

Investigation of Liquid Containers and Their Supporting Structures Under Seismic Loading

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Abstract

Liquid Storage Tanks (LSTs) are essential infrastructure systems that are used in various municipal and industrial settings. They play a critical role in storing and transporting liquids such as drinking water, oil, and gas that are used in daily life. Failure of these structures due to their poor seismic performance can have devastating consequences including the release of the stored liquid and damage to the surrounding area with potentially irreversible environmental impacts. In addition, the damage caused to the tank structure can be extensive, resulting in significant financial losses. Furthermore, the disruption of services provided by the tank such as water supply, oil and gas storage can be considerable. It is therefore crucial to study the seismic behaviour of these structures and ensure their safety and reliability to minimize the potential damages.

The aim of this study is to investigate the behavior of LSTs in terms of the contained liquid, the tank's structure, and its supports when subjected to seismic excitations. To obtain accurate results, different numerical techniques are applied in different phases of the study, including the Finite Volume Method (FVM), Finite Elements Method (FEM), Volume of Fluids (VoF) method, and Smoothed Particles Hydrodynamic (SPH) method. These techniques allow for a detailed analysis of the behavior of the tank and its supports during seismic excitation, providing a comprehensive understanding of the performance of LSTs during earthquakes.

In order to examine the reliability and accuracy of the numerical model, the first part of the study includes the validation of the developed numerical model through comparison of the model and experimental results. The validated numerical model is then used to obtain the hydrodynamic pressures at different locations on the roof of tanks subjected to base excitations. The effect of liquid impact and hydrodynamic pressures on the roof of LSTs can be significant, however, limited studies have been completed on this issue.

In the second part of the study, Artificial Intelligence (AI) techniques such as Genetic Programming are used to formulate these pressure values so that the maximum pressure can be obtained using the tank characteristics such as size and fill depth by the relationship obtained based on the AI approach.

In the third part of the study, the supporting structures of LSTs subjected to base excitations are analyzed, and their shear forces are extracted and compared with the National Building Code of Canada (NBC 2020) in order to evaluate the reliability of the code and discuss possible improvements.

The results of this study can be used to evaluate and make improvements in standards and guidelines for the seismic design of LSTs, which can help ensure the safety and reliability of these crucial infrastructures during seismic events.

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Notations

$(C_s)_c$: convective base shear coefficient

$(C_s)_i$: impulsive base shear coefficient

A_r : element or component force amplification factor

A_x : height factor

$C_h(T, 1)$: basic seismic hazard coefficient

C_p : element or component factor

$C_f(\mu, \zeta)$: correction factor

F_a : site coefficient

F_t : sum of the traction forces at the top

I_E : importance Factor

L_u : limit state factor

M_c : mass of the convective (sloshing) mode

$P_{(ij)}$: calculated value for j^{th} data based on i^{th} function

R_p : element or component response modification factor

R_{wi} : response modification factor

S_1 : mapped maximum considered earthquake spectral response acceleration at a period of 1s

S_{DS} : design spectrum response coefficient

S_{DI} : design spectrum response coefficient

S_p : horizontal force factor for part or portion of a building and its anchorage

S_P : performance factor

$S_a(0.2)$: spectral response acceleration value at $T=0.2s$

S_d : design spectrum

$S_e(T_{con})$: convective spectral acceleration

$S_e(T_{imp})$: impulsive spectral acceleration

S_e : elastic spectrum

S_t : displacement at the top

$\bar{T}$: average of the T_j values

T_B : period at which constant-acceleration range begins
 T_C : period at which constant-velocity range begins
 T_L : transition period for long-period range
 T_c : natural period of convective mode
 T_{con} : convective period
 T_i : natural period of impulsive mode
 T_{imp} : impulsive period
 T_j : value for the j^{th} data
 U_n : normal velocity
 U_τ : tangential velocity of the flow
 V_P : shear force of non-structural components of a building structure
 W_P : weight of non-structural components of a building structure
 f_i : fit function
 k_c : stiffness of the springs in a spring-mass equilibrium
 m_c : convective mass
 m_i : impulsive mass
 m_r : mass of the tank roof
 m_w : mass of the tank wall
 γ_I : importance factor
 A : displacement amplitude
 h : equivalent uniform thickness of the tank wall
 h : height of the liquid inside the tank
 $U(t)$: displacement
 ω : excitation frequency
 $Const$: constant bias term
 D : circular tank diameter
 E : modulus of elasticity of the tank material
 H : tank height

I : importance factor
 L : tank length
 M : mass of the liquid inside the tank
 R : response modification factor
 S : soil factor
 T : natural period
 V : shear force
 W : tank width
 Z : zone factor
 g : gravitational acceleration
 k : structural stiffness
 l : half the tank length of the tank
 m : empty tank mass
 n : normal vector of the boundary
 p : total pressure
 q : behaviour factor
 r : risk factor
 rad : circular tank radius
 t : time
 u : velocity in the x direction
 v : velocity in the y direction
 w : velocity in the z direction
 α : peak ground acceleration factor
 β : control volume fill indicator
 ε : gene weight (1)
 ζ : damping factor
 ζ : viscous damping ratio
 η : damping factor

μ : ductility factor

ρ : density

σ : gene weight (2)

List of Abbreviations

2D: 2-Dimensional

3D: 3-Dimensional

ACI: American Concrete Institute

AI: Artificial Intelligence

ANFIS: Adaptive Neuro-Fuzzy Inference System

ANN: Artificial Neural Networks

ASCE: American Society of Civil Engineers

ASD: Allowable Stress Design

CFD: Computational Fluid Dynamics

CSA: Canadian Standards Association

EPR: Evolutionary Polynomial Regression

FDM: Finite Difference Method

FE: Finite Elements

FEM: Finite Element Method

FSIAP: Fluid-Structure Interaction Analysis Program

FVM: Finite Volume Method

GEP: Gene Expression Programming

GMDH: Group Method of Data Handling

GP: Genetic Programming

GPTIPS: Genetic Programming Toolbox for the Identification of Physical Systems

HD: High Definition

LSTs: Liquid Storage Tanks

MGGP: Multi-gene Genetic Programming

MITC4: 4-Node Mixed Interpolation Tensorial Component

MPS: Moving Particle Semi-implicit

MT: Model Tree

NBC: National Building Code of Canada

NEWTANK: Numerical Wave Tank
NZSEE: New Zealand Society of Earthquake Engineering
OpenFOAM: Open-source Field, Operation and Manipulation
PFA: Peak Floor Acceleration
PGA: Peak Ground Acceleration
PISO: Pressure Implicit with Splitting of Operator
PLIC: Piecewise Linear Interface Construction
PSC: Pre-Stressed Concrete
RANS: Reynolds-Averaged Navier-Stokes
RC: Reinforced Concrete
RMSE: Root Mean Square Error
RRSE: Root Relative Squared Error
SD: Strength Design
SIMPLE: Semi-Implicit Method for Pressure-Linked Equations
SLIC: Simple Linear Construction
SPH: Smoothed Particles Hydrodynamic
SRSS: Square-Root-Sum-of-the-Squares
SVM: Support Vector Machine
VoF: Volume of Fluid

1. Introduction

1.1. Background

Liquid Storage Tanks (LSTs) play a critical role in many different industries and are essential in maintaining the safety and well-being of communities. LSTs have a range of applications including municipalities where they are used to store drinking water (Figure 1), energy sector to store liquids such as oil and petroleum (Figure 2), as well as nuclear facilities (Figure 3), agriculture and food industry to store liquids such as pesticides, fertilizers and irrigation water, and fire protection. LSTs come in a wide variety of sizes and shapes such as cylindrical, rectangular, or any other unique shapes (Figure 4). Additionally, LSTs can be made from a variety of different materials such as steel, concrete, plastic, fiberglass, etc. The choice of material depends on the specific requirements of their intended use, such as the type of liquid to be stored, the temperature and pressure of the liquid, and the environment in which the tank will be located. Factors such as cost, durability, and ease of maintenance also play a role in determining the material used for LSTs.



Figure 1: Municipal drinking water tank (Source: <https://www.tankconnection.com/ask-the-expert/elevated-water-tanks>)



Figure 2: Oil tanks in a refinery (Source: <https://www.honiron.com/oil-gas-storage-tank-applications-design-features/>)



Figure 3: Tanks in a nuclear facility (Source: <https://www.reuters.com/markets/commodities/ice-wall-japans-fukushima-nuclear-plant-may-have-partially-melted-nhk-2021-11-26/>)

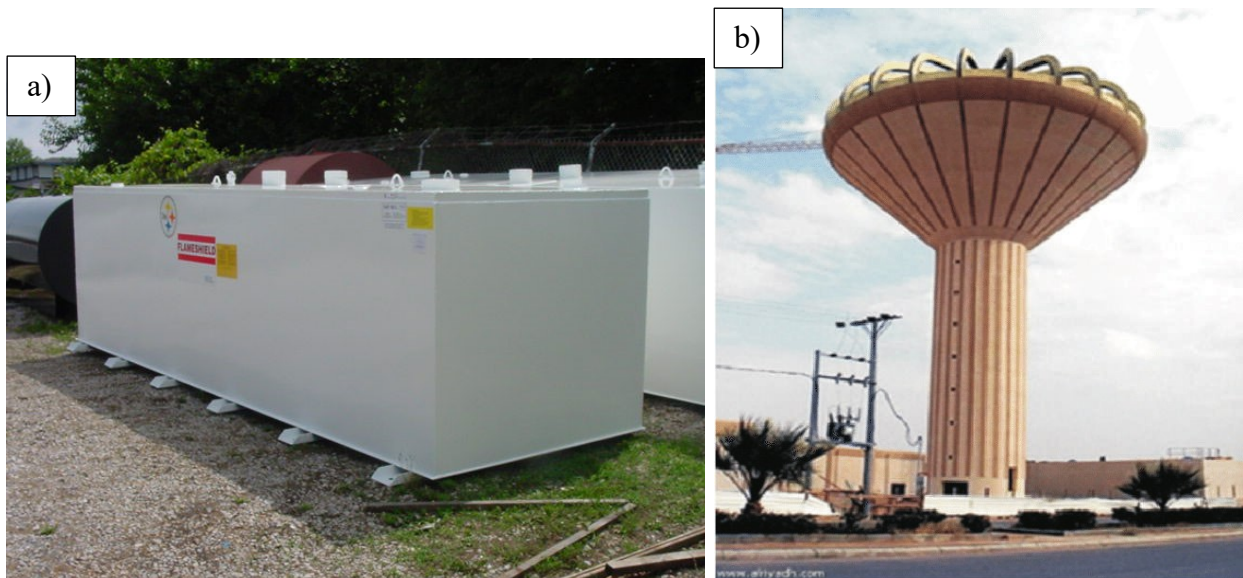


Figure 4: Tanks with different shapes; a) rectangular, b) conical (Source: <https://www.southerntank.net/rectangular-tanks/>, https://www.researchgate.net/figure/Reinforced-Concrete-Pure-Conical-Tank-in-Saudi-Arabia-in-Al-Riyadh-News-Paper-1_fig1_322569288)

With an annual average of 200 earthquakes with a magnitude of greater than 6 Richter around the world [1] (Figure 5), and over 4000 earthquakes Canada-wide each year, having proper guidelines and appropriate design recommendations and standards for such structures is important.

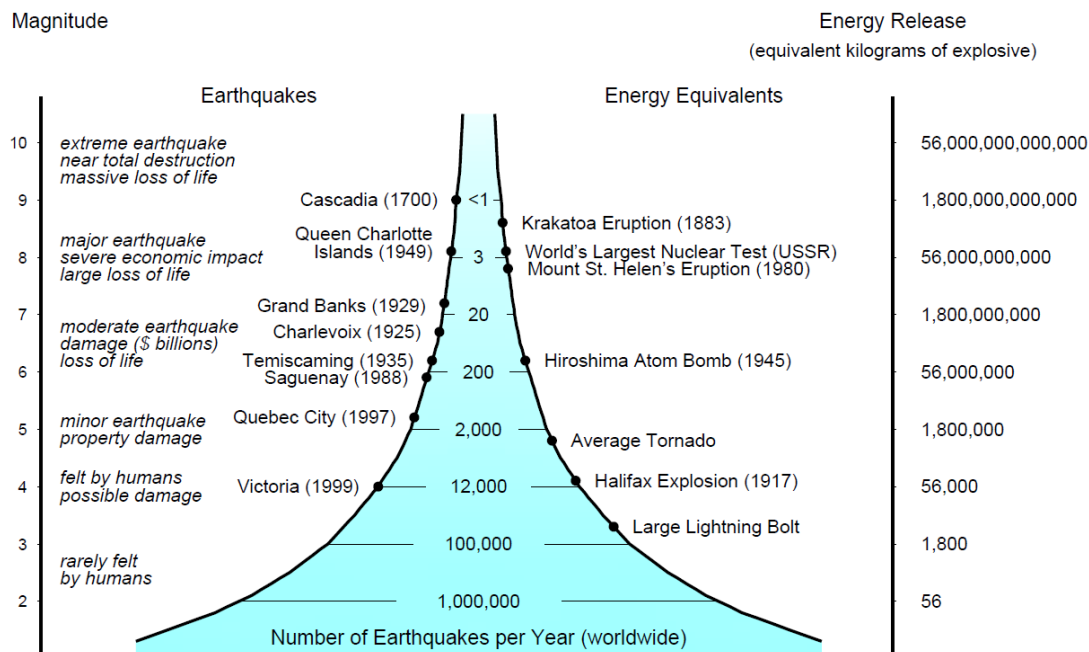


Figure 5: Global frequency of earthquakes (Source: <http://www.earthquakescanada.nrcan.gc.ca/info-gen/magfreq-en.php>)

Poor seismic performance of LSTs has led to major economic losses, structural damages, and environmental problems. Some examples include uncontrollable fires in petroleum tanks during the 1964 Niigata earthquake [2] (Figure 6) and 2011 Tokohu earthquake [3] (Figure 7) in Japan, major damage to water reservoirs during the 1960 Chilean earthquake [4] (Figure 8), and the structural failure of tanks due to the 1992 Landers earthquake [5] in California (Figure 9). Sloshing of the liquid inside a container and spillage into the surrounding environment can cause irreversible damages such as soil contamination. In addition, keeping LSTs during and after an earthquake is crucial given their post-disaster role for supplying drinking water to the people suffering from the earthquake as well as providing fire extinguishing resources.

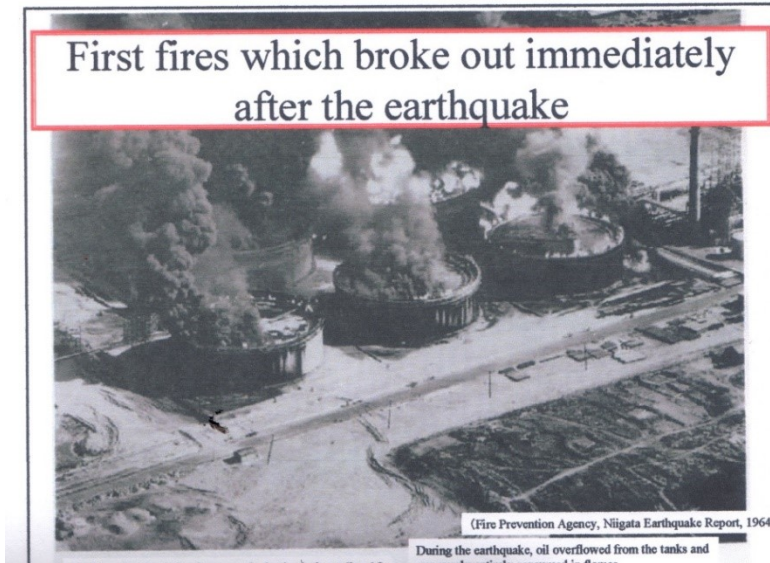


Figure 6: Fire in petroleum tanks following the 1964 Niigata earthquake (Source: <https://burnabytankfarm.com/efi-earthquake-sloshing-failures/>)



Figure 7: Fire in petroleum tanks following the 2011 Tohoku earthquake (Source: <https://ehp.niehs.nih.gov/doi/10.1289/ehp.119-a290>)

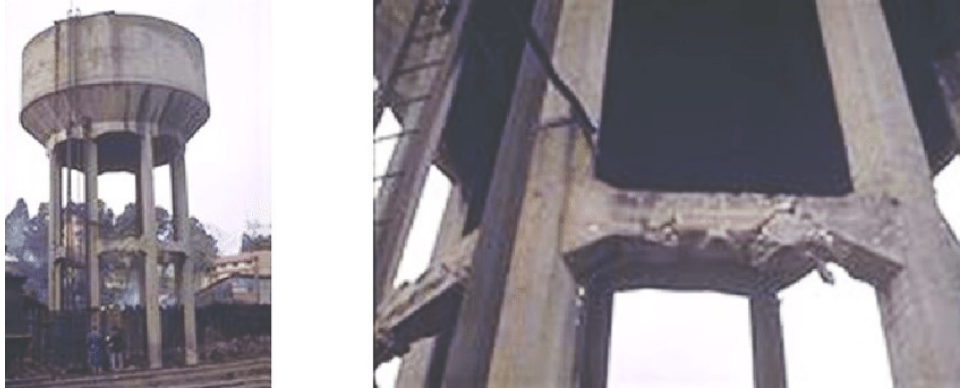


Figure 8: Damage caused to a tank by the 1960 Chilean earthquake (Source: https://www.researchgate.net/figure/Elevated-water-tank-of-Puetro-Varas-Hotel-May-22-nd-1960-Chile-earthquake-PEER_fig1_251717128)



Figure 9: Tank structure damage by the sloshing liquid following the 2010 Landers Earthquake (Source: http://www.johnmartin.com/earthquakes/eqshow/lan_0004.htm)

The damage caused by an earthquake can affect the tank structure (e.g., the walls and roof of a ground-supported tank – Figure 10) or its supporting structure (e.g., the shaft of an elevated tank – figure 11); therefore, appropriate design codes and guidelines are crucial. Models that can reasonably predict the behaviour of an LST and its supporting structures subjected to seismic loading are also useful.



Figure 10: Damage to the tank structure following an earthquake (Source: https://www.researchgate.net/figure/Sloshing-damage-to-upper-shell-of-tank_fig1_336170376)



Figure 11: Failure of the reinforced concrete support of a water tank following the 1980 El-Asnam earthquake, Algeria (Source: Soroushnia et al., 2011 [6])

The use of Artificial Intelligence (AI) in engineering is becoming increasingly prevalent in various fields, including design optimization, autonomous systems, and simulation and modeling [7]. AI methods such as Artificial Neural Networks (ANN – Figure 12), Genetic Programming (GP –

Figure 13) and Group Method of Data Handling (GMDH – Figure 14) can be implemented for prediction and data optimization, resulting in high-quality data and more accurate predictions.

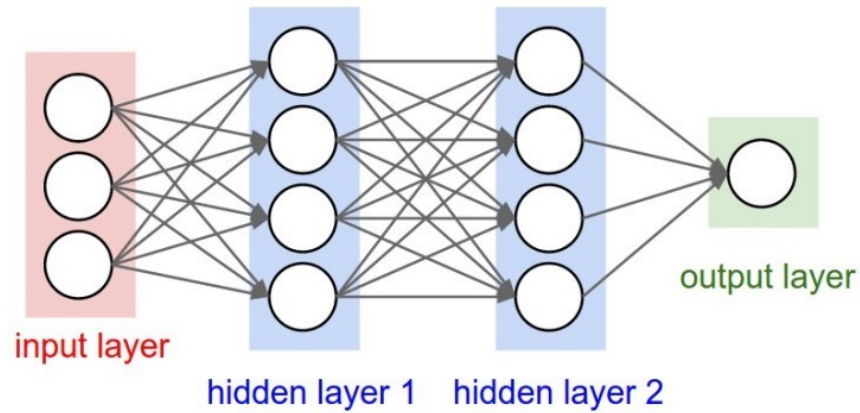


Figure 12: Artificial Neural Network (Source: <https://www.digitaltrends.com/computing/what-is-an-artificial-neural-network/>)

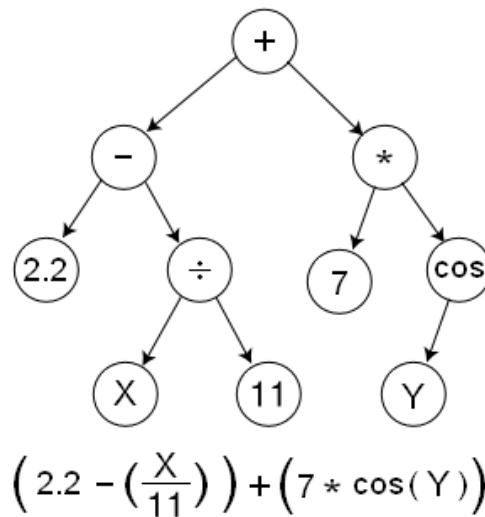


Figure 13: Genetic Programming (Source: https://en.wikipedia.org/wiki/Genetic_programming)

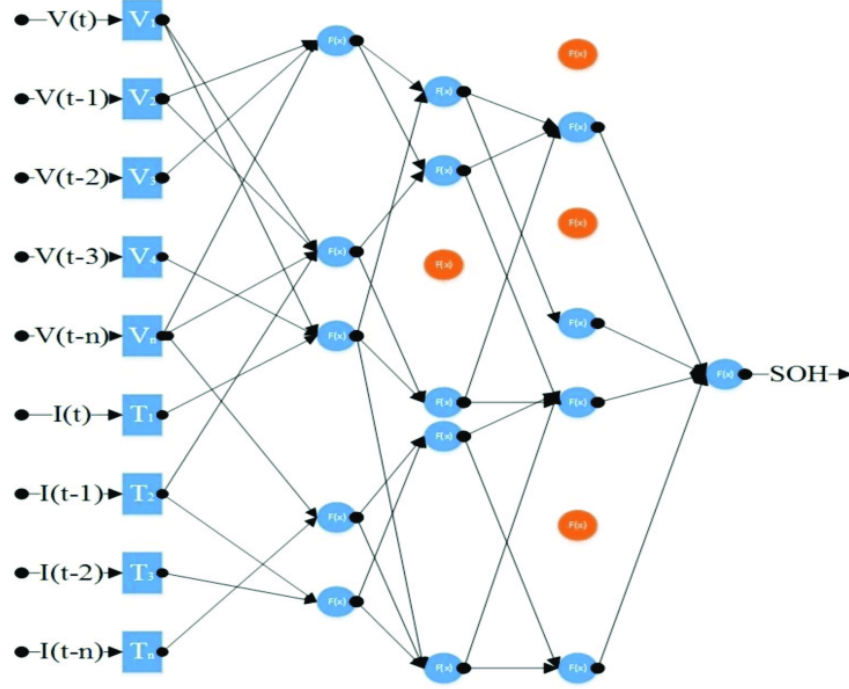


Figure 14: Group Method of Data Handling (Source: https://www.researchgate.net/figure/Group-method-of-data-handling-GMDH-structure_fig2_326827493)

This study is comprised of three major parts. For the first part of the study, the Open-source Field, Operation, and Manipulation (OpenFOAM) software [8] is used. It is a free, open-source computational fluid dynamics (CFD) software used to model and simulate fluid flow, heat transfer, and other physical processes. It provides a platform for numerical analysis and simulation of complex engineering problems, including fluid flow, heat transfer, combustion, and multiphase flow. OpenFOAM offers a range of solvers and tools to perform simulations, as well as a user-friendly interface and scripting capabilities to automate simulations. The software is widely used in a variety of industries, including aerospace, automotive, chemical, civil, and mechanical engineering [9].

In this part of the study, numerical simulations are conducted using the OpenFOAM application and the results are analyzed against experiments to validate a model based on Finite Volume Method (FVM) and the Volume of Fluid (VOF) method. To do so, various base excitations are applied to partially-filled LSTs. To capture the effects of multi-lateral excitation on them, the tanks are placed on different orientations and the results are compared with experiments of the same characteristics.

Once the model is validated visually and quantitatively, more simulations are run on different tank sizes and using various types of base excitations to generate data for the second part of the study. In this part, maximum pressures at the roof of the tank subjected to base excitation are measured. Using Artificial Intelligence (AI) techniques such as Genetic Programming (GP) and Multi-Gene Genetic Programming (MGGP), a series of formulae are generated for the prediction of those pressures which can be helpful in their design processes.

In the third part of the study, ABAQUS [10] which is a Finite Element Analysis (FEA) software is used to generate data on the effect of sloshing on supporting structures of ground-supported or roof-top tanks using a combined Finite Elements Method (FEM) and Smoothed Particles Hydrodynamic (SPH). ABAQUS can be used to simulate various engineering problems, including mechanics of materials, fluids, heat transfer, and electro-magnetics. It provides a robust environment for developing and solving FEA models, and can handle a wide range of applications, from simple linear models to highly nonlinear and complex models. ABAQUS also offers advanced capabilities such as material modeling, dynamic and multi-physics analysis, and post-processing tools to visualize and analyze results. Different types of base excitations are applied to the tank. The excitations are tuned in a way that the maximum acceleration of the excitation is equal to the Peak Ground Acceleration (PGA) of two Canadian cities of Ottawa, Ontario and Vancouver, British Columbia based on the data provided by the National Building Code of Canada (NBC) 2020. The results of base shears obtained using FEA are compared with those based on the NBC 2020.

The results of this study can provide insights into predicting the impact of seismic loads on LSTs. Specifically, the study can help predict the following:

- Hydrodynamic pressures at the roof of LSTs
- Shear forces at the base

The results of the study can be used to improve the design of the supporting structures for the tanks, whether they are ground-supported or roof-top. This includes the base shear of the supporting structures, which is an important factor in ensuring the stability of the tank during an earthquake.

1.2. Research Questions

The present research endeavors to answer the following questions:

- 1- How does the behaviour of contained liquid (e.g., sloshing) in LSTs affect the tank structure?
- 2- What are the effects of hydrodynamic pressures and impact forces on the roof of LSTs during seismic events?
- 3- How can the behavior of LSTs and their supporting structures be modeled and simulated under base excitation?
- 4- How do design codes and standards perform in predicting the forces in the tank, its supporting structures, and sloshing heights in LSTs subjected to base excitations?
- 5- What role can AI techniques, such as Genetic Programming, play in predicting the hydrodynamic pressures in LSTs subjected to seismic excitations?
- 6- What are the limitations of the current design codes and standards for LSTs subjected to seismic excitations and what improvements can be made?

1.3. Research Process

The current study focuses on various aspects of seismic loading of LSTs including the sloshing forces and pressures on the walls and roof of these tanks, the base shear and shear stresses of steel liquid structures on steel supporting structures. Different numerical models are developed to find

the values of parameters that affect the response of these tanks. The process can be broken down into different tasks as follows:

1- Collect experimental data from the literature to use for validating the numerical model.

Using a uni-lateral shaking table that can demonstrate harmonic sinusoidal as well as earthquake motions, various base excitations were applied to partially-filled tanks. Tanks were placed on the shaking table in different orientations. The tests were videotaped using high-speed video cameras—one perpendicular to, and the other one in the direction of the motion—and the recordings were used for post-processing. For the post-processing, the videos were analyzed frame-by-frame and used to validate the numerical model both visually and quantitatively. In addition, data from the experimental study by Wu et al. (2013) [11] are used for validation of the numerical model.

2- Perform numerical modelling using the OpenFOAM.

The ultimate objective of numerical modelling is to generate simulated data in order to reproduce the experimental tests. The collected and generated data is first used for validating the numerical model and once validated, more simulations are conducted to find hydrodynamic pressures and forces on the walls and roof of tanks with different sizes and different fill depths.

3- Apply Artificial Intelligence to formulate prediction of the pressure at the roof.

In this section, the data generated in the previous step is subjected to AI methods to generate formulae that can help predict the maximum pressure at the roof of LSTs based on the size and fill depth.

4- Investigate the base shear obtained using ABAQUS and compare with the National Building Code of Canada (NBC).

The ABAQUS application is utilized to investigate the base shear of LSTs subjected to base excitation. A numerical model is developed and validated and used to find the base shear for individual supports. The results are compared with those obtained from the NBC to check if the code is conservative enough. If the code is found to underestimate or overestimate the base shear, the results can be used to make improvements to the code.

1.4.Limitations

The focus of this research project is limited to ground-supported LSTs with a rectangular shape, partially filled with water.

Given the limited effect of tank flexibility on the convective (i.e., sloshing) response of the liquid [12], OpenFOAM's limitation of considering solid walls for the tank rather than flexible does not affect the first two parts of the study. In addition, although the tank's model in OpenFOAM is completely rigid, this rigidity is offset by the rigidity of the tank used in the experiments. It is worth noting that this is improved in the third part of the study where the numerical modelling is done using ABAQUS where structural elements are flexible.

Another limitation of the study is that in the current study, the Peak Ground Acceleration (PGA) is the parameter of interest, and not the Peak Floor Acceleration (PFA), hence the accuracy of the results can be debated, however, studies have shown that the PFA is higher than PGA, therefore, the results of this study can be interpreted as the lower end of the spectrum. In other words, real-world data might show even higher discrepancy from the code. It is still worth noting that while future studies on the effects of using PFA instead of PGA is essential, finding actual PFA data requires additional information about the building on top of which the tank is located including the number of floors, the building height, etc. Although the current study does not fully address the issue of roof-top liquid storage tanks and their relationship with the building they are placed on, it is a step forward in reviewing how the code addresses such tanks subjected to base excitation.

