability of simulations. Consequently, the authors recommended that the damping coefficients should be non-zero values. This observation was confirmed by Prüter et al. (2025) by evaluating the damping coefficient's impact on the fluctuating motion of flexible stems in unidirectional flow. Furthermore, Prüter et al. (2025) observed that the choice of damping coefficient affected the frequency of stem fluctuations and the resulting turbulence intensity behind the stem. While this knowledge has so far remained on an observational level, selecting appropriate damping coefficients and understanding as well as analyzing their influence on the motion solution in numerical simulations is expected to be vital for accurately modeling the stem motion under wave loading.

Different approaches can be found in the literature regarding the internal non-linear viscous damping of Cosserat rods. The model utilized by Agrawal et al. (2024) did not include the dissipative part due to internal friction for calculating the internal moments. Therefore, their study has not incorporated comparable damping coefficients to those applied by Palm and Eskilsson (2020) or Martin and Bihs (2021). While Tschisgale and Fröhlich (2020) have stated that the damping coefficients are related to the properties of the applied material, they did not evaluate the implication of the applied damping coefficients on the motion of the rod any further. Similarly, Lang et al. (2011) referred to the damping coefficients as viscoelastic material parameters

and applied coefficients to dampen their rod's motion, without further specifying the applied values. Following that, Linn and Lang (2013) theoretically determined the damping coefficients based on the rod's material parameters and retardation time constants. The relationship has been applied by Renda et al. (2014) and Till et al. (2019) to simulate soft robot arms, but has limited applicability for this study, especially for live vegetation, due to scarce parameter availability and the structural solver's requirement of a homogeneous and isotropic material. To the authors' knowledge, no other studies have explored the application of damping coefficients for a Cosserat rod to simulate vegetation dynamics in wave motion. Consequently, it remains unclear whether a relationship between the damping coefficients and the material's properties can be applied. Yet, guidance regarding applying the damping coefficients is crucial for effectively implementing field data from live vegetation.

The authors hypothesize that suitable damping coefficients must be large enough to ensure numerical stability, as observed by Martin and Bihs (2021) and concluded by Simeon (2001), but small enough to avoid non-physical damping of the stem motion. Suitable damping coefficients for field data are unknown, necessitating a workflow to determine appropriate damping coefficients. In summary, the following specific objectives are hence addressed within this study:

- To evaluate the ability of the proposed FSI model to replicate wave-induced time-dependent movement and forces of an individual stem
- To investigate the influence of the flow field in front of an individual stem on the stem motion of the proposed FSI model
- To determine the constraints of the model inherent damping coefficients on the wave-induced stem motion

2. Methodology

The methodology section of this study is divided into three parts. First, the underlying functions of the numerical model are described, emphasizing the role of the damping coefficients within the structural solver. Second, the specific model setup used within this study is introduced, including a comparison of the material properties. Third, details of the applied data analysis are provided.

2.1. Numerical model

The hydrodynamic numerical model utilized in this study is the FD solver REEF3D::CFD, distinguished by the level-set method for representing the free surface and its high-order discretization schemes. The fluid solver is based on the incompressible Navier–Stokes equation, for further details on the implementation and validation, the reader is referred to Bihs et al. (2016). The Navier–Stokes equations are herein expressed by the incompressible continuity equation (1) and the incompressible momentum equation (2).

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_f} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \nu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + f_i \quad (2)$$

In Eqs. (1) and (2), u_i represents the velocity vector in three dimensions (x, y, z), while t denotes time. The fluid density is given by ρ_f and pressure by p . The mass-specific external load f_i consists of the gravitational acceleration g_i and the coupling force f_r ($f_i = g_i + f_r$), detailed at the end of this section. The formulation includes two viscosity components: the molecular kinematic viscosity of the fluid, ν , and the eddy viscosity, ν_t . Here, the spatially filtered Navier–Stokes equation is applied to solve the subgrid-scale eddy viscosity with large eddy simulations (LES). A Smagorinsky constant of 0.1 is utilized based on the findings of Prüter et al. (2025) to represent the turbulence within the flow field appropriately for a FSI.

The structural solver is based on the geometrically exact Cosserat rod equations (Lang et al., 2011; Tschisgale and Fröhlich, 2020). Integrating the flexible structure within the fluid solver via the immersed boundary method (IBM) involves the fluid solver's Eulerian coordinates and the structural solver's Lagrangian coordinates. The flexible structure is divided into n individual rigid elements, with forces and moments calculated for each element. The coupling of the two coordinate systems is achieved through Lagrangian points on the surface of the Lagrangian volume, where the velocity components of the fluid are transferred. The structural solver has been presented in detail in Prüter et al. (2025). Selected equations are presented in the following to provide insights into the role of the damping coefficients on the structural solver. Structural motions are calculated by the two geometrically exact Cosserat rod equations:

$$\rho_S A \ddot{\mathbf{r}} = \frac{\partial \mathbf{f}}{\partial X} + \mathbf{f}_{\text{ext}} \quad (3)$$

$$\rho_S I \dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \rho_S I \boldsymbol{\omega} = \frac{\partial \mathbf{m}}{\partial X} + \frac{\partial \mathbf{r}}{\partial X} \times \mathbf{f} + \mathbf{m}_{\text{ext}} \quad (4)$$

Eq. (3) calculates the translational motion $\ddot{\mathbf{r}}$, Eq. (4) the rotational motion $\dot{\boldsymbol{\omega}}$ of the rod. In Eqs. (3) and (4), ρ_S is the density of the solid, A the area of the cross-section, I the second moment of area and $\mathbf{f}_{\text{ext}}$ and $\mathbf{m}_{\text{ext}}$ are the external force and moment. Assuming the rod aligns with a linear viscoelastic material of Kelvin-Voigt type (Tschisgale and Fröhlich, 2020; Martin and Bihs, 2021), the shearing and stretching of the rod determine the internal force $\mathbf{f}$ and bending and twisting govern the internal moment $\mathbf{m}$, which is the sum of the linear elastic part and the dissipative part due to internal friction:

$$\mathbf{f} = R \mathbf{f}_0 = R C_{\varepsilon,0} \cdot (R^T \boldsymbol{\varepsilon} - (R^T \boldsymbol{\varepsilon})|_{t=0}) + R C_{\dot{\varepsilon},0} \cdot (\dot{R}^T \boldsymbol{\varepsilon} - (R^T \dot{\boldsymbol{\varepsilon}})) \quad (5)$$

$$\mathbf{m} = R \mathbf{m}_0 = R C_{\kappa,0} \cdot (R^T \boldsymbol{\kappa} - (R^T \boldsymbol{\kappa})|_{t=0}) + R C_{\dot{\kappa},0} \cdot (\dot{R}^T \boldsymbol{\kappa} - (R^T \dot{\boldsymbol{\kappa}})) \quad (6)$$

Eq. (5) includes the strain ($\boldsymbol{\varepsilon} = \frac{\partial \mathbf{r}}{\partial X}$) and Eq. (6) the curvature ($[\boldsymbol{\kappa}]_x = \frac{\partial R}{\partial X}$) vector. Structural viscosity is described by $C_{\dot{\varepsilon},0}$ for translational damping and by $C_{\dot{\kappa},0}$ for rotational damping. The previously introduced damping coefficients are both determined by

$$C_{\dot{\varepsilon},0} = \text{diag}(c_{dx}, c_{dy}, c_{dz}) \quad (7)$$

$$C_{\dot{\kappa},0} = \text{diag}(c_{kx}, c_{ky}, c_{kz}) \quad (8)$$

In Eqs. (7) and (8), the axial extension or compression is represented by c_{dx} and the dampening of the shear force by c_{dy} and c_{dz} . The torsional dampening is determined by c_{kx} and the bending moment is dampened by c_{ky} and c_{kz} . Till et al. (2019) noticed numerical instability for stiff extension and shearing dynamics. Therefore, and due to negligible influence on the stem bending dynamics, the damping coefficients of the matrix $C_{\dot{\varepsilon},0}$ have been set equal to unity throughout this study. The influence of different values of the damping coefficients in the matrix $C_{\dot{\kappa},0}$ is evaluated in Section 3.4.

The coupling of the fluid and the structural solver is implemented based on the zero-thickness assumption of the rod on the interface Γ between the fluid and solid (Tschisgale and Fröhlich, 2020). To account for the different dimensions, the coupling force f_Γ is converted to a volumetric force via delta functions for the three-dimensional flow field and integrated over the arc's length for the one-dimensional rod. Here, the coupling force f_Γ relates to the stress vector (σn) in the fluid (hydrodynamic stress tensor σ) and the structural (Cauchy stress tensor σ_s) part. The dynamic coupling condition is fulfilled when the stress vectors of each phase at the interface Γ are equal ($\sigma n = \sigma_s n, \forall x \in \Gamma$). The kinematic coupling condition states that the fluid's velocity is the same as the solid's at the interface Γ , corresponding to a no-slip condition ($u = v, \forall x \in \Gamma$).

Based on the previously introduced conditions, the coupling on the interface Γ can be achieved in the following steps: First, a preliminary velocity $\tilde{u}$ is calculated in the fluid solver by Eqs. (1) and (2)

Table 1

Summary of the hydrodynamic conditions (including the wave height H , the wave period T and the water depth d), and investigated material properties (including the stem length L_S , width W_S , thickness T_S and density ρ_S , the Young's modulus E , the second moment of area I and the flexural stiffness EI) and the elevated stem position above the ground d_S , based on the surrogate materials used by Luhar and Nepf (2011) and Jacobsen et al. (2019), with ABS = acrylonitrile butadiene styrene.

	Luhar and Nepf (2016)	Jacobsen et al. (2019)	
Name	Material 1	Material 2	Material 3
H (m)	0.08	0.04, 0.07, 0.11	
T (s)	2.0	1.5, 2.0	
d (m)	0.30	0.45	
d_S (m)	0.04	0.00	
Material (-)	silicon foam	polystyrene	ABS
L_S (m)	0.20	0.15, 0.30	0.15, 0.30
W_S (m)	0.02	0.01	0.008
T_S (m)	1.9×10^{-3}	5.0×10^{-3}	1.6×10^{-3}
ρ_S (kg/m ³)	670	1030	1090
E (Pa)	5.0×10^5	2.3×10^9 , 3.3×10^9	2.2×10^9
I (m ⁴)	1.10×10^{-11}	1.04×10^{-13}	2.73×10^{-12}
EI (Nm ²)	0.06×10^{-4}	2.4×10^{-4} , 3.4×10^{-4}	60.1×10^{-4}

without including f_Γ . Following the kinematic coupling condition, $\tilde{u}$ is communicated to the structural solver. The structural solver then iterates for f_Γ with the Cosserat rod equations. Based on the dynamic coupling condition, f_Γ is returned to the fluid solver, which computes u_Γ utilizing the Navier–Stokes equations. Further elaboration of the coupling algorithm is provided by Tschisgale and Fröhlich (2020).

2.2. Model set-up

2.2.1. Reference experiments and measurement accuracies

Physical flume experiments from Luhar and Nepf (2016) and Jacobsen et al. (2019) have been selected to evaluate both the accuracy of the proposed FSI solver and address the raised research objectives in Section 1. Both experimental campaigns captured the motion and forces of an individual stem under wave loading. Additional measurement data, such as the water surface elevation and velocity in front or next to the experimental stem, have been provided to the authors by Luhar and Nepf (2016) as well as Jacobsen et al. (2019). The two experimental campaigns in combination provide an extensive data set, enabling the evaluation of three different materials (including different stem densities ρ_S and flexural stiffnesses EI), three different stem lengths ($L_S = 0.15, 0.20$, and 0.30 m), widths ($W_S = 0.02, 0.01$, and 0.008 m), thicknesses ($T_S = 1.9 \times 10^{-3}, 5.0 \times 10^{-3}$, and 1.6×10^{-3} m) and a variation of hydrodynamic conditions. For the 0.15 m long polystyrene stem utilized by Jacobsen et al. (2019), the lowest value of the Young's modulus from the manufacturer specification range is here applied (2.3×10^9 Pa), based on communicated measurement uncertainties. A summary of the tested materials and hydrodynamic conditions is provided in Table 1. In the following, the tested soft foam stem originating from Luhar and Nepf (2016) is referred to as Material 1, while the two selected stem tests from Jacobsen et al. (2019) are referred to as Material 2 and 3, following their terminology in the original publication. Additionally, the experimental campaigns of Luhar and Nepf (2016) and Jacobsen et al. (2019) are referred to as the reference experiments.

In the reference experiment for Material 1, a wave gauge with an accuracy of 2×10^{-4} m was positioned 0.15 m next to the stem in y -direction. The velocity was captured by PIV with an estimated resolution of 9×10^{-3} m/s. The load cell attached to the stem had a resolution of 0.001 N, with an accuracy of 10 %. The camera's spatial resolution to capture the motion of Material 1 was 3×10^{-4} m/pixel. In the reference experiment for Materials 2 and 3, the velocity was measured using an electromagnetic flow meter (EMF) provided with an accuracy of 0.025 m/s. An accuracy of 0.001 m was reported for the measurement of the water surface elevation. The range of the force transducer was 0.001 N to 3 N, with an accuracy of 0.001 N. The resolution of the camera to capture the stem motion was 4×10^{-4} m/pixel.

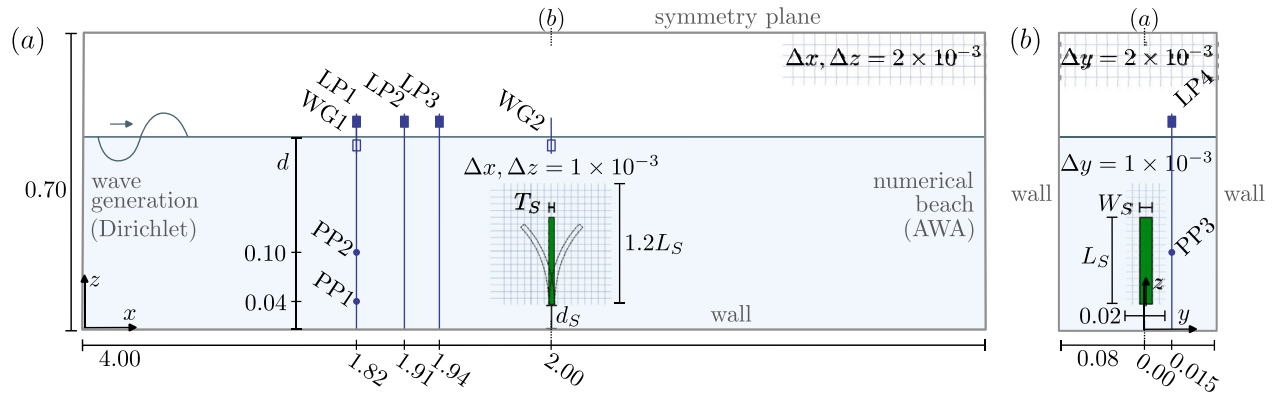


Fig. 1. Sketch of the (a) side view and (b) front view of the numerical wave flume including the positioning of the stem, the wave gauges (WG), line probes (LP), and point probes (PP), and the zone of refined cell size around them (in meters, not to scale). For the simulations of Material 1, $d = 0.30$ m and $d_s = 0.04$ m is used and for Materials 2 and 3 $d = 0.45$ m and $d_s = 0.00$ m, both in accordance with the reference experiments.

2.2.2. Numerical wave flume and reproduction of the hydrodynamic conditions

In the physical experiments, Material 1 was tested in a wave flume with 24.00 m length, 0.38 m width, and 0.60 m depth, while the wave flume used for Material 2 and 3 was 41.50 m long, 0.80 m wide and 0.90 m deep. The numerical wave flume used to replicate the experimental test conditions is visualized in Fig. 1. To ensure computational efficiency, the length and the width of the flume were reduced to 4.00 m and 0.08 m, respectively. Wave generation in the numerical wave flume, which was considerably shorter compared to the physical one used for the reference experiments, was achieved by applying a Dirichlet boundary condition to simulate shallow water waves, combined with active wave absorption at the outlet. While the top of the numerical wave flume is idealized by a symmetry plane, the remaining boundary conditions are defined as walls with a global roughness, k_s , equal to 0.001 m. Initial water levels, d , are either 0.30 m or 0.45 m (as shown in Table 1). The stem was placed in the center of the flume in x - and y -direction for all simulations. The stem with Material 1 was elevated in z -direction ($d_s = 0.04$ m) to replicate the increased height in the reference experiment due to the force measurement device, resulting in a gap between the stem and the flume bottom. As the reference experiment for Materials 2 and 3 lowered their force measurement sensor into the flume bottom, the stems were not elevated for the simulations ($d_s = 0.00$ m). The area of the refined cell size around the stem for the non-uniform grid was chosen relative to the stem length, resulting in an extent of $1.2 L_S$ in x - and z -direction. The extent in y -direction was selected as one-fourth of the flume width for all test cases, resulting in 0.02 m, both indicated in Fig. 1.

The time series of the water surface elevation and horizontal velocity are compared to ensure that the numerical flume can replicate the hydrodynamic conditions of the reference experiments. The results are presented in detail in Appendix A. Damping coefficients obtained by analysis in Section 3.4 are applied in the following sections. For Material 1, the water surface elevation at the stem (WG2) and the measured horizontal velocity in front of the stem (PP1) are compared, and good agreement has been found with a RMSE of 0.065 m/s for the compared time frame of 10 s. High agreement was achieved for the minimum and maximum values of the horizontal flow velocity, with $u_{sim,min} = -0.15$ m/s compared to $u_{exp,min} = -0.16$ m/s and $u_{sim,max} = 0.21$ m/s compared to $u_{exp,max} = 0.21$ m/s. For Materials 2 and 3, the phase-averaged horizontal flow velocity over a wave period at PP2 and over the flume height (LP1) for selected points in time of the wave period are compared. In conclusion, satisfactory agreement was achieved for all tested wave conditions, with RMSEs ranging from 0.008 m/s for the smallest wave height ($H = 0.04$ m and $T = 2.0$ s) to 0.032 m/s for the wave largest wave height ($H = 0.11$ m and $T = 2.0$ s). Further analysis of the wave non-linearity is provided by calculating the wave skewness Sk , as elaborated in Appendix A.1. The skewness

of the simulated wave replicating the experiments of Luhar and Nepf (2016) was calculated as $Sk = 0.60$, indicating non-linearity. Likewise, the 0.11 m high simulated wave replicating the Jacobsen et al. (2019) experiments showed some non-linearity with $Sk = 0.44$. In contrast, the smaller waves (0.04 m and 0.07 m) exhibited lower skewness values of 0.05 and 0.15, respectively, suggesting a linear behavior. Appendix A.2 shows, additionally, that the chosen flume width of 0.08 m for the numerical wave flume has only limited influence on the horizontal flow velocity, resulting in RMSEs smaller than 0.01 m/s, confirming the choice of reduced flume width compared to the reference experiments suitable.

After confirming the accurate representation of the hydrodynamic conditions, the sensitivity of the FSI solver to numerical parameters is evaluated. Therefore, the influence of the spatial and temporal discretization on the stem motion and resulting forces of Material 1 were tested. A variation of the refined cell size (1, 2, and 4×10^{-3} m) in the proximity of the stem and different CFL criteria (0.15, 0.30, and 0.60) have been simulated and compared. It is assumed that the discretization is independent of the selected material type and therefore a convergence based on Material 1 can be extended to the simulations using Materials 2 and 3. The detailed results of this convergence study are provided in Appendix B. The chosen grid leads to a calculated grid uncertainty of 5.68 % based on the RMS of the phase-averaged forces. Regarding the temporal discretization, a CFL criterion of 0.30 provided an optimum between accurate replication of the stem motion and ensuring that a sufficient number of waves are simulated during the available computational time of the utilized high-performance computer (HPC). As a result, the calculated uncertainty using a CFL of 0.30 based on the RMS of the phase-averaged forces is less than 1.00 %. It can be concluded that the use of a refined cell size around the stem of 1×10^{-3} m in combination with a coarse cell size of 2×10^{-3} m can accurately replicate the motion of the stem under wave load.

2.3. Data analysis

A comparison of the different test conditions is enabled by calculating non-dimensional parameters, as seen among others by Luhar and Nepf (2016) and Jacobsen et al. (2019). Such non-dimensional parameters are the Cauchy number Ca , describing the relation of the external drag to the flexural stiffness of the stem, the Buoyancy parameter B , and the Keulegan–Carpenter number KC describing the ratio of drag to inertia. The non-dimensional parameters are calculated as follows:

$$Ca = \frac{\rho W_S u_w^2 L_S^3}{EI} \quad (9)$$

$$B = \frac{(\rho - \rho_S) g W_S T_S L_S^3}{EI} \quad (10)$$

Table 2

Summary of the resulting non-dimensional parameters, with the Cauchy number Ca , the Buoyancy parameter B and the Keulegan–Carpenter number KC , for the tested hydrodynamic conditions (wave height H , wave period T , number of simulated waves N and characteristic orbital velocity u_w) and stem properties (material type and stem length L_S).

Material (–)	L_S (m)	H (m)	T (s)	N (–)	u_w (m/s)	Ca (–)	B (–)	KC (–)
1	0.20	0.08	2.0	12	0.18	942.55	178.93	18.00
2	0.15	0.07	1.5	4	0.12	2.03	–0.21	18.00
2	0.15	0.11	2.0	2	0.23	7.46	–0.21	46.00
2	0.30	0.04	2.0	2	0.09	6.37	–1.16	18.00
2	0.30	0.07	1.5	4	0.13	13.30	–1.16	19.50
3	0.15	0.04	2.0	13	0.08	0.03	–0.01	20.00
3	0.15	0.07	1.5	8	0.12	0.06	–0.01	22.50
3	0.15	0.11	2.0	3	0.23	0.24	–0.01	57.50
3	0.30	0.04	2.0	4	0.09	0.29	–0.05	22.50
3	0.30	0.07	1.5	3	0.13	0.61	–0.05	24.38

$$KC = \frac{u_w T}{W_S L_S} \quad (11)$$

where ρ is the density of the water, g is the gravitational acceleration and u_w is the characteristic orbital velocity. The characteristic orbital velocity u_w is calculated over a characteristic depth for each simulation. Here, the extent of the stem in z -direction was chosen, resulting in a characteristic depth of Material 1 from 0.04 m to 0.24 m, and for Material 2 for example with 0.15 m stem length from 0.00 m to 0.15 m in z -direction. Furthermore, the characteristic orbital velocity u_w is calculated at LP1 for each test case, ensuring hydrodynamic conditions that are not yet influenced by the stem (cf. Appendix A). Following Jacobsen et al. (2019), the RMS of the depth-averaged velocity is used to calculate u_w , resulting in $u_w = \sqrt{2} \langle u_{rms} \rangle_z$. Based on the calculated characteristic wave velocity and the material properties in Table 1, the wave conditions and the obtained non-dimensional parameters are provided in Table 2. Since the number of simulated waves differs depending on the test case and the available computational time, the number of waves available for analysis for each test case is provided in Table 2. In the following, the phase-averaging of the simulated forces is based on the peaks of simulated horizontal flow velocities in front of the stem, following the analysis in the reference experiment for Material 1.

Further insights into the resulting stem motion can be gained by decomposing the stem movement into its bending modes, as done in Jacobsen et al. (2019). The methodology of the proper orthogonal decomposition (POD) has been described in more detail by Birkemeier (1984) and Jacobsen et al. (2014). The shape of bending modes (ϕ_S) is obtained by first calculating the mean stem position, which then allows determining the perturbation relative to the mean of the stem position. Afterward, a POD is used to identify the first ten dominant modes of the motion. After utilizing harmonic filtering based on the first five frequencies to limit the influence of random noise by uncorrelated data, the contribution of the main frequencies on the stem motion is expressed by their weight $\alpha_S(t)$. The first two modes usually provide sufficient insight into the stem bending process: while the first mode includes the dominant part of stem movement, the second bending mode represents the most significant part of the occurring variation of stem bending (Birkemeier, 1984; Jacobsen et al., 2019). The comparison between the simulated and experimental bending modes is limited to Material 2 and 3 due to the difference in data availability.

Part of the simulations were run on the Phoenix-Cluster of the TU Braunschweig, which provides 304 nodes in total, each equipped with dual CPU INTEL Xeon E5-2640v4@3.4 GHz and 64 GB RAM. The remaining part of the simulation was run on the Cedar-Cluster, which is part of the Digital Research Alliance of Canada and is equipped with 100400 CPU cores with varying specifications. The grid was generated with a mesh generator DIVEMesh and the simulations used REEF3D::CFD, both version v230614.

In summary, the following four steps are carried out to achieve the research objectives introduced in Section 1:

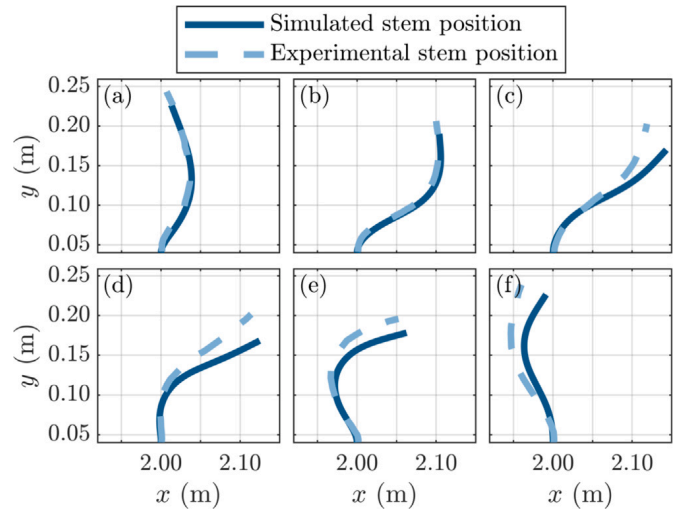


Fig. 2. Comparison of the simulated stem positions for Material 1 with $H = 0.08$ m and $T = 2.0$ s to the stem positions in the reference experiment for selected points in time with (a) $t/T = 0.00$ (b) $t/T = 0.17$ (c) $t/T = 0.34$ (d) $t/T = 0.51$ (e) $t/T = 0.67$ and (f) $t/T = 0.84$.

- Simulation of stems with Material 1, 2, and 3 were conducted, with varying wave conditions to determine the model's ability to replicate the stem motion and resulting forces for a range of hydrodynamic conditions, stem lengths, and material properties.
- Comparison of the experimental PIV measurements in front of the stem with Material 1 to the simulated flow field were done to evaluate potential differences.
- Simulation of Material 1, 2, and 3 for selected wave conditions and a range of damping coefficients were completed to evaluate their influence on stem motion and resulting forces and determine the optimum value of the damping coefficients for each material type.

3. Results

3.1. Wave-induced stem motion and forces

This section presents the results of the wave-induced stem motion and the resulting drag forces. Fig. 2 compares the simulated stem movement for Material 1 to the reference experiment for six selected time steps within the last simulated wave (cf. Table 2). The time steps were chosen according to the available stem position data from the reference experiment. Overall, the resulting stem motion of the simulation agrees well with the experimental results. Small deviations in the stem position can be observed after approximately one-third of the wave period, depicted in Fig. 2(c)–(f). Quantitatively, the largest discrepancies between simulated and experimental tip position are shown in Fig. 2(c), (d), and (f) with 0.041 m, 0.035 m, and 0.034 m, respectively. On average, that corresponds to a deviation of 18 % relative to the initial stem length. About half the discrepancies between the simulated and experimental tip position can be observed for Fig. 2(a) with 0.018 m, (b) with 0.017 m, and (e) with 0.020 m. Correspondingly, relative to the initial stem length, the latter tip positions deviate by 9 %, which lies within an acceptable ± 10 % error margin. To provide a possible explanation for the observed deviations, the influence of the flow field on the deviation of the stem tip position is evaluated in more detail in Section 3.3, see Fig. 7. In summary, Fig. 2 shows that the shape of the stem bending and the overall movement of the stem are satisfyingly reproduced. General metrics for the fit are presented together with the results of the other two simulated material types at the end of this section.

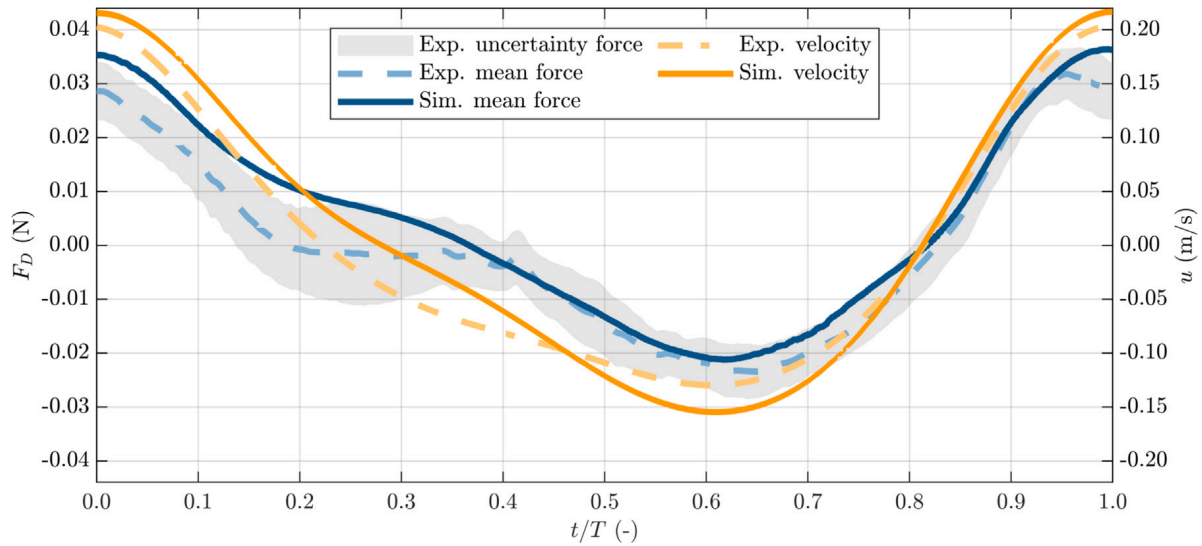


Fig. 3. Comparison of the phase-averaged simulated force and phase-averaged horizontal velocity for Material 1 with $H = 0.08$ m and $T = 2.0$ s to the measurements of the reference experiment.

Fig. 3 displays the phase average of the simulated drag force for Material 1 (over 12 wave cycles) compared to the measurements of the reference experiment. Additionally, the simulated and the experimental phase-averaged horizontal velocities measured at PP1 are provided. Very good agreement with an RMSE of 0.006 N between simulated and experimental results is achieved for the drag force, corresponding well to the previously displayed replication of the stem movement. The simulated drag forces remain within the uncertainty range for most of the normalized wave period. This uncertainty range is defined as the greater of the standard deviation from phase-averaged experimental force measurements or 10 % of the phase-averaged experimental force. Correspondingly, the RMS of the simulated forces (0.018 N) deviates by less than 10 % to the experimental RMS of the forces (0.017 N), which is considered a high agreement in this work. The largest deviation between the simulated and experimental force by about 0.01 N occurs between $t/T = 0.2$ and $t/T = 0.4$. During that range, the highest measurement uncertainty of the experimental drag force occurs due to measurement results being close to zero. A similar deviation can be observed when comparing the simulated to the experimental horizontal velocity, rendering the flow field a possible source of inaccuracy.

In the following, the performance of the proposed FSI solver to accurately simulate the stem movement and forces for Material 2 and 3 is evaluated to confirm the broad applicability of the solver. Fig. 4 presents the simulated stem movement of selected test cases for Material 2 and 3 compared to the results of the reference experiment. The ensemble-averaged stem positions enable a concise comparison of the bending for one wave period while including the resulting stem positions over the whole simulation duration. Again, a good agreement between the simulated and experimental stem positions can be observed. It becomes apparent that Material 2 and Material 3 have a higher flexural stiffness than Material 1, resulting in a more restrained stem movement. Showing the least flexibility, the short (0.15 m) stem of Material 3 remains in its initial position for all tested wave conditions. Correspondingly, both stems with Material 3 show a high agreement when comparing the distance between the average experimental to the simulated tip position, with 0.002 m for the stem depicted in Fig. 4(b), and 0.003 m for the stem depicted in Fig. 4(d). Relative to the initial stem length, the deviation of the average tip position for both the stem depicted in Fig. 4(b) and in Fig. 4(d) was 1 %. In the reference experiment, the 0.30 m long stem with Material 2 tilts asymmetrically within the direction of the wave propagation, depicted in Fig. 4(c), which is not replicated by the simulation results. The reasoning for the asymmetry is elaborated in Section 3.2. Therefore, larger discrepancies

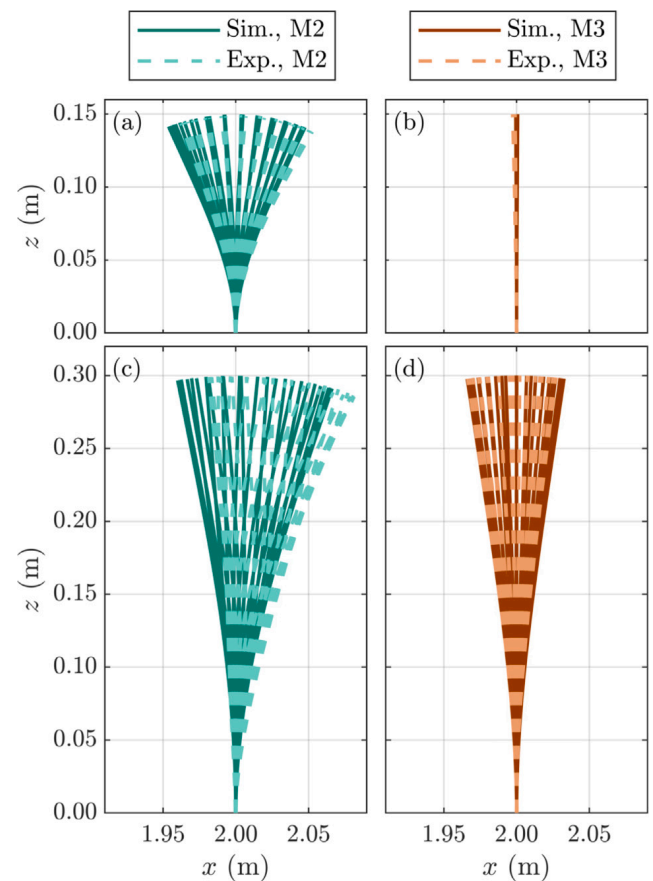


Fig. 4. Comparison of the simulated to the experimental ensemble-averaged stem motion from $t/T = 0 - 1$ with $t/T = 0.04$ increments, resulting in 25 stem positions each for (a) Material 2 with $L_S = 0.15$ m, $H = 0.07$ m and $T = 1.5$ s, (b) Material 3 with $L_S = 0.15$ m, $H = 0.04$ m and $T = 2.0$ s, (c) Material 2 with $L_S = 0.30$ m, $H = 0.04$ m and $T = 2.0$ s, and (d) Material 3 with $L_S = 0.30$ m, $H = 0.07$ m and $T = 1.5$ s.

between the average experimental to simulated tip position occur with Material 2, for the stem depicted in Fig. 4(a) by 0.010 m and for the stem shown in Fig. 4(c) by 0.019 m. With an average deviation of the tip position relative to the initial stem length of 7 % for the stem depicted in Fig. 4(c) and of 6 % for the stem shown in Fig. 4(c), both are within

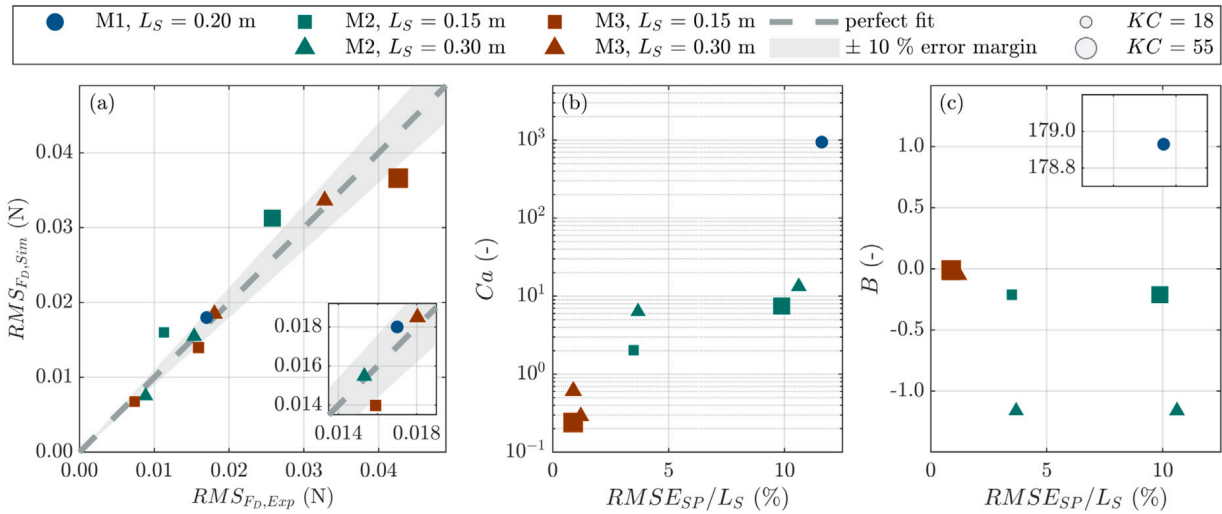


Fig. 5. Comparison between simulated and experimental results for all tested material types, stem lengths, and hydrodynamic conditions with (a) the RMS of the simulated to the experimental forces, including a line indicating the perfect fit and the RMSE of the simulated to the experimental stem position, averaged over four selected time stems ($t/T = 0.0, 0.5, 1.0$, and 1.5) and relative to the lengths L_S of the stem against (b) the Cauchy number Ca and (c) the Buoyancy number B .

the acceptable $\pm 10\%$ error margin. The bending behavior of the stems depicted in Fig. 4(c) and (d) is evaluated in more detail in Section 3.2, relating the observed deviations to varying contributions of the first two bending modes, see Fig. 6, and potential asymmetries occurring in the physical experiments.

An overview of the resulting forces and stem bending is provided in Fig. 5 for the range of tested material and hydrodynamic conditions (see Table 2). The simulated and experimental forces are compared by displaying the RMS of the simulated and experimental forces in Fig. 5(a). A linear graph is also provided, indicating a perfect fit between simulated and experimental results. The marker points' size is related to the KC number, reflecting a higher ratio of drag to inertial forces for larger marker points. As expected, the RMS of the forces increased for each simulated material with increasing KC number. A high agreement (less than 10% deviation) between the simulated and experimental forces is presented for five of the ten considered cases, independent of material type and hydrodynamic condition. Four cases show a good agreement (10% to 20%) of the simulated to the experimental RMS of the force. One exception is the 0.15 m-long stem of Material 2, where the simulation overestimates the experimental forces, by approximately 0.005 N for the RMS of the resulting forces.

Fig. 5(b) and (c) displays the normalized RMSE between the simulated to the experimental stem position over the range of Ca and B . The RMSE is averaged over four selected time stems ($t/T = 0.0, 0.5, 1.0$, and 1.5) relative to the stem length L_S , ensuring comparability between different test conditions. A logarithmic scale was applied due to the large range of Ca . In Fig. 5(b), a trend towards increasing relative RMSE of the stem position for higher values of Ca can be observed. With increasing external drag relative to the flexural stiffness of the stem, the stem dynamics become more complex, leading to larger differences between the experimental and simulated stem positions. In contrast, a similar relationship cannot be observed for B , indicating that the buoyancy does not influence the replication of the stem bending to the same extent as observed for Ca . Overall, high agreement with less than 10% error relative to the stem lengths is achieved for most tested cases. The two remaining cases show still a good agreement, with relative errors between 10% to 12%.

The evaluation of the forces and stem position in Fig. 5 leads to the conclusion that the proposed FSI solver reproduces the dynamic stem motion for a range of material properties, stem lengths, and wave properties in high agreement with corresponding reference experiments. Possible sources for observed deviations and further analysis are provided in the following sections.