It should also be noted that although Genetic Programming (GP) is an AI based model in which evolutionary algorithms are used to generate data and equation, there are more intelligent methods such as Artificial Neural Networks (ANN)[13], however, for this study GP models are more applicable as a model needs to be trained and a final equation obtained. On the other hand, ANN can provide self-correcting models with a broader application which is not in the scope of the current study.

Other limitations of the study that need to be considered are tank sizes and materials, assumption of linear elastic behaviour for the tank and its supporting structures and ignoring the effects of material non-linearity.

1.5. Novelty

To the best of the author's knowledge, no study with the combination of conducting experimental tests, developing CFD and AI models (Genetic Programming), and structural analysis on LSTs has been performed previously.

This project is the first of its kind to fully investigate the effect of seismic excitation on LSTs from both liquid and structural standpoints. Specifically, the effect of sloshing on hydrodynamic pressures at the roof and shear forces at the base, and the indirect interaction between the liquid and the supporting structures of LSTs are novel. In addition, this study combines the findings with artificial intelligence methods to obtain relationships between tank dimensions and the maximum hydrodynamic pressure it may undergo during a seismic event. Given the increased application of AI in engineering, the results of this study can pave the way for future researchers to develop simplified methods for the prediction of pressures and forces in LSTs. Finally, by comparing the results with the NBC, the results of this study can be used for future improvements in the code.

Using a combination of a CFD software (OpenFOAM) [8] and structural analysis software (ABAQUS) can improve the accuracy and broaden the scope of the work in a way that the two sections complement each other. With this combination, the limitations of each software can be overcome by using the other one. For example, the OpenFOAM does not consider the structure's flexibility, while ABAQUS is capable of modelling flexible structures.

1.6. Contributions

The following journal and conference papers have been published and/or presented on the subject of this thesis:

- 1- Bahreini Toussi, I.; Kianoush, R.; Mohammadian, A. Numerical and Experimental Investigation of Rectangular Liquid-Containing Structures under Seismic Excitation. *Infrastructures* 2021, 6, 1. <https://doi.org/10.3390/infrastructures6010001>).
- 2- Bahreini Toussi, I.; Mohammadian, A.; Kianoush, R.; Prediction of Maximum Pressure at the Roofs of Rectangular Water Tanks Subjected to Harmonic Base Excitation Using the Multi-Gene Genetic Programming Method. *Math. Comput. Appl.* 2021, 26, 6. (<https://doi.org/10.3390/mca26010006>).
- 3- Bahreini Toussi, I., Mohammadian, M., and Protic, R.; 2019. Numerical and Experimental Investigation of Rectangular Liquid Containing Structures under Seismic Excitation, Proceedings of 12th Canadian Conference on Earthquake Engineering, Quebec City, Quebec, June 2019.

The following research article is under review for submission to a peer-reviewed journal:

- Bahreini Toussi, I.; Mohammadian, A.; Shirkhani, H., Fazileh, F., Fathi-Fazl, G., Kianoush, R.; Investigation of effects of seismic excitation of liquid storage tanks on supporting structures – NBC requirements improvement.

1.7.Thesis structure

The thesis is organized as follows:

A thorough review of the available literature and design codes and standards proceeds the introduction section in chapter 2. Chapters 3, 4, and 5 will present the three components of the research, namely OpenFOAM, Artificial Intelligence, and ABAQUS numerical modelling, respectively. Summary and concluding remarks, as well as recommendations for future studies are provided in Chapter 6, and the references for the study are presented in the end.

2. Literature review

Introduction

The available literature on the effect of earthquakes and seismic loads on LSTs includes analytical studies, numerical modelling, laboratory experiments, or a combination of two or more of these methods. More recently, there have also been studies on the mitigation of the damages caused to the tanks by using internal baffles or base isolation mechanisms. The sloshing problem has been addressed by researchers since the 1950s (e.g., [14], [15], [16], etc.). Design codes and guidelines such as ACI 350.3 [17] (from the American Concrete Institute), ASCE 7 [18] (from the American Society of Civil Engineers), Eurocode 8 [19] (from the European Union), NZSEE [20] (from the New Zealand Society of Earthquake Engineering), etc. have been using different methods to address the base excitation of LSTs and their sloshing problem. These methods will be discussed in the following section.

The advancement of computing systems in recent years has led to wider application of Artificial Intelligence (AI) technics such as Genetic Programming (GP), Multi-gene Genetic Programming (MGGP), Model Tree (MT), etc. in engineering. These methods are applicable in generating formulations for prediction of a trend or in creating a regression function. The applicability of these methods for formulating the pressure at the roof of an LST subjected to base excitation will be reviewed and discussed in this chapter.

This chapter is organized as follows: first, a brief review of available design codes and guidelines is presented. Then various analytical, numerical, and experimental studies are discussed. Subsequently, damage mitigation methods are presented. Then Artificial Intelligence (AI) applications in engineering are discussed, and the chapter will be finished by concluding remarks.

Review of design codes and guidelines

Jaiswal et al. (2007) [21], studied the development of various institutional, national, and continental codes for the construction of LSTs and highlighted their differences and the methodology behind each code. It is worth noting that the hydrodynamic forces from the liquid to the walls and the base of a tank, and the serviceability of LSTs compared to buildings are the two main differences between the analysis of LSTs and buildings. Because of these differences, a tank may experience higher loads compared to a building with similar dynamic characteristics when subjected to the same base excitation. In comparison to buildings, and depending on the application, LSTs may also require higher importance factors due to their post-disaster role. Of the codes studied by Jaiswal et al. (2007) [21], some use the Strength Design (SD) level in which factored loads are applied, and the structure's strength is reduced by reduction factors while other codes use the Allowable Stress Design (ASD) level in which the loads are not increased, but the allowable stress is limited to the elastic state of the material, hence the structure does not undergo any deformation. A summary of the study by Jaiswal et al. (2007) [21] on design codes can be found in Table 1.

As mentioned earlier, lower ductility and redundancy can cause tanks to experience higher loads compared to a building with similar weight and stiffness, hence lower response modification factors must be applied. Besides, failure of LSTs can have higher consequences depending on the material inside the tank, so they also may require a higher importance factor.

To measure the effect of earthquake on the structure, each design code introduces a base shear coefficient which is a representation of the seismic forces applied to the structure based on the structure's weight. These coefficients for ASCE7 [18], Eurocode8 [19], NZSEE [20] and ACI350.3-20 [17] are presented as follows:

2.2.1. ASCE7

For impulsive mode:

$$(C_s)_i = \frac{S_{DS}I}{R} \text{ for } T_i \leq T_s$$

$$(C_s)_i = \frac{S_{DI}I}{R} \text{ for } T_s < T_i \leq T_L$$

$$(C_s)_i = \frac{S_{DI}IT_L}{RT_i^2} \text{ for } T_i > T_L$$

$$(C_s)_i \geq 0.5S_1$$

For convective mode:

$$(C_s)_c = \frac{S_{DI}I}{T_c} \leq S_{DS}I \text{ for } T_c \leq T_L$$

$$(C_s)_c = \frac{S_{DI}IT_L}{T_c^2} \text{ for } T_c > T_L$$

where I is the importance factor; R is response modification factor; T_i is the natural period of impulsive mode; T_c is the natural period of convective mode; S_{DS} and S_{DI} are the design spectra response coefficients; $T_s = S_{DI} / S_{DS}$; T_L is transition period for long-period range, and S_1 is the mapped maximum considered earthquake spectral response acceleration at a period of 1s.

Table 1: Summary of the review of codes by Jaiswal et al. (2007)

Code	Release Year	Ground Supported		Elevated		Seismic Force level
		RC or PSC	steel	On Shaft-Type Tower	On Frame-Type Tower	
ACI 350.3	2001	✓	✗	✓	✗	ASD
API 650	2005	✗	✓	✗	✗	ASD
ASCE 7	2005	✓	✓	✓	✓	SD
AWWA D-100	2005	✗	✓	✓	✓	ASD
AWWA D-110	1995	✓	✗	✗	✗	ASD
AWWA D-115	1995	✓	✗	✗	✗	ASD
Eurocode 8	1998	✓	✓	✓	✓	SD
IBC	2006	✓	✓	✓	✓	SD
NZSEE		✓	✓	✓	✓	SD

2.2.2. Eurocode8

For impulsive mode

$$(C_s)_i = IS_e \text{ or } \gamma_l S_d$$

For convective mode

$$(C_s)_c = IS_e$$

where S_e , S_d are elastic and design spectra respectively, and are calculated as follows:

$$\begin{aligned} S_e &= \alpha S \left[1 + \frac{T}{T_B(2.5\eta - 1)} \right] \text{ for } 0 \leq T < T_B \\ &= 2.5\alpha S \eta \text{ for } T_B \leq T < T_c \\ &= 2.5\alpha S \eta \left(\frac{T_c}{T} \right) \text{ for } T_c \leq T < 3 \\ &= 7.5\alpha S \eta \left(\frac{T_c}{T^2} \right) \text{ for } 3 \leq T \\ S_d &= \alpha S \left[1 + \frac{T}{T_B} \left(\frac{2.5}{q} - 1 \right) \right] \text{ for } 0 \leq T < T_B \\ &= 2.5\alpha \frac{S}{q} \text{ for } T_B \leq T < T_c \\ &= 2.5\alpha \frac{S}{q} \left(\frac{T_c}{T} \right)^{2/3} \geq 0.2\alpha \text{ for } T_c \leq T < 3 \\ &= 39\alpha \frac{S}{q} \left(\frac{T_c^{2/3}}{T^{5/3}} \right) \geq 0.2\alpha \text{ for } 3 \leq T \\ \eta &= \left(\frac{7}{2 + \zeta} \right)^{0.5} \end{aligned}$$

where α is peak ground acceleration factor; S is soil factor; η is damping factor; ζ is viscous damping ratio; q is behaviour factor; T is natural period; and T_B and T_c are periods at which constant-acceleration and constant-velocity range begin, respectively.

2.2.3. NZSEE

For both impulsive and convective modes:

$$(C_s)_i = C_h(T, 1) S_p r Z L_u C_f(\mu, \zeta)$$

where $C_h(T, 1)$ is basic seismic hazard coefficient; T is natural period; S_p is performance factor; r is the risk factor; Z is zone factor; L_u is limit state factor; and $C_f(\mu, \zeta)$ is the correction factor that depends on ductility factor, μ , and damping factor, ζ .

2.2.4. ACI350.3

For impulsive mode

$$(C_s)_i = \frac{2.75ZI}{R_{wi}} \text{ for } T_i \leq 0.31s$$
$$= \frac{1.25ZIS}{R_w T_i^{2/3}} < \frac{2.75ZI}{R_{wi}} \text{ for } T_i > 0.31s$$

For convective mode

$$(C_s)_c = \frac{1.875ZIS}{T_c^{2/3}} < 2.75ZI \text{ for } T_c < 2.4s$$
$$= \frac{6ZIS}{T_c^2} \text{ for } T_c \geq 2.4s$$

Where Z is zone factor, I is the importance factor, R_{wi} is the response modification factor, S represents soil factor, and T_i and T_c are natural periods of the impulsive and convective modes, respectively.

It is worth noting that ACI 350.3 combines the effect of horizontal and vertical accelerations using the Square-Root-Sum-of-the-Squares (SRSS) method and approximates the vertical acceleration by two-thirds of the horizontal response spectrum.

It can be seen that while these codes attempt at calculating the base shear coefficients for impulsive and convective modes, each code has a different approach in how to calculate them. For example, while the New Zealand code uses the same value for both impulsive and convective shear force coefficients, the ACI 350.3 code uses completely different formulations for them. This difference in approaches, which can be due to each code's general conservativeness, seismic force level, etc. limits the adoptability of a code in another jurisdiction. In other words, where there is no specific design code for LSTs subjected to base excitation, while taking advantage of a code from other parts of the world can be helpful in designing such structures, caution should be exercised.

Analytical Studies

There have been efforts to provide analytical solutions to find the seismic response of LSTs. Among them, Housner (1963) [15] which is an improved model of his earlier study (Housner 1957) [14] has been adopted—with modifications—by design codes such as ACI 350.3 [17] and ASCE7 [18] despite its shortcomings in some cases such as resonance conditions where non-linear waves are created inside the tank ([22], [23], [24]). This method divides the liquid into two masses of impulsive and convective, where the impulsive mass is rigidly connected to the tank walls and the convective mass is the sloshing part and is modelled as a mass-spring system (Figure 15). This method, despite being simple, can provide an accurate estimate of the natural period of the sloshing liquid.

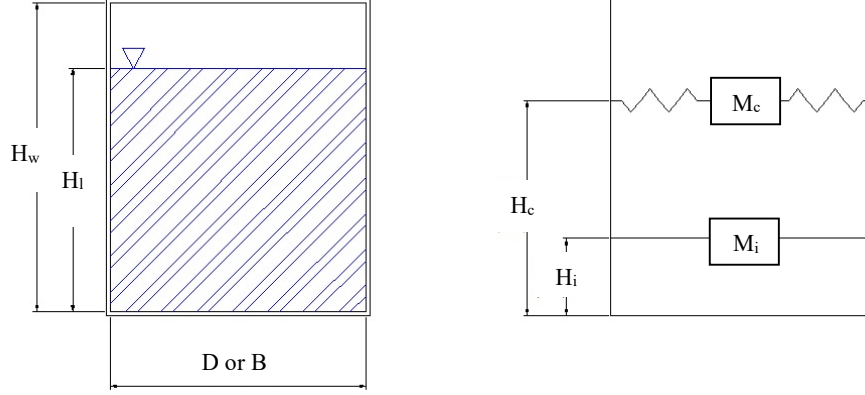


Figure 15: Schematic view of Housner's simplified model.

In a study by Veletsos (1974) [12], it was found that Housner's model [15] was applicable to tanks with rigid structures and the effect of tank flexibility has been neglected. It was found that flexibility does not affect the convective forces, and therefore, Housner's model is applicable for those forces. This was also supported by Ghaemmaghami and Kianoush (2010) [22] who found that flexibility of the tank structure does not affect the sloshing part; hence, Housner's model is applicable.

Haroun (1983) [16] investigated the effect of base excitation on LSTs using theoretical analysis and experimental tests in an effort to develop design standards. An analytical solution was proposed based on the anchorage of the tank to the base which can affect the tank behaviour. It was found that modal analysis is sufficient for anchored tanks but for the unanchored ones, non-linear analysis was found to be necessary.

Sivý and Musil (2017) [25] investigated the seismic response of LSTs and proposed a procedure for the design of such structures. Using the impulsive/convective masses, the base shear can be calculated as follows:

$$V = (m_i + m_w + m_r)S_e(T_{imp}) + m_c S_e(T_{con})$$

where m_w and m_r are the wall and the roof masses, and $S_e(T_{imp})$ and $S_e(T_{con})$ are spectral accelerations, obtained from the elastic response spectrum, respectively.

Malhotra et al. (2000) [26] proposed a simple procedure for seismic analysis and design of circular, cylindrical LSTs. Given that the first impulsive and convective modes account for 85-98% of the total liquid mass, only the first modes were considered in their study. They based their procedure on the studies by Veletsos and Yang (1977) [27], Veletsos (1984) [28], Veletsos et al. (1990) [29] with modifications. In this model, only the first modes of impulsive and convective masses were considered, but their heights were adjusted to make up for the higher modes. T_{imp} and T_{con} were measured as follows:

$$T_{imp} = C_i \frac{H\sqrt{\rho}}{\sqrt{h/rad \times \sqrt{E}}} \quad (2)$$

$$T_{con} = C_c \sqrt{rad} \quad (3)$$

where h is the equivalent uniform thickness of the tank wall, ρ the density of the liquid, rad is the circular tank radius and E is the modulus of elasticity of the tank material. The coefficients C_i and C_c are obtained from Figure 16.

The results from this method were compared with detailed modal analysis and the calculated base shear from the proposed method was 2-10% higher than the modal analysis, hence conservative but close. However, more detailed studies are required for regions with high seismicity.

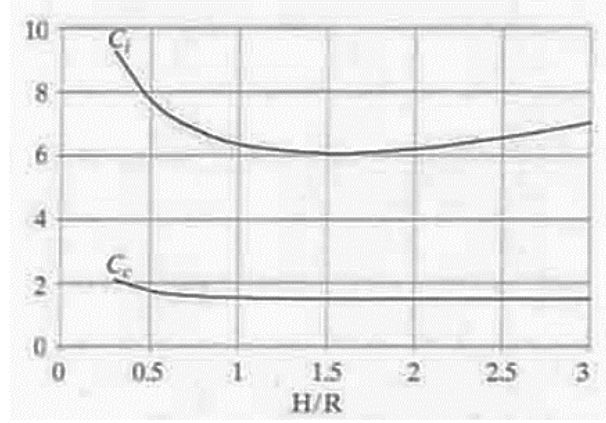


Figure 16: Impulsive and convective coefficients C_i and C_c

Kurihara et al. (1991) [30] investigated sloshing loads on the roof of cylindrical LSTs using small-, medium-, and large-scale models and proposed an empirical equation for estimating sloshing impact pressure as a function of freeboard, tank radius, liquid height, and sloshing frequency. They found that with small freeboards, the impact forces measured from experiments do not agree well with the proposed model, possibly as a result of the free surface not having enough space to form a complete wave before hitting the roof.

Malhotra (2005) [31] presented a simplified method for projecting base shear, overturning moment, wave height, and roof loads using spectral acceleration with damping ratios of 2% for steel and pre-stressed concrete and 5% for reinforced concrete for the impulsive response, and 0.5% for the convective response regardless of the tank material. A minimum freeboard based on the tank radius and spectral acceleration is found, and if the provided freeboard is less than that, the liquid hits the roof, hence causing hydrodynamic pressures at the roof which are distributed triangularly. The same concept was adopted by Malhotra (2015) [32] for tanks with cone and dome shape roofs which found that these types of roofs undergo significantly smaller loads compared to flat roofs. It was also concluded that hydrodynamic pressures on cone roofs are slightly larger than dome roofs.

Goudarzi et al. (2010) [33] conducted a series of experiments on a rectangular tank with plan dimensions of 900×460 mm and height of 1000 mm with various liquid heights and excitation frequencies and amplitudes and developed an analytical approach for finding the sloshing impact on the roof of tanks subjected to harmonic base excitations. Their proposed model can be used to

predict the maximum hydrostatic and maximum hydrodynamic impact forces separately. The two forces can then be combined using the SRSS method to find the maximum total force.

Isaacson (2010) [23] proposed an analytical method to predict hydrodynamic forces on the roof of rectangular LSTs subjected to base excitations. In this method, the tank is assumed roofless the liquid elevation is measured, then a roof is added to the tank and uplift forces are calculated. This formulation was based on consideration of impact and buoyancy force components. The impact force was estimated using the analogy with the case of flow past a flat plate. The maximum force was found to be dependent on either maximum impact or maximum buoyancy force; hence possible to calculate (Figure 17).

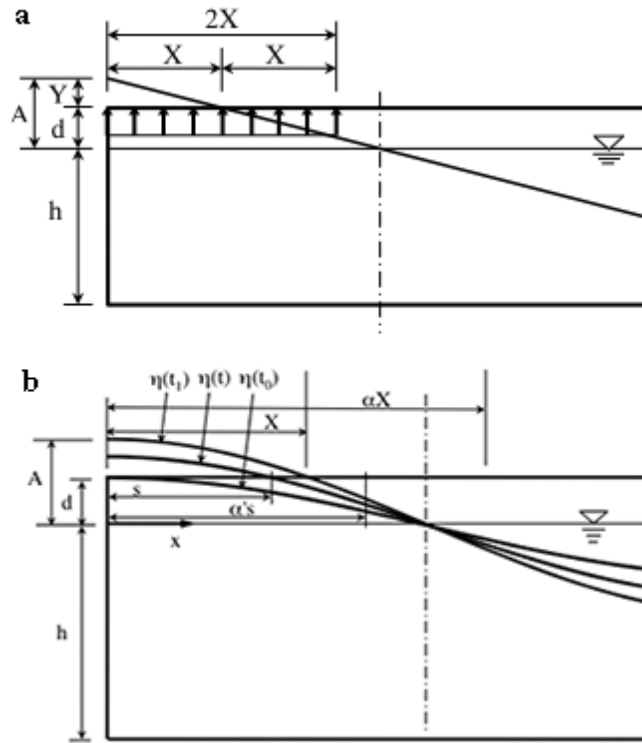


Figure 17: Definition sketch for the loading on the roof: a) San Francisco Public Utilities Commission (SFPUC 2003) formulation: b) proposed formulation by Isaacson (2010)

Numerical Studies

The development of computers in recent years has led to the increasing popularity of numerical simulations where the volume and structure are broken down into small volumes, elements, or particles and the related equations are solved on those small particles using initial and boundary conditions. Various numerical technics including Finite Element Method (FEM), Finite Volume Method (FVM-Figure 18), Finite Difference Method (FDM), Smoothed Particles Hydrodynamic (SPH) method, and some coupled methods have been used for the analysis of LSTs.

Koshizuka and Oka (1996) [34] introduced a Moving Particle Semi-Implicit (MPS) method for simulation of particles of incompressible fluids where the movement of each fluid particle is affected by its neighbouring particles. The method had a modified kernel function and used incompressible fluid as an input, hence numerical stability and computation speed were improved. The collapse of a water column was tested with this method and the results were compared with

experimental results. Generally, a good agreement was obtained, however, the model could still be improved e.g., by adding particle interaction models that can show surface tensions between different phases of a multiphase problem.

Sriram et al. (2006) [35] investigated a 2D model for rectangular tanks based on the finite element method applying excitations in both vertical and horizontal directions to explore the sway and heave modes in a ship motion. Both harmonic and random motions were studied. In the harmonic horizontal excitation, the critical sloshing motion occurred at the frequency equal to the first mode frequency of the tank (resonance), while in harmonic vertical excitation it was observed at the excitation frequency equal to twice the first mode frequency of the tank.

Mitra and Sinhamahapatra (2007) [36] studied the sloshing characteristics (e.g., displacement, frequencies, mode shapes) and the hydrodynamic pressure on the walls in rectangular liquid containers. In addition, the use of internal blocks as a wave mitigation technic was investigated. The model was defined by 4-noded quadrilateral elements and the Galerkin principle, and the results were compared with the existing analytical solutions. Due to the assumption of small amplitude waves, their analysis was limited to linear problems. The model could be used to find the pressure with a low computational cost. Besides, a computer code was developed to estimate the sloshing characteristics as well as the pressure on the walls. The estimation of sloshing height and wall displacement was found useful for the design of LSTs.

Cho and Cho (2007) [2] proposed a coupled method by combining the finite element method (for the structure) and the boundary element method (for the liquid at the boundary with the structure) for studying the seismic response of circular cylindrical tanks. A coupled dynamic system was formulated in the time domain that could find the response of the container under seismic excitation, taking the fluid-structure interaction and sloshing of the free surface into account. Equilibrium and compatibility conditions were applied at the boundary of the liquid and structure elements, so they were coupled. A numerical three-dimensional algorithm was also developed for the analysis of circular cylindrical steel tanks. Tall and shallow tanks with both flexible and rigid walls were tested and in general, flexible tanks were found to have a higher response regardless of their height. The results were compared with the ones from Haroun (1983) [16] method and the sloshing height found by this method was much greater than Haroun's, however, the base shear and overturning moment were in good agreement. It was suggested to consider more than one sloshing mode (as suggested by Haroun) so the sloshing height calculation could also be more accurate.

Lee et al. (2007) [37] adopted a coupled FEM to analyze the sloshing in fluid-shell structure interaction where the structure was modelled by 4-Node Mixed Interpolation Tensorial Component (MITC4) shell elements and the analysis of the fluid was done by the Moving Particle Semi-implicit (MPS) method. A semi-implicit time integration scheme and an explicit time integration scheme were proposed for the fluid, and the structure solvers, respectively. The study was done in a two-dimensional coordinate and the method was found helpful in solving problems related to sloshing.

Jaiswal et al. (2008) [38] studied the dynamic characteristics of non-uniform circular and rectangular liquid-containing tanks using both experimental tests and numerical modelling. In the numerical analysis, different tanks were modelled using the FEM. The ANSYS software was used and the sloshing characteristics (e.g., resonant frequency) of the LSTs were studied. The resonance frequency for regular shape tanks (circular, square, and rectangular) had a very good agreement with experimental tests and analytical results (i.e., Housner's model [15]). In irregular shapes of tanks (e.g., conical), the need for further studies was sought.

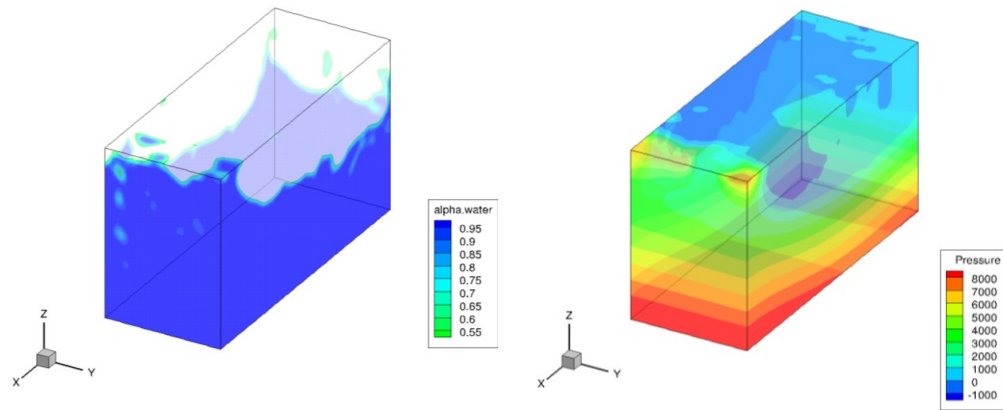


Figure 18- Finite Volume Method

In a study by Xiong and Xing (2008) [9], a finite element model based on air-water-tank interaction was developed using computer software called FSIAP (Fluid-Structure Interaction Analysis Program). Four different interactions including liquid-rigid tank, liquid-elastic tank, air-liquid-rigid tank and air-liquid-elastic tank were studied. Natural frequencies and mode shapes of each interaction type were investigated. Harmonic excitations and the El-Centro earthquake record were applied at the base. The study found that the presence of air (i.e., air-liquid-tank interactions) increased the natural frequency of the system and reduced the response amplitudes of sloshing and pressure. The effect of elasticity however was dependent on the tank's structural frequency. In a high-frequency tank, elasticity did not have a significant impact on the sloshing characteristics but in large tanks with lower frequencies, the effect of elasticity was found to be more crucial. The authors concluded entering pressurized air into sealed tanks could reduce the sloshing effects.

Liu and Lin (2008) [39] adopted the VOF method for investigation of a two-phase fluid model for solving the Navier-Stokes equations in an LST under arbitrary base excitation with six degrees of freedom and proposed a linear analytical model for prediction of the sloshing characteristics. The model, called NEWTANK (Numerical Wave Tank), was used for both viscous and inviscid liquid sloshing in rectangular tanks in 2D and 3D coordinates. The model was validated using data from previous analytical and experimental studies. The results for both 2D and 3D cases showed a good agreement for small-amplitude sloshing. As for larger amplitudes, while a good agreement was found between the model and experimental tests, there was a divergence between the NEWTANK model and analytical methods due to wave non-linearity. The study proved that the potential flow theory that had been widely used in the past could be inaccurate under resonance or close to resonance conditions due to the rotational and nonlinear effects of the sloshing.

Chen et al. (2009) [40] used the finite difference method to develop a numerical method to analyze the sloshing phenomenon in various types of liquid containers. The hydrodynamic pressures and loads at the walls of the tank were measured and a series of simulations were conducted to measure the free surface. The Reynolds-Averaged Navier-Stokes (RANS) equations were used to describe the liquid motion. Simulations were performed on a rectangular tank and two tanks with chamfers. Different fill depth and excitation frequencies were applied. The results showed a reasonable agreement with the experimental results of Kang and Lee (2005) [41] in terms of impulsive and convective pressures, however, further studies for verification of the model were deemed necessary.

Ghaemmaghami and Kianoush (2010) [22] studied two different 3D finite element models for rectangular and cylindrical liquid containers with liquid damping and measured the impulsive and convective responses separately. Various parameters such as the effect of vertical acceleration combined with the horizontal one, the effect of geometry on sloshing characteristics, and wall flexibility were investigated. The results of the study showed that the ACI code [17] could lead to inaccuracies with the impulsive response of the tank while the convective response had an acceptable agreement. The combination of vertical and horizontal accelerations in either model (i.e., rectangular, or cylindrical tanks) did not have a significant impact on the dynamic behaviour. The same Finite Elements (FE) model was used by Moslemi et al. (2011) [42] (Figure 19) to investigate the seismic response of an elevated water tank mounted on a reinforced concrete shaft. The response time history was obtained using the modal superposition technique. The damping effect of the liquid was also considered. The impulsive and convective masses were analyzed separately as an improvement compared to conventional FEM analyses. The model was able to provide solutions for tanks with complicated geometries (e.g., conical tanks) as well; hence the use of the equivalent cylindrical tank would not be necessary. Base shear and overturning moment were investigated and the effect of wall flexibility and sloshing of the liquid were examined in the analysis. Modal finite element analysis showed a good agreement with Housner's model [15] in terms of the convective and impulsive natural frequencies. Also, it was found that the impulsive and convective modes had different times to get to their respective peak values, which means that sloshing could have either a positive or a negative effect.