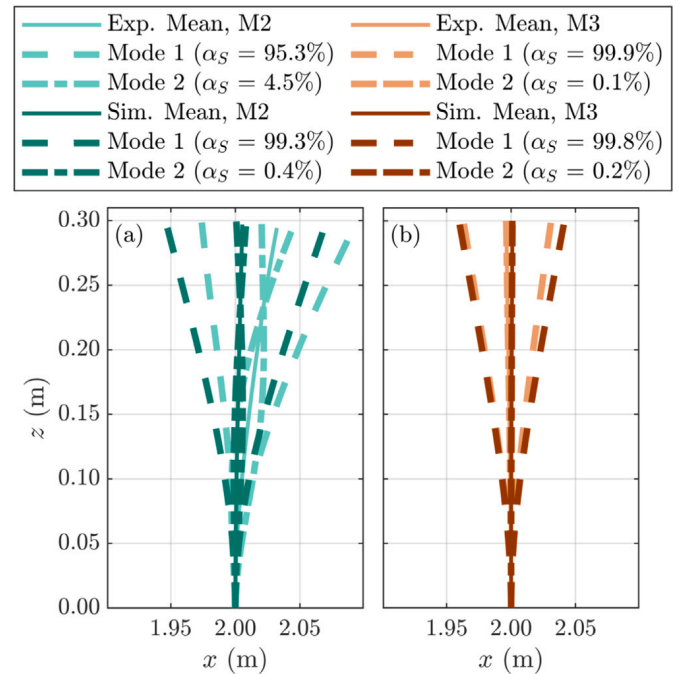


Fig. 6. Comparison of the simulated and the experimental bending modes with α_S indicating their weights for (a) Material 2 with wave conditions $H = 0.04$ m and $T = 2.0$ s and (b) Material 3 with $H = 0.07$ m and $T = 1.5$ s, both with a stem length of 0.30 m.

3.2. Evaluation of the bending modes

The decomposition of the stem bending into its bending modes allows for comparison between the simulated and experimental stem dynamics. The bending modes for the experimental stem bending of Materials 2 and 3 were presented by Jacobsen et al. (2019). Based on that approach, described in Section 2.3, the first two bending modes are sufficient to describe most of the stem movement. One example for each Material 2 and 3 is selected to compare the resulting bending modes and evaluate the FSI solver's ability to replicate the bending modes obtained from the physical experiment. For Material 2, the stem movement of the 0.30 m-long stem with the wave parameters $H =$

0.04 m and $T = 2.0$ s is depicted in Fig. 6(a). In comparison, the 0.30 m long stem of Material 3 for the test conditions with $H = 0.07$ m and $T = 1.5$ s is displayed in Fig. 6(b).

The test case depicted in Fig. 6(a) has been chosen for its deviation between the simulated and experimental results, requiring further analysis. The decomposition into bending modes may contribute to explaining the observed differences. In the experiment, the stem movement does not vary around its initial position but instead undergoes an overall shift in positive x -direction. The same shift does not occur for the simulated stem movement, most apparent in Fig. 6(a) when comparing the mean experimental and simulated stem position. Jacobsen et al. (2019) noted that this occurs despite symmetrical hydrodynamic forcing, likely due to the tip position aligning more with the flow during the wave crest, similar to the Stokes drift (van den Bremer and Breivik, 2018; Monismith, 2020). This phenomenon might be represented by the influence of the second bending mode on the overall stem dynamics. The second bending mode of the simulated stem contributes only with 0.4 % to the overall stem dynamics, compared to 4.5 % of the experimental stem. It can be concluded that the FSI solver cannot replicate the occurring variation of the experimental stem bending, leading to deviations between simulated and experimental results. In contrast, Fig. 6(b) shows the first two bending modes of the selected test case with Material 3. A high agreement between the experimental and simulated stem for the average stem position and the two bending modes can be observed here. The second bending mode contributes to a similar extent, even though negligibly small with 0.1 % and 0.2 %, to the overall stem dynamics for both the simulated and experimental stem.

3.3. Flow field in front of the wave-induced stem motion

Providing a possible explanation for the observed differences in the stem position and the resulting forces, the flow directions of the wave-induced flow field in front of the stem are evaluated for the test case with Material 1. The results of velocity line probes from the simulation are compared to PIV measurements of the reference experiment. Two positions in front of the stem in x -direction have been selected for the comparison (cf. LP2 at $x = 1.91$ m and LP3 at $x = 1.94$ m in Fig. 1). The results are displayed in Fig. 7.

Six points in time were selected for comparison, representing two distinctive wave phases. The first three selected time steps represent the forward movement of the stem (Fig. 7(b)–(d)), initiated during the first half of the wave period. The other three selected time steps correspond to the upward movement of the stem during the second half of the wave, visualized in Fig. 7(e)–(g). All time steps in Fig. 7 were selected for highlighting the difference in timing of the wave-induced flow field, enabling the analysis of the variation in the resulting simulated and experimental stem movement. The comparison of Fig. 7(b) to Fig. 7(c) reveals that the wave trough in the experiment is reached earlier than in the numerical simulation, leading to an earlier change of direction for the flow field. The longer duration of the horizontal flow velocity in the direction of approaching waves explains why the simulated stem bends further than the experimental stem, see Fig. 2(c)–(f). At $t/T = 0.34$, depicted in Fig. 7(d), the simulated flow field resembles the experimental measurements again. Similar to the first phase of the wave, the other selected points in time show that the next wave crest for the simulation is reached earlier than the experiments, most apparent in Fig. 7(f). That difference explains the resulting deviation in the stem position, which is most obvious in Fig. 7(g). It can be concluded that differences in timing over the wave period between the physical and simulated wave-induced flow field can explain the observed differences between the simulated and experimental stem positions. The observations underline that detailed and high-resolution experimental data is required to fully understand the coupled fluid–structure interactions and their implications for numerical replication.

3.4. Influence of the damping coefficient under wave loading

The influence of damping coefficients on the stem motion of the proposed FSI solver is discussed in this section. Fig. 8 shows the difference in the resulting stem position of the simulated stem for Material 1 for various damping coefficients at selected points in time over one wave period. The stems with the highest damping coefficients (particularly with $c_k = 5 \times 10^{-6}$ and $c_k = 1 \times 10^{-4}$) show a delayed and relatively stiff stem movement compared to the experimental results for all selected points in time. Further on, Fig. 8 reveals that the stems with lower damping coefficients ($c_k < 1 \times 10^{-6}$) tend to show similar bending behavior to the experimental results. The difference between the resulting stem positions diminishes with lower damping coefficients.

Next, the analysis is extended to more material types, investigating if the observed behavior of the influence of the damping coefficients for Material 1 can be generalized. Enabling a different perspective, Fig. 9 compares the evolution of the normalized tip position of the stem in x -direction and the drag force over the time for Material 2 with a length of 0.15 m and the wave conditions $H = 0.11$ m and $T = 2.0$ s with damping coefficients varying between 1×10^{-2} and 1×10^{-12} . The comparison confirms the previous observation regarding the influence of the damping coefficients. The largest damping coefficient $c_k = 1 \times 10^{-2}$ restricts the stem movement completely, resulting in the stem remaining stiff in its initial position throughout the wave period (Fig. 9(a)). Accordingly, the resulting maximum forces of the stem are overestimated by 40 % compared to the drag force measured in the reference experiment (Fig. 9(b)). Furthermore, irregular spikes around the maximum drag force can be observed for the results obtained with larger damping coefficients. With smaller damping coefficients, the stem movement becomes more flexible and closely resembles the experimental results. The simulated stems with damping coefficients between $c_k = 1 \times 10^{-6}$ and $c_k = 1 \times 10^{-12}$ show comparable stem dynamics, suggesting that even smaller damping coefficients would not influence the resulting motion further. The movement of the normalized tip position in x -direction of $c_k = 1 \times 10^{-4}$ indicates the delayed stem movement compared to the lower damping coefficients, resulting in a modified shape for the change in position over time. Fig. 9 supports the assumption that the time-dependent stem movement of the proposed FSI solver is sensitive to the selected damping coefficients in different test conditions, reflected by both the stem position and the resulting forces. Furthermore, it can be repeatedly observed that lower damping coefficients replicate the experimental results with higher accuracy.

Based on the observed spikes in the resulting maximum forces in Fig. 9(b) for the largest damping coefficient, it is assumed that the prevented stem movement causes them. Fig. 10(a) displays the phase-averaged forces for the 0.15 m long stem of Material 3 during the first 10 s of simulation time exposed to wave conditions with $H = 0.11$ m and $T = 2.0$ s. This test case is of interest since the stem position remains in its initial position throughout the simulation for all tested damping coefficients. The stem bending is not depicted here but resembles the results presented in Fig. 4(c). For the resulting forces, spikes are most apparent for the smallest tested damping coefficient ($c_k = 1 \times 10^{-12}$). Providing further insights, the resulting forces are displayed in the frequency domain in Fig. 10(b). The periodic forces induced by the wave load (here with $T = 2.0$ s corresponding to 0.5 Hz) provide information about the overall replication of the wave included forces. To gain further information about the additional fluctuations in the simulated forces, the signal was filtered using a high-pass filter for frequencies smaller than 0.7 Hz and excluded from the analysis. Prominent peaks can be observed for the simulated and experimental results in the force amplitude spectrum. These peaks occur at about 1.0 and 1.5 Hz for all simulated as well as experimental resulting forces, while the peaks around 2.5 and 3.5 Hz are only prominent for the simulated results with small damping coefficients ($c_k = 1 \times 10^{-10}$ and 1×10^{-12}). The simulations with lower damping coefficients show large deviations from

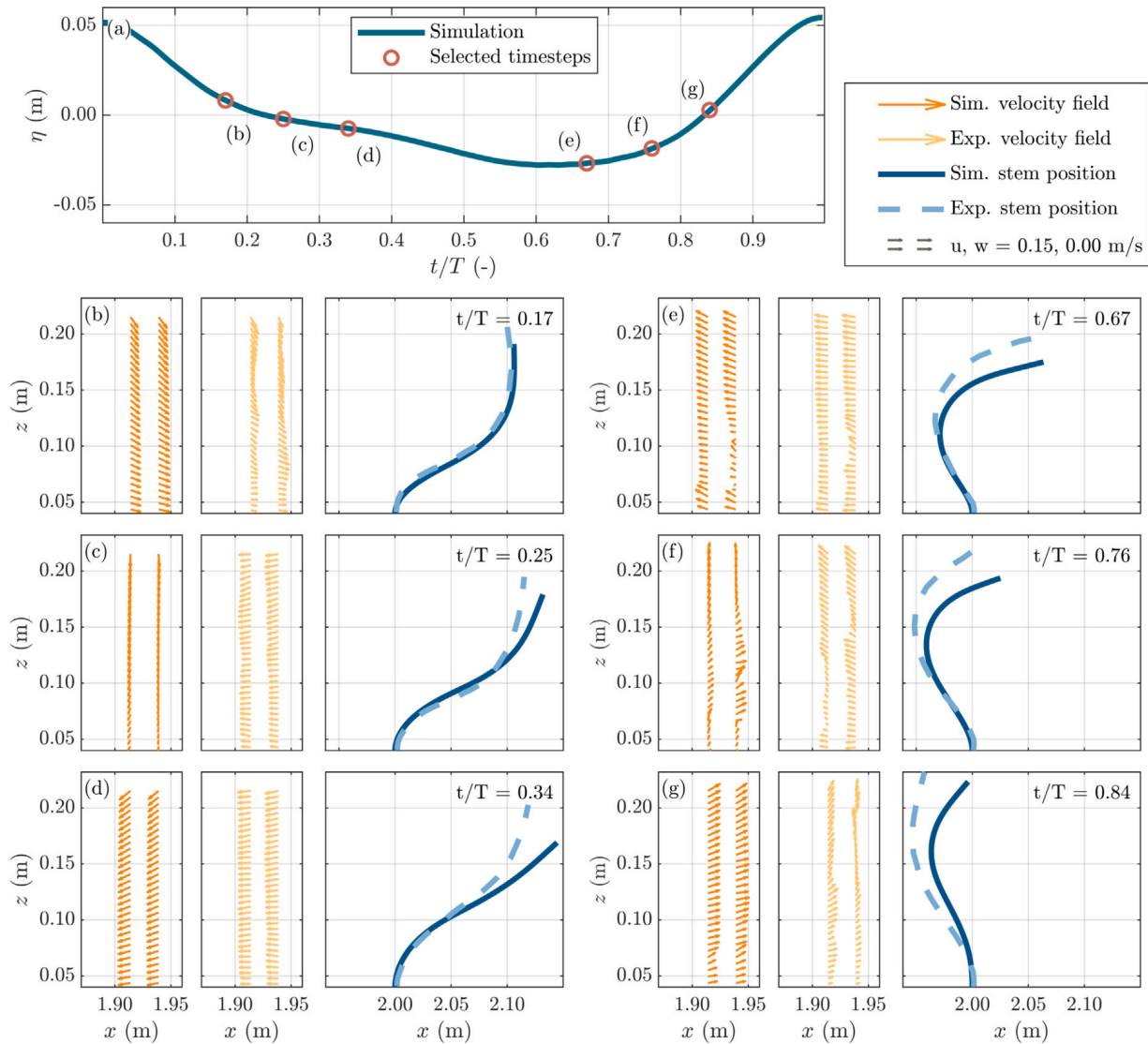


Fig. 7. Comparison of the wave-induced flow field in a x - and z -plane of the simulation to the PIV measurements of the reference experiments with (a) the phase-averaged water surface elevation η of the simulation and (b) - (g) selected time steps displaying the simulated and experimental flow field and the resulting stem bending at LP2 and LP3.

the experimental results with higher frequencies. It can be concluded that the peaks at lower frequencies replicate realistic material behavior, as they can also be observed in the experimental results. In contrast, the peaks at higher frequencies indicate non-physical inner vibrations of the stem, which lower damping coefficients cannot suppress. It is therefore crucial to select appropriate damping coefficients for test cases with minimal movement to avoid nonphysical inner forces, which can also lead to numerical instabilities.

After focusing on the resulting drag forces, an additional perspective is provided by analyzing the influence of the damping coefficient on the stem movement decomposed into its bending modes, similar to Section 3.2. The resulting comparison for Material 1 with selected damping coefficients is visualized in Fig. 11. A comparison to the experimental results is not included due to the unsuitability of the available data. Material 1 is chosen as it is the most flexible material, leading to a more straightforward comparison between the stem positions for different damping coefficients. Fig. 11(a) confirms that the proposed FSI solver can replicate stem movements characterized by a large contribution of their second bending mode. The comparison of Fig. 11(a) to Fig. 11(c) shows that the simulation of stems with different damping coefficients results in a comparable mean stem position. In contrast, the weight of the second bending mode increases with smaller damping coefficients, suggesting a larger variation within the stem movement. Overall, it can

be seen that the damping coefficients influence both the shape of the decomposed bending modes and their weight distribution.

The influence of the damping coefficient is quantified by calculating the relative RMS of the phase-averaged simulated forces of the experimental force. The relative RMS of the forces for varying damping coefficients is displayed in Fig. 12(a) for Material 1, with $L_S = 0.20$ m, $H = 0.04$ m and $T = 2.0$ s, Material 2 with $L_S = 0.15$ m, $H = 0.11$ m and $T = 2.0$ s, and Material 3 with $L_S = 0.30$ m, $H = 0.07$ m and $T = 1.5$ s. For Material 1, as expected from the previous analysis, Fig. 12 shows diminishing differences in the resulting drag forces for damping coefficients with lower values ($c_k < 1 \times 10^{-6}$). The same tendency can be seen for the resulting drag forces of Material 2. The relative RMS for Material 3 shows only minor variations, possibly due to its relatively high stiffness. Nevertheless, the relative RMS force with $c_k = 1 \times 10^{-8}$ is lower compared to the other applied damping coefficients, laying within the $\pm 10\%$ error margin. The crosses in Fig. 12 indicate simulations that resulted in diverging solutions for the FSI solver. Selecting appropriate damping coefficients is correspondingly required to ensure numerical stability.

Overall, Fig. 12 indicates that appropriate damping coefficients for all included material types and hydrodynamic conditions lie within the range of $c_k = 1 \times 10^{-8}$ – 1×10^{-6} . The results from this section confirm that each material type requires a damping coefficient that ensures

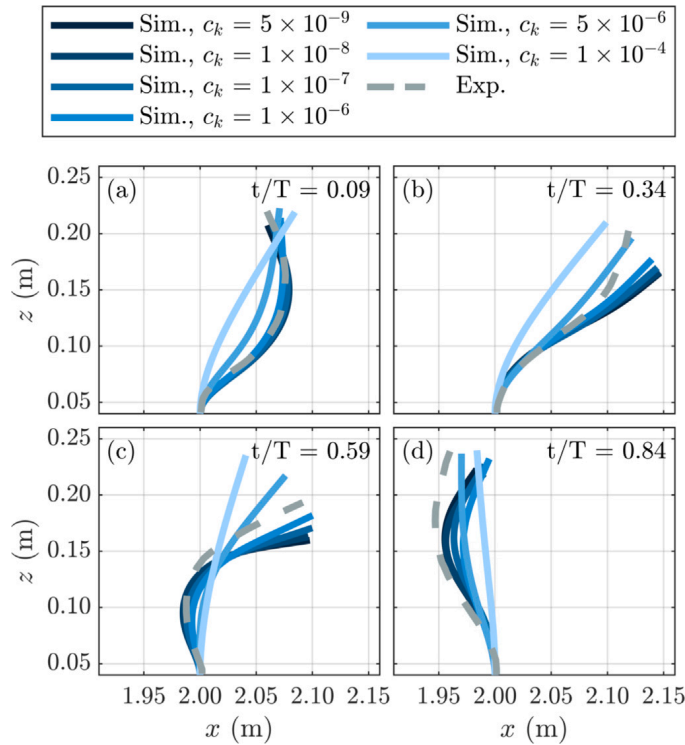


Fig. 8. Influence of varying damping coefficients c_k on the stem position for Material 1 with the wave conditions $H = 0.08$ m and $T = 2.0$ s for selected points in time.

numerical stability without artificially restricting the natural motion of the stem.

4. Discussion

This study confirms the capability of the FSI solver to replicate both stem motion and forces accurately. Most tested cases show a high agreement with less than 10% deviation for the RMS of the forces and relative RMSE of the stem bending. The suitability of the FSI solver and good agreement as compared to experimental data was first demonstrated by Prüter et al. (2025), who investigated steady-state current structure interaction. This work now extends the range of application of the FSI solver to unsteady wave excitation, showing high agreement between the simulated stem motion and the resulting forces to the reference experiments throughout the tested case studies. The comparison included different material parameters and a range of hydrodynamic conditions. The observed deviations and possible improvements are discussed in this section.

4.1. Model performance

Differences in the hydrodynamic conditions between simulation and experiment are provided in Appendix A. These differences can be attributed to the wave's shape and its corresponding horizontal flow velocity, likely influenced by the reduced dimensions of the numerical wave flume, while also considering potential measurement inaccuracies. Generally speaking, inaccuracies in the replicated wave conditions by the fluid solver do not allow for conclusions regarding the accuracy of the proposed FSI solver. One source of inaccuracy specific for the FSI solver could be the required refined cell size, which, even though being already relatively small with 1×10^{-3} m, resulted in a grid uncertainty of about 5%. Further limitations of the FSI solver, such as neglecting the skin friction of the material, have been discussed in more detail by Prüter et al. (2025).

This study has shown that the choice of damping coefficient influences the stem movement and its resulting forces to a large extent. Additionally, the choice of damping coefficients affects the distribution of the decomposed bending modes. Fig. 10 visualizes the influence of the damping coefficients on the occurrence of peaks in the frequency domain for the simulated compared to the experimental force. Providing a broader context, the first natural frequency of the 0.15 m long stem of Material 3 is calculated based on the equation for a cantilever beam in a fluid $f_i = \lambda_i^2 / 2\pi L_S^2 \sqrt{EI/(m + m_a)}$, obtained from Blevins (2016). The natural frequency is with $f_i = 3.83$ Hz higher than the observed peaks in Fig. 10(b) and seems to have limited influence. For the calculation of the vortex shedding frequency $f_v = St u_w / W_S$, a Strouhal number St of 0.15 is applied, based on experimental results of Knisely (1990) for a beam in a fluid with the same aspect ratio as Material 3. This results in a vortex shedding frequency of 1.5 Hz for the wave parameters $H = 0.04$ m and $T = 2.0$. Interestingly, this frequency resonates with the highest peak observed in Fig. 10(b), indicating that vortex shedding occurs both in the experimental and simulated stem and influences thus the resulting forces. Providing further insights into the three-dimensional nature of the FSI, the vortices for the discussed case at selected points in time are visualized in Fig. 13. The selected points in time serve as an example of the detachment process of a vortex from the stem: a coherent structure with a relatively high velocity magnitude is apparent in Fig. 13(a), compared to lower velocity magnitudes seen in Fig. 13(b). Finally, the coherent structure is detached from the back of the stem in Fig. 13(c). The time-dependent interaction of the vortices with the stem within the time frame of a wave period supports the previous comparison that the vortices influence the resulting forces beyond the overall wave-induced flow field, here shown as an example for the relatively stiff stem of Material 3. Overall, the vortices depicted in Fig. 13 develop a few centimeters in front of the stem and dissipate approximately at two-thirds of the stem length behind the stem. Longer wakes are not to be expected for the dimensions involved in this FSI – the width of the Material 3 stem ($W_S = 0.008$ m) is one-fifth of the here simulated wave height ($H = 0.04$ m).

Generally, the validation of the time-dependent stem bending and the resulting drag forces obtained by the proposed FSI solver is therefore limited to the application of appropriate damping coefficients. In the literature, different approaches can be found regarding the choice of the damping coefficients for the structural solver and their observed influence. An overview of selected damping coefficients is provided in Table 3. All selected studies have applied the same values for c_{dy} and c_{dz} as well as c_{ky} and c_{kz} , as done in this study. Lang et al. (2011) proposed their selected values to exert slight damping for torsion and bending and strong damping for extension and shearing of the stem. Till et al. (2019) aimed for some damping effect with their selected values, see Table 3, without further discussing the influence. Their applied values fall within a similar range of Lang et al. (2011). Palm and Eskilsson (2020) found the application of damping coefficients important to dampen the high-frequency response of the structural solver, with $c_{ky,z} = 2 \times 10^{-2}$ rendering most suitable. Their experiments on cable dynamics were performed using air as the surrounding fluid. When applying the cables in a marine environment, they concluded that the influence of the damping coefficients in water is negligible, which contradicts the results of this study. However, Palm and Eskilsson (2020) did not base their structural solver on the Cosserat rod equations, giving a different mathematical implementation of the damping coefficients, thus reducing the comparability of their application. Martin and Bihs (2021) selected their values for $c_{kx,y,z}$ based on the findings of Palm and Eskilsson (2020). Afterward, they compared the results for two different coefficients, finding improved results with $c_{ky} = 4 \times 10^{-2}$. Compared to the observation of this study (see Fig. 12) the values chosen by Martin and Bihs (2021) are expected to restrict the beam motion to some extent. None of the previous studies have differentiated between the damping coefficients' influence on the time-averaged compared to the

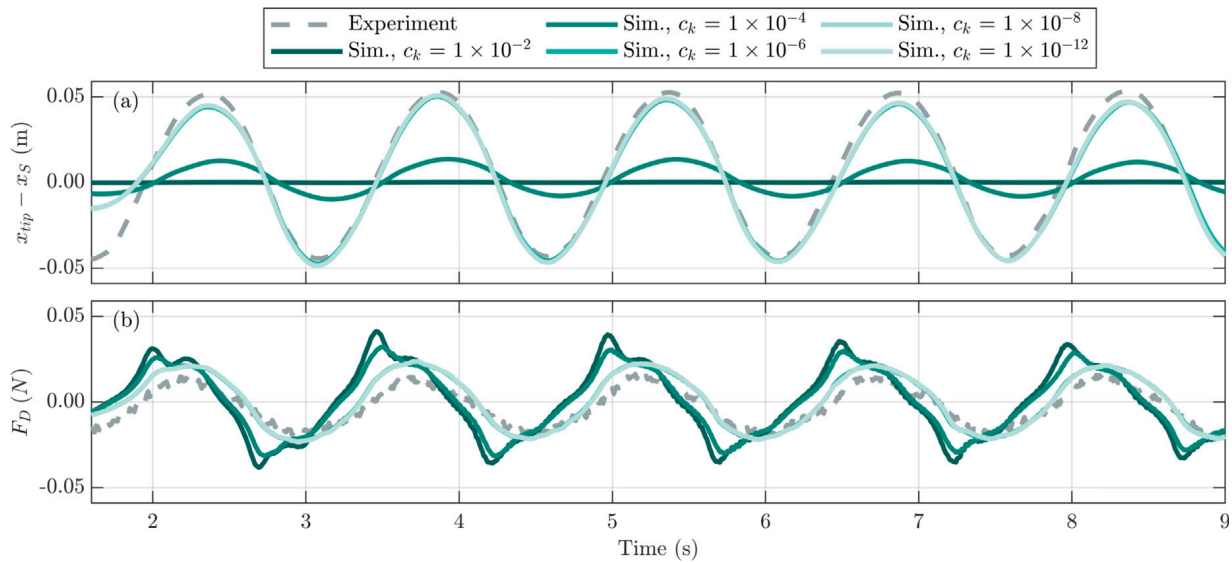


Fig. 9. Influence of a variation of damping coefficients c_k on (a) the normalized tip position of the stem in x -direction and (b) the horizontal force over the time for Material 2 with wave conditions $H = 0.07$ m and $T = 1.5$ s.

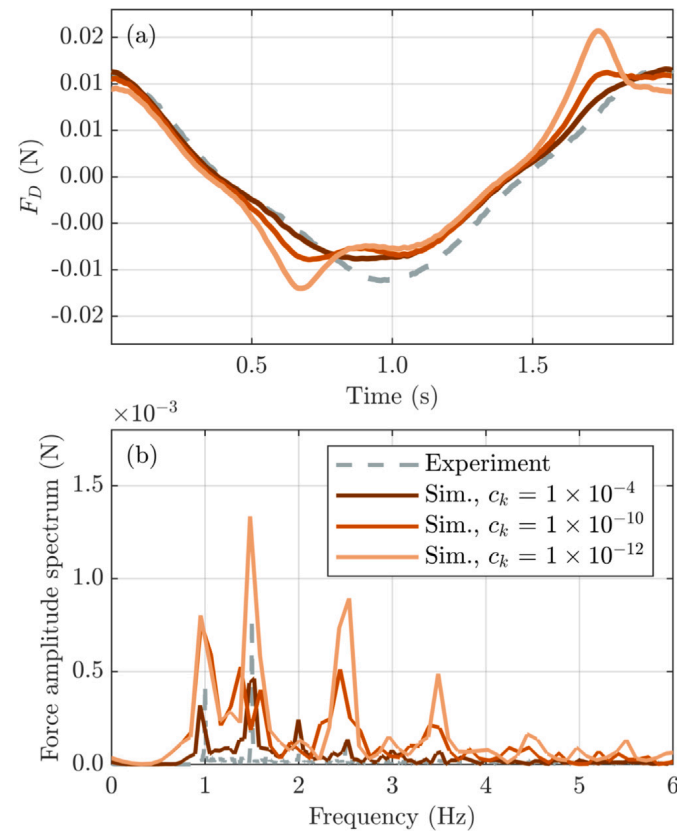


Fig. 10. Influence of selected damping coefficients on (a) the phase-averaged drag force (b) the resulting drag force amplitude spectrum in the frequency domain for the 0.15 m long stem of Material 3 with wave conditions $H = 0.04$ m and $T = 2.0$ s.

time-resolved stem movement, as observed in this study and by Prüter et al. (2025).

However, it should be noted that the application cases for each study differ. To apply such a model in robotics or cable dynamics, artificially dampening the slender body's motion could be desired. Furthermore, it is unclear to what extent the application of the damping coefficients differs depending on the properties of the surrounding fluid, such as, e.g., air or water. This study aimed to replicate the

Table 3
Comparison of the applied damping coefficients from selected literature.

	c_{dx}	c_{dy}, c_{dz}	c_{kx}	c_{ky}, c_{kz}
Lang et al. (2011)	2.0×10^2	1.0×10^{-1}	8.0×10^{-6}	2.0×10^{-4}
Till et al. (2019)	3.0×10^{-2}	2.0×10^{-2}	1.0×10^{-6}	1.0×10^{-6}
	1.0×10^{-1}	1.0×10^{-1}	5.0×10^{-4}	5.0×10^{-4}
Martin and Bihs (2021)	4.1	4.1	2.0×10^{-2}	2.0×10^{-2}
	4.1	4.1	4.0×10^{-2}	4.0×10^{-2}

stem motion of vegetation surrogates under wave load from flume experiments, with a future application of live vegetation. Therefore, the influence of the damping coefficients is desired to be limited to a minimum, replicating realistic stem movement while ensuring numerical stability. While the finding suggests that damping coefficients ranging from $c_k = 1 \times 10^{-8}$ to 1×10^{-6} are suitable for such applications independent of the simulated material properties, further simulations with an extended set of material parameters, such as higher flexibilities and further stem lengths, are recommended to confirm or improve the insights provided by this study regarding the suitability of damping coefficients.

Future studies should focus on enhancing the model's efficiency. As stated in Table 2, the number of waves modeled for each set-up with the available computational time differs depending on the hydrodynamic parameters and material properties. Due to numerical instabilities of the FSI solver, the coarse cell size for this study was set to be twice the cell size of the refined cell size, resulting in many cells while limiting the dimensions of the numerical wave flume to the available computational resources. An improved non-uniform grid would enable more flexibility regarding the extent of the numerical wave flume, allowing for a more accurate representation of experimental conditions. Another challenge lies within the required computational time for the structural solver itself. The equations of a single stem are not solved in parallel due to its implementation using the non-commercial solver RADAU5 (Hairer and Wanner, 1999) for the Runge–Kutta method (Tschisgale and Fröhlich, 2020). Correspondingly, longer stems, requiring the division into more individual rigid elements, lead to longer simulation times. Instead, calculating more than one stem has been optimized for message passing interface (MPI) by Tschisgale and Fröhlich (2020), allowing for scaling to the meadow scale, given that more CPUs than stems are available. In conclusion, improving the efficiency of the proposed FSI solver within the REEF3D::CFD framework would enable both the simulations on a meadow scale and of longer stems.

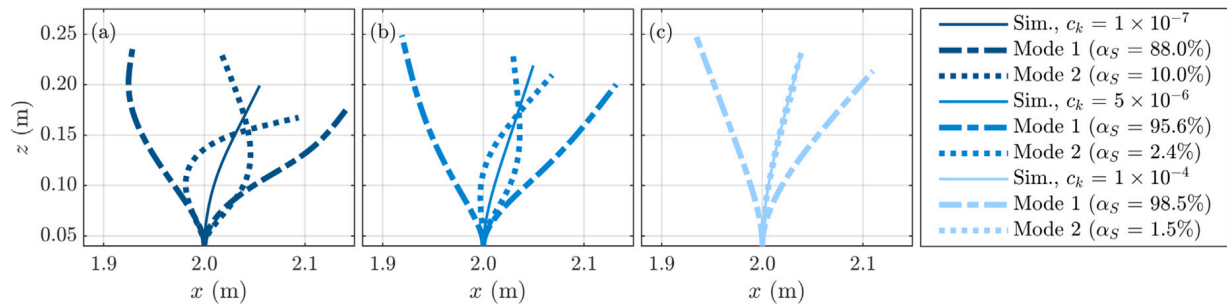


Fig. 11. Comparison of the bending modes of the simulated stem position with α_S indicating their weights for different damping coefficients for Material 1, with (a) $c_k = 1 \times 10^{-7}$, (b) $c_k = 5 \times 10^{-6}$ and (c) $c_k = 1 \times 10^{-4}$.

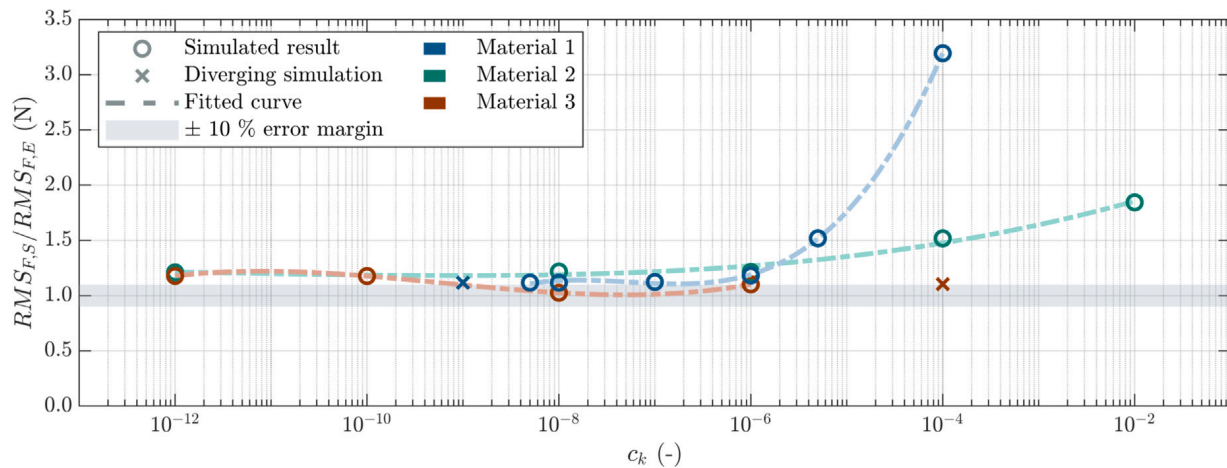


Fig. 12. Relative RMS of the phase-averaged simulated to experimental forces for different damping coefficients for Material 1, 2, and 3, including a fitted curve for each material type.

4.2. Future implementation of field data

The materials tested within this study were selected to replicate submerged aquatic vegetation in different environments. The most flexible Material 1 has been chosen by [Luhar and Nepf \(2016\)](#) to provide test conditions overlapping with those found in natural seagrass systems, considering the wide range of properties in nature. Materials 2 and 3 are comparable to conditions found in salt marshes. For example, [Markov et al. \(2023\)](#) tested two different vegetation species, which can be found in Canadian salt marshes, in flume experiments. Their tested conditions of the species *Spartina patens* ranged from $Ca = 1.40$ to 11.00 , resembling those of Material 2 ($Ca = 2.03 - 13.30$). Similarly, the range of Ca from 0.02 to 1.10 for the second tested species, *Spartina alterniflora*, is comparable to the tested Material 3 within this study ($Ca = 0.03 - 0.61$). The comparison confirms the ability of the FSI solver to replicate different environmental conditions of submerged aquatic vegetation, enabling a wide range of applications.

The replication of vegetation properties found in the field with the proposed FSI solver would be improved by incorporating the inhomogeneous material properties of live vegetation. Different vegetation properties, such as flexural stiffness, along the stem height can be observed in the field for salt marsh vegetation ([Keimer et al., 2023, 2024](#)). Neglecting the variation of the plant's stiffness can lead to an over- or underestimation of the obtained drag forces ([Marjoribanks and Paul, 2021](#)). Examples can be found in the literature for applying the Cosserat rod model with varying diameter ([Renda et al., 2014; Schoppmann et al., 2021](#)) or varying stiffness ([Wang and Rojas, 2024](#)). To what extent these approaches can be incorporated into the FSI solver in the REEF3D::CFD framework should be investigated in future studies.

Alternatively, computational fluid dynamics (CFD) models two-way coupled with a structural solver utilizing FEM are considered promising for future studies as they are better suited to replicate arbitrary shapes and geometries of live vegetation, such as the leaves, compared to rod theories.

Overall, the FSI solver can simulate stems replicating live vegetation without requiring empirical formulations, such as the Morison equation utilizing the drag coefficient, to calculate the resulting forces. It remains to be evaluated which damping coefficients are suitable to replicate the motion of live vegetation, which should be focused on in future studies. Due to the specificity of the damping coefficients to the applied structural solver, appropriate values are not known for live vegetation and how to assess them in field studies remains uncertain. Instead, the authors suggest evaluating their influence and their applicability for live vegetation numerically as performed in this study for surrogate materials, ideally including a wide range of natural species. Individual stem studies could be utilized then to investigate the sediment mobility around vegetation species with varying properties or their seasonal differences. Further, individual stem investigations should be extended to a larger vegetation meadow, enabling the investigations on their wave attenuation capacity, and focusing on variations in material properties such as seasonality. Further application scenarios, such as stem collision and emergent vegetation, have been discussed by [Prüter et al. \(2025\)](#).

5. Conclusion

This study presented novel results investigating the behavior of vegetation stems under wave action with the help of a FSI solver suitable for material parameters appropriated to aquatic submerged

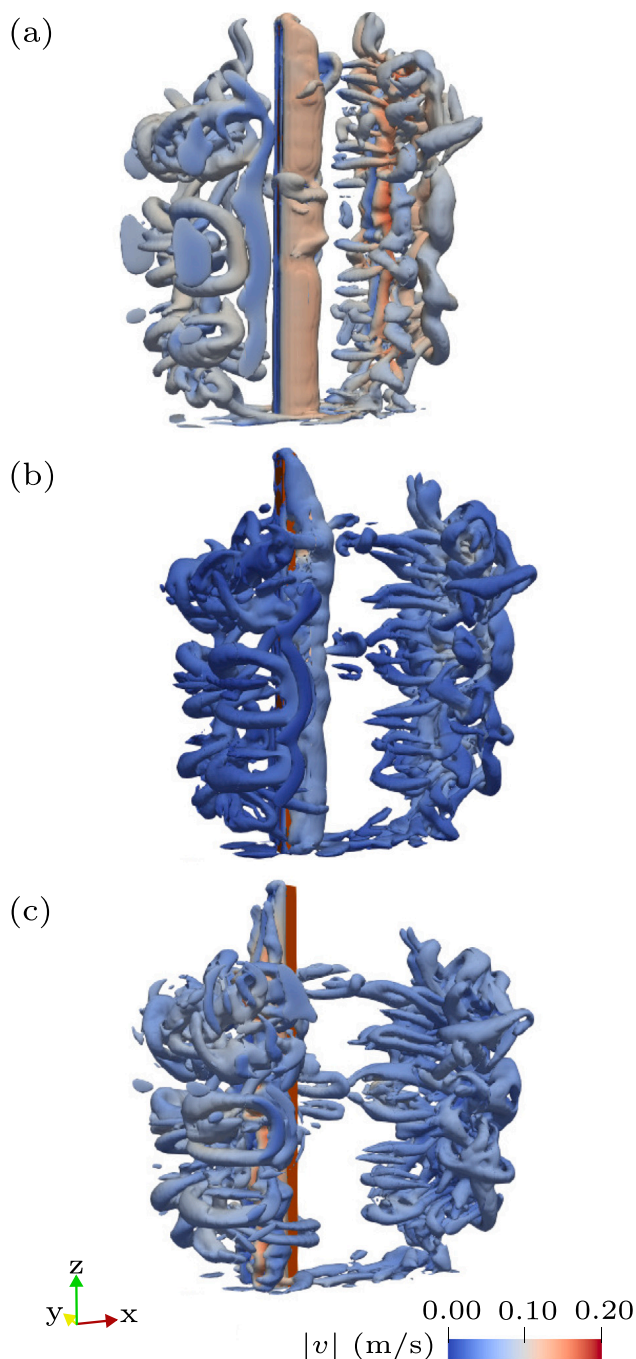


Fig. 13. Vortices around the 0.15 m long stem of Material 3 with wave conditions $H = 0.04$ m and $T = 2.0$ s, represented by Q-criterion contours equal to 1 for selected points in time with (a) $t = 4.62$ s, (b) $t = 4.95$ s, and (c) $t = 5.28$ s.

vegetation, ranging from seagrass to salt marsh vegetation. The proposed FSI solver was shown to simulate the stem motion and resulting forces under wave load accurately based on comparison to the reference experiments for different hydraulic parameters. Occurring deviations were explained by minor differences in the simulated waves within the fluid solver compared to the reference experimental results. An additional decomposition of the resulting stem movement in bending modes was validated against its reference experimental results, and the stem dynamics were evaluated. It was highlighted that the appropriate choice of damping coefficients is crucial to replicate the stem motion correctly, balancing numerical stability without artificially restricting the stem movement. Furthermore, the influence of the damping coefficients on the first two bending modes is addressed for the most

flexible simulated material. The specific research objectives presented in Section 1 can be answered as the following:

- The proposed FSI model can accurately replicate an individual stem's wave-induced motion and associated drag forces.
- The flow field in front of an individual stem was observed to have a large influence on the proposed FSI model, marking it as a source of possible model inaccuracies.
- The model's built-in damping coefficients control the time-dependent wave-induced stem motion and the resulting drag forces while ensuring numerical stability to a greater extent than previously thought. Therefore, considerate choices of damping coefficients are recommended, based on the analysis presented in this study for three different materials.