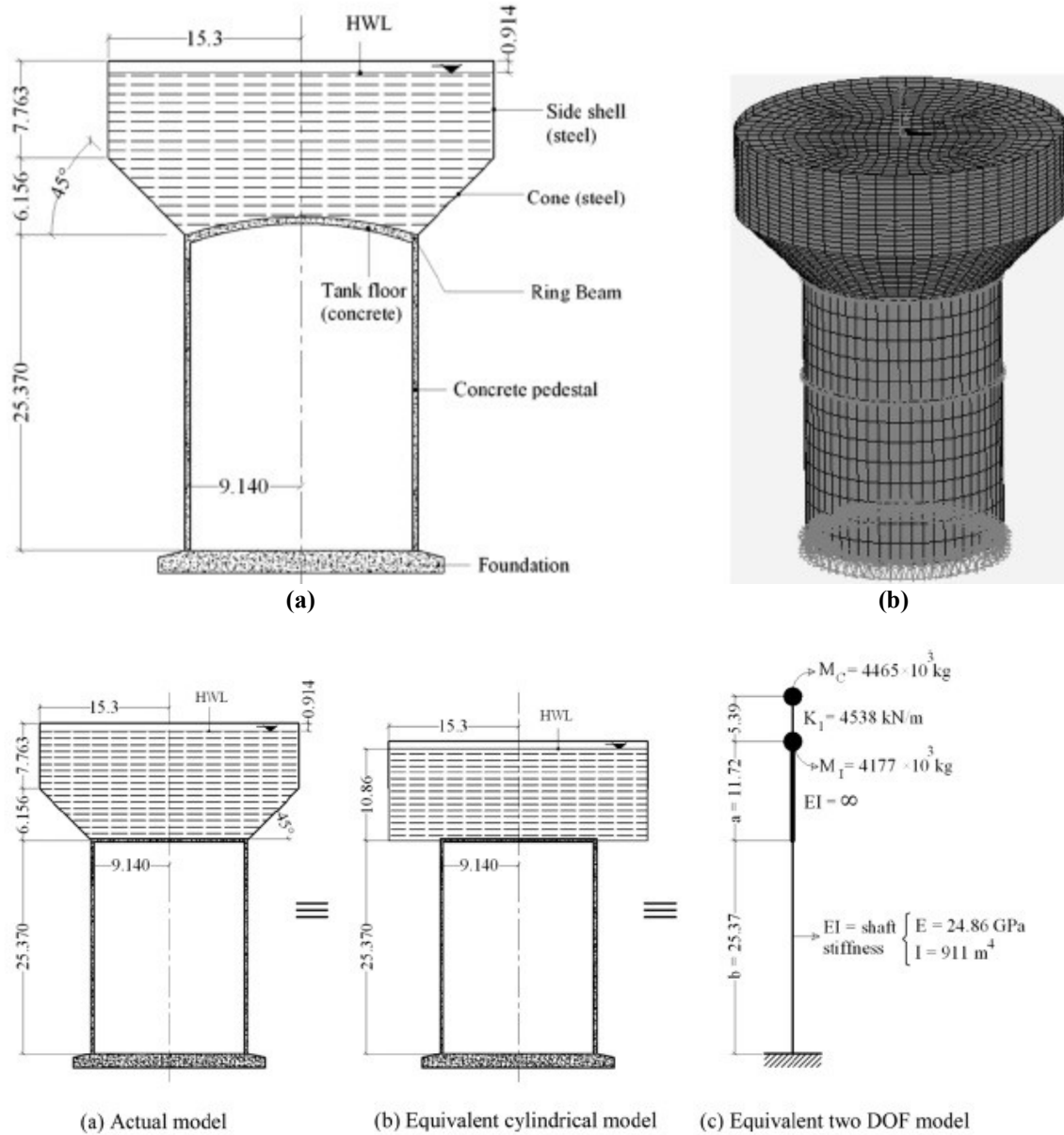
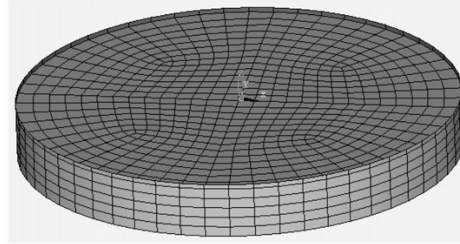
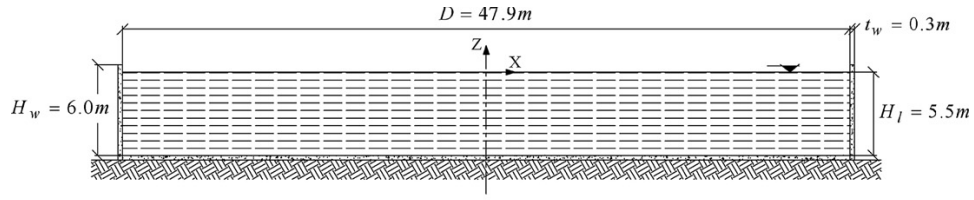


Figure 19: Tanks modelled by Moslemi et al. (2011)

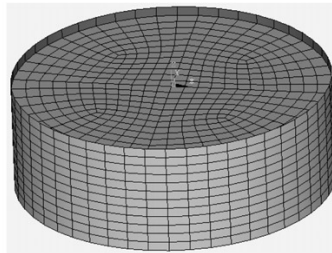
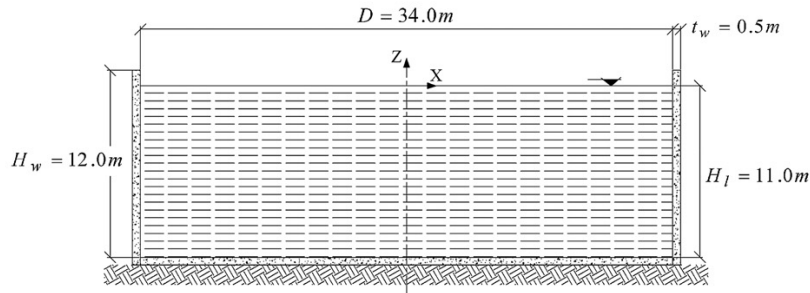
The Volume of Fluid Method (VoF) can be combined with other numerical methods and is a means for simulating the free surface of the fluid. In this method —first proposed by Hirt and Nicols (1981) [43]— the free surface of the liquid is divided into sections parallel to the coordinates. The original method, called Simple Linear Construction (SLIC) was later improved to Piecewise Linear Interface Construction (PLIC). This method can have a high computational cost as the free surface is reconstructed at each step. Ming and Duan (2010) [44] proposed a method in which the free surface was assumed as a physical discontinuity with sudden changes in properties. A rectangular tank with length $L=0.8$ m, width $W=0.35$ m and height $H=0.5$ m and fill depth of %30 with ($h_f=0.3$ H) was modelled. Excitation frequencies of 0.8, 0.9, 1.0 and 1.2 of the natural frequency of the tank respectively with the motion amplitude of 0.02 m were applied. Also, 2D and 3D models were compared where the 2D simulation was taken from the middle plane of the long direction. The

comparison showed that the 3D effects on pressure were negligible, hence the 2D model was used for the rest of the study. The results were compared with the experimental data published by South Korea's Daewoo Shipping and Marine Engineering Company in 2005 and a good agreement was observed for the lower frequencies there were some discrepancies for higher frequencies.

Moslemi and Kianoush (2012) [24] studied tall and shallow circular tanks using FEM (Figure 20). Parameters such as aspect ratio (i.e., the ratio between the tank's height and its dimension), the vertical component of an earthquake, the effect of wall flexibility, free surface sloshing, etc. were investigated assuming ideal fluid i.e., incompressible, irrotational, and inviscid with no mean flow. The aspect ratio of the tall tank was three times higher than the shallow one, but the dimensions were chosen such that the two tanks would contain the same amount of liquid. Their results showed that in the shallow tank (with an aspect ratio of about 0.115), regardless of wall flexibility, the vertical ground acceleration could affect the convective hoop force, bending moment and base shear more than the same impulsive components, however, it was generally negligible. In the tall tank (with an aspect ratio of about 0.324), combined vertical and horizontal ground accelerations showed a significant increase in all impulsive and convective components. The justification for this increase could be the stronger P- Δ effect in tall tanks. In both shallow and tall tanks, the wall flexibility increased impulsive pressures significantly, while it had minor effects on convective pressures.



(a)



(b)

Figure 20: Tanks modelled by Moslemi and Kianoush (2012)

Wu and Chen (2012) [45] proposed a finite difference method to find the response of the liquid in a tank subjected to dimensionless base excitations. A wide range of frequencies was applied to the tank in three dimensions with the action of six degrees of freedom. Different wave shapes and types were observed including single-directional, square-like, irregular and swirling. Results were compared with previous studies (e.g., Kim, 2001 [46], Frandsen, 2004 [47]) and an acceptable agreement was obtained. The study showed that square-like and irregular waves happened during a horizontal ground motion, regardless of excitation frequency and angle. It was also found that the frequency of the first impulsive mode is dominant in affecting diagonal, single-directional and square-like waves under resonance conditions. For rotating waves, in addition to the first mode, the second mode was also effective. In the case of irregular waves, the odd natural modes had a great impact on the system.

Kolukula and Chellapandi (2013) [48] applied a finite element model based on a mixed Eulerian-Lagrangian scheme with the logic that the free surface and the interior nodes have different behaviour, where the former behaves as Lagrangian and the latter has a Eulerian behaviour. Four-noded iso-parametric elements were used for the analysis. The Fourth-order Runge-Kutta method was used to advance the results in time. During the time of the simulation in the case of steep waves, numerical instability was observed due to the Lagrangian behaviour of free surface nodes that caused them to get close to each other. To overcome this, a cubic spline interpolation was used to consistently re-grid the free surface. It is worth noting that re-gridding was not necessary for small-amplitude waves. The tank in this study was assumed rigid with the liquid height half the length of the tank (i.e., an aspect ratio, h/L of 0.5). Simulations were conducted using resonance and non-resonance horizontal excitations. The results were compared with the cases of Frandsen (2004) which studied the non-linear FDM analysis on 2D tanks excited by horizontal and vertical harmonic motions separately, and together on a tank with an aspect ratio of 0.5 (i.e., the liquid height was half the tank length) assuming inviscid liquid. A good agreement between the results of the two studies was reported.

Gui and Jiang (2014) [49] investigated the sloshing problem in 2D and 3D models using the FVM. Free surface motions and hydrodynamic behaviour of the liquid under resonant excitation were studied. For the fluid part, two-phase viscous fluid flow was modelled and the differences between the 2D and 3D models were examined. For the 2D model, a rectangular tank with a length of 0.57 m, a height of 0.30 m and a liquid height of 0.15 m was subjected to a harmonic sinusoidal horizontal motion with an amplitude of 0.005m under resonance conditions. For the 3D model, the same dimensions with a width of 0.31m were used. The results from both 2D and 3D models had an agreement with the numerical and experimental results of Liu and Lin (2014). The numerical results in either model presented two peak values for the impulsive load on the tank wall; when the free surface reaches the roof, and when the free surface went back down, the latter being larger than the former. The 3D model revealed large impact loads near the sharp corners suggesting that the 2D model might underestimate these loads. The OpenFOAM was found to provide good results for the 3D model in the nonlinear range.

Experimental Studies

Experimental studies have been predominantly used as a validation/verification tool for numerical simulations. Akyildiz and Ünal (2005) [50] performed a series of experiments to study the sloshing of the liquid as well as the pressure distributions at different points in a rectangular tank. A tank with plan dimensions of 920×460 mm and a height of 620 mm was used. To investigate the effect of baffles, the tank was designed to have removable baffles in different directions on walls, roof and bottom. Piezoresistive pressure transducers were installed in different locations on the walls to measure the pressure distribution in the tank. Various sets of experiments with different excitation frequencies and different fill depths were carried out. The results showed that baffles remarkably reduce the motion of the liquid, but there was not enough data to find out the effect of fluid viscosity on pressure, hence more experimental work was necessary.

Panigrahy et al. (2009) [51] conducted a series of experiments to measure the pressure and the free surface in a sloshing tank. A square tank placed on a moving plate driven by a DC motor was used for the experiment. Pressure and displacement of the free surface were measured under different excitation frequencies and fill depths. The focus of the study was to investigate the effect of internal baffles in the tank; hence, experimental tests were carried out with different baffle placements and without them and the results were compared. It was observed that the sloshing of the liquid was a function of several factors including the liquid height (i.e., fill depth), tank size, excitation characteristics (e.g., amplitude and frequency), and liquid characteristics (e.g., density and viscosity). Pressures and sloshing height of the free surface were measured and compared for different cases. A relationship between the wave amplitude and the liquid height was obtained; The pressure on the tank wall was found a function of the excitation period and has a great variation near the free surface rather than deeper in the liquid part. Due to the self-damping property of liquids, for a specific excitation frequency, it was observed that increasing the liquid height decreased the sloshing height. As part of the study, the effect of baffles on the sloshing was investigated and a considerable reduction of sloshing and pressure was observed. Different types of baffles (e.g., blade, ring, vertical, horizontal) were tested and ring baffles were found more effective than other types.

Damage Mitigation Methods

A review of the available literature shows the importance of a thorough investigation of various methods that are used for controlling seismic loads in LSTs. Earthquake load mitigation techniques can generally be divided into two categories of internal and external methods. Internal methods are the ones where baffles (Figure 21), internal blocks, or floating roofs are used to control the motion of the liquid inside its container whereas in the external methods it is tried to control the total motion of the container by using isolation techniques (Figure 22).

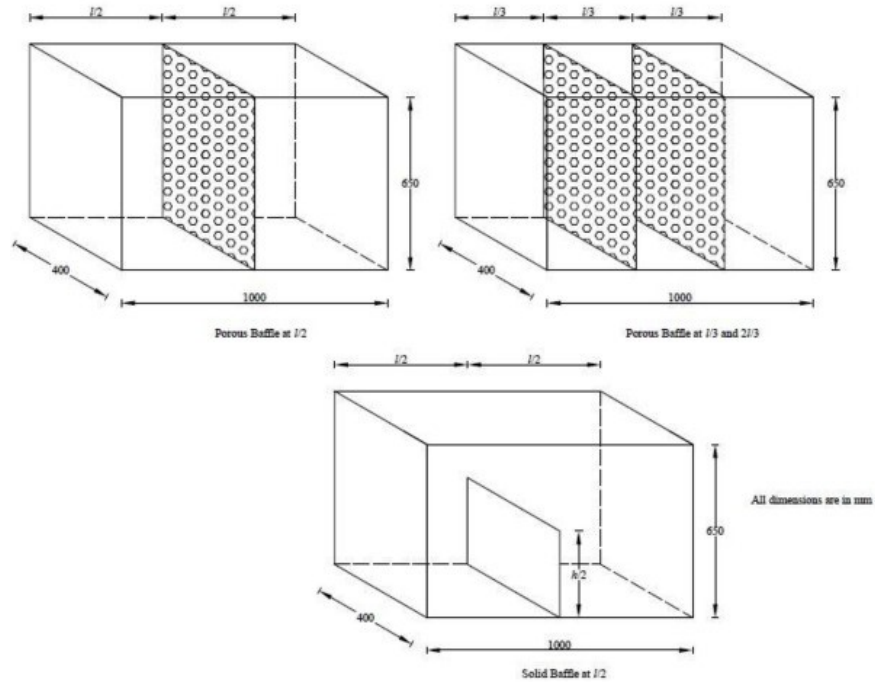


Figure 21: Use of baffles in a liquid container



Figure 22: Base isolation in a liquid container (Source: https://commons.wikimedia.org/wiki/File:Base_isolators_under_the_Utah_State_Capitol.jpg)

2.6.1. Internal Methods

Internal methods are the methods that use a physical barrier inside the container in order to control the motion of the liquid. They help reduce sloshing – i.e., the motion of the free surface of the liquid inside its container caused by disturbance of partially-filled liquid tanks. In the literature, these methods are generally divided into three categories: 1- baffles, 2- submerged blocks, and 3-

floating roofs. Despite their differences, they have the same goal of controlling and reducing liquid sloshing.

Depending on conditions and design, baffles can be found in ring or blade shape. The orientation of them can be horizontal or vertical and they can be made of porous or solid materials. The variation that can be found in shapes and types of baffles makes them a good candidate as a method for controlling liquid sloshing. According to Panigrahy et al. (2009) [51], ring baffles are as effective as a combination of horizontal and vertical baffles in mitigating hydrodynamic loads inside a tank, although there are more limitations in their installation.

Using the right configuration of baffles is crucial. Sometimes a bad configuration can cause higher impact loads on the walls. E.g., Su et al. (1982) [52] showed that putting horizontal baffles just underneath the free surface can cause higher loads than in a tank without any baffles. Based on numerical modelling by Armenio and La Rocca (1996) [53] on shallow tanks, the use of vertical baffles can reduce the liquid sloshing by up to 60% under resonance conditions. Akyildiz and Unal (2005) [50] did an extensive study on different configurations of vertical and horizontal baffles in a tank with different fill depths. Their results show that the effectiveness of each baffle configuration depends on the fill depth, in other words, a certain baffle configuration might create higher seismic loads when the liquid volume is reduced. However, Eswaran et al. (2009) [54] showed that baffles are generally effective in load reduction regardless of the liquid height. Zhao et al. (2017) [55] investigated the effect of different arrangements of ring baffles in nuclear containers. Their results show that vertical ring baffles are the most effective in reducing the seismic loads on the tank and they are more effective when placed closer to the bottom.

Solid vertical baffles whether they are ring-shaped or blade, can act as a dam in the bottom of the tank, keeping the fluid from moving from one side to the other. Porous baffles can solve this issue. Nasar and Sannasiraj (2019) [56] investigated the effect of such baffles and found them to be effective in load reduction and sloshing mitigation; however, no comparison between the two types of baffles was made, hence it is not clear whether porosity of baffles has a positive or negative effect.

Another technic in the internal category is the use of a floating roof or suspended baffle. In this method, there is a roof always in contact with the liquid's free surface that moves up and down with the liquid as the tank is filled or emptied. Hosseini et al. (2017) [57] conducted some limited experiments using suspended baffles (Figure 23) and found them reducing the vertical displacement by up to 75%. However, this method has design limitations as the structure's response is not predictable.



Figure 23: Experimental study of an annular suspended baffle, Hosseini et al. 2017

Using submerged blocks is another method for internally reducing the effects of an earthquake on liquid behaviour. These blocks that are installed at the bottom of the tank can be rigid or flexible. There are not many studies on this method, hence a comprehensive conclusion cannot be made about them. However, the limited studies —e.g., [58]— show that they can be effective in reducing sloshing heights and hydrodynamic pressures, although, the location of the blocks can play an important role in the effectiveness of this method. [36]. If the blocks are too close to a wall, they can be ineffective whereas when they are located closer to the center, they can reduce the impact loads. In addition, the sloshing height and hydrodynamic pressures are dependent on the block size, hence finding the optimal block size is important if this method is being used.

In general, internal methods such as baffles can reduce the sloshing height, hydrodynamic pressures and impact loads, however, they have their limitations. In the case baffles specifically, they require extra design provisions such as for their connections, etc. They can also develop some localized failures due to the hydrodynamic pressure that they take.

2.6.2. External Methods

External methods mainly focus on limiting the motion of the structure itself, unlike the internal methods that control the motion of the liquid. In the external methods, isolating the structure from the ground motion is sought [59], [60].

Base isolation has been used as a method of seismic damage mitigation of structures in recent years. In this method, the focus is on limiting the motion of the structure by isolating it from the ground using either elastomeric bearings, rolling isolation, or sliding bearing [60]. A base isolating system is mainly composed of three basic elements: 1- a flexible mounting that increases the period of the structure, 2- an energy dissipation system that acts as a damper, and 3- a rigid part that resists against smaller loads such as wind [61].

This method can also be applied to reduce earthquake damage in liquid containers. The technic can be used as a rehabilitation method for seismic retrofit of existing tanks, or it can be designed for new tanks. To use as a rehabilitation technic, the tank needs to be jacked up, and then the isolators can be installed on the foundation.

This method can significantly reduce overturning moments and hydrodynamic shear forces at the base of the tank[60] and impulsive loads on the walls [59]. In addition, base isolation can reduce earthquake damages and keep the structure functional after seismic activity. However, relative horizontal and vertical displacements may increase. Since a tank is attached to piping systems and electrical or mechanical systems, the increase in the displacement needs to be addressed in the design so proper actions can be taken. In addition, using base isolation can slightly increase the convective loads on the wall of the tank, although not significantly [61]–[63].

2.6.3. Discussion

Two general types of damage mitigating technics in liquid containers were discussed in this section: Internal methods (such as baffles), and external methods (e.g., base isolation). They each have their advantages and limitations. As for the baffles, they are proven to reduce sloshing height and hydrodynamic pressures; however, further studies on the effect of actual earthquakes on their behaviour are essential as the available literature is mostly focused on harmonic sinusoidal loads. External methods such as base isolation have shown to be effective in regular structures and if used properly, can improve the seismic performance of a liquid container as well, although they can cost more and require maintenance during their service life.

Which method to use depends on various conditions. In seismic retrofit and rehabilitation of existing liquid containers, base isolation is the more desired method, since it does not intervene with what is inside the structure. In new tanks, baffles might be the better solution as they are less costly compared to base isolation and require less maintenance during the service life of the structure. The application of hybrid or combined methods has been neglected in the literature. The effect of simultaneous use of both baffles and base isolation can be the topic of future studies as it has not been investigated in previous studies.

Damage mitigation technics reduce either the general movement of LSTs or the sloshing of the liquid inside the tank. While these methods are not within the scope of the current study, studying them can help identify the areas where tanks are more vulnerable. Therefore, it can be concluded that liquid sloshing in tanks that do not have these mitigation measures needs to be studied further.

Artificial Intelligence Methods and Applications

In recent years, artificial intelligence (AI) has been evolving in all aspects of human life, including engineering problems [7]. There are several methods for the estimation of a relationship between scattered data based on AI. Among them, the Group Method of Data Handling (GMDH) [64] and Evolutionary Polynomial Regression (EPR) can be mentioned. AI techniques such as Support Vector Machine (SVM), Artificial Neural Networks (ANNs), Adaptive Neuro-Fuzzy Inference System (ANFIS), Genetic Programming (GP) have recently been used for engineering problems such as water quality index and groundwater level modelling (e.g., [65]–[71]).

Model tree (MT)—a sub-class of the regression tree method—is another regression method in which an equation is generated at each node [72]. In a regression tree, a constant or a relatively simple regression model is used to demonstrate the data [73]. A genetic-based method known as GP is also used for the regression of data. In this method, a set of sub-trees is randomly generated based on user-defined specifications using arithmetic operators (i.e., +, −, ×, /), non-linear functions (e.g., sin, cos, log), etc. [74]. The goal is to minimize the errors (e.g., Root Mean Square Error (RMSE)) in newer generations until an acceptable error is reached.

Another method for formulating scattered data based on AI is Gene Expression Programming (GEP), which according to Sattar and Gharabaghi (2015) [75] was introduced by Ferreira in 1999 [76]. This method can be employed to develop relationships between data with minimal error [77]. Azamathulla (2012) [78] adopted this method to estimate the scour depth downstream of sills. To do so, he used the following procedure: (1) choose a fitness function; (2) choose a set of terminals (T) and functions (F) to shape chromosomes; (3) choose the chromosome architecture (i.e., head length and the number of genes); (4) choose the linking function (e.g., addition and multiplication operators); and (5) choose the set of genetic operators (e.g., mutation, transportation, etc.). He compared his results with the equation obtained by Chinnarasri and Kositgittiwong (2008) [79], which at the time had the lowest error value, and found that the proposed equation using the GEP model had a higher accuracy. Najafzadeh et al. (2016) [80] used three methods, i.e., GEP, MT, and EPR, to predict the maximum scour depth near piers with debris accumulation. Gholami et al. (2019) [81] used the GEP method to predict the characteristics of stable bank channels. They obtained their experimental data as well as data from previous experimental studies to complete their GEP modelling. The results were compared with available theoretical and experimental methods. Despite a good agreement and accuracy, the model's complexity was found to be higher in comparison with older analytical methods, and therefore the GEP method was not suggested by the authors. Khozani et al. (2017) [82] applied GEP to analyze shear stress distribution in circular channels with flat beds subject to sediment deposition. They proposed equations for predicting the base shear applied to the bed and the walls of such channels. It was found that the GEP model could lower errors and uncertainties, and hence the model was recommended for the base shear analysis of circular channels with flat beds.

A sub-class of the GP method known as Multi-Gene Genetic Programming (MGGP) can be used in problems with higher complexity. A gene is a weighted linear combination of outputs from a GP tree. In this method, the user has control over the maximum number of genes and the depth of the model tree [83]. In this method, multiple genes are combined to produce an MGGP model. AI techniques have shown to be capable of accurate prediction, and with the development of computing systems, they have become easier to use. However, to the best of the authors' knowledge, they have not been employed in the prediction of pressures and forces in water tanks. Previous studies in engineering applications have shown promising results for MGGP in comparison with other AI techniques such as ANN, ANFIS, traditional GP, etc. [84]–[86].

The use of GP methods in civil engineering is becoming increasingly popular. Gandomi et al. (2013) [87] proposed an empirical model for predicting the ultimate shear strength of reinforced concrete (RC) deep beams using GEP. The results were compared with design codes such as ACI

and CSA, and the model was found to give better results than the design codes when compared to the available experimental and numerical data. Gandomi et al. (2014) [88] developed a model to find the shear capacity of RC beams without stirrups using the GEP method. To avoid overfitting, they divided the data into three groups, namely learning, validation, and testing on a random basis. The developed model was tested against the available data and several design codes (e.g., ACI, CSA, NZS, etc.) for various sizes and models of RC beams and was found to give compatible results. GEP can be used in various fields of civil engineering as an optimization method. Zahiri et al. (2015) [89] investigated the applications of GEP in hydraulic engineering and found it applicable in different areas, such as estimation of scour depth, discharge rate, and land transport in rivers.

National Building Code of Canada (NBC)

Based on Article 4.1.8.18 of the National Building Code of Canada (NBC) [90], the lateral force of non-structural components and equipment are measured based on the following equation:

$$V_P = 0.3F_a S_a(0.2) I_E S_P W_P$$

where F_a is the site coefficient as defined in sentence 4.1.8.4(7) equal to $F(0.2)$. This coefficient depends on the soil type and is equal to 1.0 for soil type C. for other soil types, the values can be found in table 4.1.8.4.B using interpolation based on the Peak Ground Acceleration (PGA) of the area which can be found in the appendix C of the NBC. $S_a(0.2)$ is the spectral response acceleration value at 0.2s and is a function of the area. It can be found in Appendix C of the NBC. I_E is the importance Factor, defined in article 4.1.8.5 and is equal to 1.0 for normal structures (e.g., residential), 1.3 for high importance structures (e.g., schools), and 1.5 for post-disaster buildings (e.g., hospitals). S_P is the horizontal force factor for part or portion of a building and its anchorage. It is equal to $C_P A_r A_x / R_P$ with $\max(S_P) = 4.0$ and $\min(S_P) = 0.7$. A_x is the height factor, equal to $1 + 2h_x/h_n$ where h_x is the height above the base of the x^{th} floor where the component (in this study a tank) is located (which is the roof) and h_n is the height above the base of the n^{th} floor of an n -storey building. In this study, since the tank is located at the roof, h_x is equal to h_n , in other words, $A_x = 1 + 2(1) = 3$.

In which C_P is the element or component factor, A_r is the element or component force amplification factor, and R_P is the element or component response modification factor.

The values for C_P , A_r , and R_P can be obtained from table 4.1.8.18 as follows:

Machinery, fixtures, equipment, and tanks (including contents)	C_P	A_r	R_P
That are rigid and rigidly connected	1.00	1.00	1.25
That are flexible or flexibly connected	1.00	2.50	2.50

- According to sentence 4.1.8.18.3, to apply Sentence (1) for Categories 11 and 12 of Table 4.1.8.18., elements or components shall be assumed to be flexible or flexibly connected unless it can be shown that the fundamental period of the element or component and its

connection is less than or equal to 0.06 s, in which case the element or component is classified as being rigid or rigidly connected. In other words, the values of C_p , A_r , and R_p for a roof-top tank are equal to 1.00, 2.50, and 2.50 respectively, unless one can show that the fundamental period of the tank is less than or equal to 0.06s.

This leaves the base shear equation for a normal importance building located on soil class C as follows:

$$V_P = 0.3F_a S_a (0.2) I_E S_P W_P, \text{ where } F_a = 1.0, I_E = 1.0, S_P = 2.4; \text{ hence,}$$

$$V_P = 0.72 S_a (0.2) W_P, \text{ where } W_P \text{ is the weight of the tank with the water inside.}$$

The following are some remarks from the NBC regarding the

- When the mass of a tank plus its contents or the mass of a flexible or flexibly connected piece of machinery, fixture or equipment is greater than 10% of the mass of the supporting floor, the lateral forces shall be determined by rational analysis.
- Connections to the structure of elements and components listed in Table 4.1.8.18. shall be designed to support the component or element for gravity loads, shall conform to the requirements of Sentence (1), and shall also satisfy these additional requirements:
 - a) friction due to gravity loads shall not be considered to provide resistance to seismic forces,
 - b) R_p for non-ductile connections, such as adhesives or power-actuated fasteners, shall be taken as 1.0,
 - c) R_p for anchorage using shallow expansion, chemical, epoxy or cast-in-place anchors shall be 1.5, where shallow anchors are those with a ratio of embedment length to the diameter of less than 8,
 - d) power-actuated fasteners and drop-in anchors shall not be used for tension loads,
 - e) connections for non-structural elements or components of Category 1, 2, or 3 of Table 4.1.8.18. attached to the side of a building and above the first level above grade shall satisfy the following requirements:
 - i. for connections where the body of the connection is ductile, the body shall be designed for values of C_p , A_r and R_p given in Table 4.1.8.18., and all of the other parts of the connection, such as anchors, welds, bolts, and inserts, shall be capable of developing 2.0 times the nominal yield resistance of the body of the connection, and
 - ii. connections, where the body of the connection is not ductile, shall be designed for values of $C_p = 2.0$, $R_p = 1.0$ and A_r given in Table 4.1.8.18., and

- f) a ductile connection is one where the body of the connection is capable of dissipating energy through cyclic inelastic behaviour.

Conclusion

A thorough review of the available studies and the design codes, standards and guidelines shows that the effect of earthquake loading on the support structures of LSTs with consideration of the liquid sloshing has not been completed before. Also, the effect of earthquakes on the seismic response of roof-top liquid-containing structures has been neglected in the literature. A roof-top tank can create complexities in the design of a building structure as it may affect the seismic response of the structure depending on the seismicity of the region, dynamic characteristics of the building, the size and fill depth of the LST, etc. The available literature shows a difference in seismic characteristics, and consequently the base shear and overturning moment of tall and shallow liquid-containing structures. However, this has not been investigated in roof-top tanks, hence there is a room for more studies on this issue.

Although there have been studies on the effect of base excitations on the roof of LSTs and despite the efforts for finding formulae to predict the sloshing forces at the roof, the data in the available literature are not sufficient for a general conclusion, and do not provide a reliable method that includes all the variables affecting the roof pressures. The current study attempts to combine numerical analyses and AI technics to overcome this issue and find a general, broad, and inclusive model for predicting those pressures.

The effect of seismic loading on the supporting structures of LSTs is another overlooked issue in the available literature. While there have been efforts to find the base shear based on structural characteristics and spectral accelerations (e.g., [25]), these efforts have not resulted in improvements of design codes such as NBC and ACI350.3.

In addition, the literature has been mainly focused on one aspect of the problem. In other words, previous research studies have focused either on the structure, neglecting the liquid sloshing and its effects on the seismic behaviour of the tank, or on the liquid, without considering structural characteristics such as flexibility of the structure or supports.

In particular, the literature is lacking research on the interaction between tanks and buildings when tanks are located at the roof. Most of the previous studies investigate either ground-supported tanks, or tanks elevated on concrete shafts or steel frames/trusses. There has not been any research on the supporting structures and base shears of roof-top LSTs subjected to earthquake loads. One major reason for this gap in the literature is the specificity that is required for such a study to conduct. In other words, there cannot be a general study that captures all the parameters needed for a comprehensive answer. For instance, the height of the building on top which the tank is located, the material the building is built of, the tank size itself, etc. can all impact the interaction between the tank and the building and hence, a generalized study is not feasible.

These show the importance of and the need for a study that considers addressing these challenges and comes up with an idea of how to design future studies in a way that they can help with the development and improvements of standards, codes, and guidelines. Although the current study

does not completely resolve the issue raised above, it can pave the way for future study plans on the interaction between tanks, the liquid, and the building on which the tank is located.

3. Numerical and Experimental Investigation of Rectangular Liquid-Containing Structures under Seismic Excitation

Abstract: Liquid-containing structures are used for various municipal and industrial applications. The functionality of these structures in seismic regions is crucial. The main purpose of this study is to investigate the behavior of liquid under seismic excitations using numerical modelling. For this purpose, experimental and numerical studies are conducted. In the experimental tests, a ground-supported rectangular tank is excited on a shaking table. The tests are videotaped from two directions and subsequently analyzed frame-by-frame. Four different orientations are tested to investigate the effect of bilateral excitation. In the numerical simulations, the same tank is modeled in OpenFOAM—a computational fluid dynamics program—and the same excitations are applied. The results from the numerical and the experimental studies are compared, and reliability of the numerical model is discussed. Furthermore, using the numerical model, the pressure on the roof of the tank is obtained at various locations and examined for different excitations.

Keywords: liquid container; computational fluid dynamics; OpenFOAM; earthquake; sloshing; water tank; resonance

3.1. Introduction

Storage tanks are widely used to store various liquid types in the industry, food production, municipalities, transportation, chemical plants, etc. In numerous earthquake events, severe damage and economic losses have occurred due to the poor seismic performance of such structures. Examples include uncontrollable fires in petroleum tanks during the 1964 Niigata earthquake [24] and 2011 Tokoku earthquake [3] in Japan, major damage to water reservoirs during the 1960 Chilean earthquake [4], and the structural failure of tanks due to the 1992 Landers earthquake [5]. With an annual average of 200 earthquakes of a magnitude of greater than 6 Richter around the world [91], the seismic design of liquid-containing structures (LCSs) plays a crucial role in the design process. In addition, the serviceability of water reservoirs during and after an earthquake is important because of their importance in extinguishing fires caused by the earthquake [15] as well as for supplying drinking water to people suffering from the event.

The lateral movement of a tank can cause large liquid sloshing heights for open-top tanks, while for tanks with a roof, large hydrodynamic forces and pressures can be generated at the roof of the tank.

Numerous analytical, numerical, and experimental investigations on LSTs have been carried out by researchers during the past several decades. The sloshing problem has been studied in different aspects, from fluid viscosity to linearity or nonlinearity effects, including effects on tank wall flexibility [45].

Fluid-structure interaction problems require interdisciplinary knowledge in topics such as fluid mechanics and structural engineering. There have been efforts to propose analytical solutions to such problems. While a completely full or empty tank can be treated as a single mass system, partially filled tanks are a different story. Housner (1963) [15] proposed an improved analytical model of an earlier model that he had made some modifications to [14]. In this model, the two

contributing components, i.e., impulsive and convective masses, were calculated using analytical formulations. The impulsive mass is the lower part of the liquid that moves together with the tank, i.e., it is assumed it has a rigid connection with the walls of the tank, while the convective part is associated with the liquid and is modeled as a spring-mass system connected to the walls of the tank. The model applies to both cylindrical and rectangular tanks. The current study is mainly focused on the convective part of the liquid (i.e., the sloshing part) in a base-excited rectangular tank.

The common practice in the design of liquid containers is to divide the liquid into impulsive and convective components [92]. The former is the lower part of the liquid that moves in unison with the tank and is rigidly connected to the walls, while the latter is associated with the free surface of the liquid and is modeled as a spring-mass system (Figure 24). Veletsos (1974) [12] argued that Housner's model is only applicable to rigid tanks, and hence he introduced a method in which the effect of the tank wall flexibility is considered. He specifically investigated the impulsive forces. He argued that the convective forces are not affected by the tank's wall flexibility and that the procedure for rigid tanks introduced by Housner applies to them. This was also supported in a study by Ghaemmaghami and Kianoush (2010) [22] which found that the wall flexibility does not affect the convective force; hence, the sloshing part can be treated the same as if the wall is rigid.

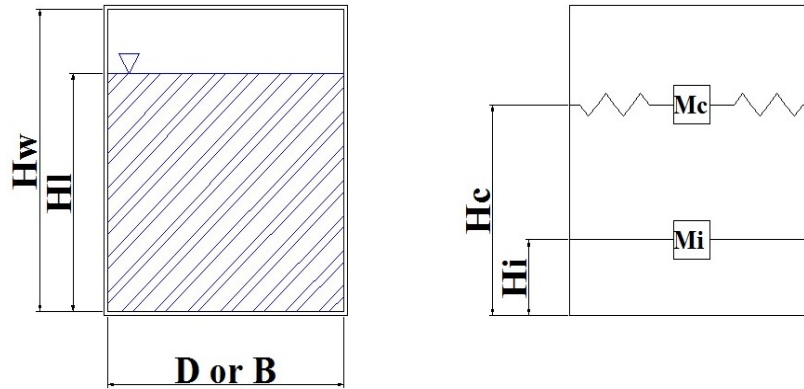


Figure 24: Schematic view of partially liquid-filled container: (a) internal profile of the tank; (b) impulsive and convective components.

Haroun (1983) [16] investigated the effect of seismic loads on liquid-containing tanks in three steps, including theoretical analysis, experimental tests, and design code development. In the initial step (i.e., theoretical analysis), he introduced an analytical solution based on the anchorage of the tank. He analyzed tanks that could either be anchored or unanchored to the base. This can change the behavior of the tank, and hence the analysis method, the location and amount of associated stresses. Although non-linear analysis is necessary for unanchored tanks, modal analysis can be used for anchored ones.

Current guidelines for seismic design of LSTs such as ACI 350.3 (2006) [17] are based on Housner's simplified method with some modifications to determine the impulsive and convective pressures. Although it is easy and appropriate to use an analytical method in finding the natural frequency of a liquid-tank system, some recent studies (e.g., [22]–[24]) have debated the accuracy of this method. As well, the ACI code provides solutions for the seismic design of open-top tanks,

but no such design load is provided for when a roof is included. It only provides the freeboard, and in the case this is insufficient, the code requires the roof to be designed for the expected water pressure exerted on it.

Isaacson (2010) [23] proposed an analytical approach to estimate the liquid surface in a seismically excited tank. While there has been interest by some researchers in using analytical methods to solve problems such as those investigated in this study, the numerical and experimental studies have their own merits. Additionally, due to difficulties in finding accurate analytical solutions [9], with the development of computational systems and laboratory equipment in recent years, researchers have become more interested in numerical and experimental studies. Moslemi et al. (2011) [42] evaluated the seismic response of a water reservoir elevated on a reinforced concrete shaft by using the finite element (FE) method. The method was validated for circular cylindrical ground-supported tanks in a previous study by the same authors [93]. In their finite element model, they accounted for damping of the liquid and considered the impulsive and convective parts separately as an advantage in comparison with previous analytical methods. Moslemi and Kianoush (2012) [24] developed a FE model for the analysis of circular cylindrical LSTs. The investigated parameters included the aspect ratio of the tank, sloshing of the free surface, wall flexibility, and higher modes of impulsive and convective masses. Additionally, the accuracy of the ACI code was evaluated. In their study, they modeled two different types of tanks, namely “shallow” and “tall”, such that the aspect ratio for the tall tank was three times greater than that of the shallow tank; however, both had the same volume. Their results showed that in both shallow and tall tanks, wall flexibility increases the impulsive pressure significantly while it has a minor effect on the convective pressures.

Minoglou et al. (2012) [94] proposed a design procedure for cylindrical thin-walled steel liquid containers based on the seismic behavior of these structures to find the optimum dimensions for different tank and liquid volumes. This study was based on the seismicity of the area in which the tank is built on and the soil type. It was found that increasing the seismicity or worsening the soil type (i.e., from A to D) the diameter of the tank should increase to achieve an optimal design. This method can be used for an efficient design of cylindrical thin-walled liquid containers.

Konstandakopoulou and Hatzigeorgiou (2017) [95] studied the effect of multiple earthquakes on elevated steel LSTs using numerical modeling. A “short” and a “tall” tank were used in the study. It was found that application of multiple ground motions in comparison with a single earthquake can significantly increase the displacement of the bottom of the structure. However, sloshing height does not follow the same rule and can decrease or remain the same when exposed to earthquake sequence in comparison with a single ground motion.

From the review by Sriram et al. (2006) [35], vertical excitation creates waves that were first experimentally inspected by Faraday in 1831 and hence are called Faraday waves. In a 2D rectangular model based on the finite element method, they investigated sloshing in the vertical and horizontal directions to explore the sway and heave modes of ship motion. Both “regular wave excitation” (i.e., harmonic excitation) and “random wave excitation” (for which the Bretschneider spectrum was used as the input wave spectrum) were studied. In regular horizontal excitation, the critical sloshing motion occurred at the frequency equal to the first convective frequency of the

tank, while in regular vertical excitation it happened at the excitation frequency equal to twice the first convective frequency; i.e., when the excitation frequency is equal to twice the value calculated as the first convective frequency, the sloshing motion becomes strong.

Jaiswal et al. (2008) [38] studied the dynamic characteristics of non-uniform circular and rectangular liquid-containing tanks by both experimental and numerical studies and found a very good agreement between the resonance period based on both types of study and the analytical solution based on Housner's model.

Gui and Jiang (2014) [49] adopted OpenFOAM [8] to investigate 2D and 3D sloshing tank problems, free-surface motions, and hydrodynamic behavior of liquid under resonant excitation using the two-phase viscous fluid flow model, and showed that calculating the convective loads based on 2D models may lead to underestimation for the tank corners. Li et al. (2012) [96] investigated the motion of sloshing liquid in a ship motion using the Finite Volume Method and found using OpenFOAM as the simulation tool is computationally efficient. Chen et al. (2009) [40] developed a numerical model for prediction and analysis of the sloshing part of the liquid in various types of tanks and measured the sloshing pressures and loads acting on the tank walls and simulated the free surface. They found an acceptable level of accuracy for the prediction of impact pressure on the tank's roof in their numerical model based on the comparison with the available data. Cho and Cho (2007) [26] proposed a coupled method combining finite element method and boundary element method to investigate the seismic response of a circular cylindrical LST and found that Haroun's method underpredicts the sloshing heights by a large margin. Koshizuka and Oka (1996) [27] introduced a moving particle semi-implicit (MPS) method for simulation of particles of incompressible fluids which was adopted by Lee et al. (2007) [28] along with the finite element method (FEM) to analyze the sloshing in fluid-shell structure interaction where the structure was modeled by 4-node quadrilateral shell elements (mixed interpolation of tensorial components, MITC4). Lee et al. showed that this coupling method can be used in solving sloshing problems, but the method was found to be reliable, more investigations and improvements were required. Liu and Lin (2008) [39] adopted volume of fluid (VOF) method to investigate a two-phase fluid flow model for solving the Navier–Stokes equations in a LST under arbitrary base excitation with 6 degrees of freedom and introduced a linear analytical model for the sloshing problem and compared their results with the linear theory introduced by Faltinsen in 1987. The agreement between their numerical model and the theoretical solution varied depending on the sloshing amplitude. While they found very good agreement for small sloshing amplitudes, the large amplitudes did not agree well. Burkacki et al. (2020) [97] studied the effect of minor earthquakes and mining activities on cylindrical steel tanks using FEM and found that the liquid height can significantly affect the tank's behavior under the above-mentioned circumstances. It was also found that mining activities and moderate earthquakes can have comparable effects on liquid containers.

Panigrahy et al. (2009) [51] conducted a series of experiments to find the pressure and changes of the free surface in a square tank placed on a shaking table driven by a DC motor. In their study, they measured the water pressure at the walls in baffled and unbaffled tanks. They concluded that the pressure very much depends on the applied excitation and the use of baffles can significantly

reduce the sloshing effects as a result of the created turbulence; however, further investigation is required for that. Akyildiz and Ünal (2005) [50] studied the sloshing of the liquid as well as the pressure distributions at different locations in a rectangular tank using piezo-resistive pressure transducers. They too found baffles effective in reducing the fluid motion but called for further studies on the effect of excitation type (e.g., multi-component random excitation) on liquid sloshing. Shekari (2020) [98] investigated the effect of sloshing in baffled thin-walled liquid containers using a coupled FE-BE method. The effect of different characteristics such as liquid height, baffle locations, and arrangements were examined and parameters such as sloshing height and base shear were measured. It was found that baffles can significantly reduce sloshing in shallow tanks with the lowest baffle having the least effect.

Eswaran et al. (2009) [54] calculated the pressure in a cubic tank using the VOF method with arbitrary Lagrangian–Eulerian formulation and compared the results with the data from a previous study by Panigrahy (2006) [99] and Panigrahy et al. (2006) [100]. A total number of six pressure sensors were mounted at various heights on a wall of their tank to measure sloshing pressures on that wall. For the experimental study, the tank was excited by a simple shaking table that created sinusoidal displacements. They found a good agreement between their results and those from the previous experimental studies.

Oblique base excitation of non-cylindrical (e.g., square-based or rectangular) liquid tanks has been an area of greater interest in recent years. Ikeda et al. (2012) [101] studied the effect of non-linear sloshing in rigid tanks with square plan shapes excited by harmonic, oblique loads. They applied excitations at three different angles, 5° , 30° , and 45° , and compared the results for different liquid levels. It was found that for oblique excitations, the first modes in the two directions were coupled and created a more complicated response than with uni-directional loading (i.e., 0° excitation). The effect was greater with the tanks that were rectangular-shaped (i.e., with different lengths and widths) compared to square tanks, as the first modes in the two directions were different. Wu et al. (2013-a) [11] studied the effects of oblique excitation on tanks by conducting numerical modeling validated by experimental tests. Five different excitation orientations were explored, and the hydrodynamic forces on the walls were investigated. Different wave types were observed depending on the excitation frequencies, tank aspect ratios, and loading orientations. Oblique excitation was found to significantly affect the hydrodynamic forces, especially under resonant conditions. Meanwhile, Wu et al. (2013-b) [102] investigated the effect of damping mechanisms such as baffles and surface-piercing flat plates in obliquely excited liquid containers. Numerical and experimental studies were conducted, and it was observed that bottom-mounted baffles caused swirling waves when oblique loading was applied. In contrast, surface-piercing plates were found to both change the frequency of the first mode of the system, and unlike with baffled tanks, in tanks with surface-piercing plates, the direction of these waves remained unchanged. In another study, Faltinsen and Timokha (2017) [103] analytically investigated the same issue. In their article, they simplified the equations and solved the problem with a rigid tank. The results were compared with the results of the experiments conducted by Ikeda et al. (2012) [101] with the three orientations of 0, 30, and 45 degrees. The results showed reasonable agreements with those of the experiments by Ikeda et al.; however, there was also room for some improvements in the analytical method for swirling waves.

API 650 [104] is an American standard for seismic design of above-ground steel storage tanks. It was extensively reviewed by Spritzer and Guzey (2017) [105] and compared with other design codes and guidelines such as New Zealand [106] and Japan [107]. Failure mechanisms such as hydrodynamic hoop stress, uplift, base plate stress, and buckling were investigated. The results showed that API 650 and the Japanese code agree well in predicting the hydrodynamic hoop, while the New Zealand code shows a large difference. In terms of the uplifting force, while the methods are different, the API, Japan, and New Zealand codes predict similar values. It was also found that the codes have different approaches and different results for buckling and are not comparable, however, the API's approach can be sufficient in this matter.

A review of the literature shows that very limited experimental studies have been carried out on the seismic responses of rectangular tanks. Therefore, the current study focuses on the behavior of rectangular, ground-supported LSTs using both experimental and numerical studies. The experimental tests were conducted in the structural laboratory at the University of Ottawa using transparent water tanks placed on a shaking table. For the numerical study, OpenFOAM software was adopted as the simulation tool. In this study, the effect of tank orientation on the liquid surface and pressure at the roof was a parameter of interest. To validate the numerical model, a series of experiments are conducted and the results from the numerical and experimental studies are compared both qualitatively and quantitatively. Once the model is validated and calibrated, more simulations are conducted to measure the pressures at the roof of the tank. The current study is mainly focused on the effect of the convective part of the liquid (i.e., the sloshing part) on the roof of base-excited rectangular tanks.

In this study, the OpenFOAM application, which is an open-source and free computational fluid dynamics (CFD) software program, is used for the numerical modeling. This software has numerous features such as different turbulence models, various solvers, etc. This application can help reduce computational costs by choosing the proper features on a case-by-case basis.

To the best of the authors' knowledge, a numerical and experimental study that involves biaxial loading conditions and in particular on a shaking table has not been previously conducted. Furthermore, in this study, the pressure at the roof of the tank, which has not been previously predicted accurately, is measured.

In this chapter, the experimental and numerical studies will be explained first, followed by a discussion on pressure distribution at the roof of the tank.

3.2. Materials and Methods

3.2.1. Theoretical Background

In this study, the liquid is assumed to be incompressible and Newtonian, with constant viscosity and density. The governing equations in this problem are Navier–Stokes equations along with the free surface equation.

3.2.1.1. Navier–Stokes Equations

The Navier–Stokes equations for incompressible three-dimensional flow are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \nabla^2 u \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \nabla^2 v \quad (3)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \nabla^2 w - g \quad (4)$$

where ρ is the density (kg/m^3), p is total pressure (Pa), u , v , and w are the velocities in the x , y , and z directions respectively (m/s), t is time (s), and $g = 9.81 \text{ m/s}^2$ (gravitational acceleration). P is calculated as follows:

$$\rho = \alpha \rho_1 + (1 - \alpha) \rho_2 \quad (5)$$

where ρ_1 and ρ_2 are the densities of the two fluid phases involved (air and water in this case) and α varies between 0 and 1 depending on the location (1 inside fluid 1, 0 inside fluid 2, and a number between 0 and 1 at the interface). Finally,

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (6)$$

3.2.1.2. Free Surface Equation

At the free surface, the pressure is equal to zero and the free surface is tracked using the volume of fluid (VoF) method, which follows the following equation:

$$\frac{\partial \alpha}{\partial t} + \frac{\partial(\alpha u)}{x} + \frac{\partial(\alpha v)}{y} + \frac{\partial(\alpha w)}{z} = 0 \quad (7)$$

It is worth noting that there are other free surface prediction methods such as the level set method and the Marker and Cell method, however, in this study, the VoF method provided reasonable results.

3.2.2. Computational Set-Up

As mentioned earlier, an OpenFOAM application was used for the numerical modeling in this study by using the finite volume method for the liquid in combination with the volume of fluid method for the free surface. The solver “interDyMFOam”, which is used for moving (i.e., dynamic) mesh situations, was adopted to solve the governing equations. A Eulerian scheme was used to discretize the temporal term, a Gauss linear scheme for the gradient term, and a Corrected Gauss linear scheme for the Laplacian term. For discretization of the divergence terms, Gauss vanLeer and Gauss linear schemes were adopted, and the interpolation term was discretized using a linear scheme. In this computation method, a tolerance level is defined for each variable where an iterative solver is run until the desired convergence is reached. The Gauss-Seidel method, which was obtained and improved from the Jacobi method, was used for this purpose with tolerance

levels of 1×10^{-5} , 1×10^{-8} , and 1×10^{-6} for the liquid fraction (α), pressure, and velocity, respectively.

3.2.2.1. Mesh

A structured cubic mesh was used in this study, and a mesh sensitivity analysis was run to find the optimum mesh size that would not affect the results. The pressure at the top right corner of the tank (as seen from the plan view) was measured as the sensitivity parameter. In the finite volume method with a rectangular shape tank, a structured cubic mesh was the optimum option. For the tank size used in this study, a mesh size of 5 mm was found to be acceptable.

3.2.2.2. Initial conditions

For the initial conditions, the velocity field was set to zero, with no initial velocity, acceleration, or displacement.

3.2.2.3. Wall boundary conditions:

In this study, no-flow, frictionless wall boundary conditions were applied at the base and the side walls. This boundary condition indicates that there is no flow across the wall, the shear stress at the wall is set to zero, while the normal gradient of tangent velocity was made equal to zero, meaning there was no liquid entering or exiting the boundary at these locations. This is an implicit boundary condition, and is applied as follows:

$$U_n = 0 \quad (8)$$

$$\frac{\partial}{\partial n} U_\tau = 0 \quad (9)$$

where U_n is the normal velocity, U_τ is the tangential velocity of the flow, and n is the normal vector of the boundary.

3.2.3. Experimental Study

In this study, various experimental tests were performed on a rectangular tank with plan dimensions of 755×300 mm and height of 300 mm. A uni-axial shaking table was used to apply base excitations to the tank. To investigate the bidirectional effect of excitation, the tank was placed on the shaking table in four different orientations of 0° , 30° , 60° , 90° , as shown in Figure 25. The tank was made of plexiglass with a density of 1190 kg/m^3 and a uniform thickness of 10 mm meaning that $t/b = t/h = 1/30$ and was fully fixed at the base. It is worth noting that plexiglass has an elastic modulus of 3.0 Gpa. In addition, a blue color was added to ease the observation of the sloshing height. The experimental setup is shown in Figure 26. The tank was filled to $1/3$ and $2/3$ of its height with colored water for each orientation in order to observe the effect of orientation on changes in the liquid free surface and the associated pressure on the walls and roof of the tank. It should be noted that the tank wall flexibility has little effect on sloshing response, but it can affect the impulsive component with little effect on the convective part. It should be noted that the experimental study is used as a means for verification of the numerical model. The size of the tank in this study was chosen based on the available laboratory equipment, particularly the size of the shaking table, considering the length-width-height ratios of tanks

commonly used in industry and that the tank's orientation on the shaking table changes from 0° to 90° .

The tests were recorded from two directions by two high-speed HD video cameras. The cameras were placed perpendicular to the tank and were fixed to the floor. Following the tests, the videos were analyzed frame-by-frame to investigate the liquid surface for each test case.

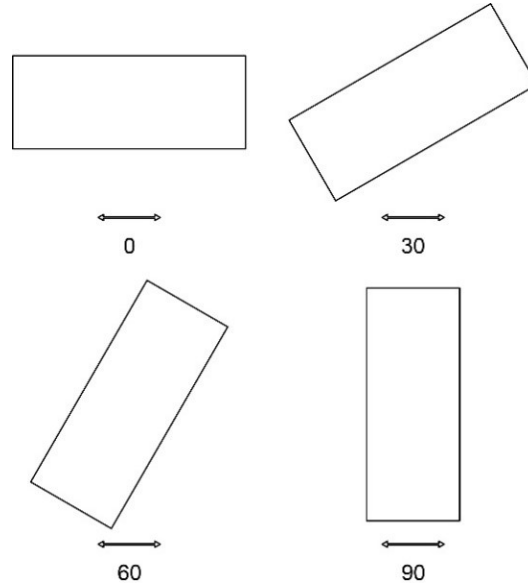


Figure 25: Plan view of excitation direction in comparison with tank orientations.

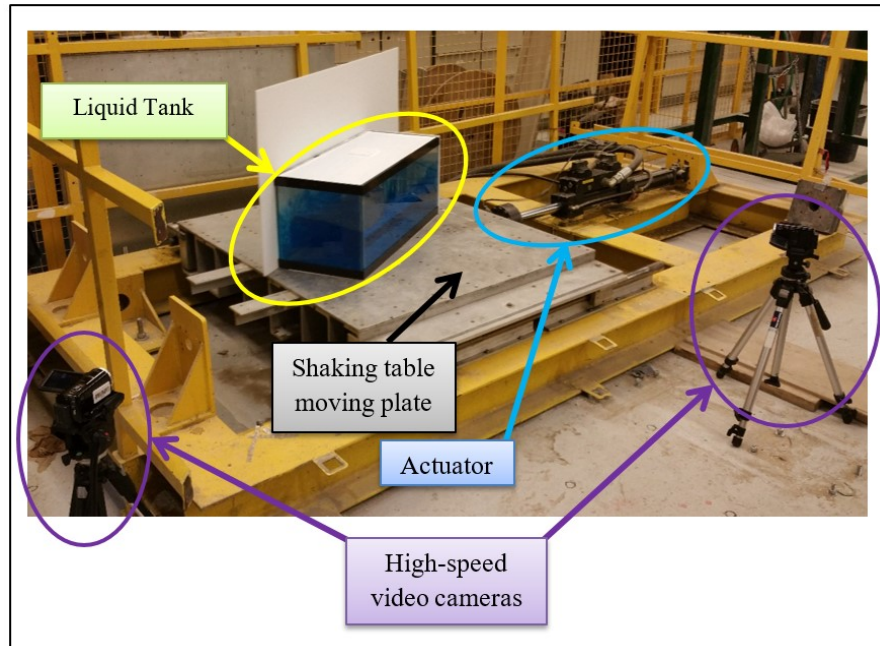


Figure 26: Plan view of excitation direction in comparison with tank orientations.

An earthquake excitation was applied to the tank. A study by Kianoush and Ghaemmaghmi (2011) [108] compared the effect of four different earthquakes on a tank using the finite element

method (FEM) and found that the longitudinal component of the 1940 El Centro earthquake caused the highest sloshing heights in the tank. Therefore, the N-S component of the 1940 El Centro ground motion was used in this study. The earthquake was used as recorded, i.e., with a scale equal to one. The acceleration, velocity, and displacement graphs of this earthquake with maximum values of 0.319 g, 361.4 mm/s (i.e., maximum absolute value), and $(-213.4; +28.6)$ mm respectively are shown in Figure 27 [109].