Future studies should extend the range of tested material properties and enhance the efficiency of the FSI solver. The applied Cosserat rod model could be adapted to account for varying vegetation properties along the stem height to improve the applicability of the proposed model to apply properties of live vegetation measured in the field.

CRediT authorship contribution statement

Inga Prüter: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Felix Spröer:** Writing – review & editing, Validation, Methodology. **Oliver Lojek:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Christian Windt:** Writing – review & editing, Methodology, Conceptualization. **David Schürenkamp:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Ioan Nistor:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Nils Goseberg:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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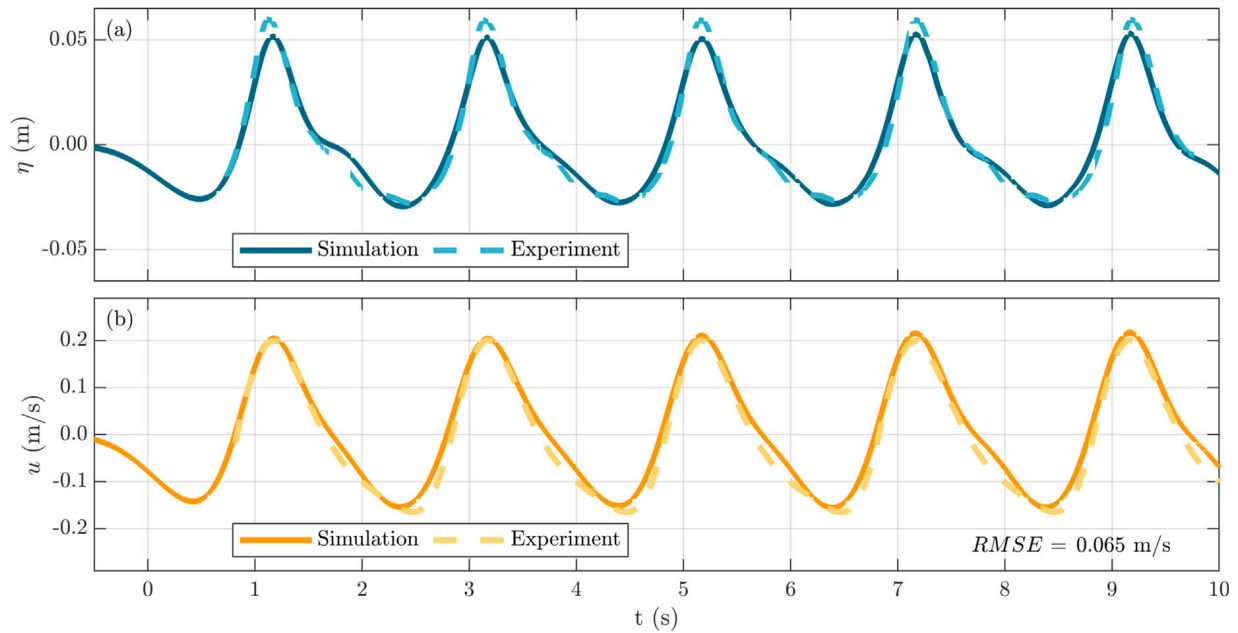


Fig. A.14. Comparison of (a) the simulated time history of the water surface elevation η at WG2 and (b) the time history of the horizontal flow velocity u for a selected time period at PP1 to the reference experiment of Material 1 (Luhar and Nepf, 2016).

Appendix A. Hydrodynamic conditions

This appendix evaluates the ability of the numerical flume with its chosen dimensions to replicate the hydrodynamic conditions for each reference experiment.

A.1. Comparability to the experimental test conditions

For the reference experiment of Material 1, both the water surface elevation above the stem (WG2), provided by Luhar and Nepf (2016), and the published horizontal velocity measured at PP1 in front of the stem are compared to the simulation results. An overview of the wave gauges, line, and point probes is provided in Fig. 1. The wave gauge in the reference experiment was placed at $x, y = 2.00, 0.15$ m. Due to its reduced width, the same position cannot be chosen for a wave gauge in the numerical flume. Comparability between the physical and numerical measurements is ensured by using the same distance of the wave gauges to the flume wall (0.04 m). Accordingly, the wave gauge has been placed in the center of the numerical flume, resulting in the coordinates $x, y = 2.00, 0.00$ m. The results are visualized in Fig. A.14. It can be observed that both the experimental and the simulated wave, initially linear, experience some deformation along the flume. A comparable wave deformation as in the reference experiment at the height of the stem in x -direction was achieved by selecting a smaller input wave height ($H = 0.068$ m). Fig. A.14 shows that the wave deformation leads to a lower wave crest than the wave crest in the reference experiment, while the wave troughs are in good agreement. Therefore, the resulting measured wave heights above the stem differ with $H_{exp} = 0.086$ and $H_{sim} = 0.078$ m. Nevertheless, the adapted wave height is necessary to achieve a comparable minimum ($u_{exp,min} = -0.16$ m/s, $u_{sim,min} = -0.15$ m/s) and maximum ($u_{exp,max} = 0.21$ m/s, $u_{sim,max} = 0.21$ m/s) horizontal flow velocities. The accurate replication of the horizontal flow velocity has been prioritized over the water surface elevation, as it is expected to be crucial to replicate the stem motion and resulting forces. The RMSE of the horizontal flow velocity for the selected time frame has been calculated at 0.065 m/s. Overall, it can be concluded that the numerical wave flume provides sufficient similar wave conditions to the reference experiment of Material 1.

Next, the hydrodynamic conditions for the reference experiment of Materials 2 and 3 are compared. Based on the measurements made

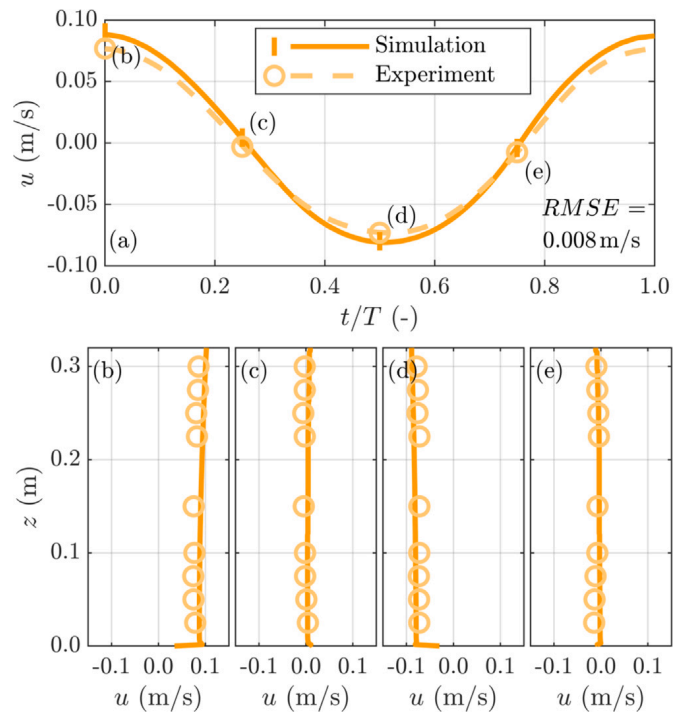


Fig. A.15. Comparison of the simulated horizontal velocity u for wave conditions $H = 0.04$ m and $T = 2.0$ s with the experimental results from the reference experiments in Material 2 and 3 (Jacobsen et al., 2019). The figure presents (a) the phase-averaged horizontal velocity at $z = 0.10$ m (PP2) over the normalized wave period, and (b) - (e) the phase-averaged horizontal velocity profiles across the water depth (LP1) at selected time steps: (b) $t/T = 0.00$, (c) $t/T = 0.25$, (d) $t/T = 0.50$, and (e) $t/T = 0.75$.

available by Jacobsen et al. (2019), the phase-averaged horizontal velocity u of the experimental and simulation results at a specific location is compared over the wave period and at selected points in time over the water depth. It has to be noted that this comparison between the numerical and experimental results again entails wave gauges and line probes at different positions within each compared wave flume. The wave gauge and velocity measurement in the reference experiment

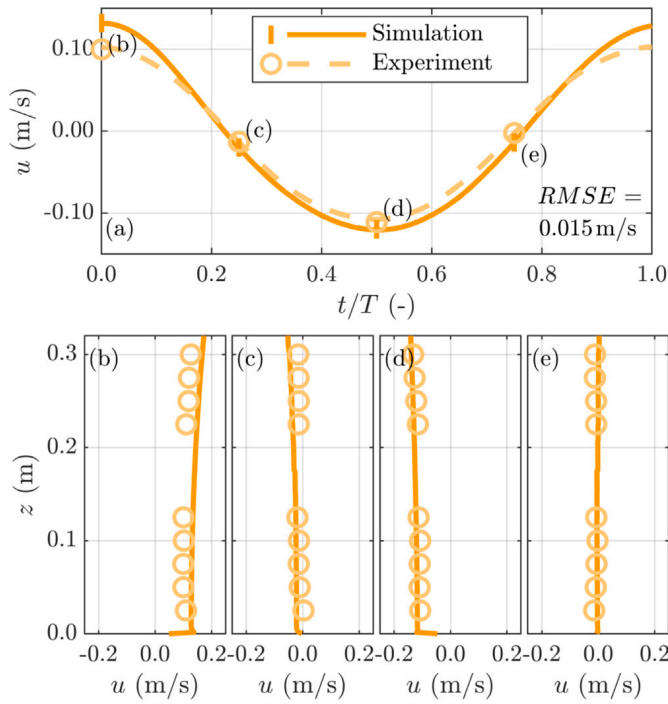


Fig. A.16. Comparison of the simulated horizontal velocity u for wave conditions $H = 0.07$ m and $T = 1.5$ s with the experimental results from the reference experiments in Material 2 and 3 (Jacobsen et al., 2019). The figure presents (a) the phase-averaged horizontal velocity at $z = 0.10$ m (PP2) over the normalized wave period, and (b) - (e) the phase-averaged horizontal velocity profiles across the water depth (LP1) at selected time steps: (b) $t/T = 0.00$, (c) $t/T = 0.25$, (d) $t/T = 0.50$, and (e) $t/T = 0.75$.

were each installed at the height of the stem in x -direction with a 0.20 m distance between the stem and the flume wall ($x, y = 2.00, 0.20$ m and $x, y = 2.00, -0.20$ m). Due to the reduced width of the numerical flume, the same placement and distance to the wall cannot be achieved in the numerical setup. Instead, a wave gauge and line probe with a distance of 0.18 m in front of the stem in x -direction in the mid of the flume width have been chosen for further evaluation (WG1 and LP1, both at $x, y = 1.82, 0.00$ m). It was assumed that both measurements represent flow conditions undisturbed by the stem and the flume wall, and are therefore suitable for comparison. The simulated and experimental horizontal flow velocities for different wave conditions are displayed in Figs. A.15 to A.17.

Fig. A.15(a) shows the horizontal velocity over the normalized period at $z = 0.10$ m (PP2) for the smallest tested wave ($H = 0.04$ m and $T = 2.0$ s), with an overall high agreement of the simulated to the experimental results. Correspondingly, a low RMSE of 0.008 m/s for the phase-averaged velocity has been calculated. The same agreement can be observed for the four selected time steps in Fig. A.15(b) to Fig. A.15(e), representing the different phases of a wave period. Overall, the comparison between the experimental and simulated horizontal velocity confirms that the hydrodynamic conditions with $H = 0.04$ m and $T = 2.0$ s are well replicated with the applied numerical wave flume.

The comparison of the horizontal velocity for the wave condition $H = 0.07$ m and $T = 1.5$ s are provided in Fig. A.16. Again, a high agreement between the experimental and simulated results can be confirmed. The RMSE of the horizontal flow velocity is 0.015 m/s, which is slightly higher compared to the previous case. That increase is potentially caused by a small overestimation of the simulated maximum horizontal velocity at the wave crest, which becomes apparent in both Fig. A.16(a) and Fig. A.16(b). Nevertheless, the simulated horizontal flow velocity agrees with the measurements of the reference experiment.

Fig. A.17 displays the comparison of the simulated and experimental horizontal flow velocity for the wave conditions $H = 0.11$ m and

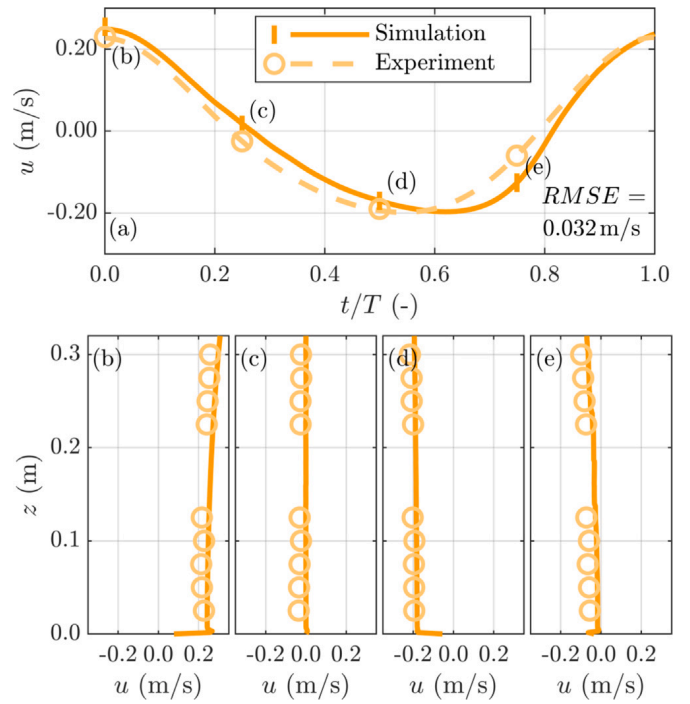


Fig. A.17. Comparison of the simulated horizontal velocity u for wave conditions $H = 0.11$ m and $T = 2.0$ s with the experimental results from the reference experiments in Material 2 and 3 (Jacobsen et al., 2019). The figure presents (a) the phase-averaged horizontal velocity at $z = 0.10$ m (PP2) over the normalized wave period, and (b) - (e) the phase-averaged horizontal velocity profiles across the water depth (LP1) at selected time steps: (b) $t/T = 0.00$, (c) $t/T = 0.25$, (d) $t/T = 0.50$, and (e) $t/T = 0.75$.

$T = 2.0$ s. A good agreement between the simulation's minimum and maximum flow velocity and its reference experiment can be observed in Fig. A.17(a). The only apparent difference between simulated and experimental results is the difference in the shape of the wave, represented by its horizontal velocity at PP2. The resulting RMSE of the horizontal flow velocity is 0.032 m/s. The simulated wave experienced a larger deformation from a linear shape than the reference experiment, possibly influenced by the relatively short numerical wave flume. Nevertheless, Fig. A.17(b) to Fig. A.17(e) confirm good agreement between the simulated and experimental velocity over the height of the flume for all selected points in time.

The simulated waves are further characterized based on their wave skewness (Sk), which quantifies the asymmetry of the surface elevation time series $\eta(t)$ with respect to the horizontal axis (Elgar, 1987). It is defined as the normalized third-order moment:

$$Sk = \frac{\langle \eta'^3 \rangle}{\langle \eta'^2 \rangle^{3/2}} \quad (\text{A.1})$$

where $\eta' = \eta - \langle \eta \rangle$ is the detrended surface elevation, and $\langle \cdot \rangle$ denotes the time-averaging operator. Calculating the skewness for the simulated wave replicating the experiments of Luhar and Nepf (2016) resulted in $Sk = 0.60$, characterizing the wave therefore as non-linear. Similarly, the simulated 0.11 m high wave replicating the Jacobsen et al. (2019) experiment show some non-linearity with Sk equal to 0.44. In contrast, the smaller waves (0.04 m and 0.07 m) can be characterized as non-linear with a Sk of 0.05 and 0.15, respectively.

A.2. Influence of the flume width

Further on, it remains to be evaluated if the reduced flume width of 0.08 m in the numerical domain compared to 0.38 m and 0.80 m in the wave flumes of the reference experiments influences the resulting horizontal flow velocity. Therefore, horizontal flow velocities obtained from simulations with varying flume widths ($W_F = 0.04, 0.08, 0.12$,

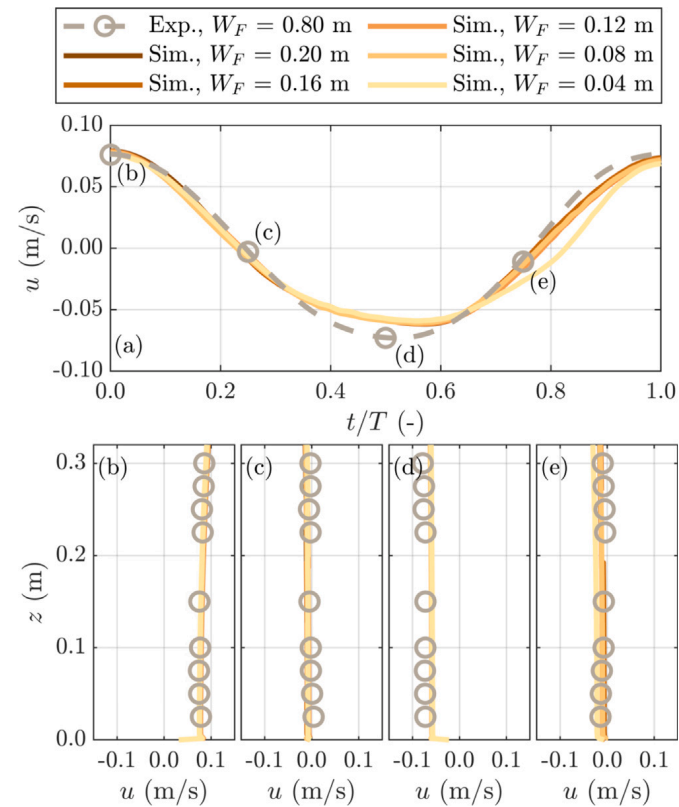


Fig. A.18. Comparison of the simulated horizontal velocity u for wave conditions $H = 0.04$ m and $T = 2.0$ s with the experimental results by Jacobsen et al. (2019). The figure presents (a) the phase-averaged horizontal velocity at $z = 0.10$ m (PP2) over the normalized wave period, and (b) - (e) the phase-averaged horizontal velocity profiles across (LP1) the water depth at selected time steps: (b) $t/T = 0.00$, (c) $t/T = 0.25$, (d) $t/T = 0.50$, and (e) $t/T = 0.75$.

Table A.4

Characteristics of the simulations to investigate the effect of the flume width W_F , with PP2 at $x = 1.82$, $y = 0.00$, $z = 0.10$ m and PP3 at $x = 2.00$, $y = 0.015$, $z = 0.10$ m, see Fig. 1.

W_F (m)	Number of cells (-)	RMSE at PP2 (m/s)	RMSE at PP3 (m/s)
0.04	34 380 080	0.0069	0.0113
0.08	54 025 840	0.0038	0.0077
0.12	73 671 600	0.0036	0.0072
0.16	93 317 360	0.0053	0.0069
0.20	112 963 120	0.0042	0.0070

0.16, and 0.20 m) are compared in the following. Wave conditions with $H = 0.04$ m and $T = 2.0$ s have been selected for this comparison. The simulations were run without FSI solver, due to the large number of resulting cells in the numerical domain with increased flume width (cf. Table A.4).

Fig. A.18 shows the resulting flow velocity for LP1, which has been utilized in the previous comparison. It becomes apparent that only the smallest tested flume width (0.04 m) shows deviations regarding the horizontal flow velocity compared to the other simulated flume widths and the experimental results (Fig. A.18(a)). Fig. A.18(b)–(c) shows the same flow velocity for selected points in time over the flume depth, independent of the applied flume width. In Fig. A.18(e) one can anticipate the influence of the flume width on the resulting horizontal flow velocity, but it remains in order of magnitudes negligible for this application case.

Table A.4 summarizes the number of cells required for the numerical grid of each simulated flume width. Additionally, each simulation's RMSE relative to the experimental results is provided. For PP2, all

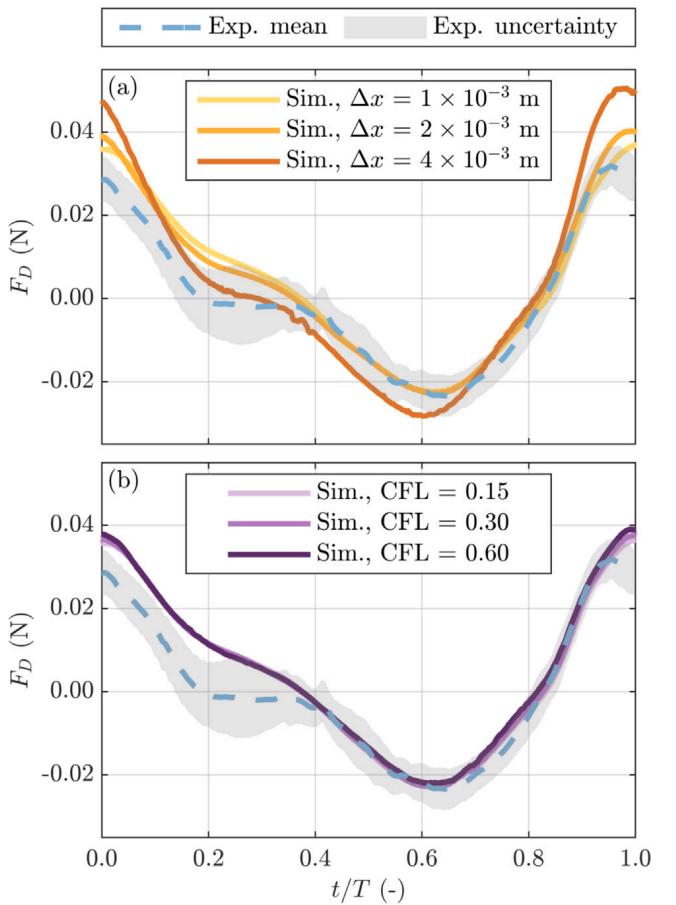


Fig. B.19. Comparison of the phase-averaged force F_D for (a) a variation of refined cell sizes and (b) different CFL-criteria in comparison to the reference experiment (Luhar and Nepf, 2016).

Table B.5

Test program of the temporal and spatial discretization using Material 1.

	Input parameters		Simulation output	
	Refined/coarse cell size Δx (m)	CFL criterion (-)	Simulation time (s)	Number of waves (-)
Spatial discretization	$1/2 \times 10^{-3}$	0.30	13.01	5
	$2/4 \times 10^{-3}$	0.30	27.94	12
	$4/8 \times 10^{-3}$	0.30	29.98	13
Temporal discretization	$1/2 \times 10^{-3}$	0.15	10.40	3
	$1/2 \times 10^{-3}$	0.30	13.01	5
	$1/2 \times 10^{-3}$	0.60	20.36	8

obtained RMSEs are less than 0.01 m/s, confirming the high agreement between the simulated and experimental horizontal flow velocity independent of the applied flume width. For PP3, positioned 0.015 m next to the stem in y -direction, see Fig. 1(b), it becomes apparent that the proximity of the numerical flume wall for the smallest flume influences the flow velocity, resulting in the highest RMSE of all test cases with over 0.01 m/s. The other test cases for PP3 show RMSEs in the same order of magnitude, leading to the conclusion that the flume width of 0.08 m is sufficient to replicate the experimental conditions without wall influence on the horizontal flow velocity in the proximity of the stem.

Overall, the comparison between numerical and experimental hydrodynamic conditions in this appendix focused on the horizontal flow velocity, which is expected to have the largest influence on the stem

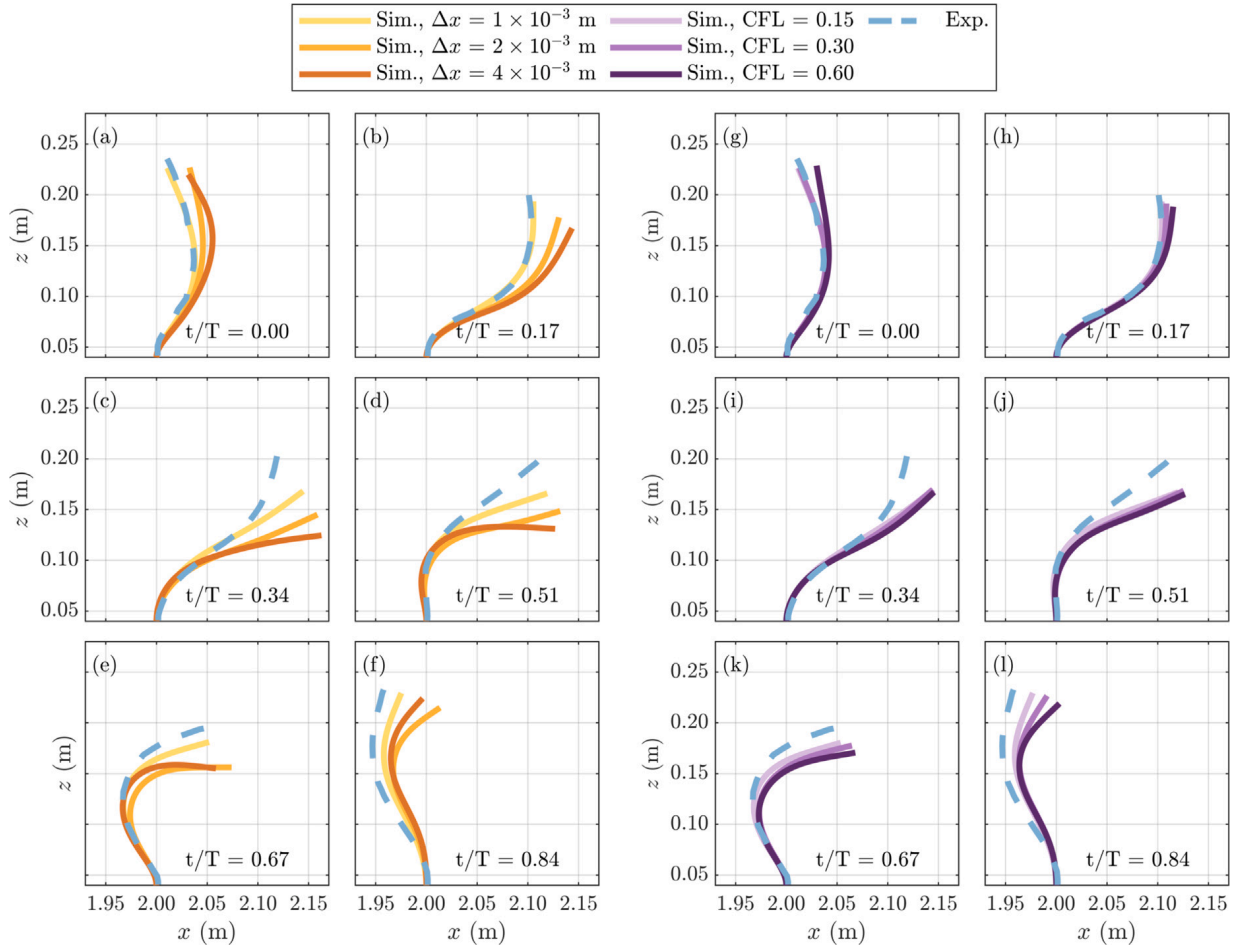


Fig. B.20. Resulting stem motion with Material 1 for (a) to (f) a variation of refined cell sizes and (g) to (l) different CFL-criteria in comparison to the reference experiment (Luhar and Nepf, 2016) for selected points in time.

movement of the FSI and its resulting forces. It can be concluded that the numerical wave flume, with its reduced dimensions, replicates all selected hydrodynamic conditions of the reference experiments with high agreement and can be utilized for further analysis.

Appendix B. Model sensitivity

This appendix focuses on the sensitivity analysis of the FSI solver concerning numerical parameters, such as temporal and spatial discretization. The FSI solver is expected to depend on both time and spatial resolution. The sensitivity of the FSI solver is tested with the stem of Material 1. Table B.5 summarizes the test program to evaluate the model's sensitivity and determine suitable parameters. The refined cell size of the grid is varied between 1, 2, and 4×10^{-3} m, and the values 0.15, 0.30, and 0.60 are tested for the CFL criterion. The refined cell size, labeled as Δx , was applied to all three dimensions of the wave flume. The coarse cell size is twice the fine cell size, ensuring numerical stability. A smaller refined cell size than 1×10^{-3} m was impossible to evaluate with the available computational resources. The comparison of the phase-averaged forces is calculated based on all simulated waves, in contrast to the stem position, where only the last simulated wave of each simulation is selected for further evaluation.

Fig. B.19(a) visualizes the influence of varying refined cell sizes, and correspondingly Fig. B.19(b) for varying CFL criteria on the resulting phase-averaged forces for Material 1. The experimental mean force and uncertainty from the reference experiment are additionally included. It can be observed that the deviation is higher for the different values of refined cell size compared to the resulting force for different CFL criteria.

The comparison of stem position for the same variation of the refined cell size and CFL criterion for selected points in time of each simulation's last wave period is depicted in Fig. B.20. The experimental results of the stem position are also visualized, to provide a reference. A difference in stem bending can be observed for all refined cell sizes. The difference in selected CFL criteria is noticeably smaller and only apparent in selected time steps, see Fig. B.20(g) and Fig. B.20(l).

The resulting uncertainty from the variation of the cell size and the CFL criterion has been determined after the approach of Cummins et al. (2017). The approach is elaborated in the following for determining the grid uncertainty based on the RMS of the resulting forces. Still, it is applied similarly for the variation of the CFL criterion. The quantification of the grid uncertainty follows the assumption of $\phi(h) = \phi_0 + \alpha h^p$, where h_i is the ratio of the cell sizes of the i th grid to that of the reference grid, and ϕ_i is the ratio of simulated forces to the force of the reference grid. The parameter ϕ_0 is the normalized force at infinite resolution. The parameters ϕ_0 and α are obtained via the least squares method based on a curve fit of a parabola, as quadratic convergence is assumed ($p = 2$). The standard error of the fit is then obtained by:

$$\sigma_{fit} = \sqrt{\frac{\sum_{i=1}^{n_g} (\phi_i - \phi(h_i))^2}{n}}, \quad (B.1)$$

where n_g is the number of compared cases (here $n_g = 3$) and $n = n_g - 2$ as the resulting degree of freedom. The reference grid error can be calculated as $\delta = |1 - \phi_0|$. The grid uncertainty is then determined by $U_g = 1.25\delta + \sigma_{fit}$, which includes a safety factor of 1.25 and the standard error of the fit. The regressions regarding the grid uncertainty and the uncertainty caused by varying CFL criteria are depicted in Fig. B.21.

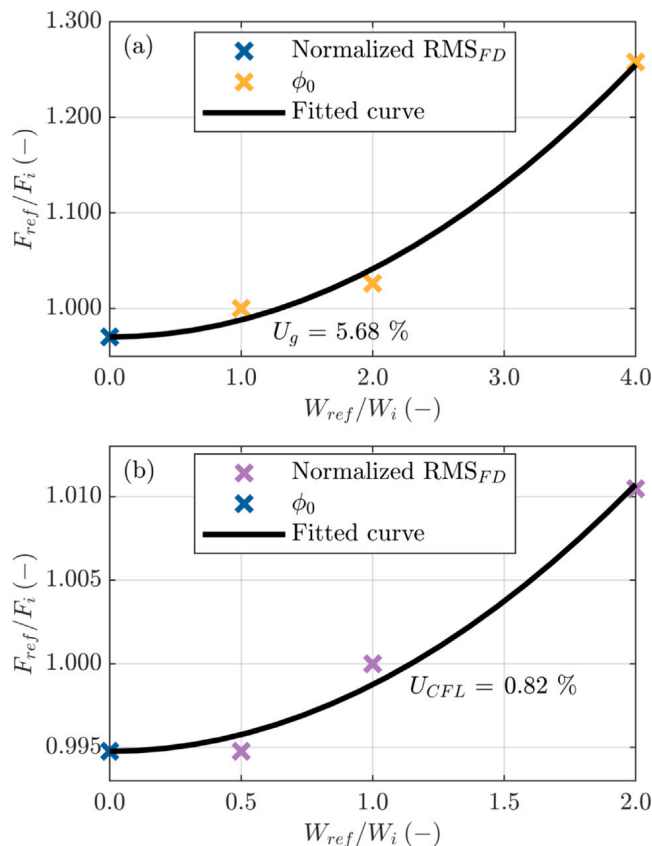


Fig. B.21. Results of the convergence analysis after Cummins et al. (2017) based on (a) the RMS of the resulting forces for different refined cell sizes ($\Delta x = 1, 2$, and $4 \times 10^{-3} \text{ m}$), and (b) the RMS of resulting forces for different CFL criteria ($CFL = 0.15, 0.30$, and 0.60).

It can be concluded that the uncertainty based on the temporal discretization is negligible ($U_{CFL} < 1\%$) for a CFL criterion of 0.30, while the smallest tested refined cell size ($1 \times 10^{-3} \text{ m}$) still leads to a grid uncertainty of 5.68%. Therefore, a refined cell size of $1 \times 10^{-3} \text{ m}$ and a CFL criterion of 0.30 is chosen for the simulations throughout this study.

Data availability

All data, models, or codes supporting the study's findings are available from the corresponding author upon reasonable request.

References

- Agrawal, V., Kulachenko, A., Scapin, N., Tammissola, O., Brandt, L., 2024. An efficient isogeometric/finite-difference immersed boundary method for the fluid-structure interactions of slender flexible structures. *Comput. Methods Appl. Mech. Engrg.* 418, <https://doi.org/10.1016/j.cma.2023.116495>.
- Ando, S., Nishikawa, M., Kaneda, M., Suga, K., 2021. A coupled lattice Boltzmann and Cosserat rod model method for three-dimensional two-way fluid-structure interactions. *AIP Adv.* 11 (7), <https://doi.org/10.1063/5.0058694>.
- Benra, F.-K., Dohmen, H.J., Pei, J., Schuster, S., Wan, B., 2011. A comparison of one-way and two-way coupling methods for numerical analysis of fluid-structure interactions. *J. Appl. Math.* 2011 (1), <https://doi.org/10.1155/2011/853560>.
- Bi, X., Zhu, Q., 2019. Fluid-structure investigation of a squid-inspired swimmer. *Phys. Fluids* 31 (10), <https://doi.org/10.1063/1.5119243>.
- Bihs, H., Kamath, A., Alagan Chella, M., Aggarwal, A., Arntsen, Ø., 2016. A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. *Comput. & Fluids* 140, 191–208. <https://doi.org/10.1016/j.compfuid.2016.09.012>.
- Birkemeier, W.A., 1984. Time scales of nearshore profile changes. *Coast. Eng.* 1507–1521. <https://doi.org/10.1061/9780872624382.103>.

- Blevins, R.D., 2016. Formulas for dynamics, acoustics and vibration. In: Wiley series in acoustics, noise and vibration, Wiley, Chichester, West Sussex. <https://doi.org/10.1002/9781119038122>.
- Bouma, T.J., Vries, M.B.d., Low, E., Peralta, G., Tanczos, I.C., van de Koppel, J., Herman, P.M.J., 2005. Trade-offs related to ecosystem engineering: A case study on stiffness of emerging macrophytes. *Ecology* 86 (8), 2187–2199. <https://doi.org/10.1890/04-1588>.
- Bradley, K., Houser, C., 2009. Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments. *J. Geophys. Res.* 114 (F1), <https://doi.org/10.1029/2007JF000951>.
- Cahoon, D.R., McKee, K.L., Morris, J.T., 2021. How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Estuaries Coasts* 44 (4), 883–898. <https://doi.org/10.1007/s12237-020-00834-w>.
- Cao, D.Q., Tucker, R.W., 2008. Nonlinear dynamics of elastic rods using the cosserat theory: Modelling and simulation. *Int. J. Solids Struct.* 45 (2), <https://doi.org/10.1016/j.ijsolstr.2007.08.016>.
- Caroppi, G., Järvelä, J., 2022. Shear layer over floodplain vegetation with a view on bending and streamlining effects. *Env. Fluid Mech.* 22 (2-3), 587–618. <https://doi.org/10.1007/s10652-022-09841-w>.
- Caroppi, G., Västilä, K., Järvelä, J., Rowiński, P.M., Giugni, M., 2019. Turbulence at water-vegetation interface in open channel flow: Experiments with natural-like plants. *Adv. Water Resour.* 127, 180–191. <https://doi.org/10.1016/j.advwatres.2019.03.013>.
- Chen, H., Zou, Q.-P., 2019. Eulerian-Lagrangian flow-vegetation interaction model using immersed boundary method and OpenFOAM. *Adv. Water Resour.* 126, 176–192. <https://doi.org/10.1016/j.advwatres.2019.02.006>.
- Cui, H., Felder, S., Kramer, M., 2023. Predicting flow resistance in open-channel flows with submerged vegetation. *Environ. Fluid Mech.* 23 (4), 757–778. <https://doi.org/10.1007/s10652-023-09929-x>.
- Cummins, C., Viola, I.M., Mastropalo, E., Nakayama, N., 2017. The effect of permeability on the flow past permeable disks at low Reynolds numbers. *Phys. Fluids* 29 (9), <https://doi.org/10.1063/1.5001342>.
- Derksen, J.J., 2021. Bending and low-frequency vortex shedding of flexible cylinders in laminar shear flow. *AIChE J.* 67 (9), <https://doi.org/10.1002/aic.17268>.
- el Rahi, J., Martínez-Estévez, I., Tagliafierro, B., Domínguez, J., Crespo, A., Stratigaki, V., Suzuki, T., Troch, P., 2023. Numerical investigation of wave-induced flexible vegetation dynamics in 3D using a coupling between DualSPHysics and the FEA module of project chrono. *Ocean Eng.* 285, <https://doi.org/10.1016/j.oceaneng.2023.115227>.
- Elgar, S., 1987. Relationships involving third moments and bispectra of a harmonic process. *IEEE Trans. Acoust. Speech Signal Process.* 35 (12), 1725–1726. <https://doi.org/10.1109/TASSP.1987.1165090>.
- Familkhali, R., Tahvildari, N., 2022. Computational modeling of coupled waves and vegetation stem dynamics in highly flexible submerged meadows. *Adv. Water Resour.* <https://doi.org/10.1016/j.advwatres.2022.104222>.
- Fonseca, M.S., Fourqurean, J.W., Koehl, M.A.R., 2019. Effect of seagrass on current speed: Importance of flexibility vs. shoot density. *Front. Mar. Sci.* 6, <https://doi.org/10.3389/fmars.2019.00376>.
- Fredriksson, D.W., Dewhurst, T., Drach, A., Beaver, W., St. Gelais, A.T., Johndrow, K., Costa-Pierce, B.A., 2020. Hydrodynamic characteristics of a full-scale kelp model for aquaculture applications. *Aquac. Eng.* 90, <https://doi.org/10.1016/j.aquaeng.2020.102086>.
- Garzon, J.L., Maza, M., Ferreira, C.M., Lara, J.L., Losada, I.J., 2019. Wave attenuation by Spartina Saltmarshes in the Chesapeake bay under storm surge conditions. *J. Geophys. Res.: Ocean.* 124 (7), 5220–5243. <https://doi.org/10.1029/2018JC014865>.
- Hagmeyer, N., Mayr, M., Popp, A., 2024. A fully coupled regularized mortar-type finite element approach for embedding one-dimensional fibers into three-dimensional fluid flow. *Numer. Meth. Eng.* 125 (8), <https://doi.org/10.1002/nme.7435>.
- Hairer, E., Wanner, G., 1999. Stiff differential equations solved by Radau methods. *J. Comput. Appl. Math.* 111 (1-2), 93–111. [https://doi.org/10.1016/S0377-0427\(99\)00134-X](https://doi.org/10.1016/S0377-0427(99)00134-X).
- Henderson, S.M., 2019. Motion of buoyant, flexible aquatic vegetation under waves: Simple theoretical models and parameterization of wave dissipation. *Coast. Eng.* 152, <https://doi.org/10.1016/j.coastaleng.2019.04.009>.
- Heuner, M., Silinski, A., Schoelynck, J., Bouma, T.J., Puijalon, S., Troch, P., Fuchs, E., Schröder, B., Schröder, U., Meire, P., Temmerman, S., 2015. Ecosystem engineering by plants on wave-exposed intertidal flats is governed by relationships between effect and response traits. *PloS One* 10 (9), e0138086. <https://doi.org/10.1371/journal.pone.0138086>.
- Hussain, A.A., Al-Obaidi, M.A., Mohammed, A.S., John, Y.M., Rashid, F.L., 2024. Distribution of the velocity profile via analytical and three-dimensional numerical vegetation modeling. *J. Appl. Fluid Mech.* 17 (9), <https://doi.org/10.47176/jafm.17.9.2487>.
- Jacobsen, N., Bakker, W., Uijtewaald, W.S.J., Uittenbogaard, R., 2019. Experimental investigation of the wave-induced motion of and force distribution along a flexible stem. *J. Fluid Mech.* 880, 1036–1069. <https://doi.org/10.1017/jfm.2019.739>.
- Jacobsen, N., van Velzen, G., Fredsøe, J., 2014. Analysis of pile scour and associated hydrodynamic forces using proper orthogonal decomposition. In: *cour and Erosion: Proceedings of the 7th International Conference on Scour and Erosion*. pp. 361–372. <https://doi.org/10.1201/b17703-45>.