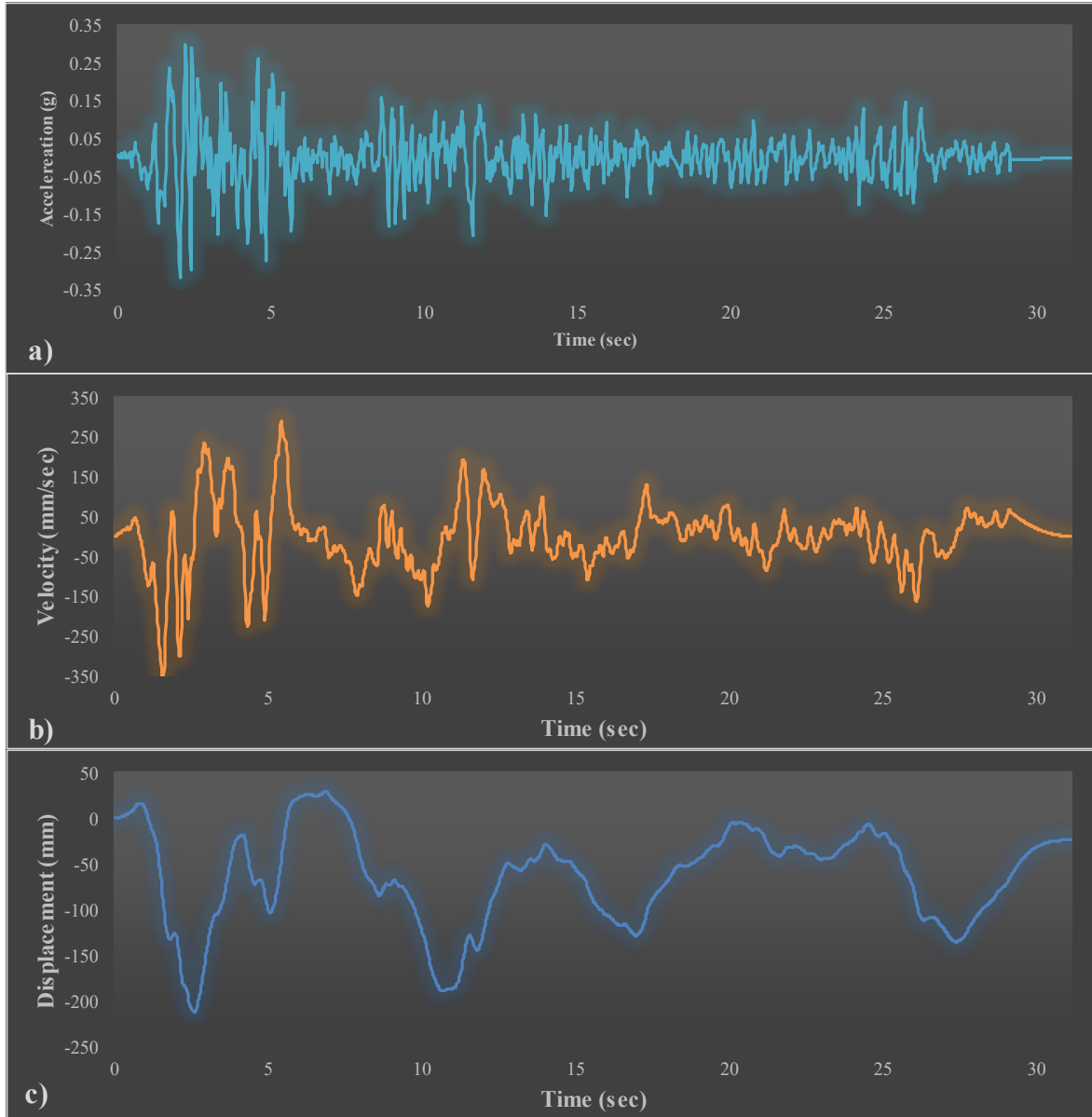


Figure 27: Time histories of the north-south component of the 1940 El Centro ground motion: (a) acceleration, (b) velocity, and (c) displacement.

Three harmonic sinusoidal base excitations with different frequencies were applied to the tank for a period of 60 s, which included the first convective frequencies of the tank and two other excitations within $\pm 50\%$ of that frequency. In order to apply the same excitation to the tank with

different orientations, the frequencies were calculated based on the 0° orientation and applied to all cases investigated in this study. The total movement domain for the sinusoidal excitations was 70 mm (i.e., about 10% of the tank length), and hence the displacement amplitude was 35 mm (close to 5% of the length). The resonance frequency used was calculated based on formulations provided by Housner (1963) [15]. The displacement response histories for the 1/3 and 2/3 fill depths (i.e., 100 mm and 200 mm respectively) are presented in Figure 28a and Figure 28b respectively.

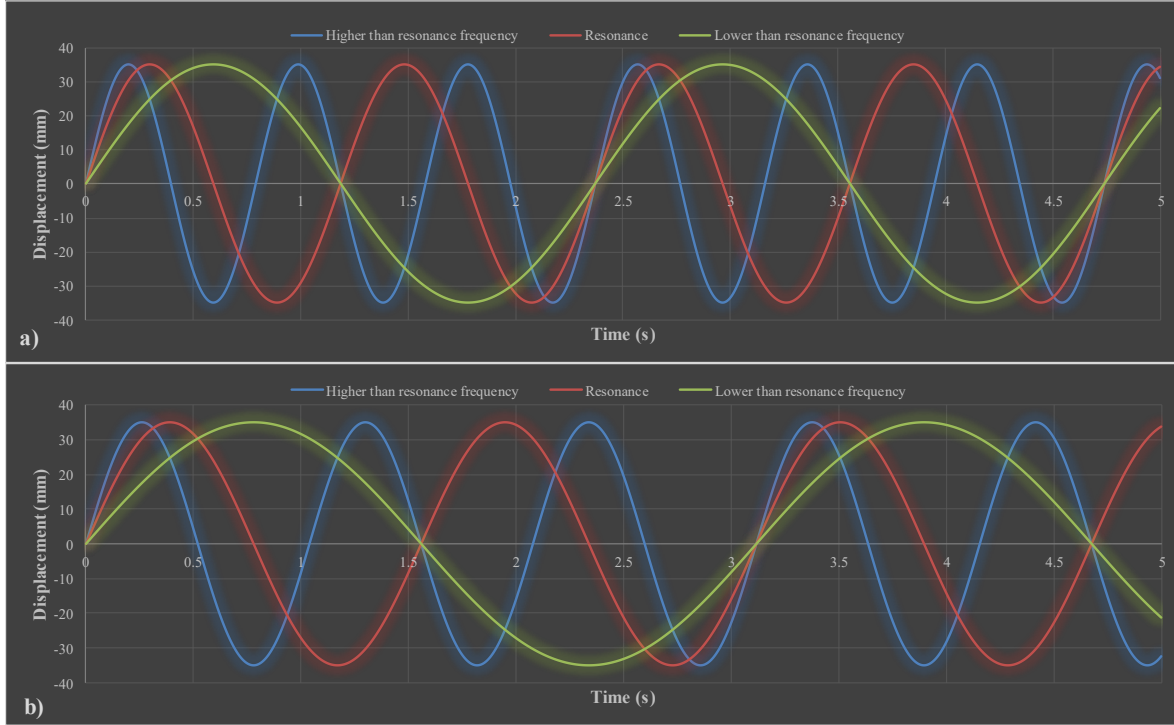


Figure 28: Displacement time-histories of the excitations applied at the base of the tank: (a) 100 mm liquid depth; (b) 200 mm liquid depth.

A harmonic sinusoidal wave can be described by the following equation:

$$U(t) = A \sin \omega t \quad (10)$$

where U is the displacement (mm), A is the displacement amplitude (mm), ω is the excitation frequency (rad/s), and t is the time (s).

The values chosen for ω in each case are presented in Table 2.

Frames captured from the videotape of each experimental test were compared with the ones of the matching simulation from the numerical study in order to validate the numerical model. The results from the numerical model and experimental tests were compared for all the excitation types, frequencies, and orientations.

It was observed from the experimental tests that the sloshing height was amplified at the tank corners in comparison with other locations of the tank. This amplification occurred regardless of the tank orientation or the liquid height, and some cases are presented in Figure 29. These include:

(a) 100 mm liquid depth, 0° orientation, lower than resonance frequency; (b) 100 mm liquid depth, 30° orientation, resonance frequency; (c) 100 mm liquid depth, 30° orientation, higher than resonance frequency; (d) 100 mm liquid depth, 60° orientation, higher than resonance frequency; (e) 100 mm liquid depth, 60° orientation, resonance frequency; (f) 100 mm liquid depth, 90° orientation, higher than resonance frequency; (g) 200 mm liquid depth, 0° orientation, higher than resonance frequency; (h) 200 mm liquid depth, 30° orientation, resonance frequency; (i) 200 mm liquid depth, 60° orientation, higher than resonance frequency; and (j) 200 mm liquid depth, 90° orientation, lower than resonance frequency. Higher sloshing heights at the corners can lead to higher pressures at those corners, including roof corners, compared to other locations. In a tank that is not aligned with the excitation direction (i.e., has a different orientation), the sloshing height at the corners is even higher than when the tank is aligned with the excitation.

Table 2: Applied frequencies for harmonic excitations.

Case	Frequency (rad/s)	
100 mm liquid depth	Lower than resonance	2.02
	Resonance	4.03
	Higher than resonance	6.05
200 mm liquid depth	Lower than resonance	2.65
	Resonance	5.30
	Higher than resonance	7.95

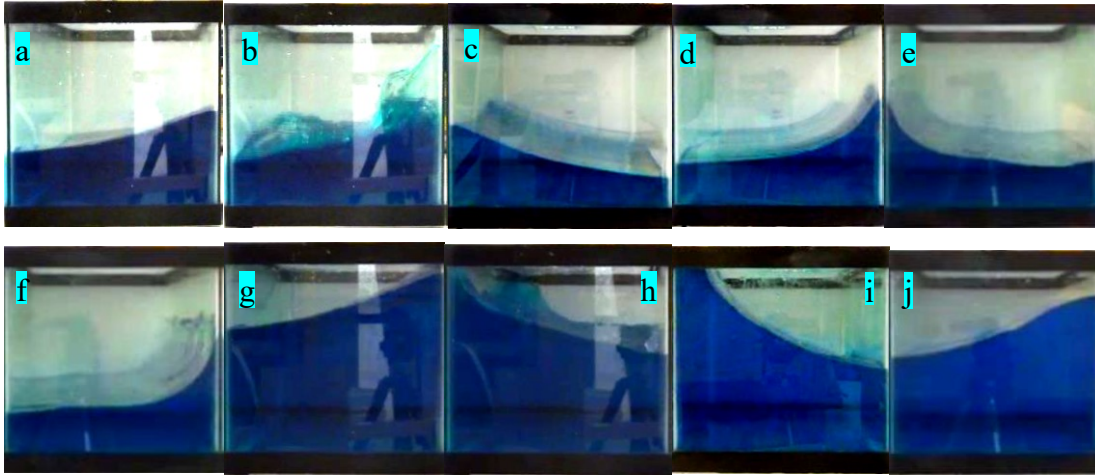


Figure 29: Higher liquid heights observed near the corners of the tank regardless of tank orientation and excitation type.

3.2.4. Numerical Modelling

The OpenFOAM application was used for the numerical modeling of the tank. It is an open-source computational fluid dynamics (CFD) software capable of solving various problems from dam breaks to heat transfers. A large variety of CFD solvers are available in this application that can

be used in the desired cases [110], [111]. The adopted numerical method was the finite volume method (FVM). In this method, the time is divided into time-steps (e.g., 0.02 s) and the liquid volume is broken down into finite volumes. The Navier–Stokes equations are solved for each finite volume at each time-step. The results are then combined, and the answer to the equation is formed for the control volume. It should be noted that the Navier–Stokes equations are non-linear, and hence OpenFOAM uses non-linear methods to solve them.

A variety of turbulence models can be used with this software [8]. The OpenFOAM solver used in this study was *interDyMFoam*, which has the ability to solve problems with dynamic mesh. In this solver, the pressure correction algorithm PIMPLE (which develops a non-linear set of equations and solves them using an iterative approach) was used for the fluid flow and the volume of fluid (VOF) method was adopted for tracking the free surface. The PIMPLE algorithm is a combination of the PISO (pressure implicit with splitting of operator) and SIMPLE (semi-implicit method for pressure-linked equations) algorithms. While PISO and PIMPLE algorithms are applicable in transient cases, SIMPLE is used for steady-state problems. However, they are all iterative solvers.

The finite volume method adopted by OpenFOAM is based on a structured mesh with non-uniform distribution. The dynamic properties of each control volume are defined by its centroid. The mesh allows for an unlimited number of points per face per control volume. In the numerical analysis, the Van Leer method is used for divergence, a corrected Gauss linear scheme is used for Laplacian terms and a linear approach is used for interpolation. An adoptive time increment is used in this analysis, meaning that each time step is chosen based on the previous time step to increase the accuracy; however, the computational cost and time increases with this scheme. In terms of turbulence, a constant eddy viscosity model is chosen in this study, as it has less computational cost and does not affect the results.

The VOF method introduced by Hirt and Nichols (1981) [43] was used in conjunction with other numerical methods to track the free surface. In this method, a function F is defined with the value of one for every spot that fluid exists and zero for other points. In each cell, the average value of F shows how much of that cell is filled with fluid. Hence, the unit value of F means the cell is fully filled by fluid, and zero means there is no fluid in the cell. An F -value between zero and one shows there is a free surface in that cell. Thus, the free surface can be tracked.

In the current study, the first step was to validate the model by using the frames captured from the videos of the experimental tests and comparing them with the ones from the numerical simulations, as shown in Figure 30. In this figure, the images from the numerical model and the experimental tests do not demonstrate the same times, but they were captured from the same excitation phase. The reason for this time difference is that the shaking table takes a slightly longer time (approximately half a second) to start operating. In other words, the shaking table's motion has a half-second lag from the input time-history. Following the validation, pressure sensors were placed at various locations on the roof of the tank in the numerical model, and simulations were conducted to find the maximum liquid pressure on the tank roof under both harmonic and earthquake excitation.

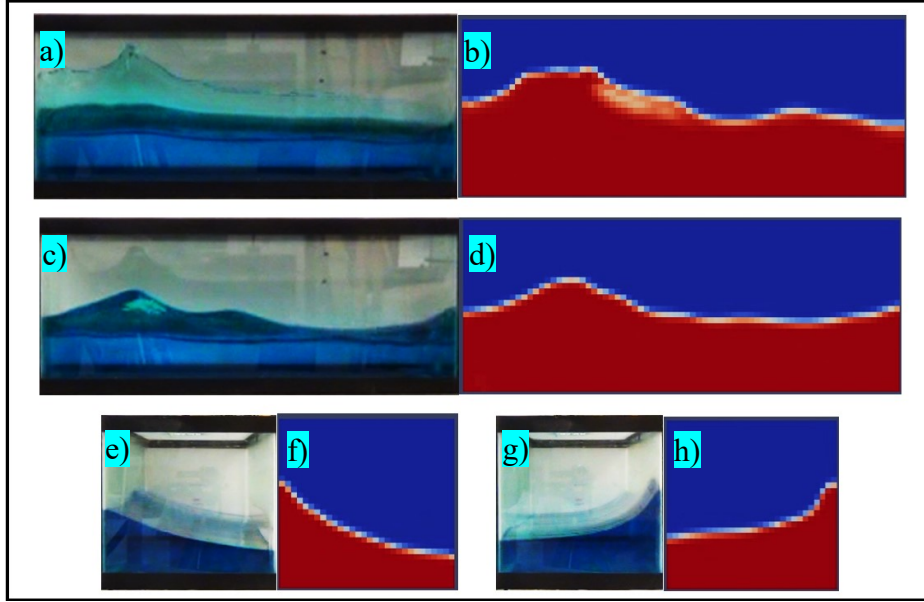


Figure 30: Qualitative comparison of liquid free surface in the experimental (a, c, e, g) and numerical (b, d, f, h) studies in the tank with 100 mm of water, 60° orientation, and frequency of higher than resonance.

To validate the model, once the qualitative comparison was deemed acceptable, the liquid surface was also digitized using MATLAB for a more detailed comparison in several cases. Figure 31 shows the free surface of the liquid considering five cases, and indicate the water height in the tank, free surface, and tank orientation. A typical time-step where a significant variation was observed was chosen for the presented cases in this figure. Then, the liquid height difference at the time step was calculated, squared, summed up, and divided by the total number of calculated points in order to find the root mean square error (RMSE) for the two sets of data. Finally, the RMSE value was calculated, as shown in Figure 31. The RMSE values ranged between 8.21 mm and 19 mm (i.e., error in the range of 1.09% to 2.53% of the tank length), which shows an acceptable agreement between the numerical model and the experimental results.

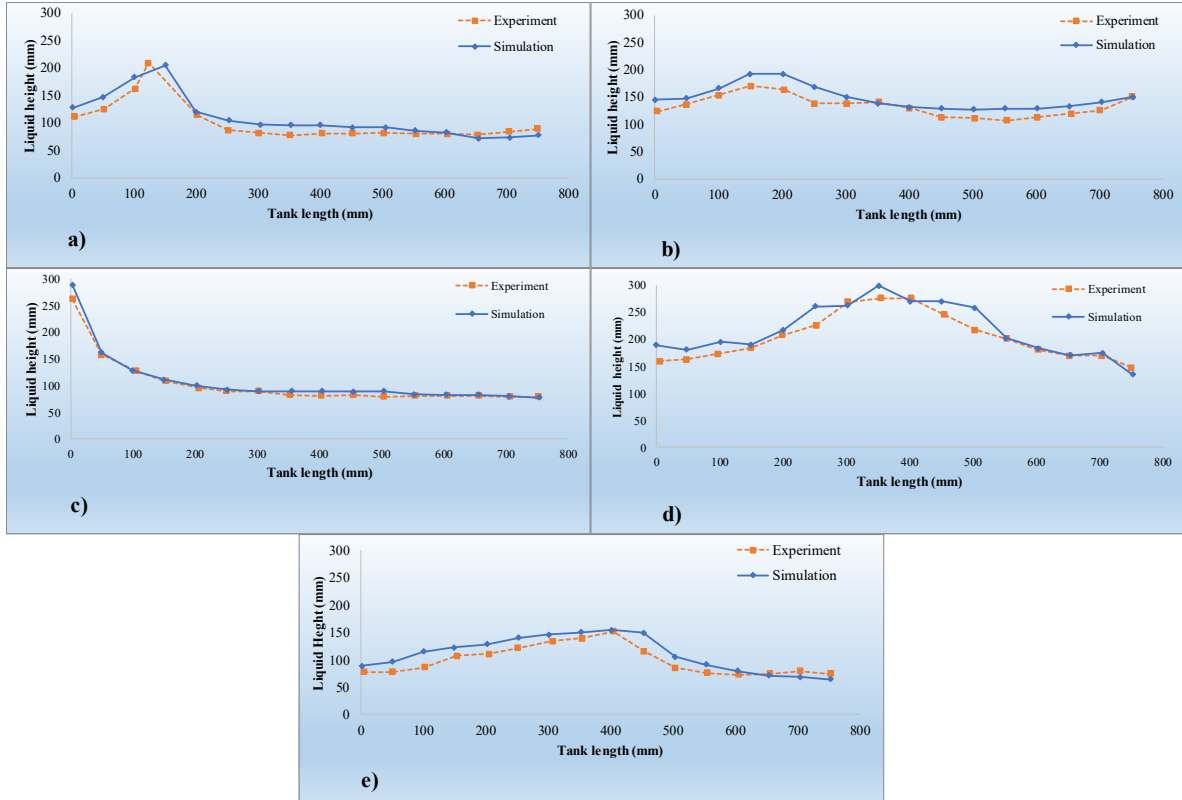


Figure 31: Comparison of free surface in numerical and experimental studies: (a) 100 mm water depth, 0° orientation, higher than resonance frequency, RMSE = 17.09 mm; (b) 100 mm water depth, 60° orientation, higher than resonance frequency, RMSE = 17.20 mm; (c) 100 mm water depth, 0° orientation, resonance frequency, RMSE = 8.21 mm; (d) 200 mm water depth, 90° orientation, higher than resonance frequency, RMSE = 19 mm; and (e) 100 mm of water, 30° orientation and resonance frequency, RMSE = 14.37 mm.

In addition to the liquid surface at different excitation phases, the liquid height over time at the corner of the tank was also measured in both numerical simulations and experimental tests for the earthquake excitations (Figure 32). The Fourier transform of the same parameter was compared for the two parts of the study (i.e., experimental tests and numerical simulations). Despite the complex dynamic behavior of the system, the maximum water elevation values are correctly predicted, but the differences increase over time due to the accumulation of errors. The comparison graphs (i.e., Figure 32) show that despite a delay at the beginning of the excitation (i.e., two seconds from the start time), the two graphs illustrate the same patterns and values for the rest of the time, especially for the time-span of 15 to 30 s where the liquid does not reach the tank roof. Additionally, a common way of comparing signals is to apply the Fourier transform to the two signals and compare them in Fourier space. It can be seen from Figure 33 that the Fourier transform in the numerical simulation's spectrum is similar to the one from the experimental tests in terms of the dominant frequencies. In other words, the main frequencies obtained from the two graphs (0.797 Hz for the experimental study and 0.833 for the numerical study) only have a 4.5% difference.

Both the qualitative and quantitative comparisons between the numerical modeling and the experimental tests show that the performance of the model is reasonably accurate in predicting the

motion of the liquid (whether the liquid motion is longitudinal or transverse) for all tank orientations and excitation frequencies. The model showed a good agreement with the tests concerning the liquid surface for the 0° and 90° orientations (i.e., uni-axial excitations), while some differences were observed for the 30° and 60° ones.

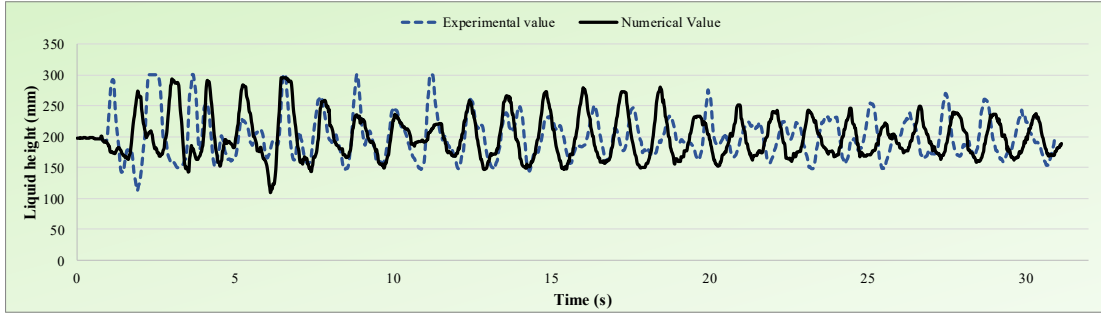


Figure 32: Comparison of experimental and numerical values for water surface at the corner of the tank filled with 200 mm of water and excited by the N-S component of the El Centro earthquake at a 0° orientation.

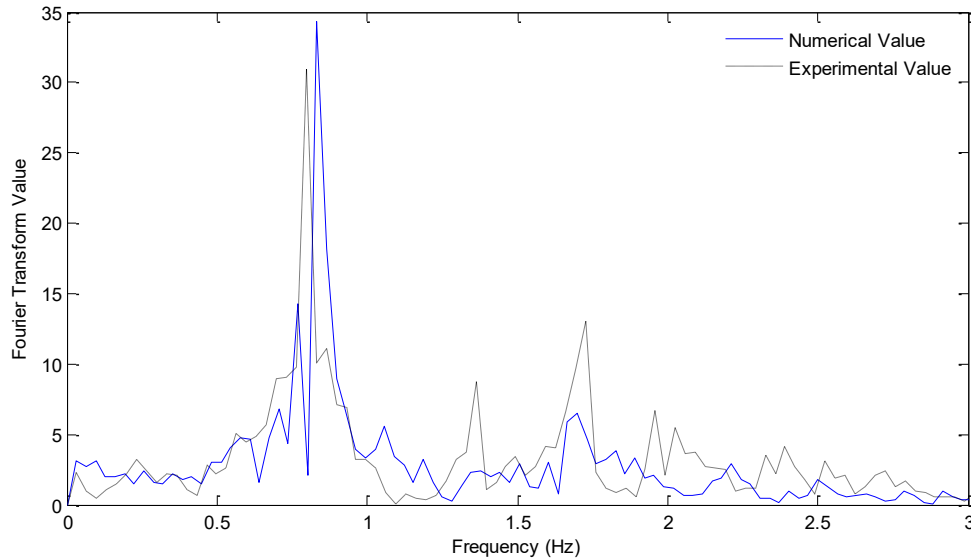


Figure 33: Comparison of Fourier transformations of the experimental and numerical values of water elevation at the corner of the tank excited by the N-S component of the El Centro earthquake at a 0° orientation.

Once the numerical model was validated, pressure sensors were placed at various locations on the tank's roof near the walls. Figure 34 shows the location of the sensors on the roof. Both earthquake and harmonic excitations were applied.

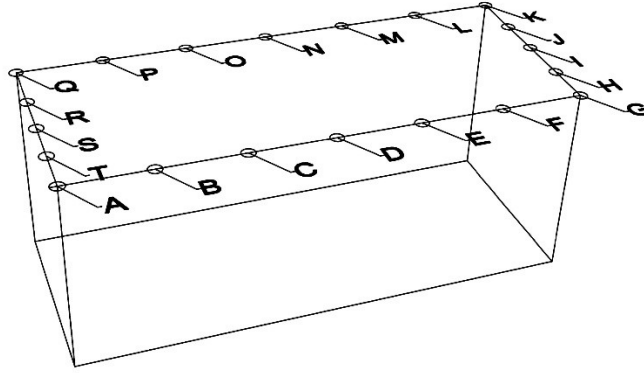


Figure 34: Pressure sensor locations in the numerical model.

Following several trial-and-error cycles, it was found that the turbulent eddy viscosity of $2 \times 10^{-4} \text{ m}^2/\text{s}$ led to the best results in terms of similarity of the free surface to the experimental work. After a reasonable calibration, the model was validated against the available experimental data. As mentioned earlier, an important goal in this study was to find a numerical model to predict the liquid surface behavior in a tank subjected to seismic loading, and hence the images from the experimental work and numerical simulations were compared to examine the validity of the proposed model. In this comparison, a number of cases were considered with respect to sloshing frequency, including frequencies higher than, equal to, and lower than the resonance frequency.

To further validate the model, the tank used by Wu et al. (2013-a) [11] was modeled in the OpenFOAM simulations for comparison. The water elevation was measured in the simulation and compared with the results from their study. The square-based tank with $1.0 \text{ m} \times 1.0 \text{ m}$ plan dimensions and height of 1.0 m was partially filled with water up to a depth of 0.25 m , and a near-resonant frequency with an amplitude of 5 mm was applied. The results from the OpenFOAM simulations were compared with the experimental results from Wu et al. (2013-a) and are presented in Figure 35. A good agreement was found in terms of predicting the peak values; however, a slight shift in time is seen, possibly due to the locations of the probe in each study. This shows that although the model is fine-tuned for the initial experimental data generated by the authors, it is a reliable model for other tank sizes.

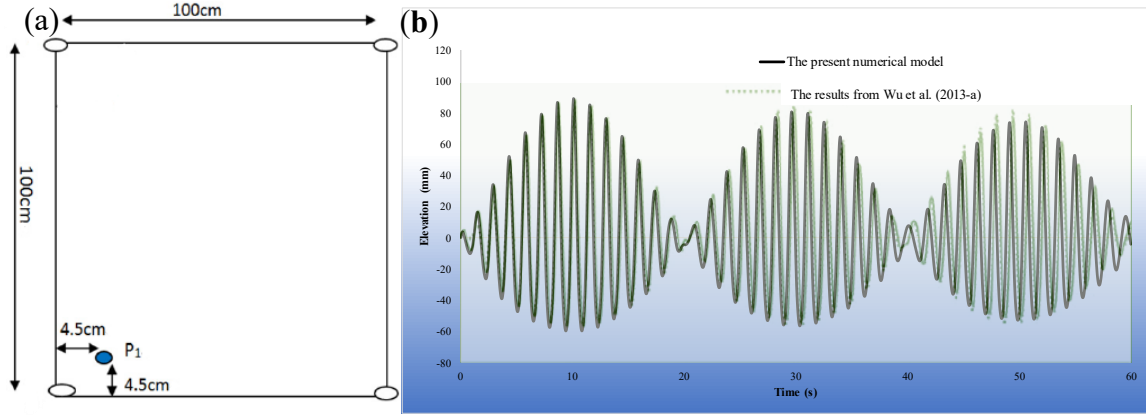


Figure 35: Comparison of numerical model used in the current study with the results from Wu et al. (2013-a) with 250 mm of water and an amplitude of 5 mm, with a rotation orientation of 30° and $\omega = 0.93\omega_{res}$ at location P_1 : (a) tank plan; (b) comparison of water elevations.

3.3. Results

3.3.1. Pressure Distribution

In this section, the results from the pressure sensors in the numerical study are presented and discussed.

From the simulations, the results from the pressure probes are presented in Figures 36 and 37 for the tanks with 100 mm and 200 mm and different orientations, respectively. The figures show that regardless of the tank orientation and type of excitation, the tank's corners show higher pressures irrespective of harmonic excitation (Figure 36) or earthquake excitation (Figure 37). In these figures, the time ranges that showed the highest variation were chosen. The pressure at the corners at times can reach up to three times higher than the pressure slightly away from the corners. An exception here is for the earthquake excitation applied on a 0° -oriented tank, in which the pressure on the tank's wall does not show a significant difference between the corner and the middle of the wall.

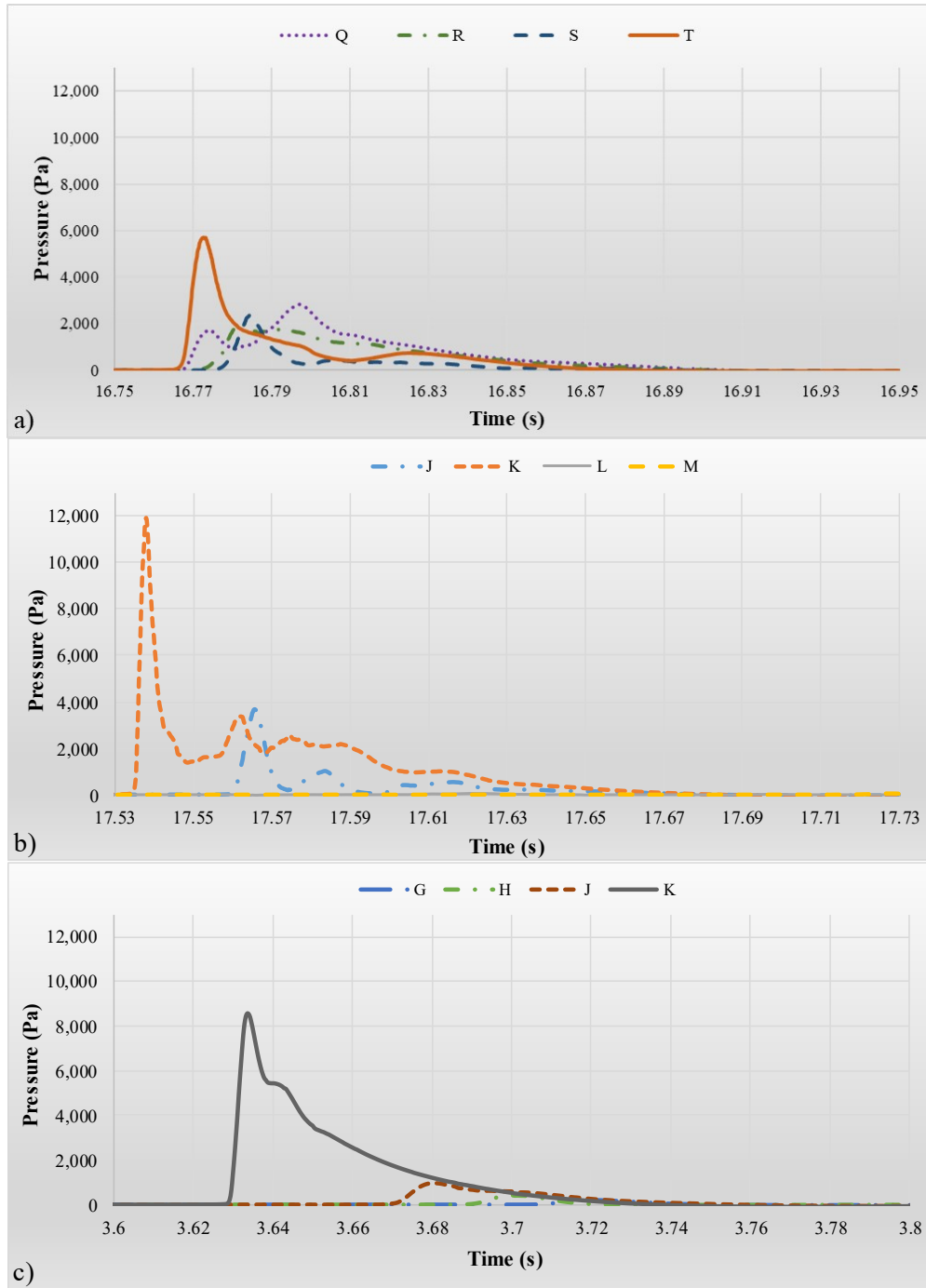


Figure 36: Comparison of pressure distributions for the tank with 100 mm water depth excited by harmonic resonance excitation at: (a) 0°, (b) 30°, and (c) 60° orientations.

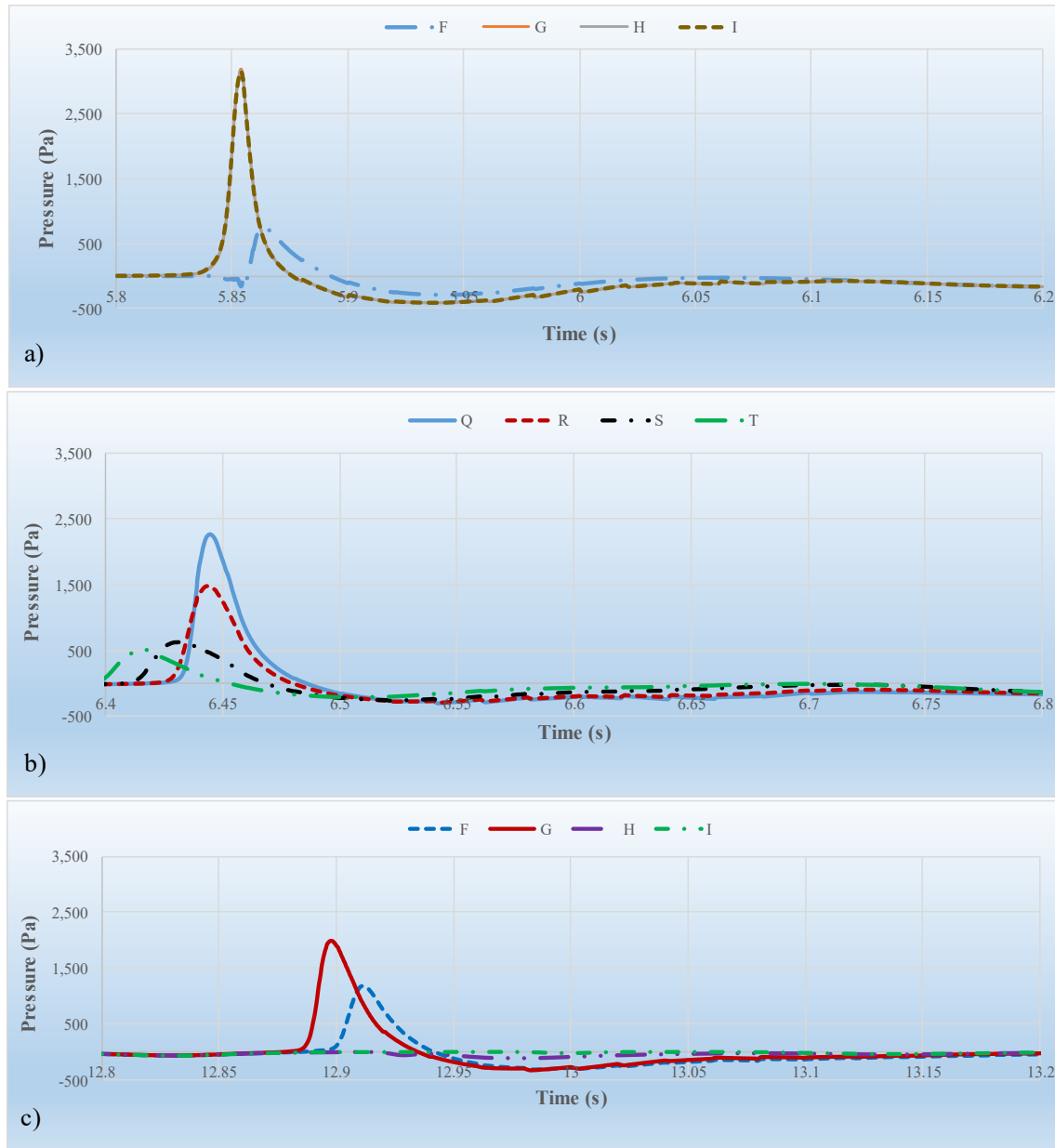


Figure 37: Comparison of pressure distributions for the tank with 200 mm water depth excited by the N-S component of the El Centro earthquake at: (a) 0°, (b) 30°, and (c) 60° orientations.

Figure 38 shows the comparison of pressure for different orientations at sensor location K, located at the corner of the tank, under resonance excitation. It can be seen that when the orientation is changed from 0° to 30° or 60° (i.e., the excitation becomes bi-directional), the maximum pressures at the corners of the tank become higher compared to the ones from the uni-directional excitations (e.g., 0° orientation), and among the cases, the highest pressure was measured at the 30° orientation. It should be noted that in the 90° case, the water did not hit the roof; thus, the pressure for the 90° case was zero, and therefore not shown. The fact that an earthquake's direction is not predictable requires attention for all these possibilities.

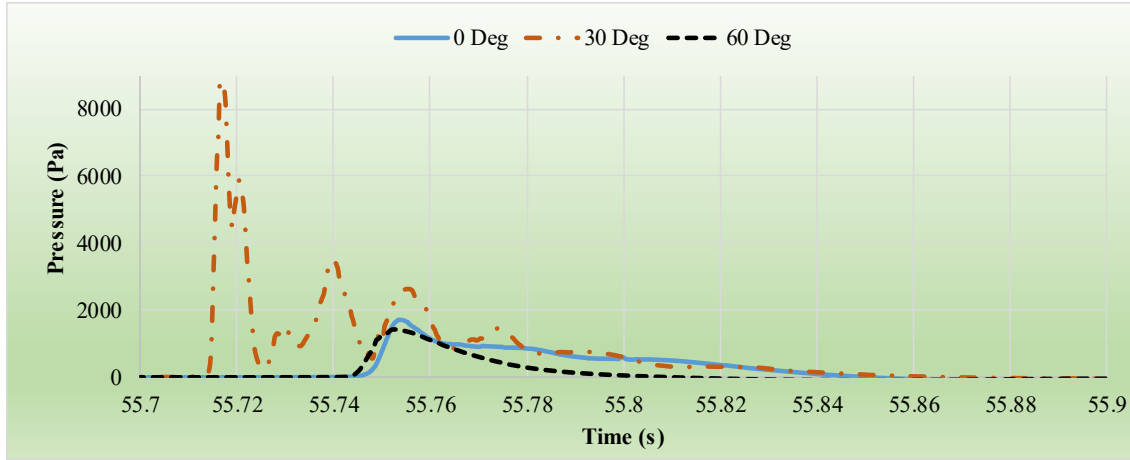


Figure 38: Comparison of pressure at the corner of the tank (sensor location K) with 100 mm water depth excited by resonance frequency at: 0° , 30° , and 60° orientations.

Based on the results from the numerical simulations, the excitation type has a significant effect on the calculated pressures in a sloshing tank. It was found that among the harmonic excitations, the resonance condition (i.e., when the tank is subject to the first convective mode frequency) creates the largest pressure values on the roof. The comparison between the harmonic resonance condition and the El Centro excitation also shows that the resonance condition is the worst case in terms of maximum pressure and can therefore be the most damaging. In Figure 39, the pressures caused by the resonance and earthquake excitations are compared, and shows that avoiding resonance conditions is ideal, although this is not always possible due to the randomness of earthquake motion.

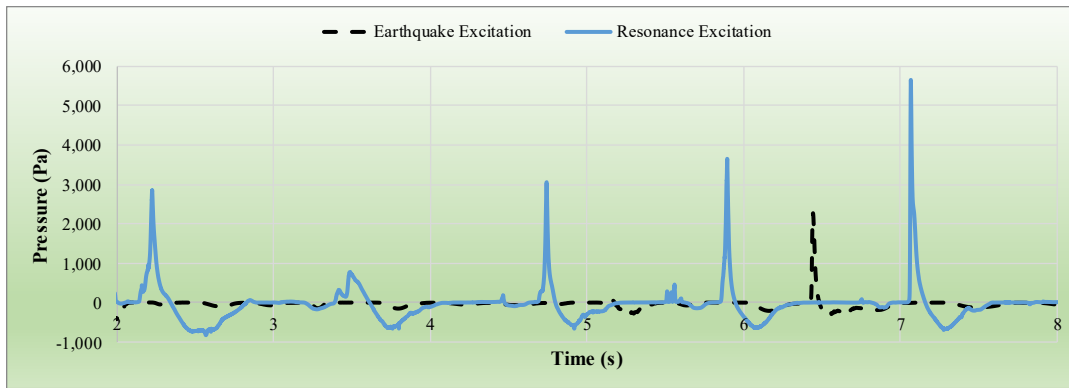


Figure 39: Comparison of maximum pressure caused by earthquake and resonance excitations (sensor location Q) at 30° orientation for tank with 200 mm water depth.

In the next step, the maximum equivalent hydrostatic pressure in each case is calculated and compared with the hydrodynamic pressure values. In this case, a tank with the same plan dimensions but with taller walls was simulated. The reason for this was to explore whether a shallower tank can be replaced with a taller tank to determine if a measured equivalent hydrostatic pressure can be used as an estimation of the hydrodynamic pressure. This approach can lead to a simple calculation of hydrodynamic pressures in the absence of sensors. Furthermore, the computational cost of a hydrostatic numerical model will be significantly less expensive than a

non-hydrostatic CFD model. The walls' heights had sufficient freeboard for the liquid not to reach the tank roof. The same excitations as those for the tanks with short walls were applied, and the liquid height above the 300 mm level was measured (Figure 40). The height can be transformed into pressure as:

$$P_h = \rho \cdot g \cdot h_0 \quad (11)$$

where ρ , g , and h_0 are the liquid density, gravitational acceleration and liquid height at a level above the top of the tank wall in the roofless tank (i.e., equal to the hydrostatic head that hits the roof in the tank with a roof) respectively.

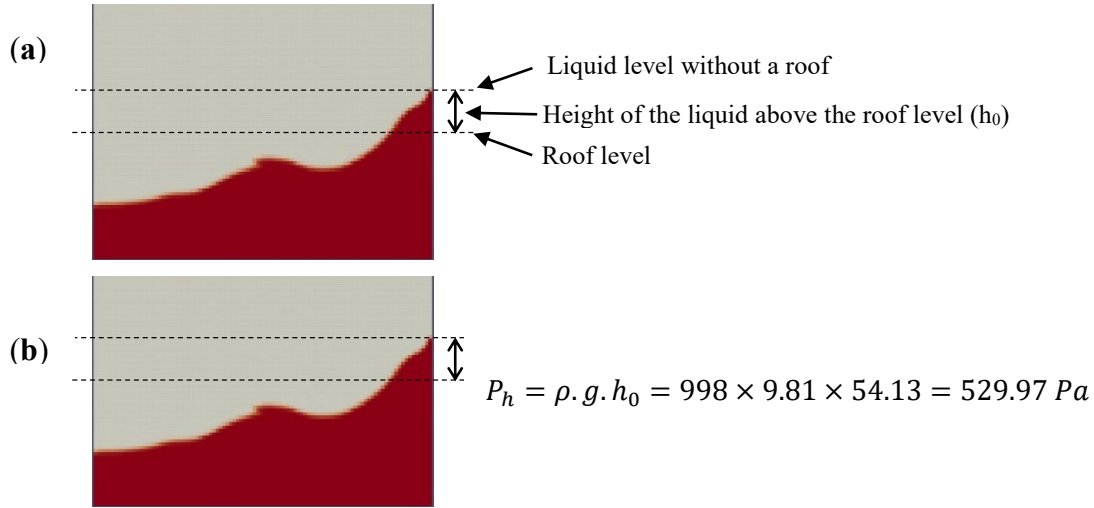


Figure 40: Hydrostatic pressure calculation method for the tank with high walls: (a) schematic view; (b) sample calculation for the tank with high roof filled to 100 mm and excited by the El Centro ground motion.

Table 3 provides the maximum hydrodynamic pressures found at each sensor location for all harmonic resonance and El Centro earthquake excitations and also presents the calculated equivalent hydrostatic pressures for each excitation case for the tank with higher walls. In this table, columns A, G, K, Q represent the sensors located at the corners of the tank. It can be seen from the table that except for one case, the highest maximum hydrodynamic pressure occurs at the corners.

The table shows that in most cases, especially under harmonic excitation, the maximum hydrostatic pressure at the roof level is lower than the maximum hydrodynamic pressure, and the hydrodynamic pressure is up to four times higher than the equivalent hydrostatic pressure. There was one exception, i.e., when the tank with 200 mm water depth as compared to the 100 mm depth was excited by the El Centro earthquake, the hydrostatic pressure was higher than the hydrodynamic pressure. The increase in pressure ranged between 6% and 332%. The reason for this pressure variation could be due to the randomness of the earthquake motion.

The results of this part of the study demonstrate that the use of equivalent hydrostatic pressure will underestimate the dynamic pressure, and thus is not recommended.

Table 3: Maximum hydrodynamic pressure calculated at each sensor location and the equivalent hydrostatic pressure.

Liquid Depth (mm)	Excitation Type	Tank Orientation (Deg)	Maximum Pressure at Each Sensor Location (Pa)																				Maximum Hydrostatic Pressure at the Roof
			A **	B	C	D	E	F	G **	H	I	J	K **	L	M	N	O	P	Q **	R	S	T	
200	Harmonic (resonance *)	0	6356	1241	310	1185	447	1372	9183	4587	4933	4672	6904	1264	727	129	377	1384	10,793	5787	6411	5652	8044
		30	8418	1779	262	368	210	1716	7940	7572	5375	3718	4779	753	480	454	916	758	8977	6676	6167	4546	8444
		60	2230	1831	744	334	137	1187	4119	3764	6438	6794	2163	991	174	158	225	1179	9144	6235	5148	3922	8357
	El Centro earthquake	0	641	2	5	33	111	842	2446	2430	2420	2431	2446	840	112	33	7	2	634	693	901	699	4616
		30	659	57	109	5	18	50	893	279	274	561	791	552	52	0	1	36	2665	1881	695	416	5132
		60	859	674	988	424	76	1179	1987	3	3	3	119	236	127	1	1	901	1801	1	0	0	4321
100	Harmonic (resonance *)	0	8641	1510	894	391	310	438	8822	4685	4175	6319	6700	1821	1049	666	278	1145	8187	8457	4988	7505	4068
		30	19,578	2633	474	929	1073	5144	9215	3768	5037	6306	12,333	1046	758	926	1407	4275	7142	6018	6067	6115	5172
		60	4082	2218	353	179	250	192	3378	1459	3413	5366	8573	4380	187	35	229	294	4618	2397	2487	2576	3337
	El Centro earthquake	0	1051	19	1	4	3	4	1028	1504	112	1099	270	4	3	3	71	18	1208	2067	2289	1798	530
		30	3111	639	295	366	1061	1157	1252	12	44	76	2780	602	63	9	16	1233	2451	373	438	502	2209
		60	658	641	623	397	1580	255	2433	246	221	196	1360	1085	811	891	1348	429	605	108	300	491	1344

* Resonance frequency is calculated based on a tank length of 755 mm.

** Sensor is located at the corner.

3.4. Study on an Actual-Sized Tank

In this part of the study, an actual-sized tank with plan dimensions of 30×15 m and a height of 15 m is numerically simulated under base excitation with resonance frequencies. The goal here is to use the model that has been verified earlier in this study and compare the results of the model with the ACI350.3 (2006). The freeboard and the pressure at the roof of the tank are the parameters of interest. Sixteen sensors are placed on one quarter of the roof (Figure 41). These sensors can capture the pressure at the roof of the tank and locate where the maximum pressure could occur. The results are presented in Figure 42. These results demonstrate that even when sufficient freeboard is provided according to the ACI Code, which is the case for all three cases (see Table 4), the liquid pressure at the roof is significant. Also, two other tanks with total heights of 300 mm and 1200 mm are simulated, and the results are shown in the same table. In addition, the pressure-time history for sensors 1 to 4 is plotted for the 14-m liquid height in Figure 43. This figure shows a significant pressure surge at sensor number 4 compared to the rest of the sensors, which indicates that the corners of a tank's roof need to be designed for much higher pressures when sufficient freeboard is not available.

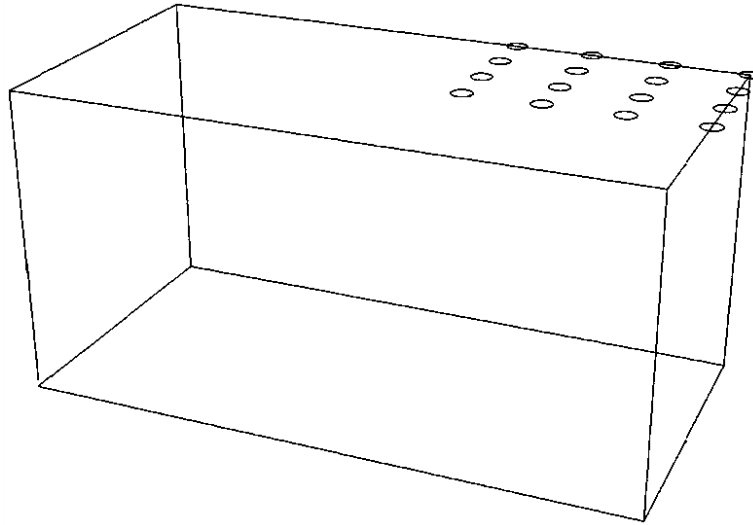


Figure 41: Location of pressure sensors at the roof of the actual-size tank.

Table 4: Comparison of available freeboard and the freeboard required by the ACI 350.3-06 and the maximum pressure at the roof with three different tank sizes.

Tank No.	Tank Height mm	Liquid Height mm	Available Free Board mm	Required Free Board Based on ACI mm	Maximum Pressure at the Roof kPa
1	300	100	200	116	19.6
		145	155	136	9.6
		200	100	153	8.9
		230	70	159	10.6
2	1200	700	500	269	29.3
		800	400	277	19.3
		900	300	283	25.4
		1000	200	287	16.4
3	15,000	10,000	5000	590	52.4
		12,000	3000	642	36.08
		14,000	1000	678	230.6

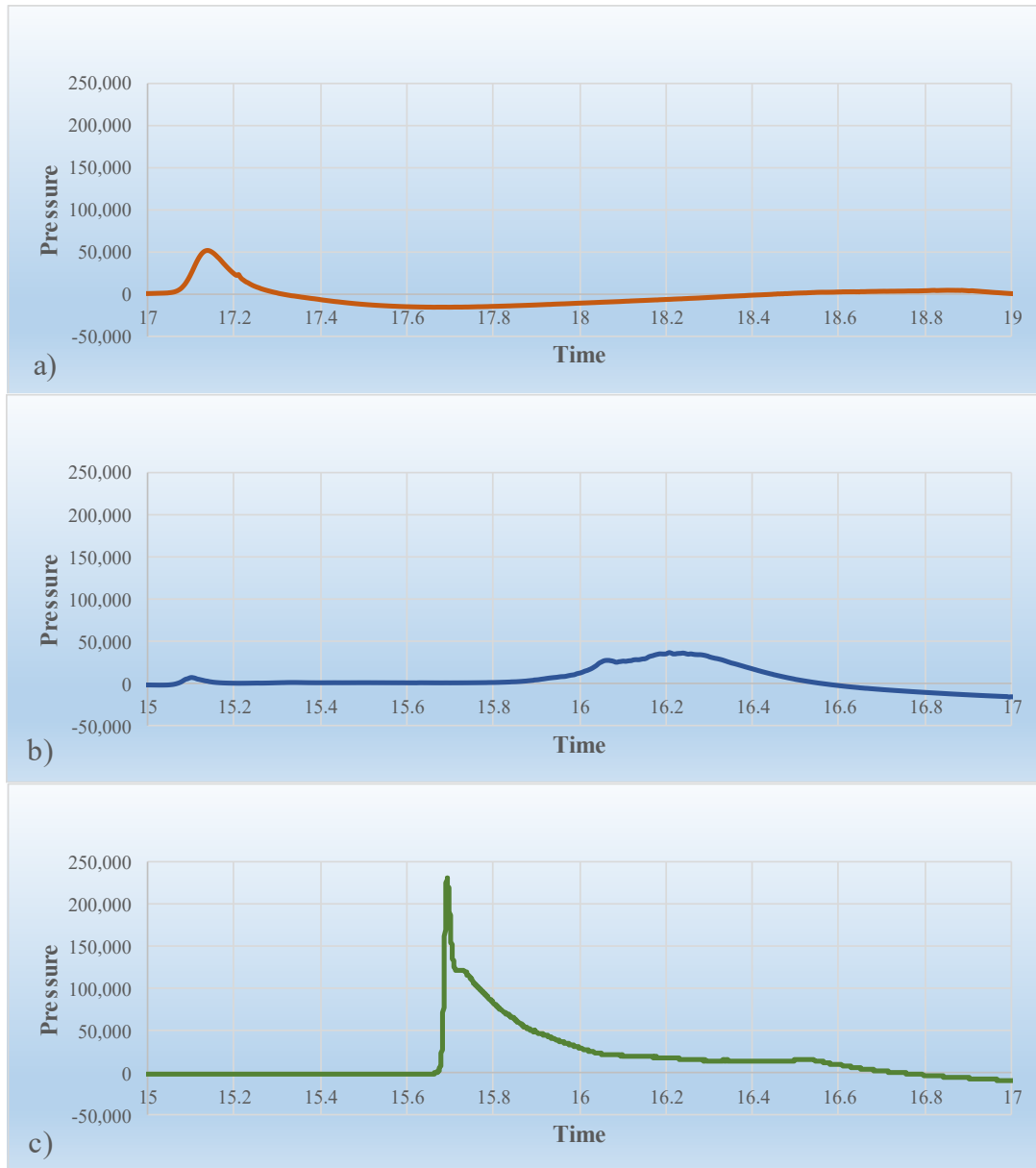


Figure 42: Comparison of pressure at the roof of the actual-size tank for different liquid depths, despite providing sufficient freeboard for all the cases based on the ACI code: (a) 10-m liquid depth; (b) 12-m liquid depth; and (c) 14-m liquid depth.

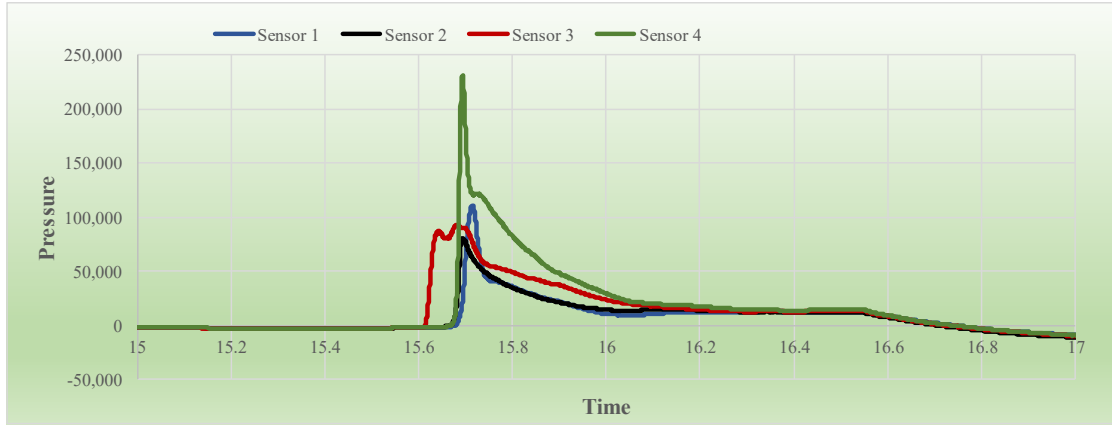


Figure 43: Comparison of pressure time-histories for sensors 1 to 4 of the actual-size tank with 14 m of water.

3.5. Discussion

In this study, a rectangular liquid-containing tank of certain dimensions was tested both experimentally on a shaking table and numerically using the OpenFOAM software. The purpose of this study was to develop a numerical model to simulate the response of LSTs under seismic excitations. Various base excitations, including harmonic as well as a simulated historical earthquake, were applied to the base of a tank that was filled with water to 1/3 and 2/3 of its height. Various excitations were applied at four different horizontal orientations in order to consider the effects of bi-directional motion.

From both the experimental tests and the numerical modeling, good agreement was obtained with Housner's simplified analytical model in predicting the frequency of the first convective mode of the liquid system. In other words, one can reasonably predict the frequency of the first mode of the liquid surface by using Housner's simplified model. In addition, it was found that regardless of excitation type and frequency and the tank orientation on the shaking table, the sloshing height at the corners of the tank was higher than at other locations on the tank walls.

For the model validation, videotapes of the harmonic excitations were captured from the experiments, analyzed frame by frame, and compared to the frames from the same cycle of the numerical simulations. Since an earthquake in terms of frequency and amplitude is a random phenomenon, in order to validate the model for the applied simulated earthquake, in addition to the frame-by-frame comparison (i.e., same as the harmonic excitations), the response histories of the liquid height at one corner of the tank as well as the Fourier transform values of the liquid height were compared for the two parts of the study. Based on this evaluation, the validated model was used to estimate the pressures on the roof of the tank to determine the effect of such pressures at the corners of the tank in comparison with those at other locations on the roof.

The data from the pressure sensors at the roof of the tank from the numerical simulations show that regardless of the excitation type and orientation of the tank, there was a higher maximum pressure at the corners of the tank in comparison with the other locations. In addition, for each excitation type, the maximum pressure at a corner of the tank excited in the 30- or 60-degree directions was higher than that of with single-directional excitations (i.e., 0° and 90° orientations). On this basis, it is recommended that design codes (e.g., ACI 350.3) consider higher pressure

values at the corners of a tank when it may be subjected to ground motions. As such, the effect of bi-directional ground motion needs to be considered. Additionally, it is recommended to use a 3D CFD model to estimate such pressures.

For the three tank sizes designed using ACI 350.3 code provisions and analyzed by providing the sufficient freeboard recommended by the code, it has been shown that the liquid height can exceed the wall height and cause impact pressure on the roof at the wall corners.

3.6. Conclusion

In this chapter, experimental tests were used to validate a combined FVM-VoF model using the OpenFOAM numerical modelling. The model was first fine-tuned based on qualitative and quantitative comparison of numerical results with the experimental results of the authors and then tested against experimental results of [11]. The results showed that the model was reasonably accurate in predicting the free surface of the liquid tanks subjected to base excitation.

Navier-Stokes equations, which are the equivalent of Newton's second law in fluid mechanics were found to be applicable in prediction of the behaviour of the liquid in tanks subjected to base excitation, and hence can be used in other numerical methods such as Finite Difference Method (FDM), Boundary Elements Method (BEM), Smoothed Particles Hydrodynamics (SPH), etc.

Following the model validation, different sizes of tanks were modeled to measure hydrodynamic pressures at the roof. It was found that regardless of tank orientation, and excitation type and frequency, higher hydrodynamic pressures occur near corners. This shows 2D models can be inaccurate in prediction of such pressures.

The results were also compared with the ACI code in terms of free board and it was demonstrated that even in cases where the provided free board is higher than the required free board, the liquid hits the roof and therefor, design standards for the roof are necessary.