- Jin, C., Zhang, J., 2022. Numerical investigation of the wave interaction with flexible vegetation: model setup and validation for a single stem study case. *Anthr. Coasts* 5, <http://dx.doi.org/10.1007/s44218-022-00003-5>.
- Jung, P., Leyendecker, S., Linn, J., Ortiz, M., 2011. A discrete mechanics approach to the Cosserat rod theory—Part I: static equilibria. *Numer. Meth. Eng.* 85 (1), 31–60. <http://dx.doi.org/10.1002/nme.2950>.
- Keimer, K., Kind, F., Prüter, I., Kosmalla, V., Lojek, O., Schürenkamp, D., Prinz, M., Niewerth, S., Aberle, J., Goseberg, N., 2024. From seasonal field study to surrogate modeling: Investigating the biomechanical dynamics of *Elymus* sp. in salt marshes. *Limnol. Ocean. Methods* <http://dx.doi.org/10.1002/lom3.10616>.
- Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Prinz, M., Schürenkamp, D., Freund, H., Goseberg, N., 2023. Proposing a novel classification of growth periods based on biomechanical properties and seasonal changes of *Spartina anglica*. *Front. Mar. Sci.* 10, <http://dx.doi.org/10.3389/fmars.2023.1095200>.
- Keimer, K., Schürenkamp, D., Miescke, F., Kosmalla, V., Lojek, O., Goseberg, N., 2021. Ecohydraulics of surrogate salt marshes for coastal protection: Wave–Vegetation interaction and related hydrodynamics on vegetated foreshores at sea dikes. *J. Waterw. Port. Coast. Ocean. Eng.* 147 (6), [http://dx.doi.org/10.1061/\(ASCE\)WW.1943-5460.0000667](http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000667).
- Knisely, C.W., 1990. Strouhal numbers of rectangular cylinders at incidence: A review and new data. *J. Fluids Struct.* 4 (4), 371–393. [http://dx.doi.org/10.1016/0889-9746\(90\)90137-T](http://dx.doi.org/10.1016/0889-9746(90)90137-T).
- Kosmalla, V., Keimer, K., Schürenkamp, D., Lojek, O., Goseberg, N., 2022. Erosion resistance of vegetation-covered soils: Impact of different grazing conditions in salt marshes and analysis of soil-vegetation interactions by the novel Di Coaster method. *Ecol. Eng.* 181, <http://dx.doi.org/10.1016/j.ecoleng.2022.106657>.
- Lang, H., Linn, J., Arnold, M., 2011. Multi-body dynamics simulation of geometrically exact Cosserat rods. *Multibody Syst. Dyn.* 25 (3), 285–312. <http://dx.doi.org/10.1007/s11044-010-9223-x>.
- Li, B.-L., Wang, Y.-w., Yin, B., Zhang, X., Zhang, X., 2021. Self-propelled swimming of a flexible filament driven by coupled plunging and pitching motions. *J. Hydrodyn.* 33 (1), 157–169. <http://dx.doi.org/10.1007/s42241-021-0018-8>.
- Lim, W.Z., Xiao, R.Y., 2019. Fluid-structure interaction analysis of flexible plate with partitioned coupling method. *China Ocean Eng.* 33 (6), 713–722. <http://dx.doi.org/10.1007/s13344-019-0069-6>.
- Linn, J., Lang, A., 2013. Geometrically exact cosserat rods with Kelvin–Voigt type viscous damping. *Mech. Sci.* 4 (1), 79–96. <http://dx.doi.org/10.5194/ms-4-79-2013>.
- Liu, J., Liu, Q., Kutschke, S., Kosmalla, V., Schürenkamp, D., Goseberg, N., Böhl, M., 2024. Seasonal variations in biomechanical properties of *elymus* species: Implications for assessing coastal ecosystem services. *PAMM* 24 (2), <http://dx.doi.org/10.1002/pamm.202400088>.
- Lo, V.B., Bouma, T.J., van Belzen, J., van Colen, C., Airoidi, L., 2017. Interactive effects of vegetation and sediment properties on erosion of salt marshes in the northern adriatic sea. *Mar. Environ. Res.* 131, 32–42. <http://dx.doi.org/10.1016/j.marenvres.2017.09.006>.
- Lou, S., Wang, H., Liu, H., Zhong, G., Radnaeva, L.D., Nikitina, E., Ma, G., Liu, S., 2021. Laboratory study of the effects of flexible vegetation on solute diffusion in unidirectional flow. *Env. Sci. Eur.* 33 (1), <http://dx.doi.org/10.1186/s12302-021-00521-y>.
- Luhar, M., Nepf, H.M., 2011. Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. *Limnol. Oceanogr.* 56, 2003–2017. <http://dx.doi.org/10.4319/lo.2011.56.6.2003>.
- Luhar, M., Nepf, H.M., 2016. Wave-induced dynamics of flexible blades. *J. Fluids Struct.* 61, 20–41. <http://dx.doi.org/10.1016/j.jfluidstructs.2015.11.007>.
- Marjoribanks, T.I., Lague, D., Hardy, R.J., Boothroyd, R.J., Leroux, J., Mony, C., Puijalon, S., 2019. Flexural rigidity and shoot reconfiguration determine wake length behind saltmarsh vegetation patches. *J. Geophys. Res. Earth Surf.* 124, 2176–2196. <http://dx.doi.org/10.1029/2019JF005012>.
- Marjoribanks, T.I., Paul, M., 2021. Modelling flow-induced reconfiguration of variable rigidity aquatic vegetation. *J. Hydraul. Res.* 1–6. <http://dx.doi.org/10.1080/00221686.2020.1866693>.
- Markov, A., Stolle, J., Henteleff, R., Nistor, I., van Pham Bang, D., Murphy, E., Cornett, A., 2023. Deformation of *Spartina patens* and *Spartina alterniflora* stems under irregular wave action. *Coast. Eng. J.* 1–22. <http://dx.doi.org/10.1080/21664250.2023.2195030>.
- Martin, T., Bihs, H., 2021. A numerical solution for modelling mooring dynamics, including bending and shearing effects, using a geometrically exact beam model. *JMSE* 9 (5), 486. <http://dx.doi.org/10.3390/jmse9050486>.
- Maza, M., Lara, J.L., Losada, I.J., 2013. A coupled model of submerged vegetation under oscillatory flow using Navier–Stokes equations. *Coast. Eng.* 80, 16–34. <http://dx.doi.org/10.1016/j.coastaleng.2013.04.009>.
- Moeller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M., Schimmels, S., 2014. Wave attenuation over coastal salt marshes under storm surge conditions. *Lett. Nat. Geosci.* 7, <http://dx.doi.org/10.1038/ngeo2251>.
- Monismith, S.G., 2020. Stokes drift: theory and experiments. *J. Fluid Mech.* 884, <http://dx.doi.org/10.1017/jfm.2019.891>.
- Mullarney, J.C., Henderson, S.M., 2010. Wave-forced motion of submerged single-stem vegetation. *J. Geophys. Res.* 115, <http://dx.doi.org/10.1029/2010JC006448>.
- O'Reilly, O.M., 2017. Modeling nonlinear problems in the mechanics of strings and rods: The role of the balance laws, 1st ed. 2017 In: *Interaction of Mechanics and Mathematics*, Springer International Publishing and Imprint, Springer, Cham.
- Palm, J., Eskilsson, C., 2020. Influence of bending stiffness on snap loads in marine cables: A study using a high-order discontinuous Galerkin method. *JMSE* 8 (10), 795. <http://dx.doi.org/10.3390/jmse8100795>.
- Paul, M., Bouma, T.J., Amos, C.L., 2012. Wave attenuation by submerged vegetation: combining the effect of organism traits and tidal current. *Mar. Ecol. Prog. Ser.* 444, 31–41. <http://dx.doi.org/10.3354/meps09489>.
- Prüter, I., Spröer, F., Keimer, K., Lojek, O., Windt, C., Schürenkamp, D., Bihs, H., Nistor, I., Goseberg, N., 2025. A comprehensive numerical study on the current-induced fluid–structure interaction of flexible submerged vegetation. *J. Fluids Struct.* 133, 104232. <http://dx.doi.org/10.1016/j.jfluidstructs.2024.104232>.
- Renda, F., Girelli, M., Calisti, M., Cianchetti, M., Laschi, C., 2014. Dynamic model of a multibending soft robot arm driven by cables. *IEEE Trans. Robot.* 30 (5), 1109–1122. <http://dx.doi.org/10.1109/TRO.2014.2325992>.
- Riffe, K.C., Henderson, S.M., Mullarney, J.C., 2011. Wave dissipation by flexible vegetation. *Geophys. Res. Lett.* 38 (18), <http://dx.doi.org/10.1029/2011GL048773>.
- Ros, À., Colomer, J., Serra, T., Pujol, D., Soler, M., Casamitjana, X., 2014. Experimental observations on sediment resuspension within submerged model canopies under oscillatory flow. *Cont. Shelf Res.* 91, 220–231. <http://dx.doi.org/10.1016/j.csr.2014.10.004>.
- Rucker, D.C., Webster III, R.J., 2011. Statics and dynamics of continuum robots with general tendon routing and external loading. *IEEE Trans. Robot.* 27 (6), 1033–1044. <http://dx.doi.org/10.1109/TRO.2011.2160469>.
- Rupprecht, F., Möller, I., Paul, M., Kudella, M., Spencer, T., van Wesenbeeck, K., B., Wolters, G., Jensen, K., Bouma, T., Miranda-Lange, M., Schimmels, S., 2017. Vegetation-wave interactions in salt marshes under storm surge conditions. *Ecol. Eng.* 100, 301–315. <http://dx.doi.org/10.1016/j.ecoleng.2016.12.030>.
- Schmucker, H., Flemming, F., Coulson, S., 2010. Two-way coupled fluid structure interaction simulation of a propeller turbine. *Int. J. Fluid Mach. Syst.* 3 (4), 342–351. <http://dx.doi.org/10.5293/IJFMS.2010.3.4.342>.
- Schoppmann, K., Löhner, B., Tschigale, S., Fröhlich, J., Langre, E.d., 2021. An efficient solver for a Cosserat rod of non-constant width applied to a problem of fluid-structure interaction. *Proc. Appl. Math. Mech.* 21 (1), <http://dx.doi.org/10.1002/pamm.202100152>.
- Schoutens, K., Silinski, A., Belliard, J.-P., Bouma, T.J., Temmerman, S., Schoelynck, J., 2024. Wave attenuation by intertidal vegetation is mediated by trade-offs between shoot- and canopy-scale plant traits. *J. Appl. Ecol.* <http://dx.doi.org/10.1111/1365-2664.14765>.
- Schulze, D., Rupprecht, F., Nolte, S., Jensen, K., 2019. Seasonal and spatial within-marsh differences of biophysical plant properties: implications for wave attenuation capacity of salt marshes. *Aquat. Sci.* 81 (4), <http://dx.doi.org/10.1007/s00027-019-0660-1>.
- Simeon, B., 2001. Numerical analysis of flexible multibody systems. *Multibody Syst. Dyn.* 6 (4), 305–325. <http://dx.doi.org/10.1023/A:1012096631385>.
- Till, J., Aloï, V., Rucker, C., 2019. Real-time dynamics of soft and continuum robots based on Cosserat rod models. *Int. J. Robot. Res.* 38 (6), 723–746. <http://dx.doi.org/10.1177/0278364919842269>.
- Tschigale, S., Fröhlich, J., 2020. An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid. *J. Comput. Phys.* 423 (7), <http://dx.doi.org/10.1016/j.jcp.2020.109801>.
- Tschigale, S., Löhner, B., Meller, R., Fröhlich, J., 2021. Large eddy simulation of the fluid-structure interaction in an abstracted aquatic canopy consisting of flexible blades. *J. Fluid Mech.* 916, <http://dx.doi.org/10.1017/jfm.2020.858>.
- van den Bremer, T.S., Breivik, Ø., 2018. Stokes drift. *Philos. Trans. Ser. A, Math. Phys. Eng. Sci.* 376 (2111), <http://dx.doi.org/10.1098/rsta.2017.0104>.
- van Veelen, T.J., Fairchild, T.P., Reeve, D.E., Karunaratna, H., 2020. Experimental study on vegetation flexibility as control parameter for wave damping and velocity structure. *Coast. Eng.* 157, <http://dx.doi.org/10.1016/j.coastaleng.2020.103648>.
- Vuik, V., Suh Heo, H.Y., Zhu, Z., Borsje, B.W., Jonkman, S.N., 2017. Stem breakage of salt marsh vegetation under wave forcing: A field and model study. *Estuar. Coast. Shelf Sci.* 200, 41–58. <http://dx.doi.org/10.1016/j.ecss.2017.09.028>.
- Wang, J., He, G., Dey, S., Fang, H., 2022. Fluid-structure interaction in a flexible vegetation canopy in an open channel. *J. Fluid Mech.* 951, <http://dx.doi.org/10.1017/jfm.2022.899>.
- Wang, X., Rojas, N., 2024. Cosserat rod modeling and validation for a soft continuum robot with self-controllable variable curvature. In: *7th International Conference on Soft Robotics. RoboSoft*, pp. 705–710. <http://dx.doi.org/10.1109/RoboSoft60065.2024.10522028>.
- Wang, H., Tang, H.-w., Zhao, H.-q., Zhao, X.-y., Lü, S.-q., 2015. Incipient motion of sediment in presence of submerged flexible vegetation. *Water Sci. Eng.* 8 (1), 63–67. <http://dx.doi.org/10.1016/j.wse.2015.01.002>.
- Wang, L., Xu, M., Zhang, C., Dai, W., 2023. Numerical investigation on solitary waves traveling over rigid vegetation by a 3D-MPS method. *Appl. Ocean Res.* 132, 103476. <http://dx.doi.org/10.1016/j.apor.2023.103476>.
- Wei, Z., Shao, Y., Kristiansen, T., Kristiansen, D., 2024. An efficient numerical solver for highly compliant slender structures in waves: Application to marine vegetation. *J. Fluids Struct.* 129, <http://dx.doi.org/10.1016/j.jfluidstructs.2024.10417>.

- Xu, D., Liu, J.-n., Wu, Y.-f., Ji, C.-n., 2022. Numerical investigation of the dynamics of flexible vegetations in turbulent open-channel flows. *J. Hydrodyn.* 34 (4), 681–699. <http://dx.doi.org/10.1007/s42241-022-0057-9>.
- Yin, K., Xu, S., Huang, W., Liu, S., Li, M., 2021. Numerical investigation of wave attenuation by coupled flexible vegetation dynamic model and XBeach wave model. *Ocean Eng.* 235, <http://dx.doi.org/10.1016/j.oceaneng.2021.109357>.
- Zhu, Z., Yang, Z., Bouma, T.J., 2020a. Biomechanical properties of marsh vegetation in space and time: effects of salinity, inundation and seasonality. *Ann. Botany* 125 (2), 277–290. <http://dx.doi.org/10.1093/aob/mcz063>.
- Zhu, L., Zou, Q.-P., Huguenard, K., Fredriksson, D.W., 2020b. Mechanisms for the asymmetric motion of submerged aquatic vegetation in waves: A consistent-mass cable model. *J. Geophys. Res. Ocean.* 125, <http://dx.doi.org/10.1029/2019JC015517>.

Response to the reviewers

Dear Editor and Reviewers,

The authors would like to express their appreciation for the time taken and effort made to evaluate the manuscript and believe that addressing the comments increased the overall quality of the revised manuscript.

Please find attached a marked version of the manuscript, indicating the amendments the authors performed, along with a clean manuscript. Detailed answers to the reviewers' comments are provided in this rebuttal letter. The line numbers refer to the revised, clean version of the manuscript.

Answers to the individual comments can be found below. The convention is as follows:

- Refers to the reviewer's comments
- *Refers to our responses to the comments*
- Refers to new text added to the manuscript
- ~~Refers to text deleted from the manuscript~~

Reviewer 1

This study focused on the dynamics of flexible vegetation stems under wave loading. Using the fluid-structure interaction solver of the REEF3D::CFD model and referring to specific experiments, it analyzed the flexible stem movement, forces, and flow fields under various materials and hydrodynamic conditions, and explored the influence of damping coefficients. In general, the paper is logically organized, the numerical results agreed with the experimental data to some extent, shedding light on the interaction of flexible vegetation and waves.

Comment 1 The authors assumed a flexible vegetation stem as a flexible cylinder and examined the hydrodynamic behavior under wave actions. It is accepted that the natural aquatic vegetation geometry is very complex with roots and leaves, and how to deal with the problem should be clearly addressed.

Response: *The authors agree with the reviewer's statement that natural aquatic vegetation occurs with complex geometries and root systems. Requiring the focus on some aspects of these complex natural systems, the framework of this study concentrates only on the above ground biomass. Furthermore, some plants can be fully characterized by their stems, for example, salt marsh vegetation during the winter season as shown by Keimer et al. (2023). Overall, the introduced model serves as a generic approach to modeling the stems of aquatic vegetation, accepting – for now – that leaves, branches, and other plant elements are omitted; further research, using more complex geometric models of flexible plants will have to be developed to deepen the research on flow-plant interaction. Possible advancements to replicate live vegetation more accurately have been additionally discussed in Section 4.2*

Actions taken: The simplifications of natural aquatic vegetation assumed in this study are now more clearly differentiated in the manuscript.

[Line 53 - 61]

[...] Accurately replicating the flexibility properties of such vegetation in a model is essential when modeling their stem dynamics. **Not only does the flexibility of the vegetation differ between species, but also their phenology and geometry. This study simplifies, as a first approach, natural vegetation to its stem, neglecting hence its roots, branches, and leaves. However, some vegetation, for example *S. anglica* in its winter state (Keimer et al., 2023), consists of only a stem and can be therefore fully characterized by the presence of only the stem.** Numerical models replicating flexible vegetation [...]

Comment 2 In section 2.2.2, for saving the computational cost, the size of the numerical wave flume is considerably shorter compared to the reference experiments by applying a Dirichlet boundary condition. Does the numerical accuracy decrease in comparison to that of a full-scale numerical model? The authors are recommended to examine their deviation for illustrating the reasonability and reliability of the small-scale numerical model.

Response: *Thank you for this comment; the authors generally agree that the short numerical wave flume is a potential source of model inaccuracies. Therefore, the authors had compared the wave height and velocity of the laboratory experiments*

to the numerical results in Appendix A. The main outcomes of the evaluation are summarized in Section 2.2.2 of the manuscript (lines 378 - 394). The authors believe the provided numbers with respect to the deviation of the experimental to the simulated horizontal flow velocity support the reasonability and reliability of the selected numerical flume dimensions. Furthermore, the influence of observed minor deviations between the experimental and simulated flow field on the fluid-structure interaction is evaluated in Section 3.3.

Comment 3 The various boundary sketch should be added in Fig.1, and the related boundary condition and setup should be addressed clearly, as well as the initial conditions of the numerical model.

Response: The authors agree with the reviewer's observation that Fig.1 would be improved by addressing the boundary conditions of the wave flume. Furthermore, they should be clearly elaborated in the text.

Actions taken: Boundary conditions have been added to Fig. 1 and their description in the text has been extended and improved for clarity.

[Line 356 - 368]

[...] The numerical wave flume used to replicate the experimental test conditions is visualized in Fig. 1. To ensure computational efficiency, the length and the width of the flume were reduced to 4.00 m and 0.08 m, respectively. Wave generation in the numerical wave flume, which was considerably shorter compared to the **physical one used for the** reference experiments, was achieved by applying a Dirichlet boundary condition to simulate shallow water waves, combined with active wave absorption at the outlet. **While the top of the numerical wave flume is idealized by a symmetry plane, the remaining boundary conditions are defined as walls with a global roughness, k_s , equal to 0.001 m. Initial water levels, d , are either 0.30 m or 0.45 m (as shown in Table 1).** The stem was placed in the center of the flume in x - and y -direction for all simulations. [...]

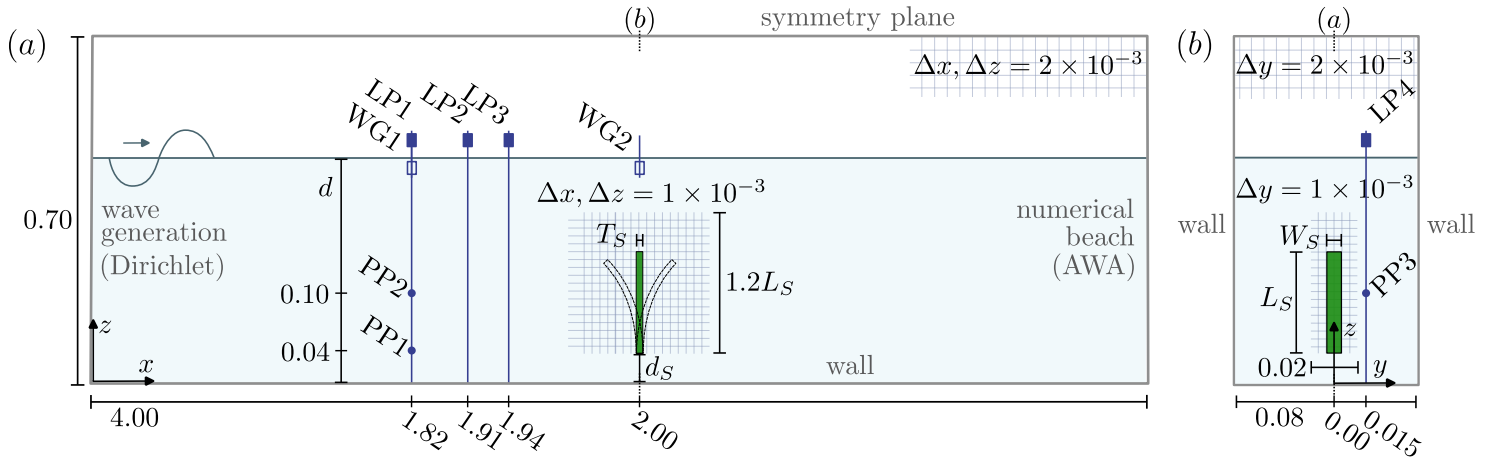


Figure 1: Sketch of the (a) side view and (b) front view of the numerical wave flume including the positioning of the stem, the wave gauges (WG), line probes (LP), and point probes (PP), and the zone of refined cell size around them (in meters, not to scale). For the simulations of Material 1, $d = 0.30$ m and $d_S = 0.04$ m is used and for Materials 2 and 3 $d = 0.45$ m and $d_S = 0.00$ m, both in accordance with the reference experiments

Comment 4 Fig. 2 shows the comparison of the simulated stem positions for Material 1 at typical times. The numerical stem position fits with the experimental data in Fig. 2 (a) and (b); however, in Fig. 2 (c) to (f), their deviations increase, especially at the stem top positions. It still lacks the quantitative explanations, which should be added. In addition, a similar problem occurs in Fig. 7, and the main reason should be discussed and explained.

Response: *Thank you for this helpful suggestion. The authors agree with the reviewer's request to add a quantitative comparison regarding the observed deviations in the stem position. Naturally, the same deviation occurs in Fig. 7 as in Fig. 2 since they depict the same stem. In fact, the comparison in Fig. 7 has been added to the manuscript to provide further evaluation of possible processes responsible for this observed deviation, here with respect to the flow field in front of the wave-induced stem motion. The authors concluded that stems with lower flexural stiffness are more sensitive to deviations between experiments and numerical simulation in the surrounding flow conditions. The nonlinearity of the wave makes it more challenging to accurately reproduce the flow conditions of the Luhar and Nepf (2016) experiments numerically. Conducting physical flume experiments with highly linear waves would be beneficial to reduce such sources of inaccuracy but are challenging to conduct and therefore scarcely available.*

Actions taken: Distances in the tip position have been calculated and added as a quantitative comparison. The explanation has been extended and improved for clarity.

[Line 497 - 513]

[...] Overall, the resulting stem motion of the simulation agrees well with the experimental results. Small deviations in the stem position can be observed after approximately one-third of the wave period, depicted in Fig. 2 (c)-(f). Quantitatively, the largest discrepancies between simulated and experimental tip position are shown in Fig. 2 (c), (d), and (f) with 0.041 m, 0.035 m, and 0.034 m, respectively. On average, that corresponds to a deviation of 18 % relative to the initial stem length. About half the discrepancies between the simulated and experimental tip position can be observed for Fig. 2 (a) with 0.018 m, (b) with 0.017 m, and (e) with 0.020 m. Correspondingly, relative to the initial stem length, the latter tip positions deviate by 9 %, which lies within an acceptable ± 10 % error margin.

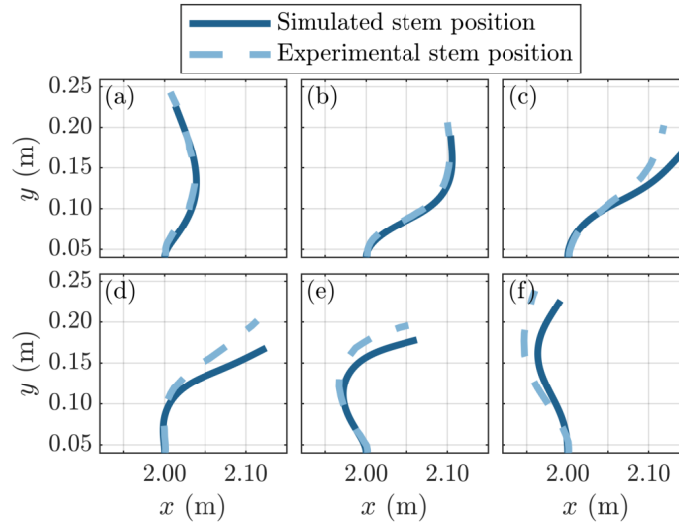


Figure 2: Comparison of the simulated stem positions for Material 1 with $H = 0.08\text{ m}$ and $T = 2.0\text{ s}$ to the stem positions in the reference experiment for selected points in time with (a) $t/T = 0.00$ (b) $t/T = 0.17$ (c) $t/T = 0.34$ (d) $t/T = 0.51$ (e) $t/T = 0.67$ and (f) $t/T = 0.84$

The influence of the flow field on the deviation of the stem tip position is evaluated in more detail in Section 3.3. Herein, it is shown that the shape of the stem bending and the overall movement of the stem are satisfyingly reproduced. General Metrics for the fit are presented at the end of this section. [...]

Comment 5 Fig. 4 shows the comparison of the simulated and the experimental ensemble-averaged stem motion, and a relatively high deviation occurs in Fig. 4 (a), (c), and (d). The authors are recommended to explain the reason quantitatively.

Response: *Thank you for raising the question of a quantitative assessment of the observed deviations in Fig. 4. The authors agree with the reviewer and extended the comparison. A reason for the shift of the stem displayed in Fig. 4 (c) had been provided in the extended analysis in Section 3.2 (lines 612 - 620), following the hypothesis of Jacobsen et al. (2019) who considered a phenomenon similar to Stoke's drift to be responsible for the asymmetry of the stem movement.*

Actions taken: Similar to the previously added quantitative comparison, the average stem tip position between the experimental and simulated stem has been calculated and the comparison has been extended and improved for clarity.

[Line 541 - 559]

[...] It becomes apparent that Material 2 and Material 3 have a higher flexural stiffness than Material 1, resulting in a more restrained stem movement. Showing the least flexibility, the short (0.15 m) stem of Material 3 remains in its initial position for all tested wave conditions. Correspondingly, both stems with Material 3 show a high agreement when comparing the distance between the average experimental to the simulated tip position, with 0.002 m for the stem depicted in Fig. 4 (b), and 0.003 m for the stem depicted in Fig. 4 (d). Relative to the initial stem length, the deviation of the average tip position for both the stem depicted in Fig. 4 (b) and in Fig. 4 (d) was 1%. In the reference experiment,

the 0.30 m long stem with Material 2 tilts asymmetrically within the direction of the wave propagation, depicted in Fig. 4 (c), which is not replicated by the simulations results. Therefore, larger discrepancies between the average experimental to simulated tip position occur with Material 2, for the stem depicted in Fig. 4 (a) by 0.010 m and for the stem shown in Fig. 4 (c) by 0.019 m. With an average deviation of the tip position relative to the initial stem length of 7 % for the stem depicted in Fig. 4 (c) and of 6 % for the stem shown in Fig. 4 (c), both are within the acceptable ± 10 % error margin. The bending behavior is evaluated in more detail in Section 3.2. [...]

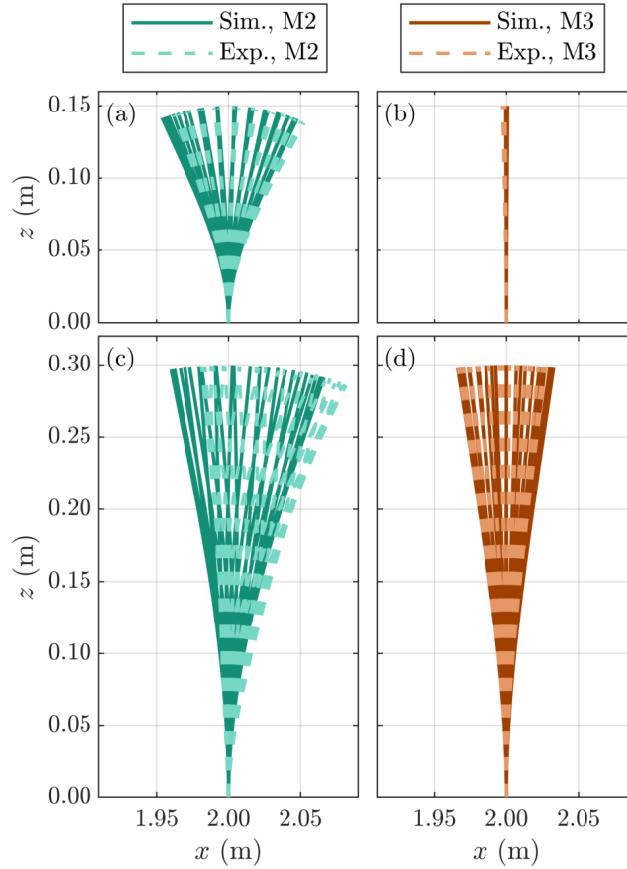


Figure 4: Comparison of the simulated to the experimental ensemble-averaged stem motion from $t/T = 0 - 1$ with $t/T = 0.04$ increments, resulting in 25 stem positions each for (a) Material 2 with $L_S = 0.15$ m, $H = 0.07$ m and $T = 1.5$ s, (b) Material 3 with $L_S = 0.15$ m, $H = 0.04$ m and $T = 2.0$ s, (c) Material 2 with $L_S = 0.30$ m, $H = 0.04$ m and $T = 2.0$ s, and (d) Material 3 with $L_S = 0.30$ m, $H = 0.07$ m and $T = 1.5$ s

Comment 6 7 curves are shown in Fig. 8, and their line types and colors differ little between each other, please redraw them for improving the readability. And a similar problem was found in Fig.11.

Response: *Thank you for your comment; the authors agree with the reviewer that the mentioned figure could be improved with respect to readability. However, an attempt was made to stay in the continuous notation of the manuscript, for example, keeping dashed lines for the experimental results only and a blue color for Material 1.*

Actions taken: For both Figures 8 and 11, the color gradient has been increased for improved legibility.

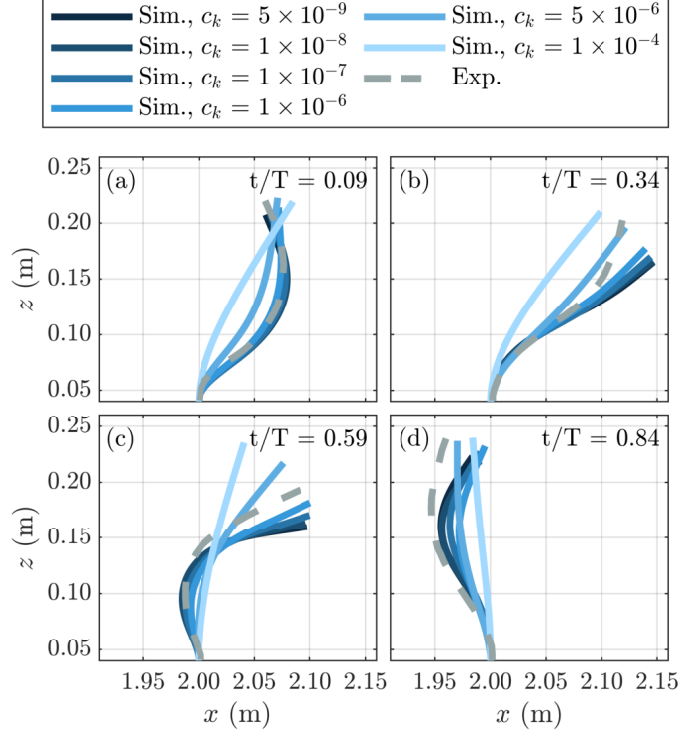


Figure 8: Influence of varying damping coefficients c_k on the stem position for Material 1 with the wave conditions $H = 0.08$ m and $T = 2.0$ s for selected points in time

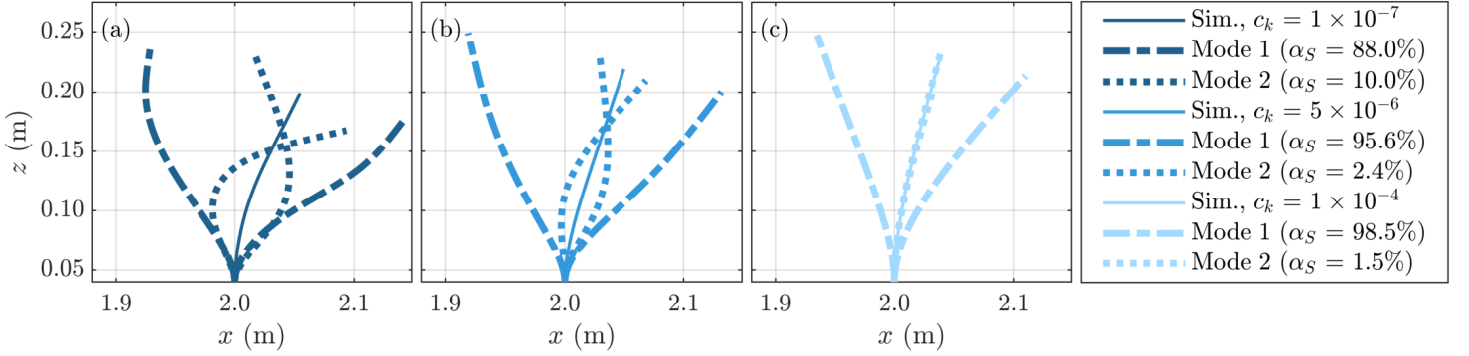


Figure 11: Comparison of the bending modes of the simulated stem position with α_S indicating their weights for different damping coefficients for Material 1, with (a) $c_k = 1 \times 10^{-7}$, (b) $c_k = 5 \times 10^{-6}$ and (c) $c_k = 1 \times 10^{-4}$

Comment 7 A relatively high deviation occurs between the numerical force amplitude spectrum and experimental data in Fig. 10 (b), especially at the horizontal coordinate of frequency higher than 2, showing the relatively low ability for simulating the force amplitude. And the main reason should be explained clearly.

Response: *Thank you for this comment. In Fig. 10 (b), the dominant amplitude, related to the wave frequency (in this case $T = 2\text{ s} = 0.5\text{ Hz}$) is excluded from the figure due to the focus on the influence of the damping coefficients on the smaller fluctuations in the force measurements. The authors agree that the deviations for higher frequencies for simulations with lower damping coefficients indicate inaccuracies, underlining the importance of considering appropriate damping coefficients.*

Actions taken: The text in the manuscript has been improved for clarity and the reasoning is extended.

[Line 711 - 730]

Providing further insights, the resulting forces are displayed in the frequency domain in Fig. 10 (b). The periodic forces induced by the wave load (here with $T = 2.0\text{ s}$ corresponding to 0.5 Hz) ~~provide information about the overall replication of the wave included forces.were not of interest,~~ To gain further information about the additional fluctuations in the simulated forces, the signal was filtered using a high-pass filter for frequencies smaller than 0.7 Hz and excluded from the analysis. Prominent peaks can be observed for the simulated and experimental results in the force amplitude spectrum. These peaks occur at about 1.0 and 1.5 Hz for all simulated as well as experimental resulting forces, while the peaks around 2.5 and 3.5 Hz are only prominent for the simulated results with small damping coefficients ($c_k = 1 \times 10^{-10}$ and 1×10^{-12}). ~~The simulations with lower damping coefficients show large deviations from the experimental results with higher frequencies.~~ It can be concluded that the peaks at lower frequencies replicate realistic material behavior, as they can also be observed in the experimental results. In contrast, the peaks at higher frequencies indicate non-physical inner vibrations of the stem, which lower damping coefficients cannot suppress. It is therefore crucial to select appropriate damping coefficients for test cases with minimal movement to avoid nonphysical inner forces, which can also lead to numerical instabilities.

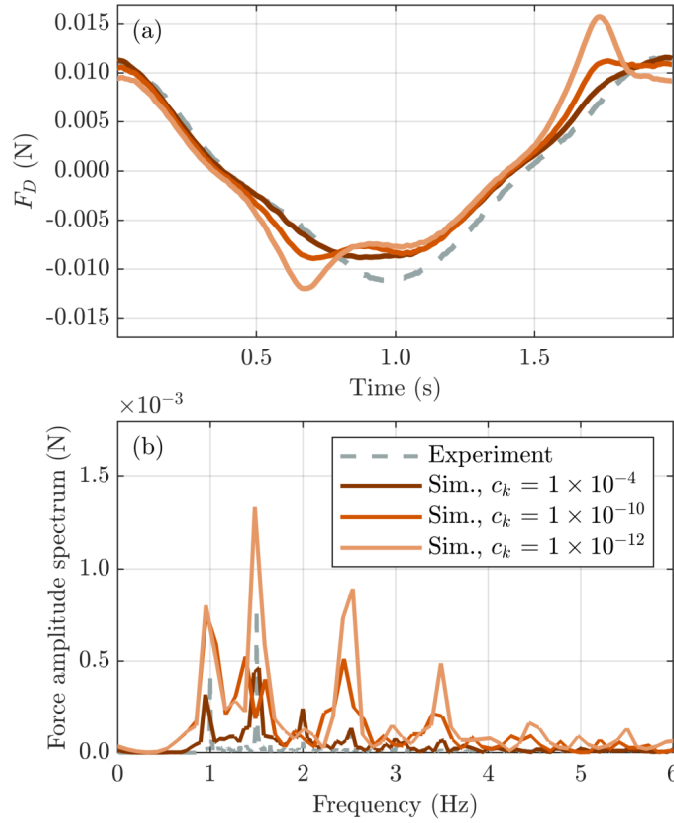


Figure 10: Influence of selected damping coefficients on (a) the phase-averaged drag force (b) the resulting drag force amplitude spectrum in the frequency domain for the 0.15 m long stem of Material 3 with wave conditions $H = 0.04$ m and $T = 2.0$ s

Comment 8 The damping coefficients are essential to account for the nonlinear viscous damping of stem, and the damping coefficient contributes greatly to the stem dynamics and the resulting drag forces. In the actual natural environment, how to get the specific values of the damping coefficient of various vegetation? Are there any feasible on-site measurement or estimation methods? Elaborate it.

Response: *The authors agree with the reviewer's comment on the relevance of the damping coefficients for simulating the wave-vegetation interaction. To date, it is not clear how to obtain damping coefficients for live vegetation stems as the damping coefficients are specific to the applied structural model. The authors hypothesize that the recommended damping coefficients derived from this study can be applied to natural vegetation given that the flexural stiffness is within a comparable order of magnitude. However, confirmation of the hypothesis should be part of a subsequent study, in particular investigating a broader range of species, which was clearly out of the scope of this study.*

Actions taken: The elaboration of the application of the investigated damping coefficients to live vegetation has been extended.

[Line 923 - 933]

It remains to be evaluated which damping coefficients are suitable to replicate the motion of live vegetation, which should be focused on in future studies. Due

to the specificity of the damping coefficients to the applied structural solver, appropriate values are not known for live vegetation and how to assess them in field studies remains uncertain. Instead, the authors suggest evaluating their influence and their applicability for live vegetation numerically as performed in this study for surrogate materials, ideally including a wide range of natural species. Individual stem studies could be utilized then to investigate the sediment mobility around vegetation species with varying properties or their seasonal differences. [...]

Comment 9 Some words are miswritten, and the grammar should be checked carefully. For example, in the title of Table 2, KS should be KC.

Response: *Thank you for recognizing the spelling mistake in the title of Table 2.*

Actions taken: The authors revised the submitted manuscript carefully with respect to spelling and grammatical errors. The spelling mistake in the title of Table 2 has been corrected.

Reviewer 2

This study presents an investigation on the behavior of flexible vegetation stems under wave action with the help of a FSI solver. The adopted solver is developed under the framework of an open-source CFD code - REEF3D by introducing sub-models for solid structures. This work is meaningful and interesting considering its potential application in a wide range of FSI problems. A major drawback lies in the insufficient depth into the mechanism on the FSI behavior of flexible vegetations. Detailed comments and suggestions are:

Comment 1 The mechanism on the FSI dynamics of vegetation stem under waves shall be revealed in more in-depth way. Currently, many details remain to be revealed, such as the influence of natural frequency of the stem and its comparison with wave period, the influence of linear and nonlinear waves with various parameters and so on.

Response: Thank you for showing interest in a more in-depth evaluation of the proposed FSI solver. The authors believe that some of the proposed topics, raised by the respected reviewer, have been at least partially covered in the original manuscript; the authors want to emphasize that one major contribution of this study is the first validation of the proposed solver for the replication of wave vegetation interaction.

*For example, in the Discussion section (lines 797 - 809) the natural frequency is compared to the wave frequency and the vortex shedding frequency for one example case, and their importance is discussed. Based on the reviewer's suggestion and **Comment 3** from Reviewer 3, the analysis has been extended with respect to occurring vortices, providing further information on the fluid-structure interaction.*

Furthermore, four different wave heights were used for the model validation and investigation, supporting the investigation of various hydrodynamic conditions. Based on the reviewer's suggestion, differentiation with respect to their linearity is considered a valuable addition to the manuscript. The results show that as a general trend, the wave linearity decreases with increasing wave height. It can be therefore concluded that the proposed FSI solver is able to replicate experimental stem movement and resulting forces for conditions with varying wave linearity. Overall, it remains challenging to accurately reproduce the non-linearity of the experimental waves resulting from transformation processes in the wave flume in numerical simulations, representing a potential source for discrepancies between experimental and numerical results.

Generally, the authors believe that the exploration of further parameters falls outside the scope of this manuscript, given both its overall length and the extensive simulation time required for each run.

Actions taken: Vortices resulting from the fluid-structure interaction have been visualized and analyzed, as detailed in the answer to **Comment 3** from Reviewer 3. Furthermore, wave skewness has been calculated for the different utilized wave conditions, clarifying the increase in non-linearity for larger wave heights. The elaboration in the text has been extended and improved for clarification.

[Line 391 - 402]

In conclusion, satisfactory agreement was achieved for all tested wave conditions, with root mean square errors (RMSEs) ranging from 0.008 m/s for the smallest wave height ($H = 0.04$ m and $T = 2.0$ s) to 0.032 m/s for the wave largest wave height ($H = 0.11$ m and $T = 2.0$ s). Further analysis of the wave non-linearity is provided by calculating the wave skewness Sk , as elaborated in Appendix A.1. The skewness of the simulated wave replicating the experiments of Luhar and Nepf (2016) was calculated as $Sk = 0.60$, indicating non-linearity. Likewise, the 0.11 m high simulated wave replicating the Jacobsen et al. (2019) experiments showed some non-linearity with $Sk = 0.44$. In contrast, the smaller waves (0.04 m and 0.07 m) exhibited lower skewness values of 0.05 and 0.15, respectively, suggesting a linear behavior. Appendix A.2 shows, additionally, that [...]

[Line 1089 - 1101] (*Appendix A.1*)

The simulated waves are further characterized based on their wave skewness (Sk), which quantifies the asymmetry of the surface elevation time series $\eta(t)$ with respect to the horizontal axis (Elgar, 1987). It is defined as the normalized third-order moment:

$$Sk = \frac{\langle \eta'^3 \rangle}{\langle \eta'^2 \rangle^{3/2}} \quad (1)$$

where $\eta' = \eta - \langle \eta \rangle$ is the detrended surface elevation, and $\langle \cdot \rangle$ denotes the time-averaging operator. Calculating the skewness for the simulated wave replicating the experiments of Luhar and Nepf (2016) resulted in $Sk = 0.60$, characterizing the wave therefore as non-linear. Similarly, the simulated 0.11 m high wave replicating the Jacobsen et al. (2019) experiment show some non-linearity with Sk equal to 0.44. In contrast, the smaller waves (0.04 m and 0.07 m) can be characterized as non-linear with a Sk of 0.05 and 0.15, respectively.

Comment 2 In LINE 100-103, the authors describe that "None of the previous studies examined the time-dependent motion of vegetation stems in detail, despite its significance, as downstream velocity and vorticity fields are directly influenced by upstream vegetation dynamics". However, this is inaccurate considering that there are quite a lot relevant literature, for example, Xu, D., et al (2022). "Numerical investigation of the dynamics of flexible vegetations in turbulent open-channel flows." Journal of Hydrodynamics 34(4): 681-699.

Response: *The authors thank the reviewer for noticing this inaccuracy. While overall studies looking at the influence of stem motion on velocity and resulting vorticity exist, like the suggested paper, the comment intended to explicitly refer to the previously introduced numerical studies concerning (single) stem-wave interaction. Nevertheless, the study of Xu et al. (2022) provides a valuable example of why the flexibility of stems should be included in simulations on the meadow scale and has been accordingly added to the manuscript.*

Actions taken: The text has been adjusted to clarify the statement and the source added based on the reviewer's suggestion.

[Line 99 - 115]

[.] Hagmeyer et al. (2024) studied configuration parameters of their numerical model for an individual stem with an inflow velocity profile similar to waves but did not validate the resulting forces exerted on the stem, before focusing their investigation on the monami phenomenon, which describes the synchronized movement of vegetation meadows in unidirectional flow. None of the previously referenced studies examined the time-dependent motion of vegetation stems under wave load in detail, despite its significance, as downstream velocity and vorticity fields are directly influenced by upstream vegetation dynamics (Caroppi et al., 2019; Hussain et al., 2024). Moreover, accurately replicating stem movement is crucial for understanding sediment dynamics, as it affects the incipient sediment motion (Wang et al., 2015). It is also important to accurately replicate stem motion to ensure that studies of meadow-scale phenomena, such as monami and large-scale vortices (Tschisgale et al., 2021; Wang et al., 2022; Xu et al., 2022), reflect the behavior of live vegetation, as well as to correctly replicate plant reconfiguration at the meadow scale, where reconfiguration can lead to the closure of gaps between individual plants (Fonseca et al., 2019).

Comment 3 For an FSI problem, both the structure and the fluid are important. However, there are no sufficient information on the fluid dynamics provided.

Response: *Thank you for your comment, which aligns with **Comment 1** of Reviewer 3. The authors agree with both reviewers that further information on the fluid solver provides a more comprehensive introduction to the proposed FSI solver.*

Actions taken: The governing equations of the fluid solver have been added to the manuscript, resulting in an extended introduction to fluid dynamics.

[Line 261 - 278]

The hydrodynamic numerical model utilized in this study is the finite difference (FD) solver REEF3D::CFD, distinguished by the level-set method for representing the free surface and its high-order discretization schemes. The fluid solver is based on the incompressible Navier-Stokes equation, for further details on the implementation and validation, the reader is referred to Bihs et al. (2016). The Navier-Stokes equations are herein expressed by the incompressible continuity equation (2) and the incompressible momentum equation (3).

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_f} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \nu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + g_i \quad (3)$$

In Eqs. (2) and (3), u_i represents the velocity vector in three dimensions (x, y, z), while t denotes time. The fluid density is given by ρ_f , gravitational acceleration by g , and pressure by p . The formulation includes two viscosity components: the molecular kinematic viscosity of the fluid, ν , and the eddy viscosity, ν_t . LES with a Smagorinsky constant of 0.1 are utilized based on the findings of Prüter et al. 2025 to represent the turbulence within the flow field. Here, the spatially filtered

Navier-Stokes equation is applied to solve the subgrid-scale eddy viscosity with large eddy simulations (LES). A Smagorinsky constant of 0.1 is utilized based on the findings of Prüter et al. (2025) to represent the turbulence within the flow field appropriately for a fluid-structure interaction (FSI).

Comment 4 The agreement between the simulation results and the experimental data shown in Figure 2 looks not quite good.

Response: *Thank you for noting the discrepancy between the simulated to the experimental stem position in Figure 2. A quantitative comparison of the tip position has been added based on the suggestions of Reviewer 1, described in the answer to their **Comment 4**. To elaborate on the reasoning for this discrepancy, the authors compared the difference in the flow field influencing the stem motion in Section 3.3. Here, Figure 7 reveals that the discrepancy between the experimental and numerical stem bending results originates from the difference in the incoming flow field, as the wave in the experimental test changes its direction earlier compared to the simulated wave. This comparison highlights how every detail of the flow field influences the structural response.*

Comment 5 Grid independence tests shall be provided.

Response: *The authors agree with the reviewer that is important to consider the grid dependence for the numerical simulations. Due to space limitations, the grid convergence is detailed in Appendix B, revealing a high sensitivity of both stem bending and resulting forces to the cell size. The main outcomes of the grid convergence analysis are summarized, together with the influence of the CFL criterion, in Section 2.2.2 (lines 405 to 424).*

Reviewer 3

In this study, simulations of vegetation stem movements are performed by a proposed FSI model and the resulting forces under wave load are investigated with comparison to the reference experiments for different hydraulic parameters. Furthermore, the decomposition of the resulting stem movement in bending modes was validated. The authors present the results in detail and discuss the reproducibility with general characteristics to find the causes of the difference from the experimental results. The limitations of the present model are also shown and explained. The information will be helpful to readers in the related fields. However, some minor but unclear points remain in the manuscript. The authors are recommended to respond to the following comments.

Comment 1 As for the FSI solver, the explanation of the fluid phase and the interaction with the structure phase is not written sufficiently. Authors are recommended to include the explanation of the fluid phase with equations in the manuscript.

Response: *Thank you for your comment. The authors agree with the reviewer that further details with respect to the fluid part are beneficial for the introduction to the FSI solver. As Reviewer 2 raised the same concern, the reviewer is referred to the authors' answer provided in **Comment 3** of Reviewer 2.*

Comment 2 The authors examined the influence of the reduced width of the numerical wave flume on the reproduced flows through the measured velocities and wave heights at the front of the target stems. However, the influence could be significant around the target structures or their backsides, which was not investigated. What was the sensitivity to the flume width around the stems?

Response: *The authors agree with the reviewer that flow properties in all directions around the stem should be considered when comparing the influence of reduced flume width. Due to the increased computational demand, it remained challenging to provide complete simulations for different flume widths including the stem.*

To provide the reviewer with a more complete impression, the comparison of the horizontal velocity at PP3 and LP4 is provided here in Figure A. Similar to Figure A.17 in the Appendix of the manuscript, only the smallest tested flume width ($W_F = 0.04\text{ m}$) shows an influence on the horizontal flow velocity. Due to the overall agreement with the obtained results for PP2/LP1 and keeping the length of the manuscript in mind, this figure was not included.

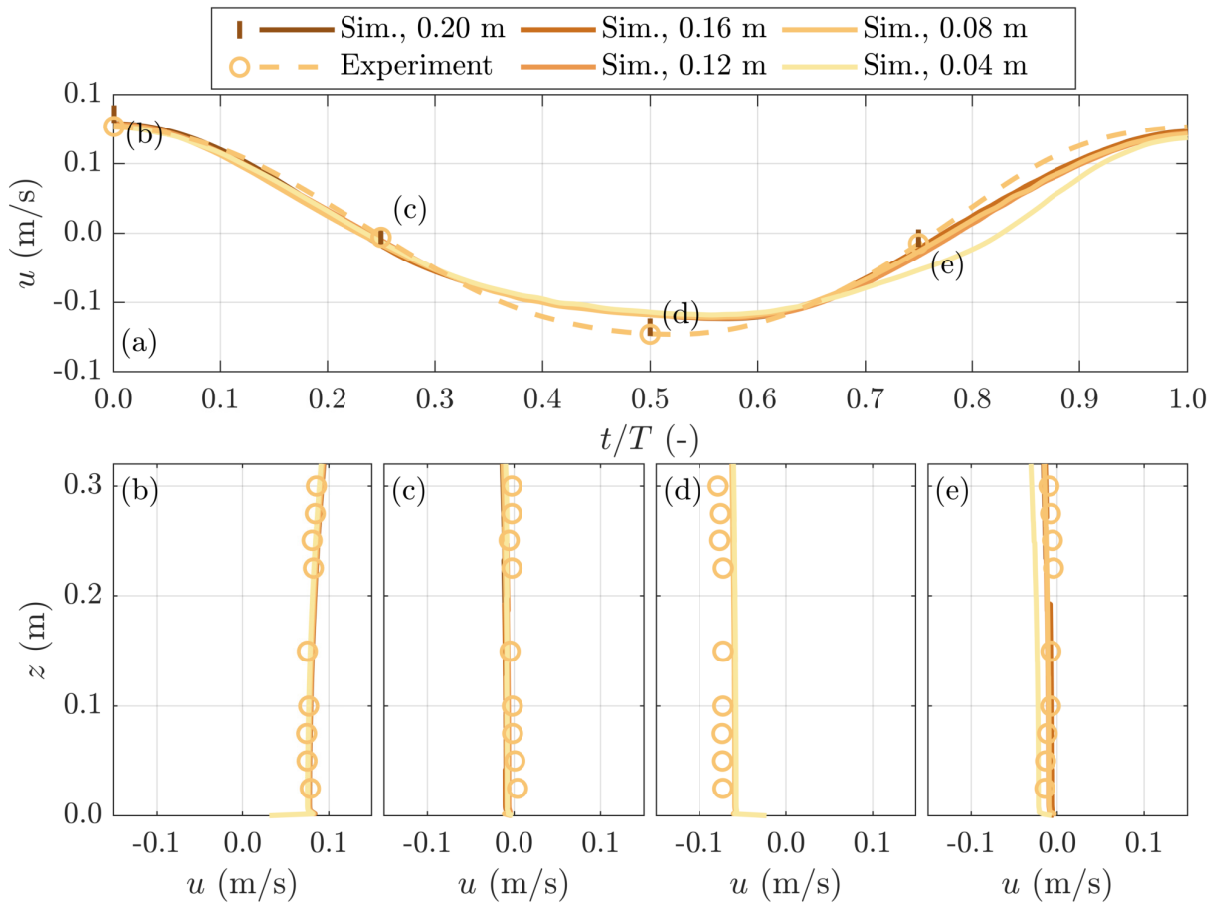


Figure A: Comparison of the simulated horizontal velocity u for wave conditions $H = 0.04$ m and $T = 2.0$ s with the experimental results by Jacobsen et al. (2019). The figure presents (a) the phase-averaged horizontal velocity at $z = 0.10$ m (PP2) over the normalized wave period, and (b) - (e) the phase-averaged horizontal velocity profiles across (LP1) the water depth at selected time steps: (b) $t/T = 0.00$, (c) $t/T = 0.25$, (d) $t/T = 0.50$, and (e) $t/T = 0.75$

To further support the hypothesis that the reduced flume width does not influence the fluid-structure interaction, the resulting forces on the stem for the first wave are compared in Figure B for $W_F = 0.06, 0.08$ and 0.10 m. It becomes apparent that the drag force, representative of the flow field surrounding the stem, does not vary with the herein-compared flume widths. Since this figure is only an approximation of the simulated conditions and further, including phase-averaged results was not possible due to computational limitations, it was decided not to include this figure in the manuscript.

The authors are confident that this extended clarification has adequately addressed the reviewer's concerns regarding the influence of the flume width.

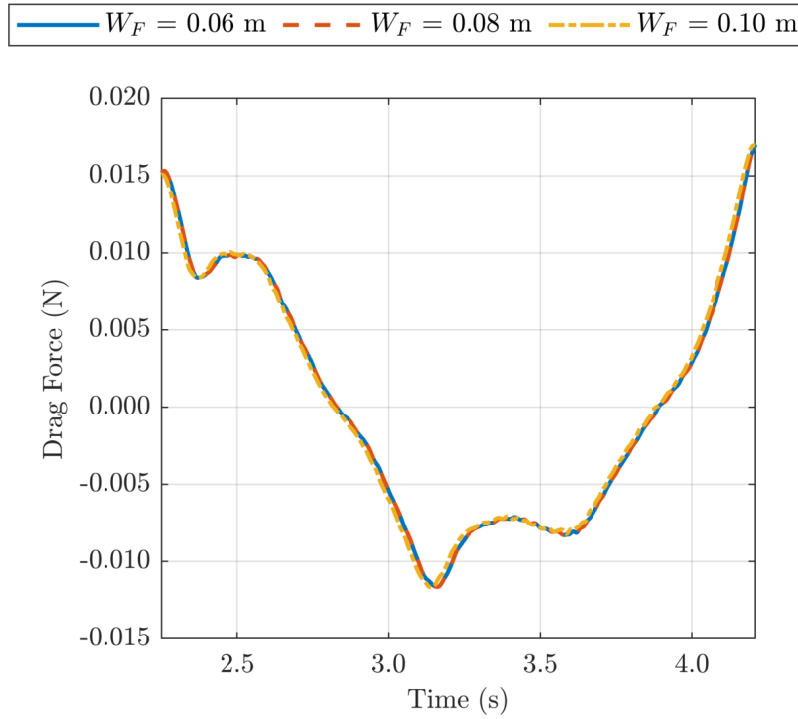


Figure B: Influence of the flume width on the resulting drag force.

Comment 3 The authors mentioned that vortex shedding occurs both in the experimental and simulated stem and influences thus the resulting forces. Could you show the vorticities around the target stems in the present simulations? This would make the discussion more convincing.

Response: *Thank you for suggesting showing the vortices around the stem which the authors agree would improve the discussion concerning the influence of the vortex shedding frequency.*

Actions taken: Vortices for the discussed test case have been visualized based on the Q-criterion, supporting the point raised in the discussion. The visualized detachment process and its implications have been added and, accordingly, the discussion is extended.

[Line 807 - 825]

Interestingly, this frequency resonates with the highest peak observed in Fig. 10 (b), indicating that vortex shedding occurs both in the experimental and simulated stem and influences thus the resulting forces. Providing further insights into the three-dimensional nature of the FSI, the vortices for the discussed case at selected points in time are visualized in Fig. 13. The selected points in time serve as an example of the detachment process of a vortex from the stem: a coherent structure with a relatively high velocity magnitude is apparent in Fig. 13 (a), compared to lower velocity magnitudes seen in Fig. 13 (b). Finally, the coherent structure is detached from the back of the stem in Fig. 13 (c). The time-dependent interaction of the vortices with the stem within the time frame of a wave period supports the previous comparison that the vortices influence

the resulting forces beyond the overall wave-induced flow field, here shown as an example for the relatively stiff stem of Material 3.

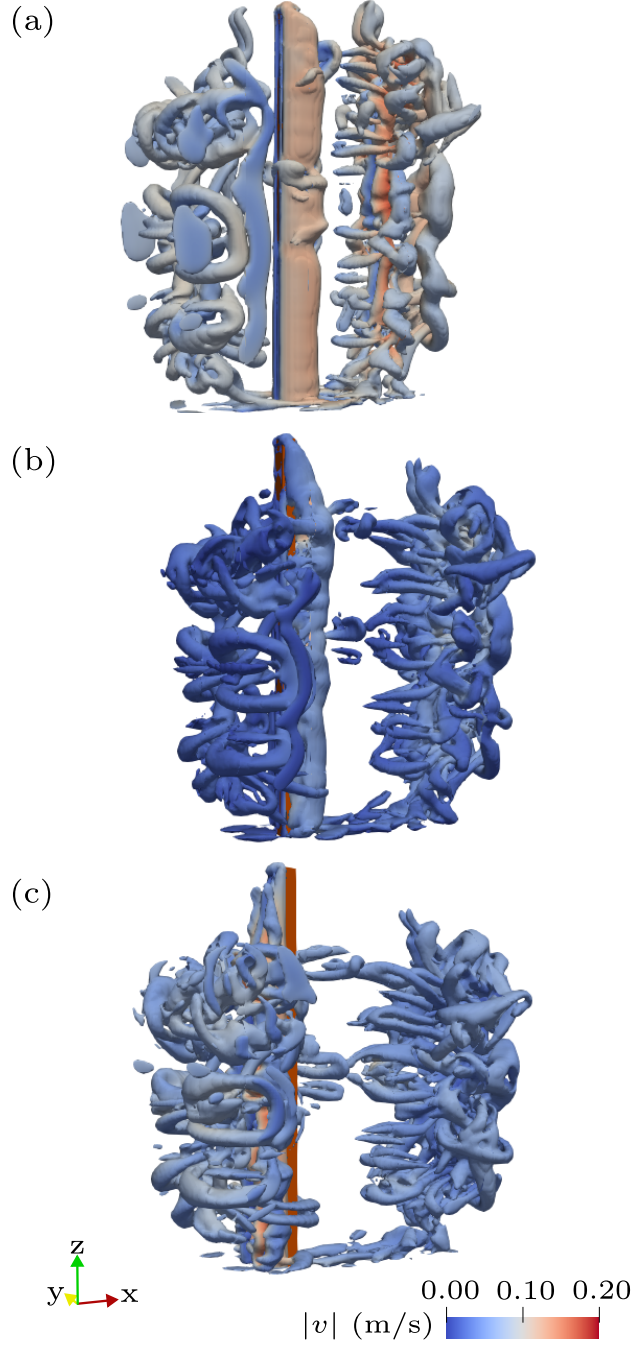


Figure 13: Vortices around the 0.15 m long stem of Material 3 with wave conditions $H = 0.04$ m and $T = 2.0$ s, represented by Q-criterion contours equal to 1 for selected points in time with (a) $t = 4.62$ s, (b) $t = 4.95$ s, and (c) $t = 5.28$ s.

Overall, the vortices depicted in Fig. 13 develop a few centimeters in front of the stem and dissipate approximately at two-thirds of the stem length behind the stem. Longer wakes are not to be expected for the dimensions involved in this FSI – the width of the Material 3 stem ($W_S = 0.008$ m) is one-fifth of the here simulated wave height ($H = 0.04$ m). [...]

References

- Bihs, H., Kamath, A., Alagan Chella, M., Aggarwal, A., Arntsen, Øivind., 2016. A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. *Computers & Fluids* 140, 191–208. doi:doi: 10.1016/j.compfluid.2016.09.012.
- Caroppi, G., Västilä, K., Järvelä, J., Rowiński, P.M., Giugni, M., 2019. Turbulence at water-vegetation interface in open channel flow: Experiments with natural-like plants. *Advances in Water Resources* 127, 180–191. doi:doi: 10.1016/j.advwatres.2019.03.013.
- Elgar, S., 1987. Relationships involving third moments and bispectra of a harmonic process. *IEEE Transactions on Acoustics, Speech, and Signal Processing* 35, 1725–1726. doi:doi: 10.1109/TASSP.1987.1165090.
- Fonseca, M.S., Fourqurean, J.W., Koehl, M.A.R., 2019. Effect of seagrass on current speed: Importance of flexibility vs. shoot density. *Frontiers in Marine Science* 6. doi:doi: 10.3389/fmars.2019.00376.
- Hagmeyer, N., Mayr, M., Popp, A., 2024. A fully coupled regularized mortar-type finite element approach for embedding one-dimensional fibers into three-dimensional fluid flow. *Numerical Meth Engineering* 125 (8). doi:doi: 10.1002/nme.7435.
- Hussain, A.A., Al-Obaidi, M.A., Mohammed, A.S., John, Y.M., Rashid, F.L., 2024. Distribution of the velocity profile via analytical and three-dimensional numerical vegetation modeling. *Journal of Applied Fluid Mechanics* 17. doi:doi: 10.47176/jafm.17.9.2487.
- Jacobsen, N., Bakker, W., Uijttewaalt, W.S.J., Uittenbogaard, R., 2019. Experimental investigation of the wave-induced motion of and force distribution along a flexible stem. *J. Fluid Mech.* 880, 1036–1069. doi:doi: 10.1017/jfm.2019.739.
- Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Prinz, M., Schürenkamp, D., Freund, H., Goseberg, N., 2023. Proposing a novel classification of growth periods based on biomechanical properties and seasonal changes of *spartina anglica*. *Front. Mar. Sci.* 10. doi:doi: 10.3389/fmars.2023.1095200.
- Luhar, M., Nepf, H.M., 2016. Wave-induced dynamics of flexible blades. *Journal of Fluids and Structures* 61, 20–41. doi:doi: 10.1016/j.jfluidstructs.2015.11.007.
- Prüter, I., Spröer, F., Keimer, K., Lojek, O., Windt, C., Schürenkamp, D., Bihs, H., Nistor, I., Goseberg, N., 2025. A comprehensive numerical study on the current-induced fluid–structure interaction of flexible submerged vegetation. *Journal of Fluids and Structures* 133, 104232. doi:doi: 10.1016/j.jfluidstructs.2024.104232.
- Tschisgale, S., Löhrer, B., Meller, R., Fröhlich, J., 2021. Large eddy simulation of the fluid–structure interaction in an abstracted aquatic canopy consisting of flexible blades. *J. Fluid Mech.* 916. doi:doi: 10.1017/jfm.2020.858.
- Wang, H., Tang, H.w., Zhao, H.q., Zhao, X.y., Lü, S.q., 2015. Incipient motion of sediment in presence of submerged flexible vegetation. *Water Science and Engineering* 8, 63–67. doi:doi: 10.1016/j.wse.2015.01.002.
- Wang, J., He, G., Dey, S., Fang, H., 2022. Fluid–structure interaction in a flexible vegetation canopy in an open channel. *Journal of Fluid Mechanics* 951. doi:doi: 10.1017/jfm.2022.899.

Xu, D., Liu, J.n., Wu, Y.f., Ji, C.n., 2022. Numerical investigation of the dynamics of flexible vegetations in turbulent open-channel flows. *J Hydrodyn* 34 (4), 681–699. doi:doi: 10.1007/s42241-022-0057-9.

Response to the reviewers

Dear Editor and Reviewers,

The authors would like to express their appreciation for the time taken and effort made to evaluate the manuscript, and believe that addressing the comments increased the overall quality of the revised manuscript.

Please find attached a marked version of the manuscript, indicating the amendments the authors performed, along with a clean manuscript. Detailed answers to the reviewers' comments are provided in this rebuttal letter. The line numbers refer to the revised, clean version of the manuscript.

Answers to the individual comments can be found below. The convention is as follows:

- Refers to the reviewer's comments
- *Refers to our responses to the comments*
- Refers to new text added to the manuscript
- ~~Refers to text deleted from the manuscript~~

Reviewer 1

The authors have made revisions related to my comments carefully, and the quality of the manuscript has been improved to a certain extent. However, there are still minor issues which should be elaborated.

Comment 1 In lines 509-513, the paragraph is introduced suddenly. For improving the context consistency, the authors are recommended to separate the main ideas into other parts, and explain with quantitative analysis method.

Response: *Thank you for noting the sudden introduction of information presented in this paragraph. The authors agree with the reviewer that the section should be improved for consistency. Based on the first round of reviews, the authors had added a quantitative description of the observed differences in the tip position in Figure 2.*

Actions taken: The text has been adapted for clarification, and the paragraph of concern has been combined with the previous text.

[Line 520 - 534]

[...] Quantitatively, the largest discrepancies between simulated and experimental tip position are shown in Fig. 2 (c), (d), and (f) with 0.041 m, 0.035 m, and 0.034 m, respectively. On average, that corresponds to a deviation of 18 % relative to the initial stem length. About half the discrepancies between the simulated and experimental tip position can be observed for Fig. 2 (a) with 0.018 m, (b) with 0.017 m, and (e) with 0.020 m. Correspondingly, relative to the initial stem length, the latter tip positions deviate by 9 %, which lies within an acceptable ± 10 % error margin. **To provide a possible explanation for the observed deviations,** ~~t~~The influence of the flow field on the deviation of the stem tip position is evaluated in more detail in Section 3.3, **see Figure 7. Herein, it is shown** **In summary, Figure 2 shows** that the shape of the stem bending and the overall movement of the stem are satisfyingly reproduced. General metrics for the fit are presented **together with the results of the other two simulated material types** at the end of this section.

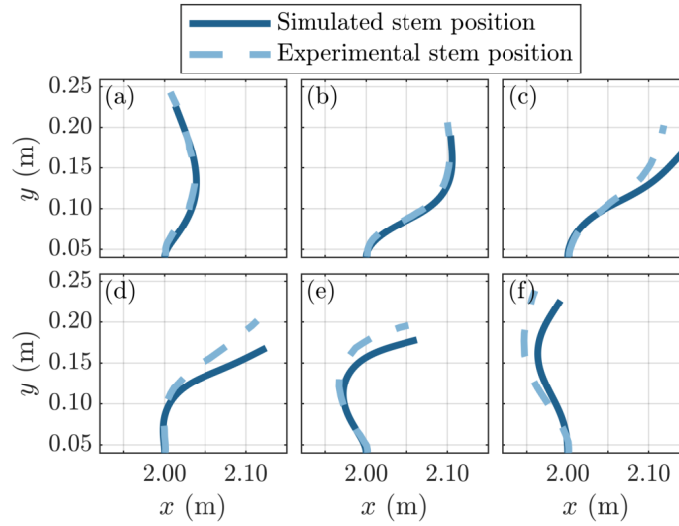


Figure 2: Comparison of the simulated stem positions for Material 1 with $H = 0.08\text{ m}$ and $T = 2.0\text{ s}$ to the stem positions in the reference experiment for selected points in time with (a) $t/T = 0.00$ (b) $t/T = 0.17$ (c) $t/T = 0.34$ (d) $t/T = 0.51$ (e) $t/T = 0.67$ and (f) $t/T = 0.84$

Comment 2 The authors have explained the reasons for the large deviation of the stem motion in lines 612 - 620 pertains to Figure 6. However, a similar problem was found in Figure 4, and it still needs further explanation.

Response: *Thank you for asking about the observed differences in Figure 4. The authors would like to clarify that Figure 6 (a) depicts the same stem and hydro-dynamic conditions as that shown in Figure 4 (c). Correspondingly, Figure 6 (a) aims to provide further insights into the differences between the experimental and simulated stem bending observed in Figure 4 (c). The authors believe that the combined elaboration of Figure 4 and Figure 6 provides a comprehensive comparison of the simulated and experimental stem bending and sufficient explanation of the observed deviations. However, the connection of the two figures should be stated more clearly in the manuscript.*

Actions taken: The text has been modified for clarification.

[Line 565 - 582]

[...] Correspondingly, both stems with Material 3 show a high agreement when comparing the distance between the average experimental to the simulated tip position, with 0.002 m for the stem depicted in Fig. 4 (b), and 0.003 m for the stem depicted in Fig. 4 (d). Relative to the initial stem length, the deviation of the average tip position for both the stem depicted in Fig. 4 (b) and in Fig. 4 (d) was 1% . In the reference experiment, the 0.30 m long stem with Material 2 tilts asymmetrically within the direction of the wave propagation, depicted in Fig. 4 (c), which is not replicated by the simulation results. **The reasoning for the asymmetry is elaborated in Section 3.2.** Therefore, larger discrepancies between the average experimental to simulated tip position occur with Material 2, for the

stem depicted in Fig. 4 (a) by 0.010 m and for the stem shown in Fig. 4 (c) by 0.019 m. With an average deviation of the tip position relative to the initial stem length of 7 % for the stem depicted in Fig. 4 (c) and of 6 % for the stem shown in Fig. 4 (c), both are within the acceptable $\pm 10\%$ error margin. The bending behavior of the stems depicted in Fig. 4 (c) and (d) is evaluated in more detail in Section 3.2, relating the observed deviations to varying contributions of the first two bending modes, see Figure 6, and potential asymmetries occurring in the physical experiments.

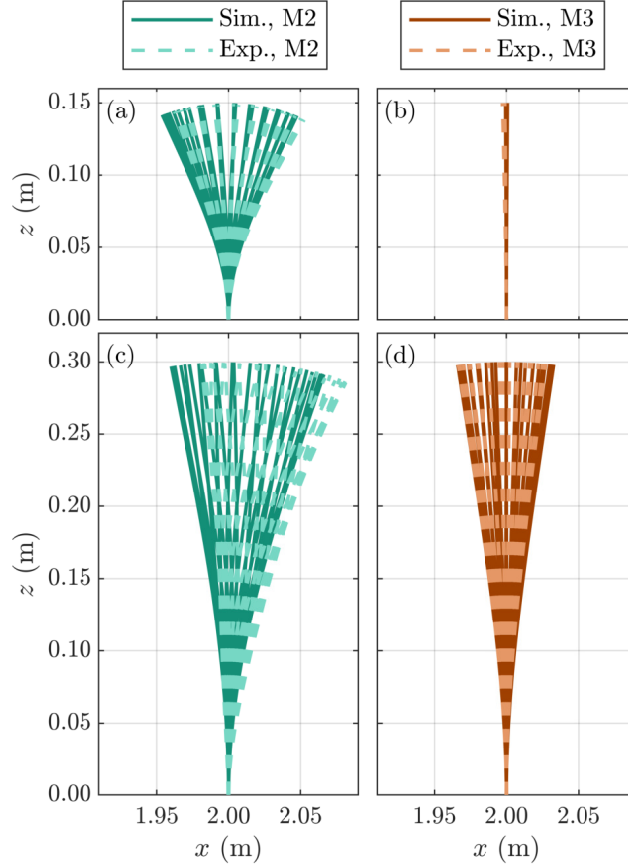


Figure 4: Comparison of the simulated to the experimental ensemble-averaged stem motion from $t/T = 0 - 1$ with $t/T = 0.04$ increments, resulting in 25 stem positions each for (a) Material 2 with $L_S = 0.15$ m, $H = 0.07$ m and $T = 1.5$ s, (b) Material 3 with $L_S = 0.15$ m, $H = 0.04$ m and $T = 2.0$ s, (c) Material 2 with $L_S = 0.30$ m, $H = 0.04$ m and $T = 2.0$ s, and (d) Material 3 with $L_S = 0.30$ m, $H = 0.07$ m and $T = 1.5$ s

Reviewer 2

The authors have well answered all questions and made corresponding revisions. I have no further comments.

Reviewer 3

Sincere responses to my questions have been given and the manuscript has been revised. However, there is still one point in Comment 1 that needs clarification.

Comment 1 The manuscript mentions as "The FSI tool within the FD-models framework uses a two-way coupling between the structural and fluid solver". However, the newly added equation (2) does not include the interaction term between Fluid and Structure. Please check the equations again.

Response: *Thank you for your comment. The authors agree that the equation did not account for the two-way coupling approach, which requires adaptation and further elaboration.*

Actions taken: Equation (2) has been adapted. A section regarding the coupling methodology has been added to the end of Subsection 2.1 - Numerical model.

[Line 266 - 273]

[...] The Navier-Stokes equations are herein expressed by the incompressible continuity equation (1) and the incompressible momentum equation (2).

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_f} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \nu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \cancel{g_i} f_i \quad (2)$$

In Eqs. (1) and (2), u_i represents the velocity vector in three dimensions (x, y, z) , while t denotes time. The fluid density is given by ρ_f , ~~gravitational acceleration by g_i~~ , and pressure by p . ~~The mass-specific external load f_i consists of the gravitational acceleration g_i and the coupling force f_Γ ($f_i = g_i + f_\Gamma$), detailed at the end of this section.~~ The formulation includes two viscosity components: the molecular kinematic viscosity of the fluid, ν , and the eddy viscosity, ν_t . [...]

[Line 315 - 335]

~~The coupling of the fluid and the structural solver is implemented based on the zero-thickness assumption of the rod on the interface Γ between the fluid and solid (Tschisgale and Fröhlich, 2020). To account for the different dimensions, the coupling force f_Γ is converted to a volumetric force via delta functions for the three-dimensional flow field and integrated over the arc's length for the one-dimensional rod. Here, the coupling force f_Γ relates to the stress vector (σn) in the fluid (hydrodynamic stress tensor σ) and the structural (Cauchy stress tensor σ_s) part. The dynamic coupling condition is fulfilled when the stress vectors of each phase at the interface Γ are equal ($\sigma n = \sigma_s n, \forall x \in \Gamma$). The kinematic coupling condition states that the fluid's velocity is the same as the solid's at the interface Γ , corresponding to a no-slip condition ($u = v, \forall x \in \Gamma$).~~

Based on the previously introduced conditions, the coupling on the interface Γ can be achieved in the following steps: First, a preliminary velocity $\tilde{u}$ is calculated in the fluid solver by Eqs. (1) and (2) without including f_Γ . Following the kinematic coupling condition, $\tilde{u}$ is transferred to the structural solver. The structural solver then iterates for f_Γ with the Cosserat rod equations. Based on the dynamic coupling condition, f_Γ is returned to the fluid solver, which computes u_Γ utilizing the Navier-Stokes equations. Further elaboration of the coupling algorithm is provided by Tschisgale and Fröhlich (2020).

References

Tschisgale, S., Fröhlich, J., 2020. An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid. *Journal of Computational Physics* 423 (7). doi:doi: 10.1016/j.jcp.2020.109801.

D Publication: Prüter et al. *under review* 282

Prüter, I., Markov, A., Lojek, O., Schürenkamp, D., Stolle, J., Nistor, I., Goseberg, N.: Linking biomechanical stem properties of salt marsh vegetation to flow field alterations: a regional and seasonal analysis, *under review* in: Coastal Engineering.