4. Prediction of Maximum Pressure at the Roofs of Rectangular Water Tanks Subjected to Harmonic Base Excitation Using the Multi-Gene Genetic Programming Method

Abstract: Liquid storage tanks subjected to base excitation can cause large impact forces on the tank roof that can lead to structural damage as well as economic and environmental losses. The use of artificial intelligence in solving engineering problems is becoming popular in various research fields, and the Genetic Programming (GP) method is receiving more attention in recent years as a regression tool, and for finding empirical expressions between data. In this study, an OpenFOAM numerical model that was validated by the authors in a previous study is used to simulate various tank sizes with different liquid heights. The tanks are excited in three different orientations with harmonic sinusoidal loadings. The excitation frequencies were chosen as equal to the tanks' natural frequencies so that they would be subject to a resonance condition. The maximum pressure in each case is recorded and made dimensionless; then, using Multi-Gene Genetic Programming (MGGP) methods, a relationship between the dimensionless maximum pressure and dimensionless liquid height is acquired. Finally, some error measurements are calculated, and the sensitivity and uncertainty of the proposed equation are analyzed.

Keywords: Liquid Storage Tanks; Base Excitation; Artificial Intelligence; Multi-Gene Genetic Programming; Computational Fluid Dynamics; Finite Volume Method

4.1. Introduction

Earthquakes cause damage to various types of structures, and buildings, dams, reservoirs, and liquid storage tanks which may be victims of an earthquake excitation. Sloshing in a liquid storage tank can cause irreversible structural failure and spillage of the liquid material into the environment, and this liquid, if toxic or flammable, may affect the area for a long time, if not permanently. Thus, protecting liquid storage tanks from damage during an earthquake is crucial. One of the causes is related to pressure exerted on roof of the tank due to sloshing of liquid. Therefore, it is necessary for a designer to know the maximum pressure caused by such effects on a tank's roof.

Analytical, numerical and experimental solutions have been introduced by various scholars. Housner (1963) [15] provided an analytical solution that is adopted in some design codes and standards such as the ACI 350.3 [17]. Housner's method divides the liquid into two parts; impulsive and convective. The former is the lower part of the liquid that moves in unison with the tank walls, while the latter is the upper part of liquid that creates sloshing in a tank. The impulsive mass is assumed to be rigidly connected to the tank's walls, while the convective mass is modeled by a mass-spring system. Figure 44 illustrates Housner's model for ground-supported tanks. Despite attempts at developing analytical solutions other than Housner's method (e.g., Isaacson 2010 [23]), most previous studies have concentrated on numerical analyses. The goal of such studies is to provide a solution to the Navier–Stokes Equations (5) to (8), which are the governing equations in fluid flow. Cho and Cho (2007) [2] developed a combined Finite Element–Boundary Element (FE–BE) method to predict liquid behavior and its interaction with a structure, and Liu and Lin (2008) [39] studied a numerical model to solve 3D nonlinear sloshing in a liquid storage tank. Their model adopted the Volume of Fluid (VOF) method for tracking a free surface in

conjunction with the Finite Difference Method (FDM). Chen et al.'s (2009) [40] numerical model, based on Reynolds-Average Navier–Stokes (RANS) fluid motion, was in good agreement with the experimental data from Daewoo Shipbuilding & Marine Engineering Co., Ltd. (DSME) (Kang and Lee, 2005) [41]. The data were obtained from tests on a rectangular tank with plan dimensions of 800×400 mm and a height of 500 mm that was horizontally excited with different frequencies.

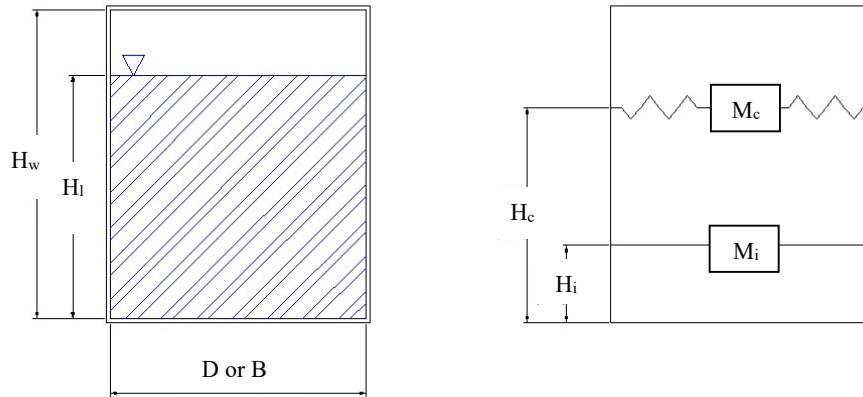


Figure 44: Schematic view of Housner's simplified model.

In recent years, Artificial Intelligence (AI) has been evolving in all aspects of human life, including engineering problems (Afan et al., 2016 [7]). There are several methods for estimation of a relationship between scattered data based on AI. Among them, Group Method of Data Handling (GMDH; Ivakhnenko and Ivakhnenko, 1995 [64]) and Evolutionary Polynomial Regression (EPR) can be mentioned. AI techniques such as Support Vector Machine (SVM), Artificial Neural Networks (ANNs), Adaptive Neuro-Fuzzy Inference System (ANFIS), Genetic Programming (GP) have been recently used for engineering problems such as water quality index and groundwater level modeling (e.g., [65], [67]–[71], [112]).

Model Tree (MT)—a sub-class of regression tree method—is another regression method in which an equation is generated at each node [73]. In a regression tree, a constant or a relatively simple regression model is used to demonstrate the data [74]. A genetic based method known as Genetic Programming (GP) is also used for regression of data. In this method, a set of sub-trees are randomly generated based on user-defined specifications using arithmetic operators (i.e., $+$, $-$, $\times$, $/$), non-linear functions (e.g., $\sin$, $\cos$, $\log$), etc. [74]. The goal is to minimize the errors (e.g., Root Mean Square Error - RMSE) in newer generations until an acceptable error is reached.

Another method for formulating scattered data based on AI is Gene Expression programming (GEP), which was introduced by Ferreira in 1999 (Sattar and Gharabaghi, 2015 [75]). This method can be employed to develop relationships between data with a minimal error [77]. Azamathulla (2012) [78] adopted this method to estimate the scour depth downstream of sills. To do so, he used the following procedure: 1- Choose a fitness function, 2- Choose a set of terminals (T) and functions (F) to shape chromosomes. 3- Choose the chromosome architecture (i.e., head length and the number of genes), 4- Choose the linking function (e.g., addition and multiplication operators) and 5- Choose the set of genetic operators (e.g., mutation, transportation, etc.). He compared his results with the equation obtained by Chinnarasri and Kositgittiwong (2008) [79],

which at the time had the lowest error value and found that the proposed equation using the GEP model had a higher accuracy. Najafzadeh et al. (2016) [80] used three methods of GEP, MT and EPR to predict the maximum scour depth near piers with debris accumulation. Gholami et al. (2019) [81] used the GEP method to predict the characteristics of stable bank channels. They obtained their own experimental data as well as data from previous experimental studies to complete their GEP modelling. The results were compared with available theoretical and experimental methods. Despite a good agreement and accuracy, the model's complexity was found to be higher in comparison with older analytical methods, and therefore, the GEP method was not suggested by the authors. Sheikh et al. (2017) [82] applied GEP to analyze shear stress distribution in circular channels with flat beds subject to sediment deposition. They proposed equations for predicting the base shear applied to the bed and the walls of such channels. It was found that the GEP model could lower the errors and uncertainties, hence recommended for base shear analysis of circular channels with flat beds.

A sub-class of the GP method, known as Multi-Gene Genetic Programming (MGGP) can be used in problems with higher complexity. A gene is a weighted linear combination of outputs from a GP tree. In this method, the user has control over the maximum number of genes and the depth of the model tree [83]. In this method, multiple genes are combined to produce an MGGP model. AI techniques have shown to be capable of accurate prediction, and with the development of computing systems, they have become easier to use. However, to the best of the authors' knowledge, they have not been employed in prediction of pressures and forces in water tanks. Previous studies in engineering applications have shown promising results for MGGP in comparison with other AI techniques such as ANN, ANFIS, traditional GP, etc. [84]–[86].

The use of genetic programming methods in civil engineering is becoming increasingly popular. Gandomi et al. (2013) [87] proposed an empirical model for prediction of the ultimate shear strength of Reinforced Concrete (RC) deep beams using GEP. The results were compared with design codes such as ACI and CSA, and the model was found to give better results than the design codes when compared to the available experimental and numerical data.

Gandomi et al. (2014) [88] developed a model to find the shear capacity of R.C. beams without stirrups using the GEP method. To avoid overfitting, they divided the data in to three groups of learning, validation, and testing on a random basis. The developed model was tested against available data and several design codes (e.g., ACI, CSA, NZS, etc.) for various sizes and models of RC beams and was found to give compatible results.

GEP can be used in various fields of civil engineering as an optimization method. Zahiri et al. (2015) [89] investigated the applications of GEP in hydraulic engineering and found it applicable in different areas such as estimation of scour depth, discharge rate, and land transport in rivers.

In the present study, data generated by a validated OpenFOAM (Open Source Field Operation and Manipulation) [8] model are used. The maximum pressure on the roof of a tank is the parameter of interest. Several tank sizes with various liquid heights are excited by a resonance frequency, and the maximum hydrodynamic pressure at the roof of the tank in each case is obtained. Using the GP method in both single-gene and multi-gene modes, an equation is proposed for prediction of the maximum pressure at the roof of the tank. Finally, the proposed equation's reliability is

investigated and discussed through error measurements, and uncertainty and sensibility analyses. Other AI methods such as Group Method of Data Handling (GMDH) were also considered for this study, however, the GP method was found to be more applicable in terms of providing simple results with reasonable accuracy while not overfitting the model.

To the best of the authors' knowledge, this study that predicts the maximum pressure at the roof of a liquid storage tank subjected to base excitation has not been addressed previously. The design codes generally provide a minimum free-board and if the provided free-board is not sufficient, it is left to the designer as to how to design the roof. No further data is provided in that manner in the design codes. Furthermore, previous studies have not investigated the pressures at the roof of the tank with the intention of finding a relationship between the tank size and the maximum pressure on the roof. The available codes and standards do not provide details for designing the roof of tanks with insufficient freeboard and only recommend designing the roof to resist uplift pressures. Therefore, this study can provide a good estimate of those pressures and help with the design process.

The results from this study can help provide empirical formulations to appropriately estimate the hydrodynamic pressures at the roof of a liquid tank subjected to base excitations. This can be adopted in design codes and standards to better address the uplift forces and hydrodynamic pressures at the roof level. In addition, the artificial intelligence component of this research can significantly reduce computational cost and time.

Although earthquake and harmonic excitations have different characteristics, it was found in a previous study [113] that harmonic resonance excitations can produce higher hydrodynamic pressures on the roof of a tank compared to earthquake excitations, which is the reason this kind of loading was applied in this study instead of earthquake excitations.

This chapter is organized as follows. Section 2 deals with the details and equations of the numerical modeling and MGGP. Section 3 presents the results, discussions and error measurements, and some concluding remarks complete the study.

4.2. Materials and Methods

4.2.1. Numerical Modelling

An OpenFOAM model was previously developed and validated by the authors [113]. The same model is used to generate data for the current study. The maximum hydrodynamic pressure at the roof of rectangular tanks is the parameter of interest in this study. Hence, pressure sensors are distributed on one quarter of the roof for each simulation.

Four different tank sizes are used in the study, the dimensions of which are presented in Table 5. The tank sizes are selected based on different factors such as market commonality and the size of available shaking tables so possible future experimental studies can be conducted. For each tank, a minimum of six different liquid heights are simulated as will be discussed later. Since the direction of an earthquake cannot be predicted, four different tank orientations are tested, and among them, the highest roof pressure for each liquid height in each tank is found.

Many previous studies (e.g., [2], [24], [38]) have shown that Housner's simplified method (Housner 1963) [15] predicts resonance frequency accurately, and hence in this study the same method is applied.

Based on Housner's method, the resonance frequency in a rectangular tank can be calculated as follows:

$$M_c = M \frac{\tanh 1.7 L/h}{1.7 L/h} \quad (10)$$

$$k_c = 3 \frac{M_1^2 g h}{M L^2} \quad (11)$$

$$\omega_c = \sqrt{\frac{k_c}{M_c}} \quad (12)$$

$$T_c = \frac{2\pi}{\omega_c} \quad (13)$$

where M_c is the mass of the convective part of the liquid (c = convective), M is the total liquid mass, L is half of the tank length, h is the total liquid height, k_c is the stiffness of the assumed spring that connects the convective mass to the tank's walls in the direction of movement, g is ground acceleration equal to 9.81 m/s^2 , and ω_c and T_c are the resonance frequency and resonance period of the first (fundamental) mode of the oscillating liquid, respectively. In lieu of Housner's method to determine the natural frequency of the tank, Lamb's formula can be used for simplicity [114]. In Table 6, the resonance frequencies that are applied to each tank based on the size and liquid height are presented. Each tank size - liquid height combination is simulated at four different orientations of 0° , 30° , 60° , and 90° . Since the direction of an earthquake is not predictable, the maximum pressure among all orientations was used as the input for the genetic programming section. In other words, the maximum of maximums was found and applied to the GP. The excitation orientations of 0° , 30° , and 60° are presented in Figure 45.

Table 5: Dimensions of tanks used in the study.

	Length (mm)	Width (mm)	Height (mm)
Size 1	755	300	300
Size 2	1978	779	1200
Size 3	1283	327	1200
Size 4	683	342	1200

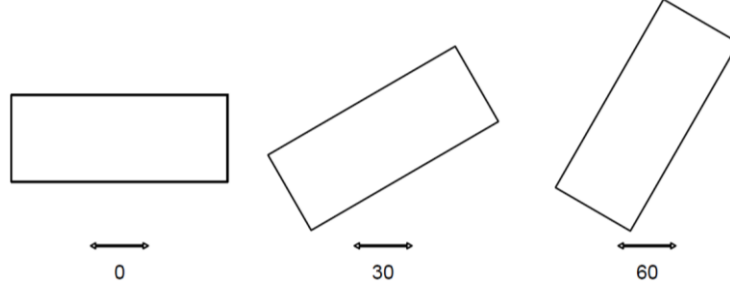


Figure 45: Tank orientations for simulations.

After finding the resonance frequency for each tank size and liquid height, the numerical modelling is performed using OpenFOAM software. The OpenFOAM model can provide numerical solutions for various types of engineering problems, such as heat transfer, mass transport, liquid flow, etc. It can also solve fluid-structure interaction problems based on Computational Fluid Dynamics (CFD) modelling [115]. Navier–Stokes Equations (5) – (8), are solved for these types of problems.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (14)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \nabla^2 u \quad (15)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \nabla^2 v \quad (16)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \nabla^2 w - g \quad (17)$$

in which

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (18)$$

and ρ and p are the liquid density (kg/m^3) and total pressure (Pa) respectively, u , v and w are the particle speeds in the x , y and z directions (m/s), t is time (s), and $g = 9.81 \text{ m/s}^2$ is the gravity acceleration and

$$\rho = \alpha \rho_1 + (1 - \alpha) \rho_2 \quad (19)$$

where ρ_1 and ρ_2 are the densities of air and water respectively and α indicates the volume of each particle that is filled with each of the fluids. The value of α varies between 0.0 and 1.0 with 1.0 meaning the cell is filled with water, and 0.0 indicating air. A value of 0.5 is allocated to the free surface. Any value between 0.0 and 0.5 indicates air and a value between 0.5 and 1.0 indicates water.

Given the very high momentum of the flow, turbulent stresses have a negligible effect on the on the flow in comparison with the liquid sloshing forces, and hence, turbulence was not modeled in this study.

4.2.1.1. Computational Set-Up

Mesh

In this study, a structured cubic mesh is used. By running a mesh sensitivity analysis, the optimum mesh size is found. To do so, the pressure at the top corner of the tank was measured with various mesh sizes.

Initial conditions

For the initial conditions, the velocity, acceleration, and displacement fields are set to zero.

Wall boundary conditions

The “no flow, frictionless” wall boundary condition is applied to the base and the side walls of the tank. This implicit boundary condition is used when no flow crosses the wall and the shear stress at the wall and normal gradient of tangent velocity are set to zero. In other words, no fluid enters or exits the boundary where this condition is applied. This boundary condition is applied as follows:

$$U_n = 0 \quad (20)$$

$$\frac{\partial}{\partial n} U_\tau = 0 \quad (21)$$

where U_n and U_τ are the normal and the tangential velocities of the flow, respectively and n is the normal vector of the boundary.

Free surface boundary conditions

The pressure at the free surface is set to zero and the free surface is modelled using the Volume of Fluid (VoF) method according to the following equation:

$$\frac{\partial \alpha}{\partial t} + \frac{\partial(\alpha u)}{x} + \frac{\partial(\alpha v)}{y} + \frac{\partial(\alpha w)}{z} = 0 \quad (22)$$

Table 6: Frequency applied to each tank based on the tank size and liquid height.

	Length (mm)	Width (mm)	Tank Height (mm)	Liquid Height (mm)	Dimensionless Liquid Height (h/L)	ω_i (rad/s)	T_i (s)
Size 1	755	300	300	100	0.265	4.023	1.562
				120	0.318	4.354	1.443
				145	0.384	4.705	1.335
				200	0.53	5.282	1.190
				230	0.609	5.510	1.140
				250	0.662	5.636	1.115
				280	0.742	5.792	1.085
Size2	1978	779	1200	1100	1.112	3.819	1.645
				1000	1.011	3.777	1.663
				900	0.910	3.721	1.689
				800	0.809	3.644	1.724
				700	0.708	3.540	1.775
				600	0.607	3.400	1.848
Size3	1283	327	1200	1100	1.714	4.858	1.293
				1000	1.559	4.845	1.297
				900	1.403	4.824	1.303
				800	1.247	4.789	1.312
				700	1.091	4.732	1.328
				600	0.935	4.640	1.354
Size4	683	327	1200	1100	3.221	6.686	0.940
				1000	2.928	6.686	0.940
				900	2.635	6.685	0.940
				800	2.343	6.682	0.940
				700	2.05	6.677	0.941
				600	1.757	6.662	0.943

4.2.1.2. CFD Details

In the mesh sensitivity analysis, a mesh size of $6 \text{ mm} \times 6 \text{ mm} \times 6 \text{ mm}$ was found to be reasonably accurate. An adjustable scheme was chosen for the time-step, with a maximum step size of 0.05 s. This means each time-step is chosen based on the previous step. This helps with the accuracy of the simulation results; however, it has higher computational costs.

In the validated OpenFOAM model, an eddy viscosity of $2 \times 10^{-4} \text{ m}^2/\text{s}$ was found to provide the best results compared to the experimental data.

A total of eighteen pressure sensors (probes) are distributed on one quarter of the roof for each of the simulated tanks. The sensors are placed on the direction of motion where the highest hydrodynamic pressures are captured based on the results obtained in chapter 3, and the long

duration of the simulations is expected that the pressure distribution on a quarter of the domain can be representative of the entire roof. In addition, in this study, the quarter of the roof with the highest pressure was selected for the GP analysis. The placement of sensors on the roof of the tank are presented in Figure 46. Using these sensors, the pressure distribution on the roofs of the tanks can be found. Figure 47 shows a sample of the CFD output; more details on the OpenFOAM model are given by Bahreini et al. (2020) [113].

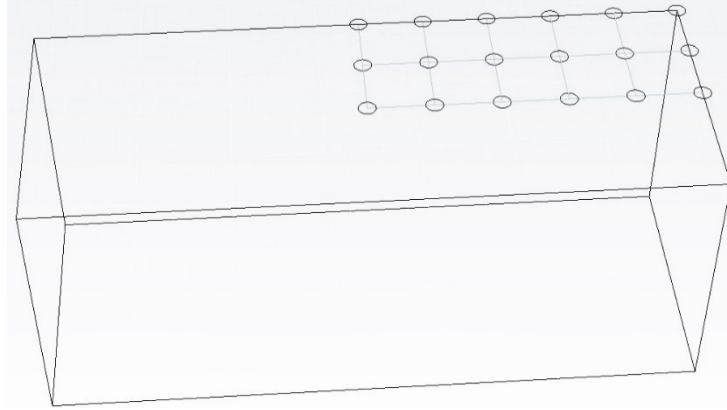


Figure 46: Sensor arrangement at the roof of the tank.

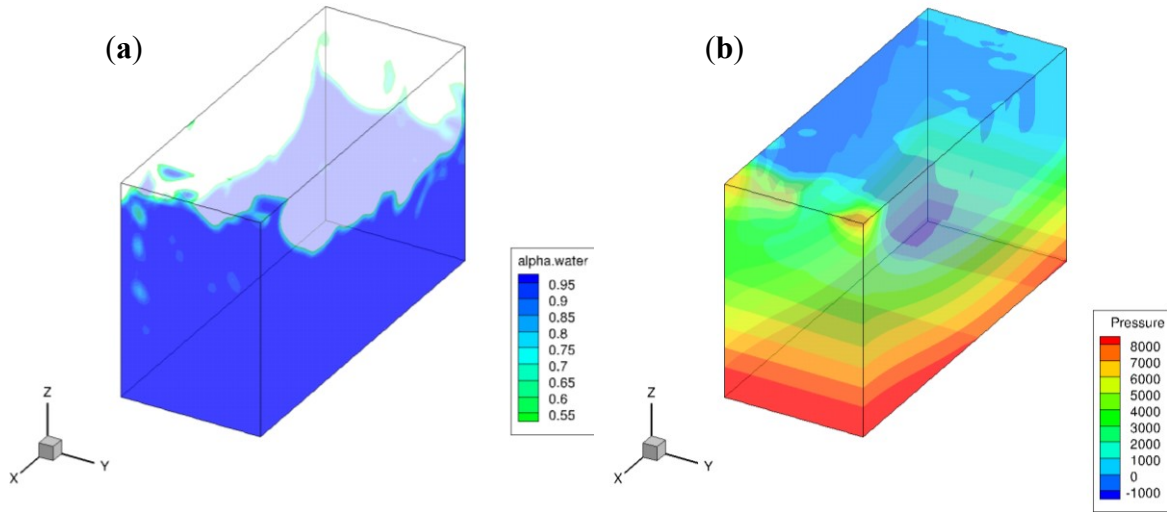


Figure 47: Computational fluid dynamics (CFD) outputs for tank size 2, with 800 mm water depth at 0° orientation and time $t = 9.50$ s; (a) liquid surface and (b) pressure.

4.2.2. Genetic Programming

Genetic programming (GP) is a method based on artificial intelligence that can be used in optimization problems. This method can be applied in Single-Gene and Multi-Gene models. In this method, the structure of the solution is not specified at the beginning and is shaped throughout the evolution [116]. Initial chromosomes are created, and during generations of evolutions and mutations, newer chromosomes with optimized characteristics are created. These cycles continue until the maximum number of iterations is reached or until the optimization reaches a point that is

close to the solution (i.e., the error is negligible). In the Single-Gene model, mutations occur to one gene, while in the Multi-Gene method, there are mutations and crossovers across several genes.

In this method, the goal is to find the best-fit expression using the fit function (Equation (23)). This function has a value between 0 to 1000, with 1000 being the fittest, i.e., with the minimum error.

$$f_i = 1000 \frac{1}{1 + RRSE_i} \quad (23)$$

where

$$RRSE_i = \sqrt{\frac{\sum_{j=1}^n (P_{(ij)} - T_j)^2}{\sum_{j=1}^n (T_j - \bar{T})^2}} \quad (24)$$

and i is the number of the fit function, j is the number of data, $P_{(ij)}$ is the calculated value for j^{th} data based on i^{th} function, T_j is the actual value for the j^{th} data, and $\bar{T}$ is the average of the T_j values.

In GP-based methods, an initial gene or tree is randomly created, and the process starts. Several reproductions, including mutation (i.e., random changes in a gene and replacing a material with another material) and crossover (i.e., interchange of materials between the parent genes) operations, take place until the termination conditions are fulfilled.

Each gene is in a shape of a tree and consists of two types of nodes: (1) operator nodes, being mathematical operators (e.g., +, -, ×, /, power, sin, cos, log, etc.); and (2) operand nodes, which are the input variables, e.g., x_1 , x_2 , etc. (Pandey et al. [117]).

Here, an example is presented for further explanation and a better understanding. In a regression problem with two operands of x_1 and x_2 (i.e., $y = f(x_1, x_2)$), y is dependent on two variables of x_1 and x_2 , A_1 and B_1 are randomly created parent genes as follows:

$$A_1 = (2.3 \times x_1) - (\sin x_2) \quad (25)$$

$$B_1 = (1.1 \times x_1^2) + (\log x_2) \quad (26)$$

In a crossover process, a sub-tree of the parent gene A_1 is switched with a sub-tree of the parent gene B_1 , resulting in second generation genes, A_2 and B_2 :

$$A_2 = (2.3 \times x_1) - (1.1 \times x_1^2) \quad (27)$$

$$B_2 = (\log x_2) + (\sin x_2) \quad (28)$$

And in a mutation process, a sub-tree of each of the genes A_2 and B_2 is replaced by a new randomly chosen sub-tree, creating the third-generation genes, A_3 and B_3 :

$$A_3 = (1.3 \times x_2^3) - (1.1 \times x_1^2) \quad (29)$$

$$B_3 = (\log x_2) + \left(\frac{x_1}{x_2}\right) \quad (30)$$

This sequence continues until the termination conditions are fulfilled. At the end, the two genes are combined to form the equation:

$$Y_i = \alpha(A_i) + \beta(B_i) + C \quad (31)$$

which, in this three-generation example, is as follows:

$$y = \alpha[(1.3 \times x_2^3) - (1.1 \times x_1^2)] + \beta[(\log x_2) + \left(\frac{x_1}{x_2}\right)] + C \quad (32)$$

where α and β are called gene weights, and C is a constant bias term. The gene weights and bias term are calculated by an ordinary least-squared method. Figure 48 shows the procedure of this example in the form of MGGP trees.



Figure 48: An example of a Multi-Gene Genetic Programming (MGGP) procedure.

In the current study, using MATLAB, an open-source MGGP algorithm (Genetic Programming Toolbox for the Identification of Physical Systems; GPTIPS) [118] is run to provide the general shape of the prediction function. In this algorithm, there is a random initial assumption for the function; then, the function is developed through generations until the error is minimized. Finally, using non-linear least squared optimization, an optimized equation is obtained that can be used for further analysis, as described in the following. This algorithm uses Pareto theory to find a balance between the fitness and complexity of the model in order to select the optimum model.

Figure 49 shows an example output tree of the MGGP algorithm. In this tree, the operators plus (+), minus (-), division (/), and multiplication ($\times$) are used. The tree depth in this example is 12, and it has a total of 35 nodes.

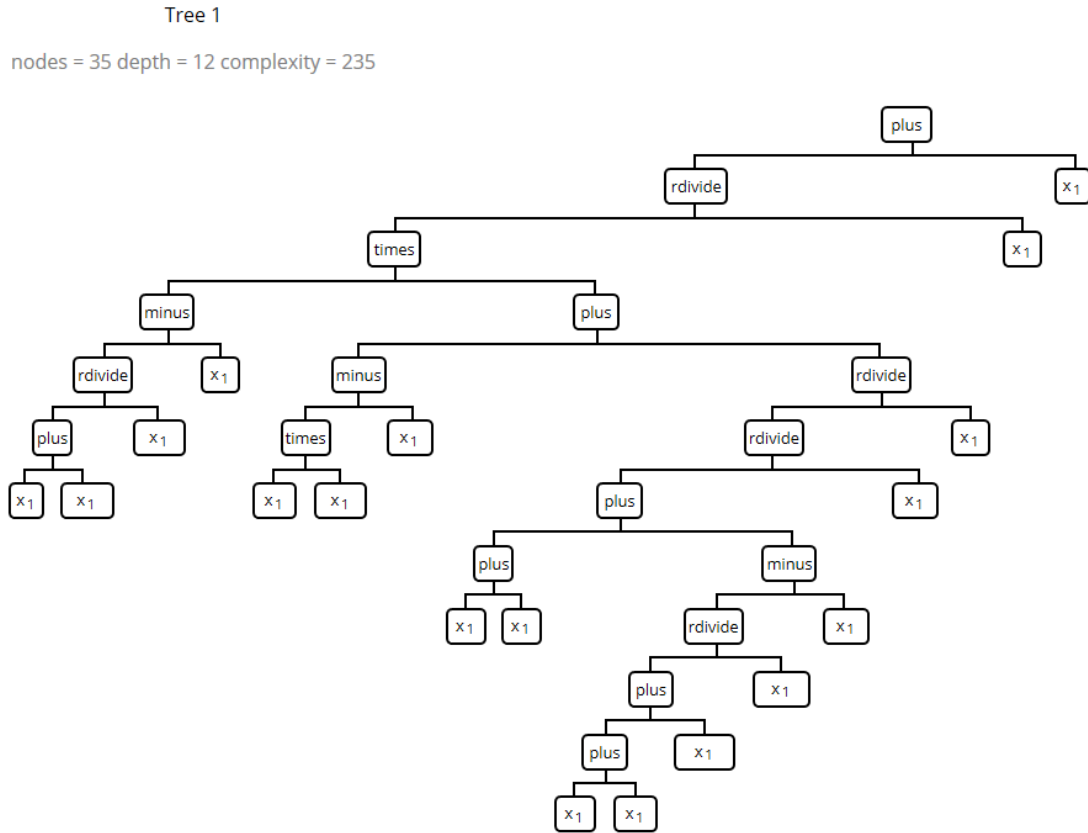


Figure 49: MGGP example output.