A summary of the manuscript can be found in Section 3.4 of this thesis. The following document shows the submitted study.

Linking biomechanical stem properties of salt marsh vegetation to flow field alterations: a regional and seasonal analysis

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Abstract

Salt marshes play a crucial role in coastal defense, yet quantifying their protective contribution requires understanding the seasonal and regional variability of their biomechanical properties. Stem characteristics such as bending stiffness, diameter, and geometry determine plant motion and the resulting hydrodynamic forces under wave and current exposure. The first field-based quantification of flexural stiffness and its seasonal variation for Canadian *Spartina alterniflora* was obtained through in situ measurements. To link these measurements with hydrodynamic processes, the fluid–structure interaction solver in REEF3D::CFD was employed to simulate stem-scale flow field alterations. Extending the analysis to a broader geographical context, biomechanical properties of *Spartina anglica* from Southeast North Sea marshes were incorporated to assess the influence of seasonal and regional variation on the local

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flow field. Field data for *S. alterniflora* indicates pronounced seasonal changes, with stems increasing substantially in stiffness and size from early-season to adult stages. Comparison with *S. anglica* shows, for the first time, that Canadian stems are smaller and more flexible. Numerical results demonstrate that stem-induced flow modifications, expressed as turbulence intensity in currents and turbulent kinetic energy in waves, exhibit stronger regional than seasonal differences. Corresponding drag coefficients, differentiated by season and region and ranging from 1.5 to 2.0, are provided for future hydrodynamic modeling. The findings highlight that regional variation in stem biomechanics influences the flow–vegetation interaction, emphasizing the importance of cross-regional assessments for nature-based coastal protection strategies. *Keywords:* fluid-structure interaction, flexible vegetation, seasonality, nature-based solutions, salt marsh

1. Introduction

Salt marshes occur globally in temperate climates (Mcowen et al., 2017) and are widely recognized as effective nature-based solution (NbS) for coastal protection due to their ability to attenuate waves, stabilize sediments, and enhance deposition (Barbier et al., 2011; Rupprecht et al., 2017; Vuik et al., 2019). In the Southeast North Sea region, salt marshes extend along the coasts of the Wadden Sea and the Scheldt estuary in Germany and the Netherlands (Mcowen et al., 2017). This region is among the most intensively managed coastal systems worldwide, where centuries of land reclamation and embankment construction have constrained natural sediment dynamics to a great extent (Esselink et al., 2017; Zijlstra et al., 2017). Currently, about 3.7 million inhabitants along the Wadden Sea coastlines of the Netherlands, Germany, and Denmark depend on continuous coastal defense maintenance (Strem-

pel et al., 2017; Zijlstra et al., 2017). In contrast, at the southern Canadian East Coast – the region which the North Sea situation is being compared to in this work –, salt marshes occur throughout the Bay of Fundy, the Gulf of St. Lawrence, and the St. Lawrence Estuary (Mcowen et al., 2017; Markov et al., 2023). However, the St. Lawrence Estuary represents a comparatively understudied salt marsh system, potentially due to the smaller coastal population of approximately 1 million, living within a 10 km distance from the shoreline (Beauchesne et al., 2020).

Adapted to the environmental conditions in each region, salt-tolerant marsh plants can withstand frequent flooding and low-energy waves in coastal environments, swaying in response to wave motion (Puijalon et al., 2011) and thereby dissipating some of the incoming wave energy. This plant movement reduces both the frontal area presented to the flow and the relative velocity between the plant and the surrounding water, as flexible stems deform under external loading (van Veelen et al., 2020). Field investigations in salt marshes, an often employed approach to better understand the biomechanical properties of salt marsh vegetation, are predominantly conducted during summer (Riffe et al., 2011; Meixler et al., 2018; Schoutens et al., 2020), omitting the seasonal variation of the stem properties. However, previous work (Reents et al., 2022; Keimer et al., 2023b) has shown that stem geometry and stiffness differ significantly between early and late growing seasons. The natural variability of hydrodynamic and environmental conditions influencing the salt marshes presents challenges in quantifying these ecosystem services reliably.

Ecosystem services provided by salt marshes are generally valued independently of their geographical location (Barbier et al., 2011; Thomsen et al., 2022; Koplin et al., 2025). Nevertheless, regional variations of salt marshes include which plant species are dominating, such as *Spartina alterniflora* (*Sporobolus alternifloris*) being widely distributed in North American salt marshes, compared to *Spartina anglica* (*Sporobo-*

39 *lus anglicus*) in European salt marshes along the Southeast North Sea (Keimer et al.,
 40 2023b; Markov et al., 2023). Both species occupy the same ecological niche in the
 41 lower salt marsh (Zhi et al., 2007) and are, along with *Salicornia* species (Steinigeweg
 42 et al., 2025), among the first to interact with hydrodynamic forces. Due to their sea-
 43 ward distribution, high structural exposure, and flexural stiffness, these species play
 44 a key role in wave attenuation and sediment stabilization, rendering them particu-
 45 larly relevant for assessing vegetation–flow interactions in NbS (Bouma et al., 2009;
 46 Moeller et al., 2014; Paul et al., 2016). As pioneer species, they are typically one of
 47 the first species to establish following restoration or sediment accretion, where their
 48 stem geometry, flexibility, and stiffness control drag forces and turbulent energy dis-
 49 sipation (Tempest et al., 2015). Regarding their geometry, *S. alterniflora* generally
 50 has a larger stem diameter and grows taller than *S. anglica* (Zhang and Nepf, 2021).
 51 Due to logistical, environmental, and temporal constraints, field investigations of
 52 salt marsh plant properties typically cover limited areas and time periods, making it
 53 difficult to compare seasonal and regional variations.

54 Biomechanical properties of salt marsh vegetation along the Southeast North
 55 Sea coast are comparably well studied in the field, for example by Bouma et al.
 56 (2007); Vuik et al. (2017); Schulze et al. (2019); Zhu et al. (2020b); Baaij et al.
 57 (2021); Steinigeweg et al. (2025) and Keimer et al. (2023b, 2024), partly including
 58 its seasonal variation. In contrast, field measurements of biomechanical vegetation
 59 properties for Canadian salt marshes are scarce. Recent field investigations from the
 60 Canadian East coast have highlighted the seasonal variation of salt marsh properties,
 61 such as stem length and diameter (Markov et al., 2025). However, biomechanical
 62 properties and the associated fluid-structure interaction (FSI) remain unaddressed.
 63 To date, little evidence exists on how insights from one region can be accurately
 64 transferred to another. Establishing such knowledge transfer requires cross-regional

65 studies, which are essential for developing a comprehensive understanding of salt
66 marsh properties. Understanding how insights from site-specific field studies can
67 be transferred to other coastal contexts is essential to avoid misjudging salt marsh
68 ecosystem services, as exemplified here by investigations along the southern Canadian
69 East Coast and the Southeastern North Sea coast.

70 Numerical simulations enable projections of the ecosystem services provided by
71 salt marsh vegetation (Henderson, 2019; Marjoribanks et al., 2019). Biomechanical
72 parameters derived from field measurements are essential for assessing the wave
73 attenuation capacity of salt marshes, either directly through field studies (Garzon
74 et al., 2019) or through hydrodynamic modeling. Commonly measured traits include
75 vegetation height, stem diameter, and density (Garzon et al., 2019; Hadadpour et al.,
76 2019; Coleman et al., 2022). The difference in biomechanical stem properties found in
77 salt marshes, depending on plant species, season, and site-specific conditions (Keimer
78 et al., 2024), underscores the need for models that can capture this variability. The
79 importance of accounting for plant flexibility at the meadow scale has been demon-
80 strated in previous studies, particularly regarding wave attenuation capacity, which
81 can decrease by 30 % to 70 % with increasing plant flexibility (Mullarney and Hen-
82 derson, 2010; van Veelen et al., 2020; Familkhalili and Tahvildari, 2022). In addition,
83 vegetation flexibility influences flow dynamics: Caroppi et al. (2021) showed that in
84 unidirectional flow, flexible vegetation facilitates deeper vortex penetration into the
85 meadow along the main channel, while Yang and Choi (2009) found that flexible
86 plants increase the vertical component of turbulent intensity within the water col-
87 umn. The flexural stiffness has been investigated in studies by Marjoribanks et al.
88 (2019) to research wake dynamics or by Vuik et al. (2017) to discern the variable
89 diameters along the plant height to simulate with the aim of understanding wave
90 loads on dikes. However, these studies employed live vegetation that was either not

91 representative of salt marsh species or used idealized surrogates, limiting their direct
92 applicability to salt marsh ecosystem processes.

93 Accurately replicating the complex properties of live vegetation, particularly the
94 flexibility of plant structures, remains a significant challenge (Wang et al., 2023; Cui
95 et al., 2023) in the quest to obtain predictive capabilities over salt marshes' effects.
96 Following a semi-empirical approach, drag forces are calculated using the Morison
97 equation, as performed in the works of Dijkstra and Uittenbogaard (2010); Mullarney
98 and Henderson (2010); Maza et al. (2013) and Jin and Zhang (2022). However,
99 these studies rely on drag coefficients that cannot be measured directly in the field,
100 underlining the need for small-scale modeling approaches to derive them. This work
101 hypothesizes that an integrated workflow is required to assess the variability and
102 complexity found in salt marshes: field measurements provide the input for small-
103 scale modeling of FSI, allowing for the investigation of the fluid-vegetation interaction
104 and the derivation of drag coefficients. These can then be transferred to be employed
105 in medium-scale hydro- and morphodynamic models (patch or coastal flat scale) to
106 evaluate the coastal protection potential of salt marshes, including their seasonal or
107 regional variability.

108 To date, the literature has not yet sufficiently addressed how differences in grow-
109 ing season and environmental conditions affect the biomechanical properties of salt
110 marsh vegetation and the associated ecosystem services. Caldera et al. (2025) re-
111 cently demonstrated that early vegetation stages dissipate less wave energy than
112 mature plants, yet still provide greater protection than bare soil. However, it re-
113 mains unclear to what extent such flume-based findings can be replicated under
114 natural field conditions, where vegetation is exposed to more complex hydrodynamic
115 and environmental forcing. Furthermore, the transferability of results between re-
116 gions with contrasting climates, such as between the Southeast North Sea and the

southern Canadian East Coast, has not been systematically examined. Regional variability in plant morphology, species composition, and stiffness, combined with seasonal changes in stem geometry and flexibility, may lead to substantial differences in drag forces and wave attenuation capacity. Consequently, there is a need for cross-regional, seasonally resolved field studies that couple in situ measurements with numerical modeling to improve our understanding of fluid-vegetation interactions and to enhance the predictive capability of NbS-based coastal protection strategies. In summary, the following specific research objectives are addressed within this study, aiming to fill the above-mentioned research gaps:

- To examine the seasonal variation of biomechanical stem properties from a Canadian salt marsh
- To compare the biomechanical stem properties of a Canadian salt marsh to field studies from the literature
- To evaluate the influence of the variation in biomechanical stem properties on the stem motion in unidirectional and oscillatory flow and their resulting flow field alterations
- To determine drag coefficients considering modeled salt marsh stems' seasonal and regional variation

2. Materials and Methods

2.1. Study sites and compiled stem properties

Biomechanical stem properties were measured in a Canadian salt marsh, located near the St. Lawrence Estuary in Quebec, Canada, depicted in Figure 1 (a). The salt marsh is located at the Petites-Bergeronnes River, an area influenced by tides, with

140 a mean tidal range increasing from 1.39 m upstream to 1.98 m at the river mouth,
 141 where it meets the St. Lawrence River, but exposed to lower wave energy than the
 142 main estuary (Figure 1c). A detailed description of the local conditions is provided
 143 in Markov et al. (2025). At this estuarine salt marsh, the lower salt marsh species *S.*
 144 *alterniflora* is dominant, a native species to the Canadian east coast (Markov et al.,
 145 2023). Section 2.2 further details the determination of biomechanical stem properties
 146 at this location.

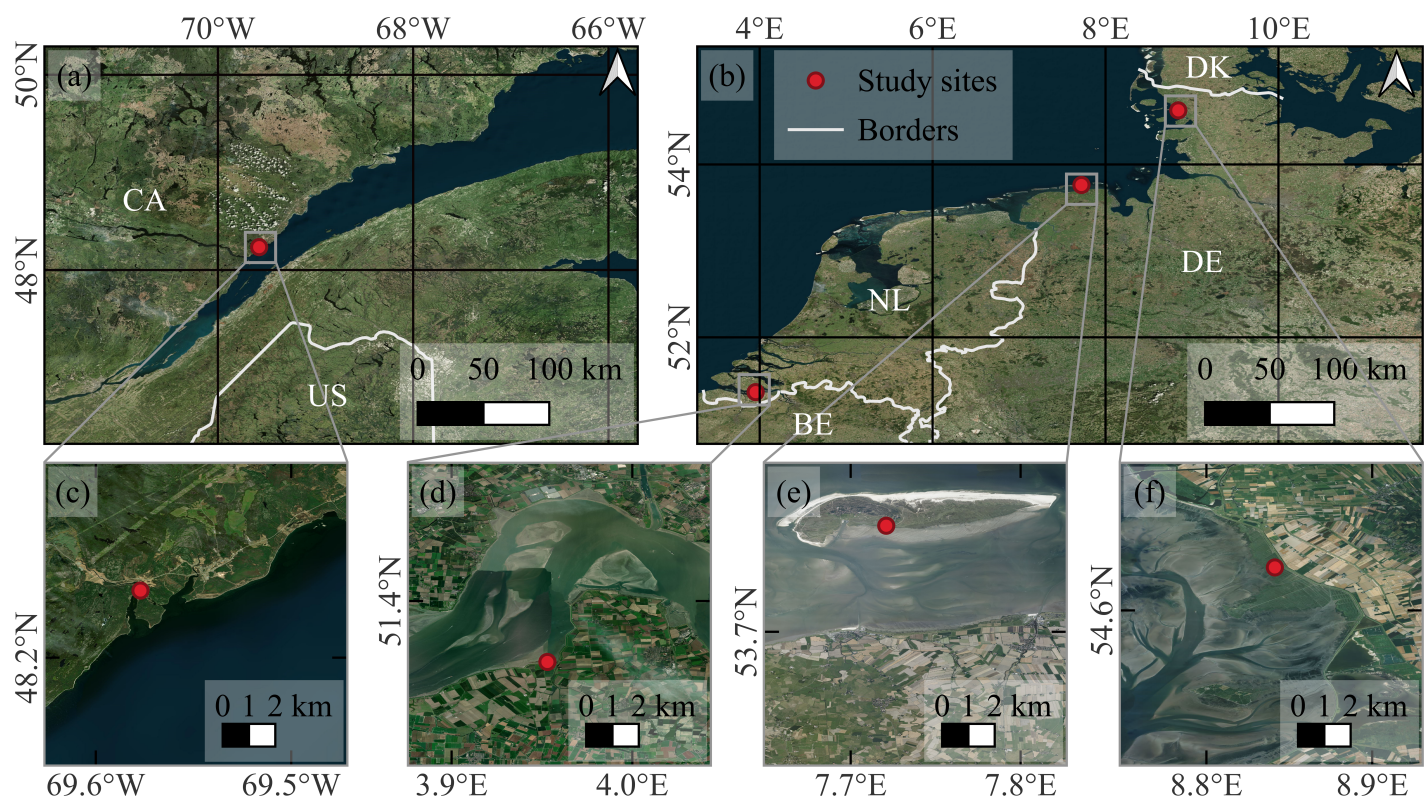


Figure 1: (a) Overview of the Canadian study site at the St. Lawrence Estuary, (c) located at the Petites-Bergeronnes River and (b) selected study sites, located at the North Sea coast, including measurements of seasonal variation of biomechanical salt marsh stem properties with (d) Vuik et al. (2017), (e) Keimer et al. (2023a), and (f) Schulze et al. (2019) (Aerial image retrieved via the QMS (Quick Map Services) plugin in QGIS from Microsoft Bing Maps (accessed September 2025)).

147 For the biomechanical stem properties of the Southeastern North Sea coastline,
 148 including seasonal variation, published data were compiled based on the investiga-
 149 tions of Vuik et al. (2017); Schulze et al. (2019) and Keimer et al. (2023a). Fig-
 150 ure 1 (b) provides an overview of each European location. The salt marshes grow
 151 in distinct local environments, such as the location in an estuary (Vuik et al., 2017),
 152 see Figure 1 (d), on the sheltered site of a barrier island (Keimer et al., 2023a), see
 153 Figure 1 (e), and along the mainland coast, but with barrier islands in front (Schulze
 154 et al., 2019), Figure 1 (f). In the following, the study sites are referred to based on
 155 their site characteristics and country: Figure 1 (c) is Estuary (CA), (e) is Barrier
 156 island (DE), (f) is Mainland (DE), and (d) is Estuary (NL). For all study sites at the
 157 Southeast North Sea, the lower salt marsh species *S. anglica* has been the focal point.
 158 Illustrating the characteristics of the two different regions, potential anthropogenic
 159 influence on the salt marshes, environmental factors, such as average temperatures
 160 and length of growing season, and hydrodynamic conditions, here characterized by
 161 the tidal range, are provided in Table 1.

162 Seasonal temperature variation is a key driver of plant development, influencing
 163 the growing season's length and the presence of sea ice. During summer, both regions
 164 exhibit comparable mean temperatures (cf. Table 1), whereas winter temperatures
 165 along the Canadian East Coast are lower than those of the Southeast North Sea,
 166 potentially restricting vegetation appearance. However, in the Gulf of St. Lawrence,
 167 ice cover has already declined from an average of 80 days (1960–1995) to 55 days
 168 (1995–2007) and is projected to decrease further to 36 days per year (Savard et al.,
 169 2016). Along the Southeast North Sea, frost days (minimum daily temperature below
 170 0 °C) occur regularly, but ice days remain rare (cf. Table 1) (Das Helmholtz-Zentrum
 171 Hereon, 2025a). The growing season is substantially shorter along the Canadian East
 172 Coast, compared to the Southeastern North Sea Coast, but has lengthened in recent

Table 1: Comparison of average environmental conditions for the Canadian Southeast coast and the Southeastern North Sea coastline, which is further separated by the study locations with E = Estuary, BI = Barrier Island, and ML = Mainland (Dietz and Arnold, 2021; Philippart et al., 2024; Murphy et al., 2024; Das Helmholtz-Zentrum Hereon, 2025a,b; Natural Resources Canada, 2025; Environmental and Natural Resources Canada, 2025)

Parameter	Unit	Canadian Southeast coast	Southeastern North Sea coast		
Average temperature	°C	4.5 - 6.4	9.5 - 10.0		
Summer temperature	°C	14.0 - 16.0	16.9		
Winter temperature	°C	-10.0 - -2.0	2.0		
Ice days*	d	55	14		
Length of growing season**	d	100 - 140	267		
Parameter	Unit	E (CA)	BI (DE)	ML (DE)	E (NL)
Tidal range	m	1.4 - 2.0	2.7	3.4	4.0 - 5.0

* maximum daily temperature below 0 °C
 ** defined as the number of days between the start of the vegetation season (first emergence of at least 6 consecutive days with an average temperature above 5 °C) and the end of the vegetation season (first occurrence of at least 6 consecutive days with an average temperature below 5 °C)

decades and is expected to continue increasing under projected climate change (Natural Resources Canada, 2025). Outside this period, salt marsh plants remain dormant, with above-ground stems degrading and metabolic activity minimized, while below-ground tissues persist to survive cold and environmental stress (Paul and Kerpen, 2022; Menzel et al., 2025). The duration of the growing season directly affects plant development: longer periods allow for greater stem growth, increased flexural stiffness, and denser vegetation, whereas a shorter growing period limits above-ground biomass and overall plant development (Charles and Dukes, 2009; Li and Pennings, 2017).

Hydrodynamic conditions, particularly tidal range and wave energy, are key determinants for salt marsh establishment. Seedling survival depends on the duration of low tide, the so-called window of opportunity (Balke et al., 2011, 2014). Along the Southeast North Sea, the tidal range varies spatially (cf. Table 1), with the lowest amplitude found at the back site of the barrier island and the largest amplitudes in

187 the Scheldt estuary. On the Canadian East Coast, the Gulf of St. Lawrence exhibits
188 a relatively small tidal range, but it increases within the St. Lawrence Estuary (Mur-
189 phy et al., 2024). Salt marsh vegetation generally tolerates only small to moderate
190 wave heights: Roland and Douglass (2005) determined an upper threshold for non-
191 eroding marsh conditions at a median significant wave height of about 0.10 m (80th
192 percentile $\approx$ 0.20 m), below which vegetation typically persists along the shoreline.
193 Higher and more frequent waves impose greater mechanical stress on plants, which
194 respond by allocating more biomass to their roots to improve anchorage against wave
195 impact (Shao et al., 2020). The regional wave climate along the Canadian East Coast
196 spans from negligible in sheltered areas to very high along exposed Atlantic coasts
197 (Murphy et al., 2024). Along the German North Sea coast, hindcast simulations of
198 storm events indicate significant wave heights of up to 5 m, which progressively de-
199 crease toward the shoreline (Hagen et al., 2021). At more sheltered locations, such as
200 the Scheldt Estuary, Vuik et al. (2016) reported maximum significant wave heights
201 of 0.69 m during storm surge conditions. In comparison, analysis of the monthly
202 wave condition dataset by Meier et al. (2020) for 2019 yielded a significant wave
203 height of 0.12 m for the study site on the barrier island of Spiekeroog, reflecting the
204 considerably attenuated wave climate in this nearshore environment.

205 It can be summarized that environmental conditions differ markedly between the
206 two regions, leading to an approximately twofold longer growing season for salt marsh
207 vegetation along the North Sea compared to the Canadian East Coast. Understand-
208 ing the implications of the shorter growing period for the biomechanical properties
209 of vegetation is crucial for evaluating seasonal variability in salt marsh function-
210 ing. Based on the outlined environmental contrasts, previous studies (Keimer et al.,
211 2023b; Markov et al., 2025), and field observations, the conceptual seasonal cycle of
212 stem flexural stiffness is illustrated for a salt marsh along the Southeast North Sea

213 in Figure 2 (a) and for one in the St. Lawrence Estuary in Figure 2 (b).

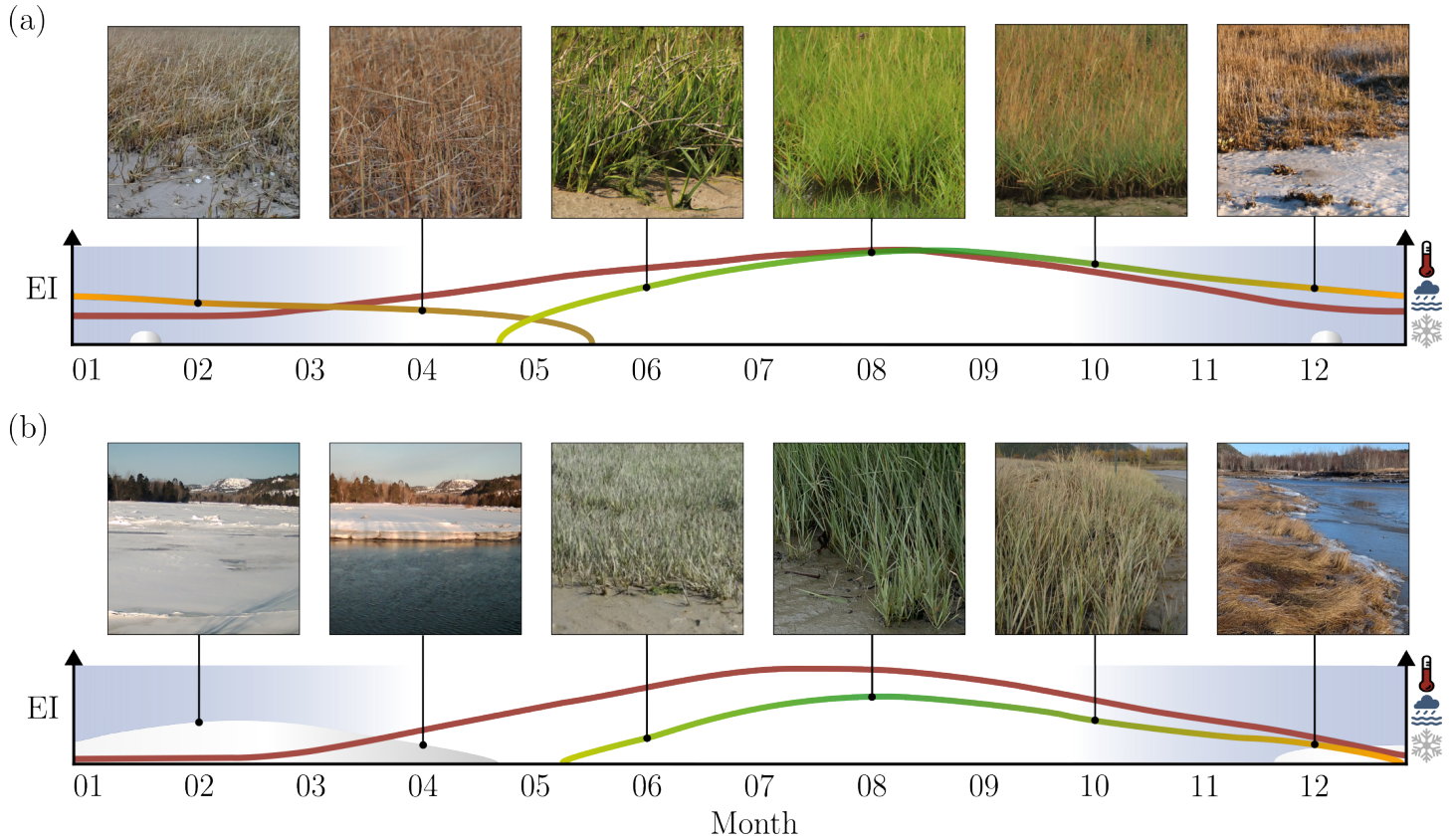


Figure 2: Conceptual sketch of annual environmental conditions (temperature shown by the red line, storm surge season by the shaded background, and the white/grey areas indicating snow and ice coverage) and the seasonal cycle of stem flexural stiffness, with line shading reflecting the dominant plant coloration throughout the year. Field photos capturing different seasons are provided for (a) A salt marsh along the Southeast North Sea, here by example for *S. anglica* on Spiekeroog and (b) a salt marsh located within the St. Lawrence Estuary, here by example for *S. alterniflora* at the Petites-Bergeronnes River in Quebec (photo courtesy of Kara Keimer and Acacia Markov)

214 It is assumed that the shorter growing season along the Canadian East Coast
 215 (cf. Table 1) compared to the southeastern North Sea contributes to smaller stem
 216 diameters and lower flexural stiffness of the sprouting stems, as shown in Figure 2.
 217 Along the southeastern North Sea, the coast is expected to experience the highest
 218 exposure in March and April, when senescent vegetation stems prevail (Keimer et al.,

219 2023b). In contrast, on the Canadian East Coast, maximum exposure typically oc-
220 curs in May and June, after ice melt but before full vegetation development (Dionne,
221 1969; Bégin and Lavoie, 1988), when plants are still in an early sprouting stage. A
222 second critical period arises in October and November, when vegetation has entered
223 dormancy, sea ice has not yet formed, and strong storms are frequent (Forbes et al.,
224 2002; Caldera et al., 2025).

225 Table 2 shows the data compiled for *S. anglica* along the Southeast North Sea
226 coast. Here, the seasonality of stems is differentiated between early-season stems
227 (covering senescent stems and new shoots), in contrast to adult stems (mature and
228 during late-season), in alignment with the seasonal phenology framework seen in
229 Reents et al. (2022) and Keimer et al. (2023b). The published data sets have been
230 selected as they include measurements at relevant points in time within the seasonal
231 cycle. For the salt marshes along the Southeast North Sea, measurements taken in
232 March and April are assumed to represent early-season vegetation, while those in
233 August and September reflect adult plants. Sampling times as close as possible were
234 selected to ensure comparability between studies. For example, Schulze et al. (2019)
235 conducted their field investigation in late August, rendering the data of Keimer et al.
236 (2023a) in early September as the best alignment. The material density of individual
237 stems has not yet been directly measured in field campaigns. However, Zhang and
238 Nepf (2021) reported a material density ρ of 900 kg/m³ for live *S. alterniflora*, which
239 is therefore adopted here as an approximate value for all stems simulated throughout
240 this study.

241 2.2. Measurement of biomechanical stem properties

242 Salt marsh stem properties at the St. Lawrence Estuary study site were assessed
243 in June, July, and September. June marked the first month of the year when stems

Table 2: Summary of the investigated material properties for *S. Anglica*

	Schulze et al. (2019)		Vuik et al. (2017)		Keimer et al. (2023a)	
Location	Sönke-Nissen-Koog (DE)		Hellegat (NL)		Spiekeroog (DE)	
Site	Mainland		Estuary		Barrier island	
characteristic	<i>S. anglica</i>		<i>S. anglica</i>		<i>S. anglica</i>	
Species	<i>S. anglica</i>		<i>S. anglica</i>		<i>S. anglica</i>	
Growth state	Early-season	Adult	Early-season	Adult	Early-season	Adult
Sampling date	03/2014	08/2014	04/2015	09/2015	04/2022	09/2022
Sampling size	20	20	20	20	90	90
L_S (cm)	27.10	37.50	28.50	54.4	39.75	49.42
	± 6.26	± 6.27	± 6.3	± 11.1	± 11.65	± 12.69
D_S (mm)	2.64	3.9	3.3	4.1	3.99	3.29
	± 0.42	± 0.54	± 0.5	± 0.9	± 0.88	± 0.65
E (MPa)	484.90	632.01	318.00	224.00	189.67	994.55
	± 231.44	± 244.69	± 178.00	± 151.00	± 115.10	± 438.08
I (mm ⁴)	2.38	11.36	5.82	13.87	16.54	13.35
	± 1.52	± 6.29	± 3.53	± 12.18	± 12.81	± 8.85
EI (N mm ²)	961.57	6415.29	1600	2500	2216.15	4342.97
	± 573.86	± 2297.74	± 500	± 1600	± 1092.37	± 1807.12

244 were sufficiently developed (> 0.08 m) to allow determination of flexural stiffness,
 245 whereas by September, the vegetation had reached full growth. In total, 12 plants
 246 were analyzed in June, 10 in July, and 20 in September. For each specimen, roots
 247 were removed at the transition from the white to the green stem section. The total
 248 plant length, including leaves, was recorded before removing the leaves to measure the
 249 bare stem length. Stems were then cut into segments of approximately 0.10 m. The
 250 uppermost segment was retained for testing if its length exceeded 0.08 m. Diameters
 251 of each 0.10 m stem segment were measured at the midpoint positions (0.05, 0.15 m,
 252 0.25 m, and 0.35 m) using high-precision calipers, as illustrated in Figure 3 (a).

253 Mechanical measurements were conducted using a CellScale UniVert S universal
 254 testing machine equipped with a 4.5 N load cell (Figure 3 b). Three-point bending
 255 tests were performed with the span length set to 15 times the diameter of each re-
 256 spective sample, following the recommendations of Zhu et al. (2020b). For specimens
 257 with particularly small diameters, a higher span length ratio was occasionally applied
 258 to ensure accurate measurements. The loading edge and supports were cylindrical,

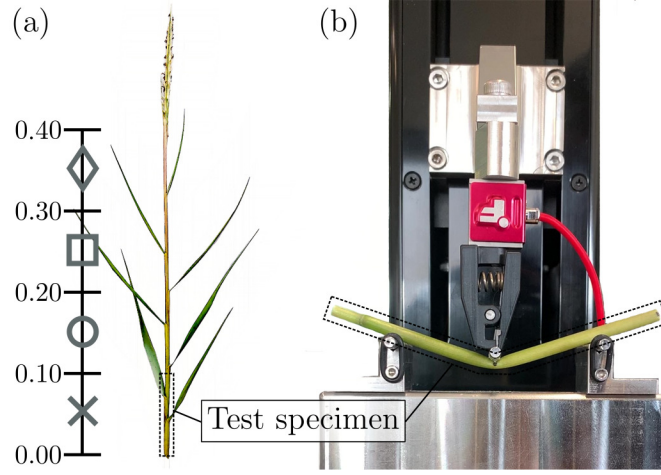


Figure 3: Assessment of biomechanical stem properties with (a) differentiation of test specimens over the stem height, and (b) illustration of the 3-point bending tests

each with a diameter of 3.18 mm, maintaining consistent contact during testing. Load data were acquired at a sampling rate of 15 Hz using semiconductor strain gauge-based load cells with an accuracy of 0.2 % of the rated full-scale load.

To minimize evaporation and preserve native biomechanical properties, the *S. alterniflora* samples were extracted with root and rhizome sections intact. Samples remained submerged in saltwater until testing, which was conducted within 24 h of collection. Force-displacement data were recorded throughout each bending test. A constant displacement rate of 0.08 mm/s was used to ensure quasi-static deformation conditions (Liu et al., 2021). From the resulting force-displacement curves, the slope within the linear deformation range, here defined between 0.2 and 1.0 mm, was determined as $S = \Delta F / \Delta D$. This slope, S , and the length of the support span, s_l , were subsequently used to calculate the flexural stiffness, EI ,

$$EI = \frac{s_l^3 \cdot S}{48}. \quad (1)$$

The Young's modulus was then derived using the calculated flexural stiffness and the

272 second moment of inertia, I , based on the measured stem diameters as

$$I = \frac{\pi}{64} D_s^4 \text{ and } E = \frac{EI}{I}. \quad (2)$$

273 The derived parameters I and E were further utilized as input values in numerical
274 modeling approaches.

275 *2.3. Numerical model and setup*

276 Recently, a new solver able to replicate the vegetation stem dynamics and result-
277 ing forces has been presented by Prüter et al. (2025a,b). The FSI solver is suitable to
278 represent both regional and seasonal variation of stems, due to its ability to directly
279 incorporate in situ measured field properties without requiring further empirical co-
280 efficients. It has furthermore shown versatility in replicating the stem motions for
281 a great range of flexural stiffness, which is especially relevant when considering the
282 range of properties found in natural salt marsh vegetation. The potential regional
283 differences between the Southeast North Sea North Sea coastline and the Canadian
284 East Coast can be explored by incorporating in situ measured field data of individual
285 stems into the previously proposed FSI solver. Based on that, regional and seasonal
286 differences can be evaluated regarding the forces exerted and feedback mechanisms
287 on the surrounding flow field.

288 The model utilized for this study is the FSI solver within the open-source hy-
289 drodynamic toolbox REEF3D::CFD (Bihs et al., 2016). The three dimensional (3D)
290 hydrodynamic component is based on finite difference (FD) and solves the incom-
291 pressible Navier-Stokes equations. The one dimensional (1D) structural component
292 solves the geometrically exact Cosserat rod equations, which can represent a great
293 range of motion by accounting for structural bending, twisting, stretching, and shear-
294 ing. The coupling of the Lagrangian fluid solver with the Eulerian structural solver

is achieved via the immersed boundary method (IBM). The FSI solver for the ap-
plication of vegetation has been previously validated by Prüter et al. (2025a) in
unidirectional and by Prüter et al. (2025b) for oscillatory flow conditions. For fur-
ther details regarding the implementation specifications and coupling, the reader is
referred to Prüter et al. (2025a,b).

The flume setup and numerical settings were selected based on the convergence study and further analysis of Prüter et al. (2025a,b). Details of the setup, including the positioning of the stem, wave gauges (WGs), and line probes (LPs), are provided in Figure 4. The dimensions are detailed in Table 3, differentiating between unidirectional and oscillatory flow conditions.

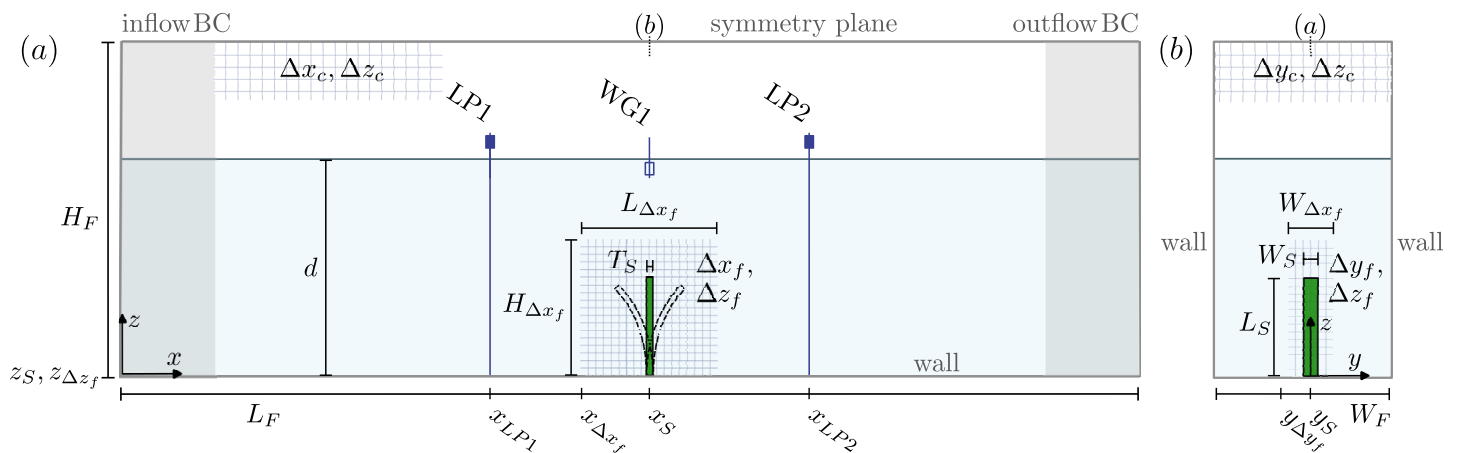


Figure 4: Visualization of the numerical flume (dimensions not to scale), utilized to simulate unidirectional and oscillatory flow conditions, including the boundary conditions (BC), and positioning of the wave gauges (WG) and line probes (LP)

To simulate the unidirectional flow, zero gradient conditions and a fixed level-set are utilized for both the inlet and outlet boundary condition (BC). Oscillatory flow conditions were simulated with a Dirichlet wave generation for the inflow and active wave absorption (AWA) for the outflow BC. Hydrodynamic conditions were chosen based on long-term observations of the Spiekeroog Coastal Observatory (Zielinski

Table 3: Numerical setup for the unidirectional and oscillatory flow simulations, including the flume dimensions (L_F , W_F , H_F), the cell size of the course (Δx_c , Δy_c , Δz_c) and fine (Δx_f , Δy_f , Δz_f) grid, the extent of the refined cell area ($L_{\Delta x_f}$, $W_{\Delta y_f}$, $H_{\Delta z_f}$) and its origin ($x_{\Delta x_f}$, $y_{\Delta y_f}$, $z_{\Delta z_f}$), the origin of the stem (x_S , y_S , z_S), the still water depth d , and the inflow and outflow boundary conditions (BC), including active wave absorption (AWA)

Parameter	Unit	Unidirectional	Oscillatory
L_F	m	1.20	4.00
W_F	m	0.16	0.08
H_F	m	0.50	0.50
$\Delta x_c, \Delta y_c, \Delta z_c$	m	2×10^{-3}	2×10^{-3}
$\Delta x_f, \Delta y_f, \Delta z_f$	m	1×10^{-3}	1×10^{-3}
$L_{\Delta x_f}$	m	$1.20 L_S$	$1.80 L_S$
$W_{\Delta y_f}$	m	0.04	0.02
$H_{\Delta z_f}$	m	$1.20 L_S$	$1.80 L_S$
$x_{\Delta x_f}$	m	0.15	$x_S - 0.5 L_{\Delta x_f}$
$y_{\Delta y_f}$	m	-0.02	-0.01
$z_{\Delta z_f}$	m	0.00	0.00
x_S	m	0.20	2.00
y_S	m	0.00	0.00
z_S	m	0.00	0.00
d	m	0.30	0.30
x_{LP1}, y_{LP1}	m	0.10, 0.00	1.95, 0.00
x_{LP1}, y_{LP1}	m	0.40, 0.00	2.05, 0.00
x_{WG1}, y_{WG1}	m	-	2.00, 0.00
Inflow BC	-	zero gradient	Dirichlet
Outflow BC	-	zero gradient	AWA

et al., 2022), including wave (Zielinski et al., 2017) and current (Meier et al., 2020) measurements. Here, a current velocity, u_c , of 0.30 m/s was chosen, representing either the upper range of mean current velocities or the lower range of maximum current velocities. A wave height, H , of 0.08 m and a wave period, T , of 1.5 s were selected for the oscillatory flow conditions, corresponding to the mean of the highest wave conditions measured at Spiekeroog. A water density, ρ , of 1000 kg/m³ was applied throughout the simulations to ensure comparability. In nature, however, freshwater discharge affects salinity, and seasonal changes influence temperature. Together, these factors determine the water density at the study sites, but varying salinity was beyond the scope of this work and remains for future investigation.

The grid convergence in Prüter et al. (2025a) and Prüter et al. (2025b) revealed

321 the importance of a fine cell size in the proximity of the stem. Accordingly, a non-
 322 uniform grid with a fine cell size of 0.001 m is chosen next to the stem and a coarse
 323 cell size of 0.002 m for the remaining numerical domain. For an accurate represen-
 324 tation of the near-stem turbulence, large eddy simulations (LES) were utilized with
 325 a Smagorinsky coefficient of 0.1. In Prüter et al. (2025b), a range of damping coef-
 326 ficients between 1×10^{-8} and 1×10^{-6} has been recommended for the replication of
 327 the motion and resulting forces of flexible vegetation. Accordingly, damping coeffi-
 328 cients within that range have been applied throughout this study. With the available
 329 computational resources, unidirectional flow conditions were simulated for about 12 s
 330 and oscillatory flow conditions for about 6 s. Based on the analysis in Prüter et al.
 331 (2025a) and Prüter et al. (2025b), the achieved simulation durations are considered
 332 sufficient for further analysis. Figure 5 displays the resulting water surface elevation
 333 over time of the simulations in oscillatory flow conditions as a reference.

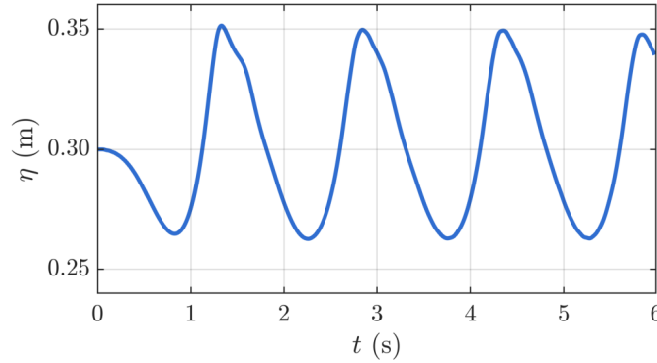


Figure 5: Water surface elevation over time of the simulations in oscillatory flow conditions

334 The hydrodynamic conditions are further quantified for unidirectional flow con-
 335 ditions based on the stem Reynolds number Re and for oscillatory flow conditions
 336 with the Keulegan-Carpenter number KC :

$$Re = \frac{u_c W_S \rho}{\nu}, \quad KC = \frac{u_{max} T}{W_S} \quad (3)$$

with u_{max} as the maximum phase-averaged horizontal velocity component and ν as the dynamic viscosity of water at 20 °C.

2.4. Further data analysis

Using the simulation results based on the previously introduced field data, it is possible to assess whether seasonal or regional differences dominate the stem dynamics. To this end, stem motion, turbulence intensity (TI), turbulent kinetic energy (TKE), drag force (F_D), and derived drag coefficients are analyzed, allowing conclusions on the transferability of ecosystem services across seasons and regions. The turbulence intensity TI is calculated, allowing for a comparison of the turbulence across different test conditions in unidirectional flow. Here, the mean velocity $\bar{u}$ in the x direction was selected as a reference due to its dominance in the flow field, resulting in

$$TI = \frac{\sqrt{\frac{1}{3} [(u - \bar{u})^2 + (v - \bar{v})^2 + (w - \bar{w})^2]}}{\bar{u}} \quad (4)$$

with u and v as the instantaneous horizontal velocity components and w as the vertical velocity component.

The velocity components for the oscillatory flow experiments were phase-averaged before calculating flow characteristics. Then, to characterize the turbulence in the flow field, the TKE for each point in time throughout the wave phase is calculated:

$$TKE = \frac{1}{3} (u'^2 + v'^2 + w'^2) \quad (5)$$

354 with u' , v' and w' representing the fluctuating components of the velocity field (e.g.
 355 $u' = u - \bar{u}$).

356 Drag coefficients were derived from the calculated drag forces. Under unidirec-
 357 tional flow conditions, the steady-state drag forces were averaged over the second half
 358 of the simulation period. For oscillatory flow conditions, all force and velocity com-
 359 ponents were phase-averaged, and the maximum drag, together with the correspond-
 360 ing horizontal velocity component, was then used to determine the drag coefficient.
 361 Stem deflection profiles provide geometric data used to calculate the bending angle ϕ
 362 from the relative displacement between mid-point and tip coordinates. Finally, the
 363 drag coefficient is evaluated per unit stem length using a Morison-type formulation,
 364 following Luhar and Nepf (2011):

$$C_D = \frac{F_D/L_S}{\frac{1}{2}\rho W_S u^2 \cos^2(\phi)} \quad (6)$$

365 incorporating the measured mean or maximum drag force F_D , fluid density ρ , stem
 366 width W_S , unidirectional or maximum phase-averaged flow velocity u . The bending
 367 angle ϕ is determined for the bent stem position, with the stem's initial position
 368 corresponding to $\phi = 0^\circ$.

369 **3. Results**

370 *3.1. Biomechanical properties of salt marsh stems at the St. Lawrence Estuary*

371 Figure 6 visualizes the seasonal variation of the flexural stiffness for the study
 372 site at the Petites-Bergeronnes River, differentiated measurement position over the
 373 stem height (cf. Figure 3) and the measurement month.

374 Figure 6 reveals clear seasonal differences in stem flexural stiffness. The stems in
 375 June exhibit distinctly lower EI values ($101.57 \pm 97.31 \text{ N mm}^2$), reflecting their early

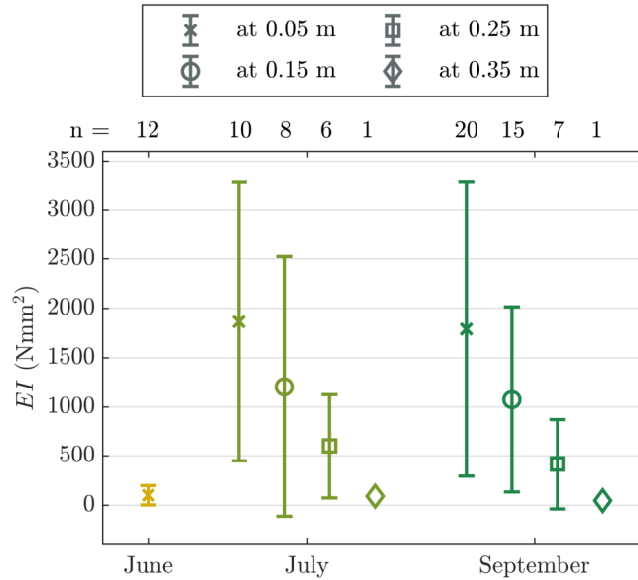


Figure 6: Flexural stiffness and standard deviation of *S. alterniflora* at the Petites-Bergeronnes River at different heights of the stem measured in June, July, and September

growth stage and shorter height. Between June and July, EI increases noticeably ($EI = 1279.80 \pm 255.90 \text{ N mm}^2$), indicating a rapid maturing and growth of the plant in this time period. In September, stiffness levels were with $1276.22 \pm 195.00 \text{ N mm}^2$ similar to those in July. The shorter stem height in June permitted only a single EI measurement per stem, whereas in July and September, EI was measured along the stem height. Across all sampling times, a general decrease in stiffness with height can be observed, with the highest EI values also showing the largest standard deviations.

Based on the measured biomechanical stem properties in the field, averaged values were calculated to represent the properties of a salt marsh stem for June and September. These will be further used as input parameters for the numerical stem and allow for a comparison to the published stem properties from the literature (cf. Table 2), representing early-season and adult stems, respectively. The derived stem properties for June and September at the Petites-Bergeronnes River are summarized

389 in Table 4.

Table 4: Derived averaged biomechanical stem properties from the study site at the St. Lawrence Estuary for *S. alterniflora* which are utilized as input parameters for the numerical modeling

Location	Petites-Bergeronnes, QC (CA)	
Site	Estuary	
characteristic	<i>S. alterniflora</i>	
Species	<i>S. alterniflora</i>	
Sampling date	06/2024	09/2023
Growth state	Early-season	Adult
Sampling size	12	35
L_S (cm)	9.75	22.28
	± 2.90	± 10.22
D_S (mm)	2.50	2.95
	± 0.52	± 0.61
E (MPa)	45.45	255.28
	± 27.98	± 120.29
I (mm ⁴)	2.45	6.55
	± 2.62	± 6.74
EI (Nmm ²)	101.57	1483.29
	± 97.31	± 1320.05

390 Next, the flexural stiffness and the outer stem diameter of the previously compiled
391 field data (cf. Table 2) and the averaged measured stem properties (cf. Table 4) are
392 compared. In Figure 7, for each study, the herein compared stem properties are
393 differentiated by their growth state, separated by diameter, Figure 7 (a) and flexural
394 stiffness, Figure 7 (b).

395 Figure 7 (a) highlights that the average measured diameter for *S. anglica* through-
396 out the different field studies and growth states ranges between 3 and 4 mm. Based
397 on the diameter alone, it can be observed that the *S. alterniflora* located at the
398 St. Lawrence Estuary are in the same order of magnitude as the *S. anglica* of the
399 Southeast North Sea coastline. For most field studies, except that of Keimer et al.
400 (2023a), an increased stem diameter for the adult compared to the early-season plant
401 can be observed. Similar observations regarding the flexural stiffness are apparent
402 in Figure 7 (b). For all measurement locations, the flexural stiffness is lower in the
403 early-season compared to the adult stage. For both early-season and adult states,

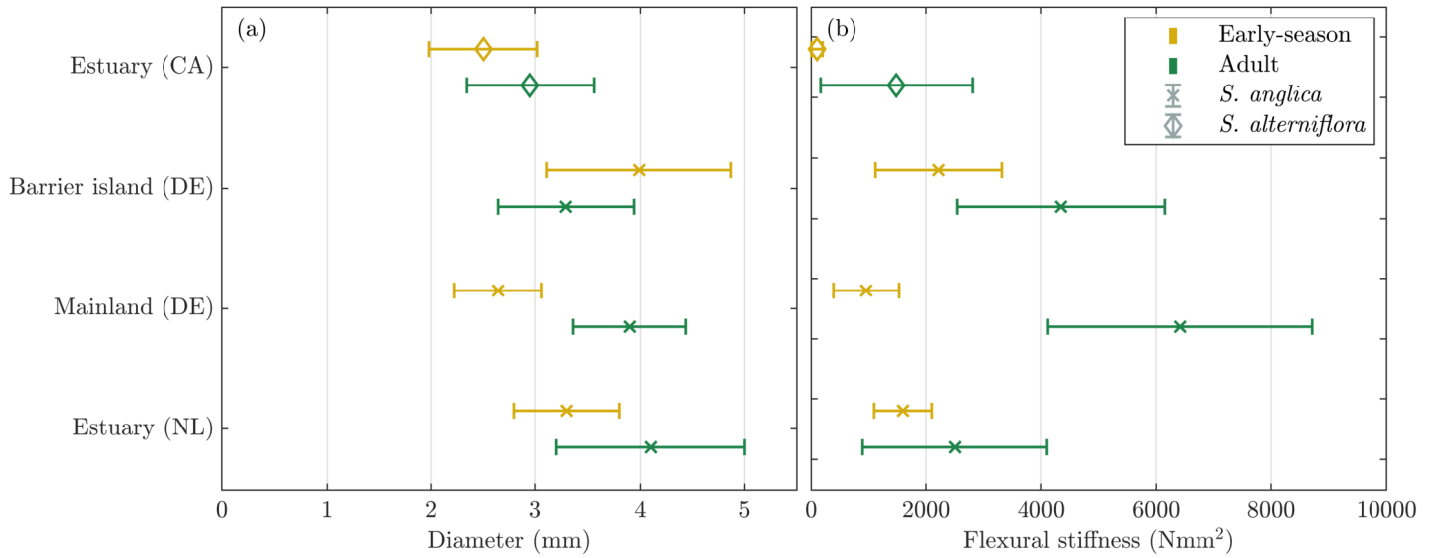


Figure 7: Comparison of (a) the diameter and (b) the flexural stiffness of *S. anglica* and *S. alterniflora* stems from salt marshes representing different site characteristics and differentiated by season

the *S. alterniflora* stem located at the St. Lawrence Estuary has the lowest flexural stiffness compared to the remaining in-situ data.

Putting the measurements of *S. alterniflora* into context, the diameters of adult *S. alterniflora* reported by Jadhav and Chen (2013) were about 8 mm, and thus considerably larger than those measured at the St. Lawrence Estuary study site, where diameters averaged approximately 3 mm. The stiffness of the *S. alterniflora* stem measured by Jadhav and Chen (2013) is 15 000 N/mm², and thus approximately ten-fold higher than the *S. alterniflora* located at the St. Lawrence Estuary. It should be noted that the two *S. alterniflora* measurement sites, Terrebonne Bay (Louisiana, USA) and Petites-Bergeronnes (Quebec, Canada), are separated by a linear distance of approximately 2600 km and a longitude difference of about 20°. This highlights that biomechanical stem properties are influenced not only by species identity but also by the local environment in which the plants thrive.

417 3.2. Stem motion and resulting flow field alterations

418 3.2.1. Unidirectional flow conditions

419 Figure 8 depicts the bent stem position under unidirectional flow conditions (u_c
420 $= 0.30$ m/s), for all simulated stems. The flow field alterations are visualized by
421 comparing the relative flow velocity (u/v) and the turbulence intensity (TI), both
422 in front of ($x = 0.10$ m) and in the wake of each stem ($x = 0.40$ m).

423 Comparing the stem positions in Figure 8 (a), (d), (g), and (j) shows that all
424 early-season stems bent further ($\phi = 17.23^\circ \pm 4.70^\circ$) compared to the stems repre-
425 senting the adult growth state ($\phi = 10.72^\circ \pm 5.17^\circ$), as expected due to their lower
426 flexural stiffness (cf. Figure 7). The adult stems, whose properties are based on field
427 measurements in salt marshes along the Southeast North Sea, remain more upright
428 ($\phi = 9.95^\circ \pm 6.03^\circ$), some almost in their initial position, see Figure 8 (d) and (g). In
429 contrast, based on measurements in the salt marsh at the St. Lawrence Estuary, the
430 adult stem bends further ($\phi = 13.05^\circ$), almost to the same extent as its early-season
431 stem ($\phi = 14.18^\circ$). It can be summarized that both seasonal and regional differences
432 are apparent concerning the stem bending in unidirectional flow conditions.

433 The influence of each stem on the flow velocity is depicted in Figure 8 (b), (e),
434 (h), and (k). Generally, the vertical extent of the flow field alteration in the wake
435 of the stem correlates with the tip of the bent stem position, most pronounced
436 in Figure 8 (c). The resulting relative flow velocity at $x = 0.40$ m in the wake
437 of them stems varies between 0.70 and 0.90, compared to 1.00 in the undisturbed
438 incoming flow field ($x = 0.10$ m). Differences in the extent of the relative profile can
439 be associated with the stem widths, as the stems in Figure 8 (d) have a comparable
440 width (0.0025 and 0.0030 m), leading to a similar maximum deviation of the relative
441 velocity in Figure 8 (e) with 0.78 and 0.80. In contrast, the stems in Figure 8 (g)

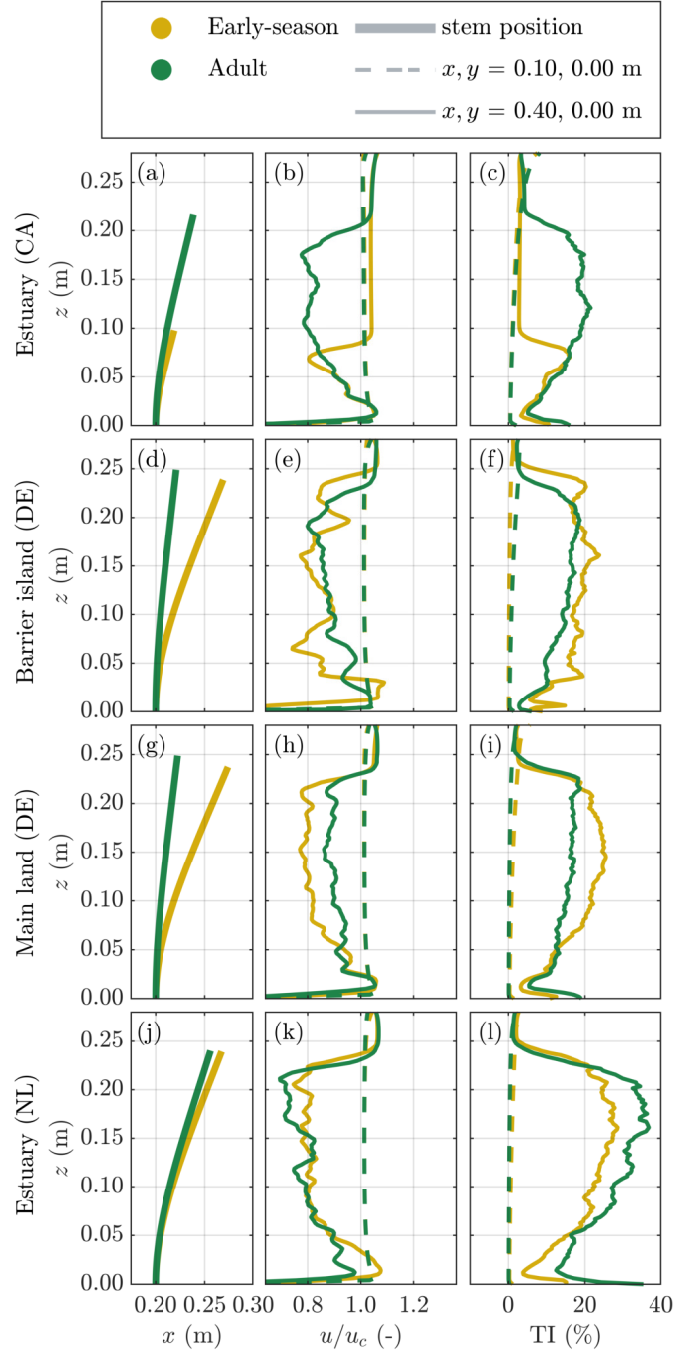


Figure 8: Comparison of simulated fluid–structure interactions using biomechanical stem properties from different study locations (cf. Figure 1) under unidirectional flow conditions ($u_c = 0.30$ m/s). Panels (a), (d), (g), and (j) show the bent stem position; panels (b), (e), (h), and (k) present the relative flow velocity profiles before and behind the stem (c f. Figure 4); and panels (c), (f), (i), and (l) display the turbulence intensity (TI) profiles before and behind the stem.

442 have a comparably large deviation in their thickness (0.0026 and 0.0039 m) and a
 443 clear distinction regarding their relative velocity in Figure 8 (h) with 0.78 and 0.87.
 444 The turbulence intensity profiles, depicted in Figure 8 (c), (f), (i), and (l), show
 445 similar patterns to the relative flow velocity profiles. For all simulated stems, the
 446 turbulence in their wake can be classified as high, as TI is exceeding 10 % (Windt
 447 et al., 2021).

448 Figure 9 shows turbulence intensity profiles normalized over the stem height,
 449 allowing for a profound comparison across the different stems. In Figure 9 (a), the
 450 resulting TI profiles behind each stem are averaged by each season, in comparison
 451 to Figure 9 (b) with TI profiles averaged for each region. The comparison of the
 452 turbulence intensity profiles shows a clear distinction between those of the Southeast
 453 North Sea and salt marsh stems from the St. Lawrence Estuary (TI averaged over the
 454 height of the stems = 17.67 vs. 11.95 %), while the profiles differentiated by seasons
 455 are much more aligned (TI averaged over the height for early-season stems: 15.74 %
 456 and for adult stems: 16.75 %). For all averaged test cases, considerable variation,
 457 though comparable across the tested conditions, should be noted, as indicated by
 458 the standard deviation in Figure 9.

459 It can hence further be concluded that the stems bent differently depending on
 460 their biomechanical properties, even in moderate flow conditions ($u_c = 0.30$ m/s).
 461 The stems representing the St. Lawrence Estuary can be distinguished from their
 462 Southeast North Sea counterparts due to their lower flexural stiffness, stem height,
 463 and thickness measured in the field. Based on the stems' variation in frontal area and
 464 thus obstruction to the flow field, differences in the corresponding relative velocity
 465 and turbulent intensity profiles in the wake of the stem can be observed. While the
 466 seasonal variation dominates the bent stem position, the turbulence intensity profiles
 467 are more distinct between the regional variations.

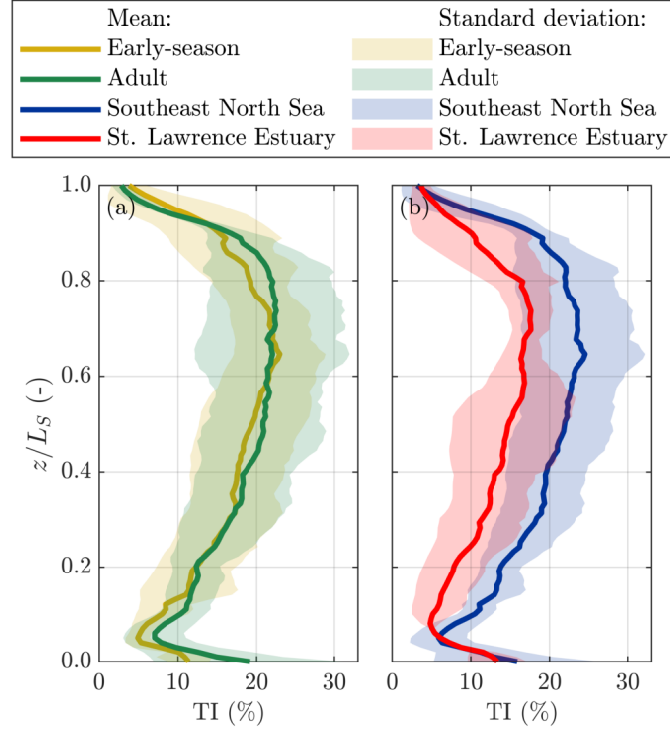


Figure 9: Comparison of the averaged turbulence intensity (TI) profiles, differentiated by seasonality (a) and region (b), in the wake of the stem ($x = 0.40$ m) over the normalized stem height.

3.2.2. Oscillatory flow conditions

For the oscillatory flow conditions, the time instant $t/T = 1.0$ in the phase-averaged wave cycle is analyzed, when the stem is bent furthest in the downstream direction, as indicated with the solid line in Figures 10 (a), (d), (g), and (j). Additionally, the phase-averaged stem positions over the wave cycle are depicted as an area in the same figures. The LP positioned 0.05 m downstream of the stem is evaluated to determine the stem's influence on the flow field. The phase-averaged horizontal velocity component u is depicted in Figures 10 (b), (e), (h), and (k). The phase-averaged TKE at the same position is shown in Figures 10 (c), (f), (i), and (l).

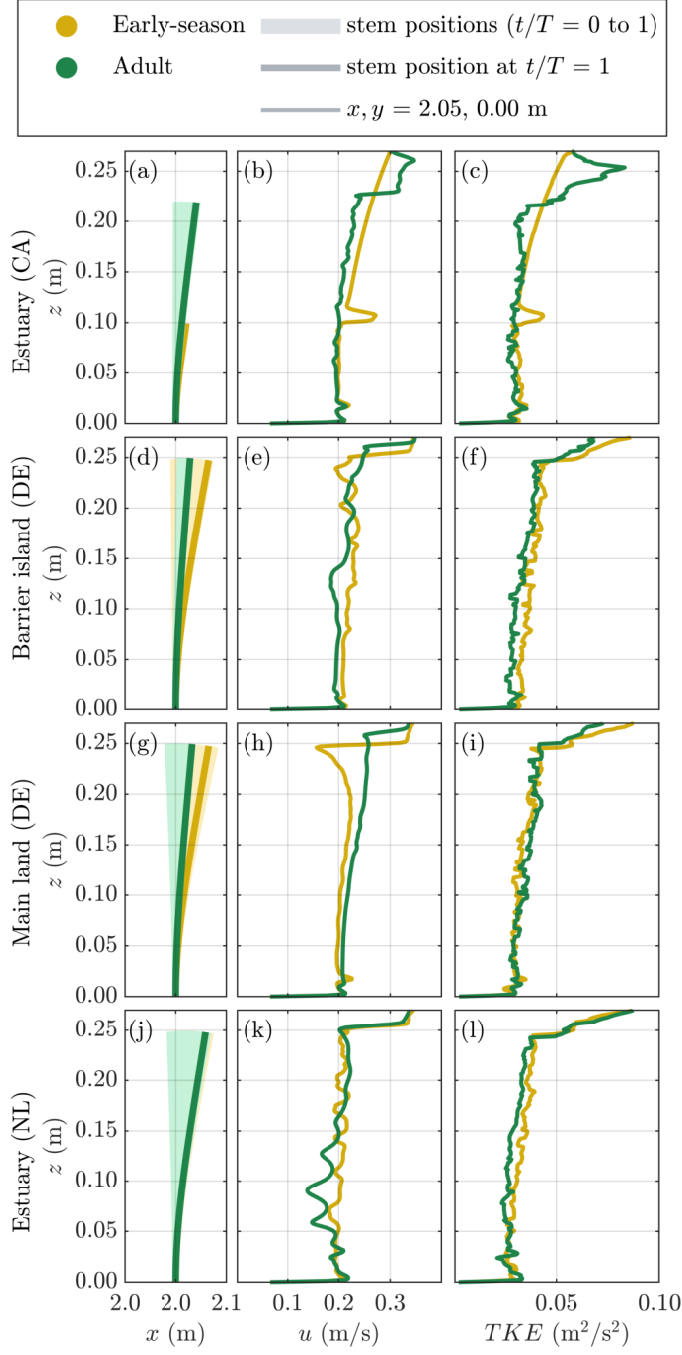


Figure 10: Comparison of simulated fluid–structure interactions using biomechanical stem properties from different study locations (cf. Figure 1) in oscillatory flow conditions ($H = 0.08$ m, $T = 1.50$ s). Panels (a), (d), (g), (j) show the bent stem position; panels (b), (e), (h), and (k) the relative flow velocity profile; and panels (c), (f), (i), and (l) the turbulent kinetic energy (TKE) profile behind the stem

478 The stem bending in Figure 10 shows that the stems replicating the biomechanical
 479 properties of the early-season exhibit a wider stem movement compared to those
 480 replicating the adult stems. That range of motion is expected due to their lower
 481 flexural stiffness, similarly to the behavior observed in Figure 8. Further evaluation of
 482 the range of movement concerning the stem tip position is provided in Figure 11. The
 483 phase-averaged horizontal velocity component u in Figure 10 ranges in the proximity
 484 of the stems between 0.15 and 0.25 m/s, and shows higher velocities between the
 485 height of the stem tip and the water surface for all tested stems. Only for the
 486 shortest stem with 0.11 m height, representing *S. alterniflora* in Figure 10 (a), the
 487 velocity profile returns to its undisturbed shape above the stems' influence. Similar
 488 trends can be observed regarding the phase-averaged TKE in Figure 10 (c), (f), (i),
 489 and (l). The TKE varies for all stems between 0.03 and 0.04 m²/s² over the height
 490 of the stem. Above the stem tip, a pronounced increase in the TKE occurs for all
 491 stems, with a mean maximum TKE of 0.08 m²/s². While the extent of the stem
 492 motion was observed to differ between stems representing early-season and adult
 493 stems, minimum seasonal variation is apparent concerning the TKE. In Figure 11,
 494 the seasonal (a) and the regional (b) influence on the stem motion are compared
 495 based on averaging the stem tip position for each component.

496 Figure 11 shows the averaged stem tip positions for each season and region, in-
 497 dicating that both factors affect the extent of stem motion. Stems representing
 498 early-season conditions, as well as those from the St. Lawrence Estuary, exhibit a
 499 more limited motion (0.017 and 0.014 m, respectively), compared to their counter-
 500 parts (0.031 and 0.028 m, respectively). However, no definitive conclusion can be
 501 drawn regarding the relative influence of seasonality versus regionality.

502 Therefore, the mean of the phase-averaged TKE profiles is calculated by region
 503 and by season, visualized in Figure 12. The mean TKE over the stem height for

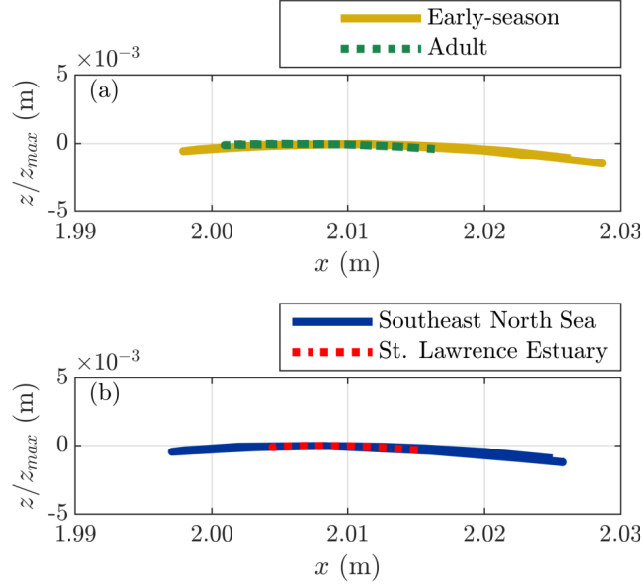


Figure 11: Comparison of the stem tip excursion averaged by (a) the seasonal variation and (b) the regional variation

the early-season stems is $0.034 \text{ m}^2/\text{s}^2$, for adult stems $0.033 \text{ m}^2/\text{s}^2$, for stems from the St. Lawrence Estuary, the mean TKE is $0.031 \text{ m}^2/\text{s}^2$, and from the Southeast North Sea $0.035 \text{ m}^2/\text{s}^2$. Although less distinctive than in Figure 9, it can be seen in Figure 12 (b) that the regional variation of the biomechanical stem properties leads to a larger difference regarding the TKE in the proximity of the stem than the seasonal variation in Figure 12 (a). Overall, the two TKE profiles in Figure 12 (a) are closely aligned.

3.3. Forces and drag coefficients

3.3.1. Unidirectional flow conditions

Figure 13 (a) shows the resulting drag force F_D against the Reynolds number Re for each simulated stem in unidirectional flow conditions ($u_c = 0.30 \text{ m/s}$). The resulting forces vary around 0.02 and 0.10 N/m . Increased drag forces can be correlated

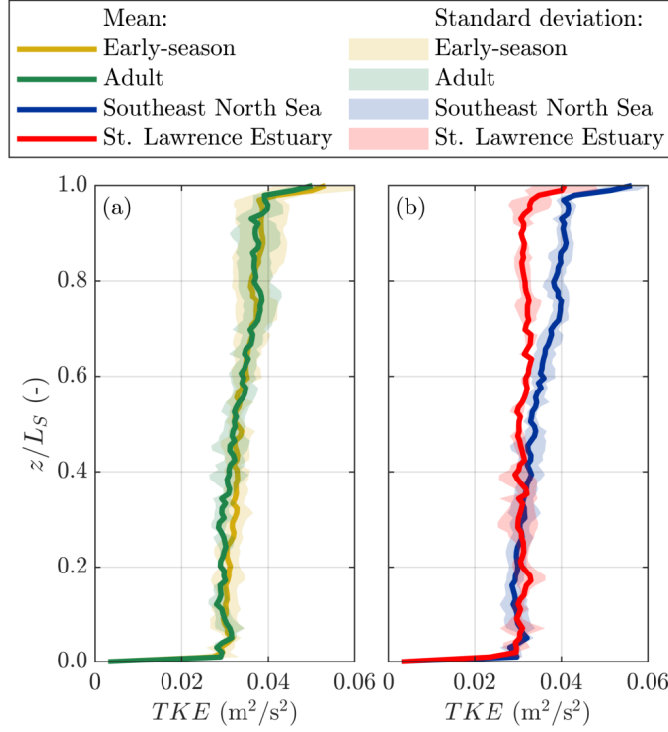


Figure 12: Comparison of the averaged turbulent kinetic energy (TKE) profiles, differentiated by seasonality (a) and region (b), in the wake of the stem ($x = 2.05$ m) over the normalized stem height.

516 with higher Re , independent of seasonal and regional variation.

517 Figure 13 (b) depicts derived drag coefficients, averaged by season and region
 518 across all simulated stems, which vary between 1.5 and 2.0. Larger deviations due
 519 to the averaging, indicated by the error bar in Figure 13 (b), can be observed for the
 520 early-season stems and the stems located at the Southeast North Sea, with the latter
 521 containing the largest sample size ($n = 6$). The averaged drag coefficients exhibit
 522 slightly greater variation across seasons than across regions.

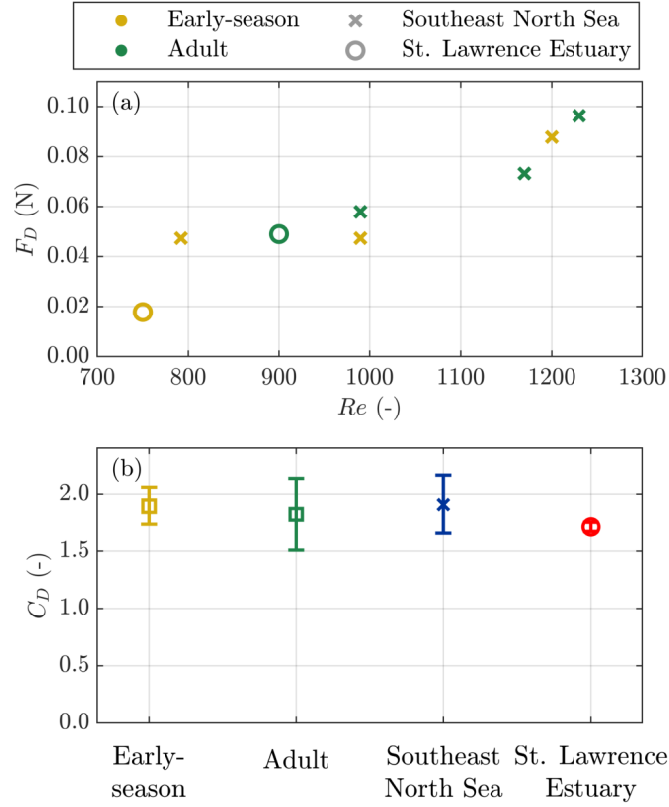


Figure 13: (a) Drag force F_D against the Reynolds number Re for all simulated stems and (b) derived drag coefficients C_D , averaged by seasonality and region in unidirectional flow conditions

3.3.2. Oscillatory flow conditions

Figure 13 (a) depicts the maximum drag force $F_{D,max}$ in relation to KC for oscillatory flow conditions ($H = 0.08$ m, $T = 1.5$ s). Figure 13 (b) shows the derived drag coefficients, averaged by season and region to enable a generalized comparison.

In Figure 14 (a), a correlation between $F_{D,max}$ and KC can be observed, aligning with the previously observed relationship of F_D in unidirectional flow conditions and Re (Figure 13 (a)). Figure 14 (a) compares the drag coefficients derived for the maximum drag force, and the associated horizontal velocity component and bent stem position. In agreement with the observations in Figure 14 (b), the derived drag

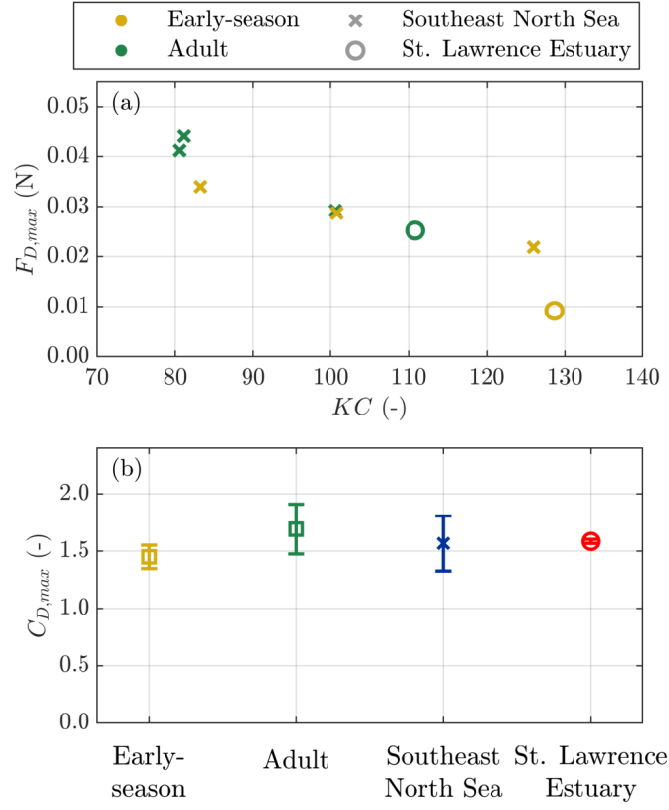


Figure 14: (a) Drag force normalized by the stem length (F_D) against the Reynolds number Re for all simulated stems and (b) Derived drag coefficients $C_{D,max}$, averaged by seasonality and region in oscillatory flow conditions

coefficients vary between approximately 1.5 and 2.0 across the different seasons and regions. The distinction between early-season and adult stems is more pronounced than that between stems from the Southeast North Sea and the St. Lawrence Estuary, taking the high standard deviation into account. Overall, adult stems exhibit higher drag coefficients based on the maximum force.

4. Discussion

4.1. Measurement and model limitations

This study highlights the necessity of investigating the biomechanical stem properties at different salt marsh locations; the need to gather further biomechanical properties in regions that have remained unaddressed in the literature so far is exemplified by the St. Lawrence Estuary region in Canada. However, a single location within Canadian territorial waters, sampled at only three points in the seasonal cycle, is still insufficient to fully capture the seasonal and regional variation of biomechanical stem properties, particularly given the high variability of coastal features such as tidal elevation or climatic conditions (cf. Table 1). Subsequent studies should hence extend the utilized data set to enable the evaluation of the influence of site-specific features, such as the difference between salt marshes located in an estuarine, on a mainland, or a barrier island, as indicated in Figure 1. Based on previous investigations (Silinski et al., 2018; Cao et al., 2020), regional and site-specific differences in wave exposure are expected to influence the biomechanical properties of vegetation stems. This study compared the salt marsh species *S. anglica* and *S. alterniflora* across regions. To better isolate intra-species effects of either *S. anglica* or *S. alterniflora*, future research should specifically examine regional variability within a single species.

Furthermore, this study outlines the workflow from assessing biomechanical properties in the field to incorporating the measured stem characteristics into numerical models. The proposed procedure thus enables the investigation of flow field modifications induced by live vegetation, which would be difficult to quantify directly in the field otherwise. However, the numerical model still has limitations due to modeling constraints and simplifications, summarized by Prüter et al. (2025a,b). While the

biomechanical properties of the salt marsh stems are accurately represented, other
 vegetation characteristics, such as the skin friction, leaves, or other geometrical fea-
 tures, are not yet captured by the FSI solver. Subsequent studies, hence, should focus
 on enhancing the efficiency of the FSI solver in REEF3D::CFD, while extending the
 structural solver to replicate a broader range of vegetation features besides the stem.
 While all models simplify certain aspects of vegetation, some studies have adapted
 the surface to account for skin friction (Abdelrhman, 2007; Zhu et al., 2020a), others
 have incorporated the variation in flexibility along the stem height (Marjoribanks
 and Paul, 2021), and some have included the influence of leaves (Zhang et al., 2022).
 Furthermore, simulation durations were limited by computational constraints. How-
 ever, steady-state conditions in unidirectional flow were reached within a few seconds
 (Prüter et al., 2025a), and previous studies showed no relevant variation in FSI over
 additional wave cycles in oscillatory flow (see Figure 9 in Prüter et al., 2025b). Over-
 all, simplifications in this study, such as neglecting within-stem stiffness gradients,
 may partly lead to remaining discrepancies between simulated flow fields and those
 found in nature.

Furthermore, this study focused exclusively on individual salt marsh stems, based
 on in situ measurements of stem properties. However, salt marsh vegetation occurs
 in dense meadows, with horizontal stem densities of *S. anglica* ranging from ap-
 proximately 1000 to 2000 stems per m^2 (Keimer et al., 2023b), and *S. alterniflora*
 ranging for example from 300 to 400 stems per m^2 (Smith et al., 2018). The effects
 of sheltering or stem collisions within a meadow were not addressed in this study.
 Future research should examine the regional and seasonal variation in stem density
 and its impact on flow field modifications, including the investigation of vegetation-
 vegetation interaction, reaching validity on the meadow scale.

587 4.2. The influence of seasonal and regional variation

588 Based on the observations in Section 3.1, it can be concluded that both seasonal
589 and regional variations are relevant when assessing the biomechanical properties of
590 salt marsh stems. As this is the first assessment of its kind, generalizing the results
591 beyond the evaluated salt marshes should be done with caution. Additional field
592 studies are needed to determine whether these observations are broadly applicable.
593 The variation in stem flexural stiffness along the height of adult *S. alterniflora* stems
594 align with literature findings, such as those reported by Keimer et al. (2023b).

595 It is known that plant traits such as density, height, and flexibility govern the
596 fluid-vegetation dynamics in salt marshes (Tempest et al., 2015; Zhu et al., 2020b).
597 The results presented in Sections 3.2 to 3.3 indicate that seasonal and regional varia-
598 tions in stem biomechanics affect the FSI parameter dependent. Under unidirectional
599 flow, seasonal changes primarily influence stem bending and mean drag coefficients.
600 In contrast, turbulence intensity near the stems is more sensitive to regional dif-
601 ferences, reflecting species-specific morphology and environmental exposure. Under
602 wave impact, (Reents et al., 2022) reported seasonal changes in the mechanical resis-
603 tance of salt marsh vegetation. However, compared to unidirectional flow conditions,
604 flow field alterations are generally less pronounced in oscillatory flow (Rupprecht
605 et al., 2015), though regional variability in the TKE near stem tips remains evident
606 in the findings of this study. Differences in stiffness and stem height further modulate
607 stem deformation, drag, and local energy dissipation, underscoring the importance
608 of representing both flexibility and vertical property distribution along the stem in
609 models (Tempest et al., 2015). These findings highlight the need to incorporate sea-
610 sonally and regionally adaptive biomechanical parameters to improve predictions of
611 vegetation–flow interactions and the associated ecosystem services of salt marshes.

612 A wide range of drag coefficients for flexible submerged vegetation has been re-

ported in the literature (Losada et al., 2016; Twomey et al., 2020; Li et al., 2024). Recently, Caldera et al. (2025) measured mean drag coefficients for *S. alterniflora* in wave flume experiments representing seasonal variation in Canada, obtaining $C_D = 0.98 \pm 1.04$. The comparatively lower values likely reflect the limited establishment of flume-grown vegetation relative to natural plants, particularly in terms of root development. The derived drag coefficients in this study display a more pronounced seasonal than regional difference. Further, relationships of C_D to either Re or KC have been derived in the literature,, as seen in Zhu et al. (2023)

$$C_D = 0.57 + \left(\frac{1546}{Re} \right)^{1.1}, \quad 54 < Re < 5164 \quad (7)$$

and Zhang and Nepf (2021)

$$C_D = \max(1, 2.9KC^{-0.2}). \quad (8)$$

These two relationships are displayed together with the drag coefficients derived in this study in Figure 15 (a) for unidirectional flow conditions and Figure 15 (b) for oscillatory flow conditions.

In Figure 15 (a), the proposed relationship between C_D and Re (Equation 7) deviates from the coefficients derived in this study, with an over-prediction of C_D of about 66 % for the lower Reynolds numbers and an under-prediction of 18 % for the highest simulated Re . Likewise, Figure 15 (b) shows that the derived drag coefficients exceed those predicted by Equation 8 across KC , with an averaged underestimation of 25 %. Future studies should include simulations using additional hydrodynamic conditions to enable a more comprehensive comparison.

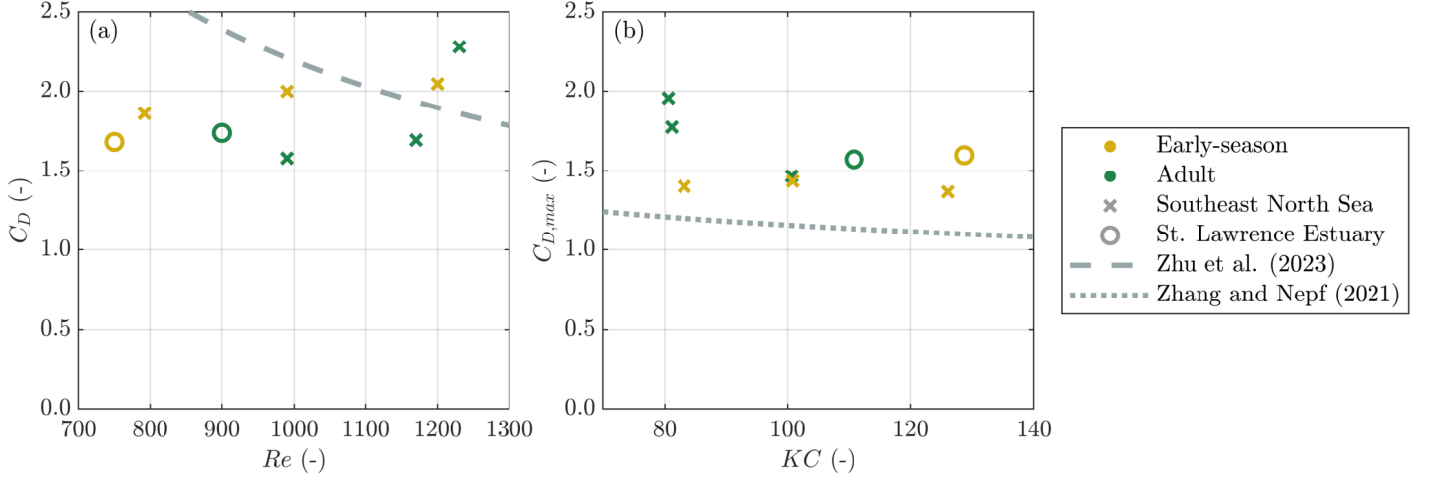


Figure 15: (a) Derived drag coefficients C_D against the Reynolds number Re for all simulated stems in unidirectional flow and (b) Derived maximum drag coefficients $C_{D,max}$, against the Keulegan-Carpenter number KC

4.3. Implications for salt marshes as nature-based solutions

The results of this study indicate that longer growing seasons in temperate climates lead to increased stem diameters and higher flexural stiffness (cf. Figure 2), which in turn enhance wave attenuation. Accordingly, ecosystem assessments of Canadian salt marshes should not rely on measurements from other regions, as smaller stems with lower stiffness are likely to provide reduced coastal protection (van Veelen et al., 2020). In the St. Lawrence Estuary, winter measurements were precluded by ice cover (Figure 2 (b)), leaving the extent to which an ice-covered shoreline contributes to erosion stability relative to dormant vegetation in other regions worldwide uncertain. Further research is required to clarify how seasonal and regional variability in salt marshes influences ecosystem services such as wave attenuation and sediment retention. Caldera et al. (2025) demonstrated a strong relationship between plants' biophysical traits and wave attenuation, with maximum energy

dissipation occurring in summer. These findings emphasize the need for site-specific, seasonally resolved field data to be incorporated into NbS for coastal protection. The framework developed in this study, linking field measurements to stem-scale modeling, provides drag coefficients that capture regional and seasonal variability. Such models enable the quantitative assessment of ecosystem services in the next step, including sediment accretion and wave attenuation potential.

5. Conclusion

This study presents the first field measurements of flexural stiffness and its seasonal variation for *S. alterniflora*, investigated at the Petites-Bergeronnes River shores in Quebec, Canada. Comparison of regionally- and seasonally-varying biomechanical stem properties reveals that the *S. alterniflora* at the St. Lawrence Estuary is smaller and more flexible than *S. anglica* from the Southeast North Sea for both early-season and adult stems. In combination with measurements of biomechanical properties of *S. anglica*, the influence of seasonal and regional variation of the flow field through numerical modeling on the stem level is investigated. The FSI solver in REEF3D::CFD, able to model the stem motion and resulting forces based on the in situ measured biomechanical stem properties, was employed to simulate the seasonally and regionally varying stems. Due to their lower flexural stiffness, early-season vegetation exhibits greater stem bending under unidirectional flow, as expected. However, the stem-induced flow field, expressed here by turbulence intensity, shows stronger differences between regions than between seasons. A similar pattern is observed under oscillatory flow, where variations are reflected in the TKE of the stem wake. Drag coefficients, derived based on the force exerted by the flow field on the stems and averaged by season and region, are provided, applicable for

669 future large-scale modeling approaches. The research objectives introduced in Sec-
 670 tion 1 have been addressed as follows:

- 671 • Field measurements of *Spartina alterniflora* at the Petites-Bergeronnes River
 672 in Quebec, Canada, showed seasonal variation of biomechanical stem proper-
 673 ties. A lower flexural stiffness was measured in June ($101.57 \pm 97.31 \text{ N mm}^2$)
 674 compared to July and September ($1279.80 \pm 255.9 \text{ N mm}^2$ and $1276.22 \pm$
 675 195.00 N mm^2). In July and September, the flexural stiffness reduced with
 676 increasing stem height.
- 677 • The investigated *Spartina alterniflora* stems at the St. Lawrence Estuary show
 678 smaller stem diameters ($2.50 \pm 0.52 \text{ mm}$ in early-season and $2.95 \pm 0.61 \text{ mm}$
 679 as adult stems) and a lower flexural stiffness ($101.57 \pm 97.31 \text{ N mm}^2$ in early-
 680 season and $1483.29 \pm 1320.05 \text{ N mm}^2$ as adult stems) for each season compared
 681 to measurements of *Spartina anglica* in salt marshes along the Southeast North
 682 Sea ($D_S = 3.31 \pm 0.67 \text{ mm}$ on average in early-season and $3.76 \pm 0.61 \text{ mm}$ as
 683 adult stems, $EI = 1592.57 \pm 810.65 \text{ N mm}^2$ on average in early-season and
 684 $4419.42 \pm 1917.28 \text{ N mm}^2$ as adult stems).
- 685 • Regional variation exerts a stronger influence than seasonal variation on tur-
 686 bulence intensity in the stem wake under unidirectional flow and on turbulent
 687 kinetic energy under oscillatory flow.
- 688 • Derived drag coefficients under unidirectional and oscillatory flow conditions
 689 range between 1.5 and 2.0, without showing clear trends regarding seasonal or
 690 regional variation.

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718 **Declarations:**

719 **Availability of data and materials:** All data, models, or codes supporting
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References

- Abdelrhman, M.A., 2007. Modeling coupling between eelgrass *zostera marina* and water flow. *Mar. Ecol. Prog. Ser.* 338, 81–96. doi:10.3354/meps338081.
- Baaij, B.M., Kooijman, J., Limpens, J., Marijnissen, R.J.C., van Loon-Steensma, J.M., 2021. Monitoring impact of salt-marsh vegetation characteristics on sedimentation: an outlook for nature-based flood protection. *Wetlands* 41. doi:10.1007/s13157-021-01467-w.
- Balke, T., Bouma, T.J., Horstman, E.M., Webb, E.L., Erftemeijer, P.L., Herman, P.M., 2011. Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. *Marine Ecology Progress Series* 440, 1–9. doi:10.3354/meps09364.
- Balke, T., Herman, P.M.J., Bouma, T.J., 2014. Critical transitions in disturbance-driven ecosystems: identifying windows of opportunity for recovery. *Journal of Ecology* 102, 700–708. doi:10.1111/1365-2745.12241.
- Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81, 169–193. doi:10.1890/10-1510.1.
- Beauchesne, D., Daigle, R.M., Vissault, S., Gravel, D., Bastien, A., Bélanger, S., Bernatchez, P., Blais, M., Bourdages, H., Chion, C., Galbraith, P.S., Halpern, B.S., Lavoie, C., McKindsey, C.W., Mucci, A., Pineault, S., Starr, M., Ste-Marie, A.S., Archambault, P., 2020. Characterizing exposure to and sharing knowledge of drivers of environmental change in the st. lawrence system in canada. *Frontiers in Marine Science* 7. doi:10.3389/fmars.2020.00383.

- 748 Bégin, Y., Lavoie, J., 1988. Dynamique d'une bordure forestière et variations récentes
749 du niveau du fleuve saint-laurent. *Canadian Journal of Botany* 66, 1905–1913.
750 doi:10.1139/b88-261.
- 751 Bihs, H., Kamath, A., Alagan Chella, M., Aggarwal, A., Arntsen, Øivind., 2016.
752 A new level set numerical wave tank with improved density interpolation for
753 complex wave hydrodynamics. *Computers & Fluids* 140, 191–208. doi:10.1016/j.
754 compfluid.2016.09.012.
- 755 Bouma, T.J., van Duren, L.A., Temmerman, S., Claverie, T., Blanco-Garcia,
756 A., Ysebaert, T., Herman, P., 2007. Spatial flow and sedimentation patterns
757 within patches of epibenthic structures: Combining field, flume and modelling
758 experiments. *Continental Shelf Research* 27 (8), 1020–1045. doi:10.1016/j.
759 csr.2005.12.019.
- 760 Bouma, T.J., Friedrichs, M., Klaassen, P., van Wesenbeeck, B.K., Brun, F.G.,
761 Temmerman, S., van Katwijk, M.M., Graf, G., Herman, P.M., 2009. Effects
762 of shoot stiffness, shoot size and current velocity on scouring sediment from
763 around seedlings and propagules. *Marine Ecology Progress Series* 388, 293–297.
764 doi:10.3354/meps08130.
- 765 Caldera, G., Stolle, J., van Pham Bang, D., Murphy, E., Knox, P., 2025. Seasonal and
766 inter-annual changes in wave attenuation by a constructed salt marsh on a sloping
767 bed. *Ecological Engineering* 221, 107758. doi:10.1016/j.ecoleng.2025.107758.
- 768 Cao, H., Zhu, Z., James, R., Herman, P.M.J., Zhang, L., Yuan, L., Bouma,
769 T.J., 2020. Wave effects on seedling establishment of three pioneer marsh
770 species: survival, morphology and biomechanics. *Annals of botany* 125, 345–352.
771 doi:10.1093/aob/mcz136.

- 772 Caroppi, G., Västilä, K., Gualtieri, P., Järvelä, J., Giugni, M., Rowiński, P.M.,
773 2021. Comparison of flexible and rigid vegetation induced shear layers in partly
774 vegetated channels. *Water Resources Research* 57. doi:10.1029/2020WR028243.
- 775 Charles, H., Dukes, J.S., 2009. Effects of warming and altered precipitation on plant
776 and nutrient dynamics of a new england salt marsh. *Ecological applications: a*
777 *publication of the Ecological Society of America* 19, 1758–1773. doi:10.1890/08-
778 0172.1.
- 779 Coleman, D.J., Cassalho, F., Miesse, T.W., Ferreira, C.M., 2022. The role of invasive
780 phragmites australis in wave attenuation in the eastern united states. *Estuaries*
781 *and Coasts* doi:10.1007/s12237-022-01138-x.
- 782 Cui, H., Felder, S., Kramer, M., 2023. Predicting flow resistance in open-channel
783 flows with submerged vegetation. *Environmental Fluid Mechanics* 23, 757–778.
784 doi:10.1007/s10652-023-09929-x.
- 785 Das Helmholtz-Zentrum Hereon, 2025a. Nordseeküste: Bisherige Entwicklung der
786 durchschnittlichen Temperatur im Jahr.
- 787 Das Helmholtz-Zentrum Hereon, 2025b. Nordseeküste: Bisherige Entwicklung der
788 Vegetationsperiode im Jahr.
- 789 Dietz, S., Arnold, S., 2021. Atlantic provinces: Chapter 1, in: Warren, F.J., Lulham,
790 N., Lemmen, D.S. (Eds.), *Canada in a Changing Climate: Regional Perspectives*
791 *Report*. Government of Canada, Ottawa, ON, pp. 1–85.
- 792 Dijkstra, J.T., Uittenbogaard, R.E., 2010. Modeling the interaction be-
793 tween flow and highly flexible aquatic vegetation. *Water Resour. Res.* 46.
794 doi:10.1029/2010WR009246.

- 795 Dionne, J.C., 1969. Tidal flat erosion by ice at la pociatiere, saint lawrence estuary.
796 Journal of Sedimentary Research 39, 1174–1181. doi:10.1306/74d71dc0-2b21-11d7-
797 8648000102c1865d.
- 798 Environmental and Natural Resources Canada, 2025. Climatology of temperature
799 and precipitation.
- 800 Esselink, P., van Duin, W.E., Bunje, J., Cremer, J., Folmer, E.O., Frikke, J., Glahn,
801 M., de Groot, A.V., Hecker, N., Hellwig, U., Jensen, K., Körber, P., Petersen,
802 J., Stock, M., 2017. Cwss: Salt marshes, in: Kloepper, S., Baptist, M.J., Bostel-
803 mann A., Busch J.A., Buschbaum C., Gutow L., Janssen G., Jensen K. (Eds.),
804 Wadden Sea Quality Status Report. Common Wadden Sea Secretariat (CWSS),
805 Wilhelmshaven, Germany, pp. 1–39.
- 806 Familkhalili, R., Tahvildari, N., 2022. Computational modeling of coupled waves
807 and vegetation stem dynamics in highly flexible submerged meadows. Advances
808 in Water Resources doi:10.1016/j.advwatres.2022.104222.
- 809 Forbes, D., Manson, G., Chagnon, R., Solomon, S., Sanden, J.J., Lynds, T., 2002.
810 Nearshore ice and climate change in the southern gulf of st. lawrence. Ice in the
811 environment. Proceedings of the 16th IAHR international symposium on ice in
812 Dunedin, New Zealand .
- 813 Garzon, J.L., Maza, M., Ferreira, C.M., Lara, J.L., Losada, I.J., 2019.
814 Wave attenuation by spartina saltmarshes in the chesapeake bay under storm
815 surge conditions. Journal of Geophysical Research: Oceans 124, 5220–5243.
816 doi:10.1029/2018JC014865.
- 817 Hadadpour, S., Paul, M., Oumeraci, H., 2019. Numerical investigation of wave

818 attenuation by rigid vegetation based on a porous media approach. Journal of
819 Coastal Research 92, 92. doi:10.2112/SI92-011.1.

820 Hagen, R., Plüß, A., Ihde, R., Freund, J., Dreier, N., Nehlsen, E., Schrage, N.,
821 Fröhle, P., Kösters, F., 2021. An integrated marine data collection for the german
822 bight – part 2: Tides, salinity, and waves (1996–2015). Earth System Science Data
823 13, 2573–2594. doi:10.5194/essd-13-2573-2021.

824 Henderson, S.M., 2019. Motion of buoyant, flexible aquatic vegetation under waves:
825 Simple theoretical models and parameterization of wave dissipation. Coastal En-
826 gineering 152. doi:10.1016/j.coastaleng.2019.04.009.

827 Jadhav, R.S., Chen, Q., 2013. Probability distribution of wave heights attenuated
828 by salt marsh vegetation during tropical cyclone. Coastal Engineering 82, 47–55.
829 doi:10.1016/j.coastaleng.2013.08.006.

830 Jin, C., Zhang, J., 2022. Numerical investigation of the wave interaction with flexible
831 vegetation: model setup and validation for a single stem study case. Anthropocene
832 Coasts 5. doi:10.1007/s44218-022-00003-5.

833 Keimer, K., Kind, F., Prüter, I., Kosmalla, V., Lojek, O., Schürenkamp, D.,
834 Prinz, M., Niewerth, S., Aberle, J., Goseberg, N., 2024. From seasonal
835 field study to surrogate modeling: Investigating the biomechanical dynam-
836 ics of *elymus* sp. in salt marshes. Limnography and Oceanography Methods
837 doi:doi.org/10.1002/lom3.10616.

838 Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Schürenkamp, D., Gose-
839 berg, N., 2023a. Field measurements of geometrical and mechani-
840 cal properties of *Spartina anglica* on spiekeroog, germany, from de-

841 cember 2021 to december 2022. TU Braunschweig Open Research
 842 Data Repository. <https://doi.org/10.24355/dbbs.084-202311010949-0>.
 843 doi:10.24355/dbbs.084-202311010949-0. dataset.

844 Keimer, K., Kosmalla, V., Prüter, I., Lojek, O., Prinz, M., Schürenkamp, D., Freund,
 845 H., Goseberg, N., 2023b. Proposing a novel classification of growth periods based
 846 on biomechanical properties and seasonal changes of *spartina anglica*. *Front. Mar.*
 847 *Sci.* 10. doi:10.3389/fmars.2023.1095200.

848 Koplin, J., Peter, C., Bischof, K., Böttcher, M.E., Kuhn, A., Logemann, E.,
 849 Dolch, T., Henkel, S., McCarthy, D., Mueller, P., Morys, C., Pineda-Metz, S.E.,
 850 Reents, S., Reusch, T.B., Röschel, L., Rupprecht, F., Stevenson, A., Wiltshire,
 851 K.H., Zimmer, M., Pogoda, B., 2025. Blue carbon potential in germany: Sta-
 852 tus and future development. *Estuarine, Coastal and Shelf Science* 323, 109354.
 853 doi:10.1016/j.ecss.2025.109354.

854 Li, C., Peng, Z., Zhao, Y., Fang, D., Chen, X., Xu, F., Wang, X., 2024. Seasonal
 855 variations in drag coefficient of salt marsh vegetation. *Coastal Engineering* 193,
 856 104575. doi:10.1016/j.coastaleng.2024.104575.

857 Li, S., Pennings, S.C., 2017. Timing of disturbance affects biomass and flower-
 858 ing of a saltmarsh plant and attack by stem-boring herbivores. *Ecosphere* 8.
 859 doi:10.1002/ecs2.1675.

860 Liu, J., Kutschke, S., Keimer, K., Kosmalla, V., Schürenkamp, D., Goseberg, N.,
 861 Böl, M., 2021. Experimental characterisation and three-dimensional modelling
 862 of *elymus* for the assessment of ecosystem services. *Ecological Engineering* 166.
 863 doi:10.1016/j.ecoleng.2021.106233.

- 864 Losada, I.J., Maza, M., Lara, J.L., 2016. A new formulation for vegetation-induced
865 damping under combined waves and currents. *Coastal Engineering* 107, 1–13.
866 doi:10.1016/j.coastaleng.2015.09.011.
- 867 Luhar, M., Nepf, H.M., 2011. Flow-induced reconfiguration of buoyant and
868 flexible aquatic vegetation. *Limnology and Oceanography* 56, 2003–2017.
869 doi:10.4319/lo.2011.56.6.2003.
- 870 Marjoribanks, T.I., Lague, D., Hardy, R.J., Boothroyd, R.J., Leroux, J., Mony, C.,
871 Puijalon, S., 2019. Flexural rigidity and shoot reconfiguration determine wake
872 length behind saltmarsh vegetation patches. *J. Geophys. Res. Earth Surf.* 124,
873 2176–2196. doi:10.1029/2019 JF005012.
- 874 Marjoribanks, T.I., Paul, M., 2021. Modelling flow-induced reconfiguration
875 of variable rigidity aquatic vegetation. *Journal of Hydraulic Research* , 1–
876 6doi:10.1080/00221686.2020.1866693.
- 877 Markov, A., Stolle, J., Henteleff, R., Nistor, I., van Pham Bang, D., Mur-
878 phy, E., Cornett, A., 2023. Deformation of spartina patens and spartina al-
879 terniflora stems under irregular wave action. *Coastal Engineering Journal* ,
880 1–22doi:10.1080/21664250.2023.2195030.
- 881 Markov, A., Stolle, J., Nistor, I., Desrochers, V., Murphy, E., 2025. Modeling cold
882 climate saltmarsh evolution: tools for restoration and prediction. *Coastal Engi-
883 neering Proceedings* , 139doi:10.9753/icce.v38.management.139.
- 884 Maza, M., Lara, J.L., Losada, I.J., 2013. A coupled model of submerged vegeta-
885 tion under oscillatory flow using navier–stokes equations. *Coastal Engineering* 80,
886 16–34. doi:10.1016/j.coastaleng.2013.04.009.

- 887 Mcowen, C.J., Weatherdon, L.V., van Bochove, J.W., Sullivan, E., Blyth, S., Zock-
888 ler, C., Stanwell-Smith, D., Kingston, N., Martin, C.S., Spalding, M., Fletcher,
889 S., 2017. A global map of saltmarshes. *Biodiversity data journal* 5, e11764.
890 doi:10.3897/BDJ.5.e11764.
- 891 Meier, D., Thölen, C., Hillebrand, H., Kleyer, M., Löhmus, K., Zielinski,
892 O., 2020. Continuous wave and tide observations at dynacom artificial is-
893 lands in the back-barrier tidal flat, spiekeroog, germany, 2019-01 to 2019-12.
894 doi:10.1594/PANGAEA.918521.
- 895 Meixler, M.S., Kennish, M.J., Crowley, K.F., 2018. Assessment of plant community
896 characteristics in natural and human-altered coastal marsh ecosystems. *Estuaries
897 and Coasts* 41, 52–64. doi:10.1007/s12237-017-0296-0.
- 898 Menzel, A.C., Ostertag, E.J.M., Mueller, P., Nolte, S., Rich, R., Jensen, K., 2025.
899 Hydrology mediates salt marsh belowground biomass response to warming. *Lim-
900 nology and Oceanography* 70, 1725–1739. doi:10.1002/lno.70080.
- 901 Moeller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck,
902 B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M., Schimmels, S.,
903 2014. Wave attenuation over coastal salt marshes under storm surge conditions.
904 *Letters Nature Geoscience* 7.
- 905 Mullarney, J.C., Henderson, S.M., 2010. Wave-forced motion of submerged single-
906 stem vegetation. *J. Geophys. Res.* 115. doi:10.1029/2010 JC006448.
- 907 Murphy, E., Cornett, A., van Proosdij, D., Mulligan, R.P. (Eds.), 2024. Nature-based
908 infrastructure for coastal flood and erosion risk management: a Canadian design
909 guide. National Research Council of Canada. doi:10.4224/40003325.

- 910 Natural Resources Canada, 2025. Growing season.
- 911 Paul, M., Kerpen, N.B., 2022. Erosion protection by winter state of salt marsh vege-
 912 tation. *Journal of Ecohydraulics* 7, 144–153. doi:10.1080/24705357.2021.1938252.
- 913 Paul, M., Rupprecht, F., Möller, I., Bouma, T.J., Spencer, T., Kudella, M.,
 914 Wolters, G., van Wesenbeeck, B.K., Jensen, K., Miranda-Lange, M., Schim-
 915 mels, S., 2016. Plant stiffness and biomass as drivers for drag forces under ex-
 916 treme wave loading: A flume study on mimics. *Coastal Engineering* 117, 70–78.
 917 doi:10.1016/j.coastaleng.2016.07.004.
- 918 Philippart, C., Baptist, M.J., Bastmeijer, C.J., Bregnballe, T., Buschbaum, C.,
 919 Hoekstra, P., Laursen, K., van Leeuwen, S.M., 2024. Cwss: Climate change, in:
 920 Kloepper, S., Baptist, M.J., Bostelmann A., Busch J.A., Buschbaum C., Gutow
 921 L., Janssen G., Jensen K. (Eds.), *Wadden Sea Quality Status Report*. Common
 922 Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany, pp. 1–44.
- 923 Prüter, I., Spröer, F., Keimer, K., Lojek, O., Windt, C., Schürenkamp, D., Bihs, H.,
 924 Nistor, I., Goseberg, N., 2025a. A comprehensive numerical study on the current-
 925 induced fluid–structure interaction of flexible submerged vegetation. *Journal of*
 926 *Fluids and Structures* 133, 104232. doi:10.1016/j.jfluidstructs.2024.104232.
- 927 Prüter, I., Spröer, F., Lojek, O., Windt, C., Schürenkamp, D., Nistor, I., Gose-
 928 berg, N., 2025b. Vegetation stem dynamics under wave loading: Insights
 929 from a coupled fluid–structure model. *Applied Ocean Research* 159, 104597.
 930 doi:10.1016/j.apor.2025.104597.
- 931 Puijalon, S., Bouma, T.J., Douady, C.J., van Groenendael, J., Anten, N.P.R.,
 932 Martel, E., Bornette, G., 2011. Plant resistance to mechanical stress: evidence

- 933 of an avoidance-tolerance trade-off. *The New phytologist* 191 (4), 1141–1149.
934 doi:10.1111/j.1469-8137.2011.03763.x.
- 935 Reents, S., Möller, I., Evans, B.R., Schoutens, K., Jensen, K., Paul, M., Bouma,
936 T.J., Temmerman, S., Lustig, J., Kudella, M., Nolte, S., 2022. Species-specific
937 and seasonal differences in the resistance of salt-marsh vegetation to wave impact.
938 *Frontiers in Marine Science* 9. doi:10.3389/fmars.2022.898080.
- 939 Riffe, K.C., Henderson, S.M., Mullarney, J.C., 2011. Wave dissipation by flexible
940 vegetation. *Geophysical Research Letters* 38. doi:10.1029/2011GL048773.
- 941 Roland, R.M., Douglass, S.L., 2005. Estimating wave tolerance of *spartina alterni-*
942 *flora* in coastal alabama. *Journal of Coastal Research* 213, 453–463. doi:10.2112/03-
943 0079.1.
- 944 Rupprecht, F., Möller, I., Evans, B., Spencer, T., Jensen, K., 2015. Biophysical prop-
945 erties of salt marsh canopies — quantifying plant stem flexibility and above ground
946 biomass. *Coastal Engineering* 100, 48–57. doi:10.1016/j.coastaleng.2015.03.009.
- 947 Rupprecht, F., Möller, I., Paul, M., Kudella, M., Spencer, T., van Wesenbeeck, K.,
948 B., Wolters, G., Jensen, K., Bouma, T., Miranda-Lange, M., Schimmels, S., 2017.
949 Vegetation-wave interactions in salt marshes under storm surge conditions. *Ecol.*
950 *Eng.* 100, 301–315. doi:10.1016/j .ecoleng.2016.12.030.
- 951 Savard, J.P., van Proosdij, D., O’Carroll, S., 2016. Perspectives on canada’s east
952 coast region, in: D.S. Lemmen, F.J. Warren, T.S. James, C.S.L. Mercer Clarke
953 (Eds.), *Canada’s Marine Coasts in a Changing Climate*. Government of Canada,
954 Ottawa, ON, pp. 99–152.

- 955 Schoutens, K., Heuner, M., Fuchs, E., Minden, V., Schulte-Ostermann, T., Bel-
 956 liard, J.P., Bouma, T.J., Temmerman, S., 2020. Nature-based shoreline protec-
 957 tion by tidal marsh plants depends on trade-offs between avoidance and attenu-
 958 ation of hydrodynamic forces. *Estuarine, Coastal and Shelf Science* 236, 106645.
 959 doi:10.1016/j.ecss.2020.106645.
- 960 Schulze, D., Rupprecht, F., Nolte, S., Jensen, K., 2019. Seasonal and spatial within-
 961 marsh differences of biophysical plant properties: implications for wave attenuation
 962 capacity of salt marshes. *Aquat Sci* 81 (4). doi:10.1007/s00027-019-0660-1.
- 963 Shao, D., Zhou, W., Bouma, T.J., Asaeda, T., Wang, Z.B., Liu, X., Sun, T.,
 964 Cui, B., 2020. Physiological and biochemical responses of the salt-marsh plant
 965 *spartina alterniflora* to long-term wave exposure. *Annals of botany* 125, 291–300.
 966 doi:10.1093/aob/mcz067.
- 967 Silinski, A., Schoutens, K., Puijalon, S., Schoelynck, J., Luyckx, D., Troch, P., Meire,
 968 P., Temmerman, S., 2018. Coping with waves: Plasticity in tidal marsh plants as
 969 self-adapting coastal ecosystem engineers. *Limnology and Oceanography* 63, 799–
 970 815. doi:10.1002/lno.10671.
- 971 Smith, C.S., Puckett, B., Gittman, R.K., Peterson, C.H., 2018. Living shorelines
 972 enhanced the resilience of saltmarshes to hurricane matthew (2016). *Ecologi-
 973 cal applications: a publication of the Ecological Society of America* 28, 871–877.
 974 doi:10.1002/eap.1722.
- 975 Steinigeweg, C.S., Siebeneicher, O.J., Schröder, B., Kleyer, M., Löhmus, K.,
 976 Löbel, S., 2025. Elevational ranges of pioneer marsh species are site spe-
 977 cific and likely shaped by different abiotic and biotic factors. *Ecosphere* 16.
 978 doi:10.1002/ecs2.70148.

- 979 Stempel, R., Bostelmann, A., Busch, J., Klöpper, S., 2017. Cwss: Introduction, in:
980 Kloepper, S., Baptist, M.J., Bostelmann A., Busch J.A., Buschbaum C., Gutow
981 L., Janssen G., Jensen K. (Eds.), Wadden Sea Quality Status Report. Common
982 Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany, pp. 1–17.
- 983 Tempest, J.A., Möller, I., Spencer, T., 2015. A review of plant–flow interactions
984 on salt marshes: the importance of vegetation structure and plant mechanical
985 characteristics. *WIREs Water* 2, 669–681. doi:10.1002/wat2.1103.
- 986 Thomsen, A.S., Krause, J., Appiano, M., Tanner, K.E., Endris, C., Haskins, J.,
987 Watson, E., Woolfolk, A., Fountain, M.C., Wasson, K., 2022. Monitoring vegeta-
988 tion dynamics at a tidal marsh restoration site: Integrating field methods, remote
989 sensing and modeling. *Estuaries and Coasts* 45, 523–538. doi:10.1007/s12237-021-
990 00977-4.
- 991 Twomey, A.J., O’Brien, K.R., Callaghan, D.P., Saunders, M.I., 2020. Synthesising
992 wave attenuation for seagrass: Drag coefficient as a unifying indicator. *Marine*
993 *Pollution Bulletin* 160, 111661. doi:10.1016/j.marpolbul.2020.111661.
- 994 van Veelen, T.J., Fairchild, T.P., Reeve, D.E., Karunarathna, H., 2020. Experimental
995 study on vegetation flexibility as control parameter for wave damping and velocity
996 structure. *Coastal Engineering* 157. doi:10.1016/j.coastaleng.2020.103648.
- 997 Vuik, V., Borsje, B.W., Willemsen, P.W., Jonkman, S.N., 2019. Salt marshes for
998 flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. *Ocean*
999 *& Coastal Management* 171, 96–110. doi:10.1016/j.ocecoaman.2019.01.010.
- 1000 Vuik, V., Jonkman, S.N., Borsje, B.W., Suzuki, T., 2016. Nature-based flood pro-

- tection: The efficiency of vegetated foreshores for reducing wave loads on coastal
dikes. *Coastal Engineering* 116, 42–56. doi:10.1016/j.coastaleng.2016.06.001.
- Vuik, V., Suh Heo, H.Y., Zhu, Z., Borsje, B.W., Jonkman, S.N., 2017. Stem breakage
of salt marsh vegetation under wave forcing: A field and model study. *Estuarine,
Coastal and Shelf Science* 200, 41–58. doi:10.1016/j.ecss.2017.09.028.
- Wang, L., Xu, M., Zhang, C., Dai, W., 2023. Numerical investigation on solitary
waves traveling over rigid vegetation by a 3d-mps method. *Applied Ocean Research*
132, 103476. doi:10.1016/j.apor.2023.103476.
- Windt, C., Davidson, J., Ringwood, J., 2021. Investigation of turbulence
modeling for point-absorber type wave energy converters. *Energies* 14 (26).
doi:https://dx.doi.org/10.3390/en14010026.
- Yang, W., Choi, S.U., 2009. Impact of stem flexibility on mean flow and turbulence
structure in depth-limited open channel flows with submerged vegetation. *Journal
of Hydraulic Research* 47, 445–454. doi:10.1080/00221686.2009.9522020.
- Zhang, X., Lin, P., Nepf, H., 2022. A wave damping model for flexible marsh plants
with leaves considering linear to weakly nonlinear wave conditions. *Coastal Engi-
neering* 175. doi:10.1016/j.coastaleng.2022.104124.
- Zhang, X., Nepf, H., 2021. Wave-induced reconfiguration of and drag
on marsh plants. *Journal of Fluids and Structures* 100, 103192.
doi:10.1016/j.jfluidstructs.2020.103192.
- Zhi, Y., Li, H., An, S., Zhao, L., Zhou, C., Deng, Z., 2007. Inter-specific competi-
tion: *Spartina alterniflora* is replacing *spartina anglica* in coastal china. *Estuarine,
Coastal and Shelf Science* 74, 437–448. doi:10.1016/j.ecss.2007.04.026.

- 1024 Zhu, L., Chen, Q., Ding, Y., Jafari, N., Wang, H., Johnson, B.D., 2023. Towards
1025 a unified drag coefficient formula for quantifying wave energy reduction by salt
1026 marshes. *Coastal Engineering* 180, 104256. doi:10.1016/j.coastaleng.2022.104256.
- 1027 Zhu, L., Zou, Q., Huguenard, K., Fredriksson, D.W., 2020a. Mechanisms for the
1028 asymmetric motion of submerged aquatic vegetation in waves: A consistent-mass
1029 cable model. *J. Geophys. Res. Oceans* 125. doi:10.1029/2019JC015517.
- 1030 Zhu, Z., Yang, Z., Bouma, T.J., 2020b. Biomechanical properties of marsh vegetation
1031 in space and time: effects of salinity, inundation and seasonality. *Annals of botany*
1032 125 (2), 277–290. doi:10.1093/aob/mcz063.
- 1033 Zielinski, O., Meier, D., Kleyer, M., Hillebrand, H., 2017. Continuous current ob-
1034 servations at BEFmate artificial islands in the back-barrier tidal flat, Spiekeroog,
1035 Germany, 2013-11 to 2015-10. doi:10.1594/PANGAEA.877265.
- 1036 Zielinski, O., Pieck, D., Schulz, J., Thölen, C., Wollschläger, J., Albinus, M.,
1037 Badewien, T.H., Braun, A., Engelen, B., Feenders, C., Fock, S., Lehnert,
1038 C., Löhmus, K., Lübben, A., Massmann, G., Meyerjürgens, J., Nicolai, H.,
1039 Pollmann, T., Schwalfenberg, K., Stone, J., Waska, H., Winkler, H., 2022.
1040 The Spiekeroog Coastal Observatory: A Scientific Infrastructure at the Land-
1041 Sea Transition Zone (Southern North Sea). *Frontiers in Marine Science* 8.
1042 doi:10.3389/fmars.2021.754905.
- 1043 Zijlstra, R., Hofstede, J., Piontkowitz, T., Thorenz, F., 2017. Cwss: Coastal
1044 risk management, in: Kloepper, S., Baptist, M.J., Bostelmann A., Busch J.A.,
1045 Buschbaum C., Gutow L., Janssen G., Jensen K. (Eds.), *Wadden Sea Quality Sta-*
1046 *tus Report*. Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany,
1047 pp. 1–14.