In this method, chromosomes are introduced as computer programs of different shapes and sizes, with each consisting of sub-programs called genes, i.e., each chromosome is composed of genes. A typical GP method procedure is as follows:

1. A set of variables is initiated.
2. The chromosomes' architecture is defined.
3. The chromosomes are randomly formulated.

This cycle continues until the function that best fits the data is found. For this study, from a total of 25 samples, 80% (20 samples) were used to train the model while 20% (5 samples) were used for testing (i.e., for validating the model). The trained data are expected to show higher accuracy and smaller errors since the model is directly obtained from this set of data. The tested and trained data are chosen on a random basis.

4.3. Results and Discussion

4.3.1. Numerical Modelling

Following a mesh sensitivity analysis and the completion of the simulations, the results were analyzed for each case. At this stage, contours illustrating the maximum pressure distribution (not at a specific time-step but over the simulation time) on the roof are plotted for each simulation. Contours associated with the 755 mm $\times$ 300 mm tank are presented in Figures 50–52. In the figures, the bottom left represents the center of the roof with dimension of (0, 0), while the top right shows the corner (375.5, 150). The results from the numerical models show that in 46 out of 67 simulations (67%), the maximum pressure on the roof of the tank occurs at the corner. It is worth noting that in the 90° orientation, the liquid did not hit the roof, hence no pressure was captured for those cases and they are eliminated from the results in the following sections.

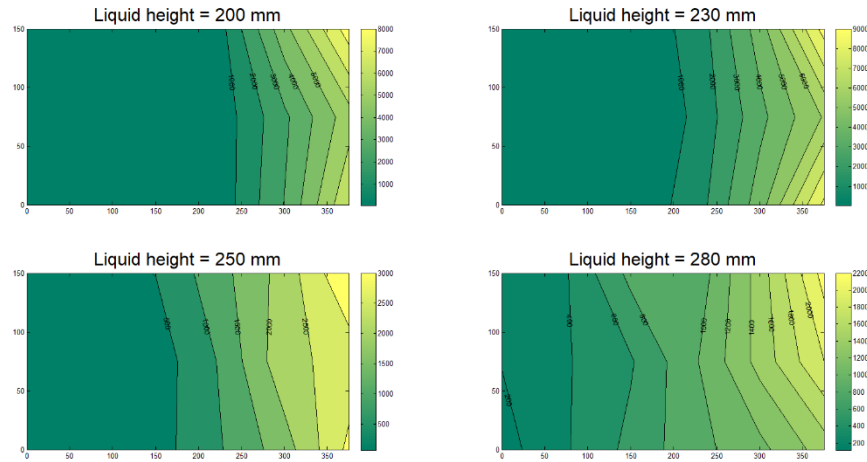


Figure 50: Pressure distribution at the roof of the 755 mm $\times$ 300 mm tank, 0° orientation.

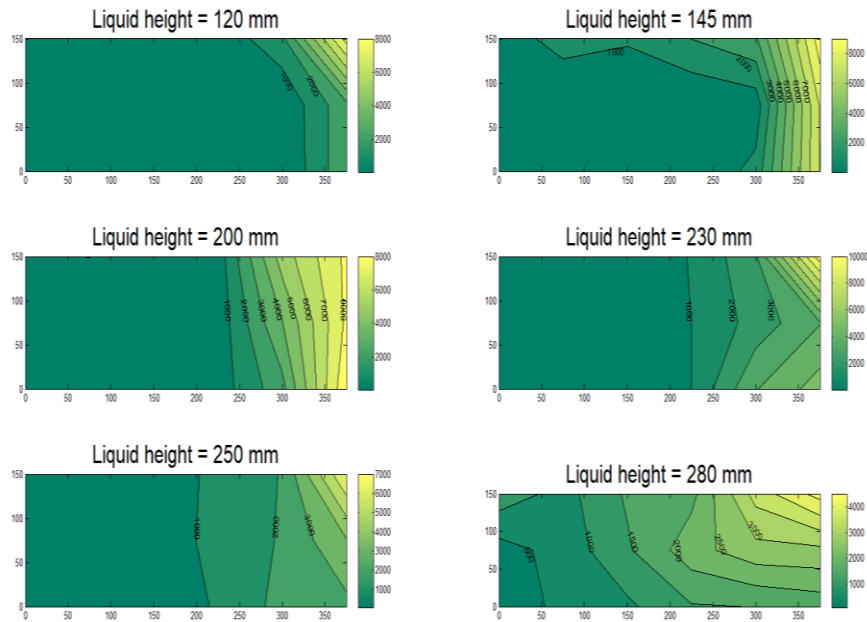


Figure 51: Pressure distribution at the roof of the 755 mm $\times$ 300 mm tank, 30° orientation.

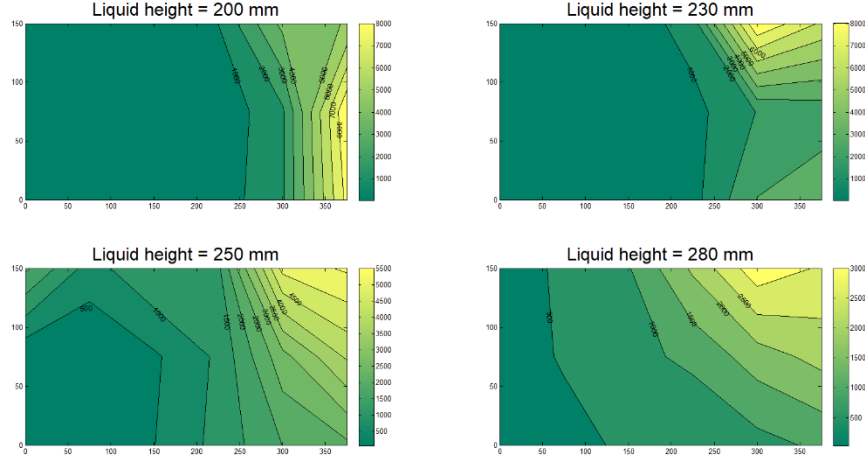


Figure 52: Pressure distribution at the roof of the 755 mm × 300 mm tank, 60° orientation.

To find a relationship to predict the maximum pressure for any tank size with any liquid height, the pressure and liquid height need to be dimensionless. It should be noted that the dimensionless maximum pressure needs to consider all factors that might affect the value of the pressure, and hence, the dimensionless pressure and dimensionless liquid height can be calculated by Equations (33) and (34). These coefficients are selected on a trial-and-error basis. Various equations for dimensionless pressure and dimensionless liquid height were tested until a trend was found.

$$P_d = \frac{P_{max}}{(a \cdot \rho \cdot h \cdot L \cdot H) / (Fb)^2} \quad (33)$$

$$h_d = h/L \quad (34)$$

where P_d is the dimensionless pressure, P_{max} is the maximum pressure on the roof, a is the maximum acceleration of the harmonic excitation, ρ is the density of water, h is the liquid height in the tank, H is the height of the tank, L is half of the length of the tank (i.e., the tank's length is $2L$), and Fb is the available freeboard. The parameters a and Fb can be calculated by Equations (35) and (36):

$$a = A \cdot \omega_i^2 \quad (35)$$

$$Fb = H - h \quad (36)$$

In Equation (35), A is the displacement amplitude of the harmonic motion and ω_i is the excitation frequency of the tank. In Figure 53, the dimensionless maximum pressure plotted against the dimensionless liquid height are presented in a scatter graph. It should be noted that the results presented in this study are valid for cases when the sloshing height exceeds the wall height, which then generates pressure on the roof of a tank.

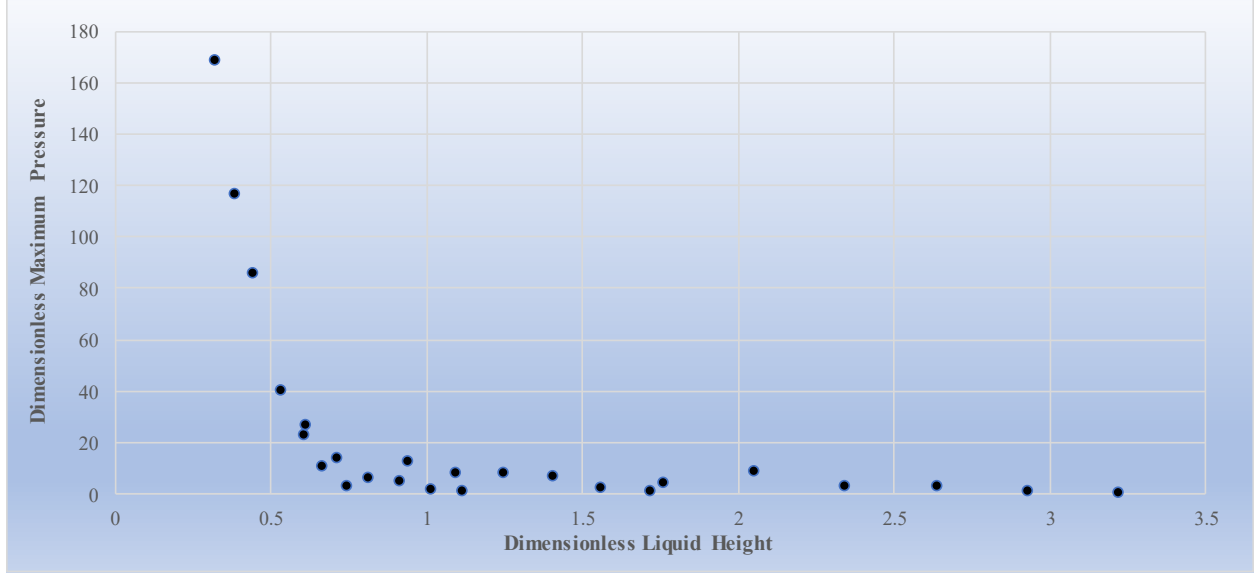


Figure 53: Dimensionless maximum pressure versus dimensionless liquid height for the observed (CFD) data.

4.3.2. Genetic Programming

The GPTIPS algorithm allows the user to choose between Single-Gene and Multi-Gene solutions. Single-Gene is the more traditional way of GP and results in simpler equations. Although the Multi-Gene process is more complex, it may lead to solutions with higher accuracy. In this study, the default crossover and mutation coefficients were used as follows: probability of Multi-Gene GP tree cross over = 0.85, probability of Multi-Gene GP tree mutation = 0.1, and probability of Multi-Gene GP tree direct copy = 0.05.

In this section, both Single-Gene and Multi-Gene solutions are examined and explained, and the results are presented.

4.3.2.1. Single-Gene Solution

In the single-Gene solution, the procedure is simple. There is only one gene and a bias term; hence, there is no crossover of sub-trees. Mutations, however, occur in this solution. The equation obtained from the GPTIPS algorithm in the Single-Gene mode is presented in Equation (28):

$$P_{d,S} = 4.6489 - \frac{12.498 \times \ln(h_d)}{h_d^3 + 0.0534} \quad (37)$$

where, $P_{d,S}$ is the dimensionless maximum pressure obtained by the Single-Gene solution.

To obtain this equation, the algorithm was set to have 200 generations, with a population size of 300. The maximum tree depth was set to 4, and operators plus, minus, multiply, divide, and log (which in MATLAB means the Napierian logarithm, i.e., $\ln$) were used. This equation is obtained in generation 184. It should be noted that for the simulated tanks, h_d (i.e., dimensionless liquid height) has a value between 0.3179 and 3.2211, and hence the results are valid for tanks with dimensionless liquid height in that range. Since this relationship is obtained based on the maximum

pressure in all tank orientations, it is not affected by the angle of tank orientation. Figure 54 presents the complexity of the model plotted against its accuracy level ($1 - R^2$) for the population on the training set of data. In this figure, green dots represent Pareto models which represent an acceptable balance between complexity and error, and blue dots represent non-Pareto models. The green dot with a red circle shows the best model in terms of R^2 on the training data.

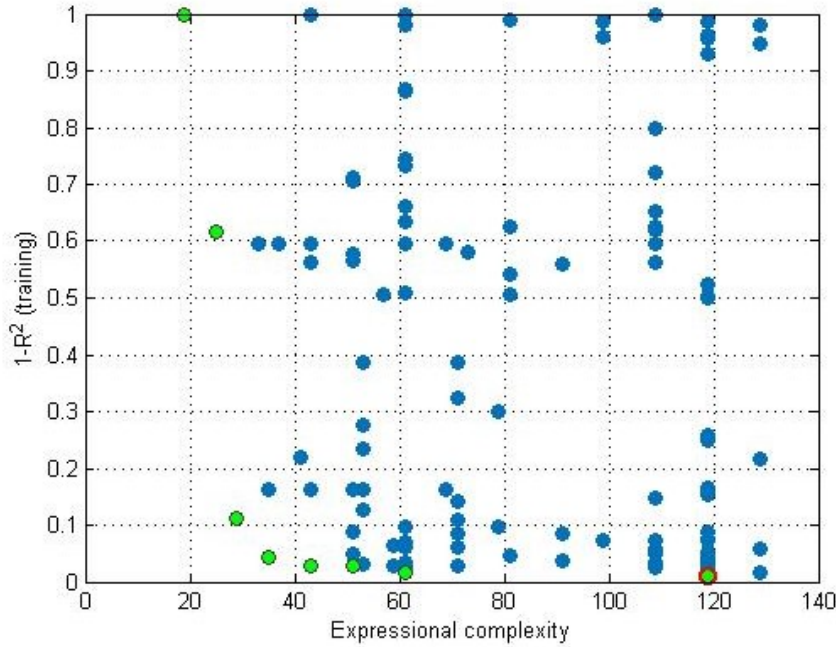


Figure 54: Expressional complexity of the proposed Single-Gene model.

4.3.2.2. Multi-Gene Solution (MGGP)

In this step, the algorithm is modified to use multiple genes. This mode has both crossover and mutation processes. The following equation (Equation (29)) is obtained from the Multi-Gene procedure.

$$P_{d,M} = 5.1961 + \frac{(2.383h_d^3 - 16.846h_d^2 + 17.484h_d - 3.402)}{h_d^5} \quad (38)$$

In this equation, $P_{d,M}$ is the dimensionless maximum roof pressure obtained by the Multi-Gene program. The number of generations was set to 500 with a population of 300. Equation (29) was obtained in generation 473. This equation is composed of the following genes:

$$\text{Gene 1: } -\frac{0.920h_d + 3.402}{h_d^5} \quad (39)$$

$$\text{Gene 2: } \frac{2.383h_d^2 - 16.85h_d + 18.4}{h_d^4} \quad (40)$$

A bias term equal to 5.196 was obtained. Figure 55 presents the complexity of the model plotted against its accuracy level ($1 - R^2$) for the population on the training set of data.

The reason for having a different number of maximum generations for the GP and MGGP models is that for the GP model, the optimum equation was found in the 184th generation, and for the MGGP model it was in the 473rd generation. Therefore, while the 200 maximum generations sufficed for the GP model, the MGGP model required a higher number of maximum generations. These numbers were chosen on a trial-and-error basis, starting from 100 generations until the optimum equation was obtained at a generation smaller than the maximum number of generations. This could ensure that the obtained equation was the optimal one.

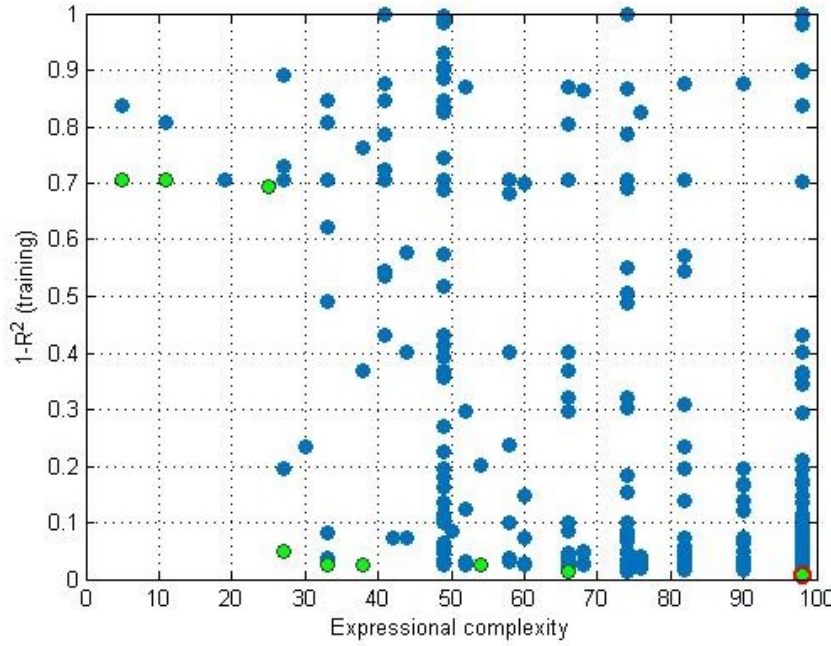


Figure 55: Expressional complexity of the proposed Multi-Gene model.

4.3.2.3. Error Estimations

In this section, some error measures of the Single-Gene and Multi-Gene models are presented and compared. These measurements can help determine the accuracy of the presented models and the choice of each option. Errors were measured for both Single-Gene and Multi-Gene programs on the trained and tested data and were finally compared against each other.

a. R-Squared (R^2)

In this section, the calculated dimensionless maximum pressure (based on Equations (28) and (29) for Single-Gene and Multi-Gene solutions, respectively) are plotted against the observed dimensionless maximum pressure in Figure 56. The R^2 , is calculated as

$$R^2 = 1 - \frac{\sum (P_d - P_{d,GP})^2}{\sum (P_d - \overline{P_d})^2} \quad (41)$$

where $P_{d,GP}$ is the dimensionless maximum pressure obtained by the MGGP, and $\overline{P_d}$ is the average of the observed dimensionless maximum pressures. Table 7 presents the R^2 values for the Single-Gene and Multi-Gene solutions.

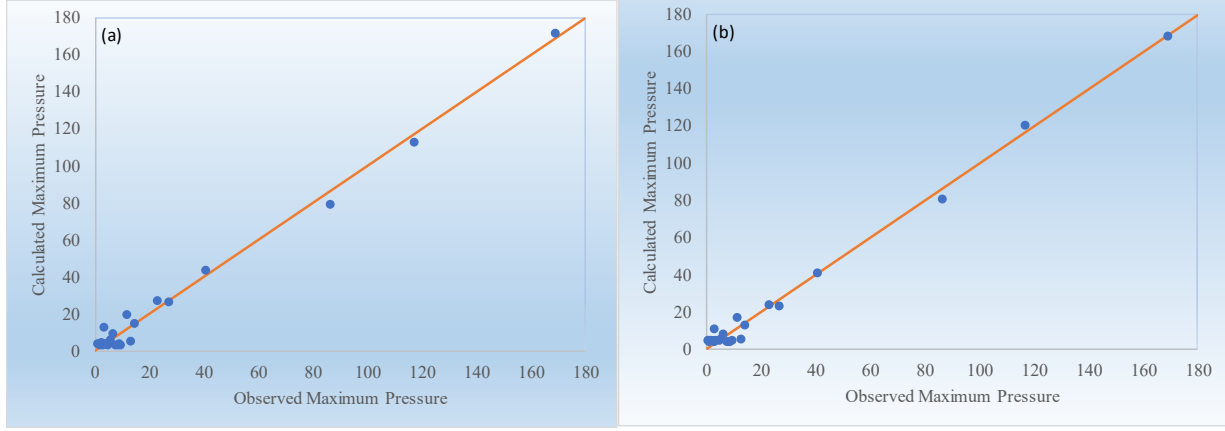


Figure 56: Observed dimensionless maximum pressure plotted against the dimensionless maximum pressure obtained by (a) Single-Gene procedure and (b) Multi-Gene procedure, for the overall data sets.

b. Root Mean Squared Error (RMSE)

The standard deviation of the residuals, known as root mean squared error (RMSE) is another way of error reporting. It shows the concentration of data near the regression graph. RMSE is calculated based on the following equation:

$$RMSE = \sqrt{\frac{\sum (P_d - P_{d,GP})^2}{N}} \quad (42)$$

where N is the number of observed data, which in this study is 20 for the trained data set, 5 for the test data set, and 25 for the overall data. RMSE has the same dimensions as the original data. In this case, since the input data set is dimensionless, the RMSE is also dimensionless. RMSE values for each of the data sets are presented in Table 7.

c. Mean Absolute Deviation (MAD)

Mean absolute deviation or MAD is a tool for showing the scatteredness of data around the mean. It can be measured by the following equation:

$$MAD = \frac{\sum |P_d - \bar{P}_d|}{N} \text{ or } MAD = \sqrt{\frac{\sum (P_d - \bar{P}_d)^2}{N}} \quad (43)$$

The MAD measurements for each data set are presented in Table 8.

d. Mean Absolute Error (MAE)

Mean absolute error (MAE) is the average of the absolute values of the difference between the observed and measured data. In other words,

$$MAE = \frac{\sum |P_d - P_{d,GP}|}{N} = \sqrt{\frac{\sum (P_d - P_{d,GP})^2}{N}} \quad (44)$$

The MAE values are presented in Table 7.

e. Mean Absolute Percentage Error (MAPE)

This error measures the accuracy of the model as a percentage and is calculated as follows:

$$MAPE = \frac{1}{N} \sum \frac{P_d - P_{d,GP}}{P_d} \times 100\% \quad (45)$$

The MAPE values found in this study for different data sets of Single-Gene and Multi-Gene modes are presented in Table 7.

The reason for such high MAPE values is the shape of the fitted curve in which the graph has a steep slope in the beginning and smoothens later. This steep slope can significantly increase errors between the model and observed results. However, other error estimates show that the generated models are reasonable in their predictions.

f. Akaike Information Criterion (AIC):

The results were also compared using the Akaike information criterion (AIC) using the following equation [119]:

$$AIC = N \times \log(\sqrt{RMSE}) + 2k \quad (46)$$

where k is the number of optimized coefficients. The results are presented in Table 7. The value of the AIC can help compare the complexity and the accuracy of the models at the same time, [120]. Although not intended to, but AIC also shows if overfitting happens during a model generation. Higher AIC values may suggest overfitting in a model [121]. The results show that when combined, the simplicity and accuracy of the two models (i.e., Single-Gene and Multi-Gene methods) are very close, and there is a difference of 3.1%, 13%, and 1.2% between the Single-Gene and Multi-Gene models for the trained, test, and overall data sets.

g. Performance Index (PI):

In addition to error estimates, evaluating the model performance is helpful in the comparison of different models. The performance index (PI) can be used for this purpose as follows [122]:

$$PI = \frac{RRMSE}{R + 1} \quad (47)$$

$$RRMSE = \frac{RMSE}{|\bar{P}_d|} \quad (39)$$

$$R = \frac{\sum (P_d - \bar{P}_d)(P_{d,GP} - \bar{P}_{d,GP})}{\sqrt{\sum (P_d - \bar{P}_d)^2 \sum (P_{d,GP} - \bar{P}_{d,GP})^2}} \quad (40)$$

where RRMSE is relative root mean square error and R is the correlation coefficient. The lower the PI, the more precise the model. The results of the PI are presented in Table 7. The results show that in all data sets—i.e., test, trained, and overall—the Multi-Gene model has a lower PI, and therefore it is a more precise model than the Single-Gene model.

The error measurements demonstrate that the Multi-Gene method provides a relatively more accurate results compared to the Single-Gene method; however, a rather more complicated formula is required. It is suggested that in the situations where a rough estimate is needed, the Single-Gene

method can lead to a reasonable answer in a relatively shorter time with less computational cost, but when a more accurate answer is required, the Multi-Gene formula is recommended.

The error estimates show that the test data sets in both Single-Gene and Multi-Gene models have a lower R^2 and higher MAPE, which can be indicators of higher errors and overfitting of the model. However, the RMSE and MAE values provide comparable results for the test and trained data sets with fewer errors. In other words, two of the four error indicators show better results in test data sets, while the other two may indicate overfitting. Given the circumstances, the results for both Single-Gene and Multi-Gene models are reasonably acceptable.

Table 7: Error Estimations

Data Set		R-Squared	RMSE			MAE	MAPE (%)	AIC	PI
			Value	% of Maximum P _d	% of Mean P _d				
Single-Gene	Trained	0.989	4.54	2.69	17.09	3.64	68%	21.15	0.086
	Test	0.844	3.23	14.17	46.30	3.03	260%	10.55	0.241
	Overall	0.989	4.31	2.55	19.03	3.52	107%	23.87	0.114
Multi-Gene	Trained	0.992	3.89	2.30	14.63	3.28	76%	21.8	0.073
	Test	0.889	2.73	11.99	39.18	2.19	302%	12.18	0.202
	Overall	0.992	3.69	2.18	16.26	3.06	121%	24.17	0.082

Table 8: MAD calculations

Data Set	MAD		
	Observed Data	Single-Gene Results	Multi-Gene Results
Trained	30.63	30.27	30.44
Test	6.32	17.30	5.90
Overall	26.08	25.90	25.56

4.3.3. Uncertainty Analysis and Confidence Bands

After finding the equation, its credibility needs to be investigated and verified by uncertainty and sensitivity analyses.

A Monte Carlo analysis was also performed for the uncertainty analysis of the resulting equation. The objective of this analysis is to calculate the uncertainty of the final function. To do so, 1,000,000 random inputs of h_d were generated in the range of 0.3179 to 3.2211. Then, the equation was run for each random number. To generate random data with normal-shaped distribution in a specific range, a truncated Gaussian function was used. The histogram of the generated data using the truncated Gaussian function is shown in Figure 57.

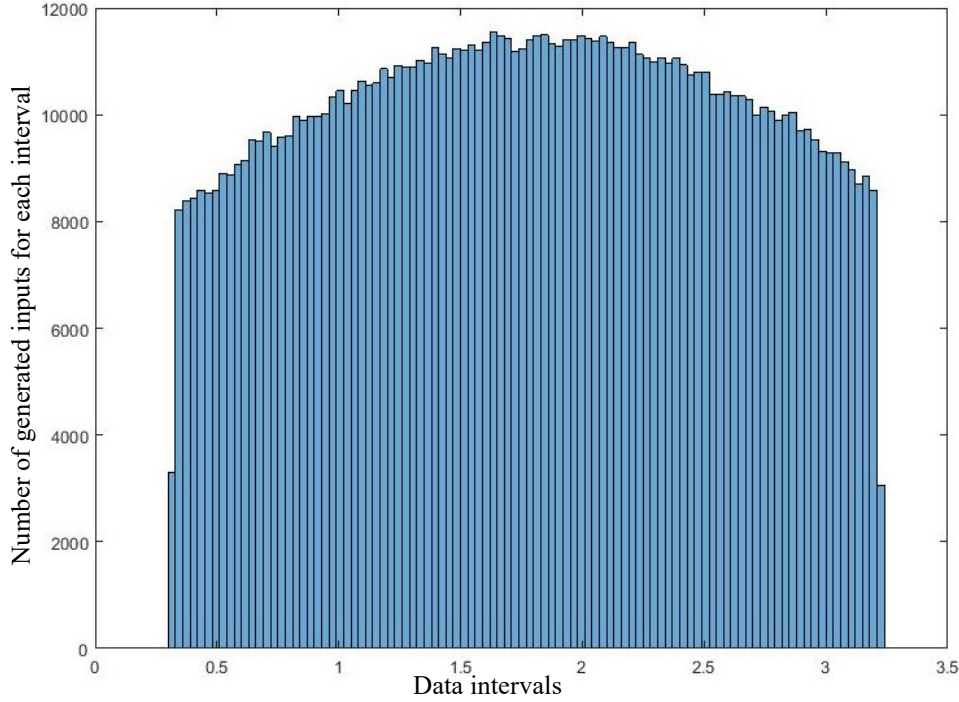


Figure 57: Histogram of generated random inputs created with truncated Gaussian function.

These random numbers were then put into the GP model, and 1,000,000 values for P_d , namely P_{mc} , were calculated. The mean absolute deviation (MAD) was calculated around the average using Equation (41)

$$MAD = \frac{1}{n} \sum_{i=1}^n |P_{mc_i} - P_{avg}| \quad (41)$$

where n is the number of samples (i.e., $n = 1,000,000$ in this case) and P_{avg} is the average of the pressures calculated by the Monte Carlo simulation [75], thus leading to

$$MAD_{SG} = 11.718 \text{ and } MAD_{MG} = 11.4728$$

This can be used to calculate the uncertainty percentage of the function by using the following equation [75]:

$$U = 100 \times \frac{MAD}{P_{avg}} \quad (42)$$

The above leads to

$$U_{SG} = 100 \times \frac{11.718}{10.7485} = 109.02 \text{ and } U_{MG} = 100 \times \frac{11.4728}{11.430} = 100.3738$$

where U_{SG} and U_{MG} are the uncertainty percentages for the Single-Gene and Multi-Gene equations, respectively. Due to the high slope of the graph of the equation in the beginning, these amounts of uncertainty are reasonable.

Confidence bands of the graph are then obtained using a 2nd-order approach in the calculation of the Jacobian Matrix with the central difference scheme. The MATLAB internal function “nlpredci” (non-linear regression prediction confidence intervals) is used. This function can provide the user with 95% confidence band widths of the given equation. According to Dolan et al. [123], this function gives a symmetric confidence interval at each point; hence, the two confidence bands have the same distance from the main equation. The 95% confidence bands for Equations (28) and (29) are plotted in Figure 58 a, and b, respectively. The average confidence band width for Equation (28) (i.e., Single-Gene mode) is 20.54, and for Equation (29) (i.e., Multi-Gene mode) is 15.27. These values show that the multi-gene model has narrower confidence intervals, which means there is a higher confidence in the multi-gene model. In addition, it can be seen that for both single- and multi-gene models, the observed data is inside the confidence intervals.

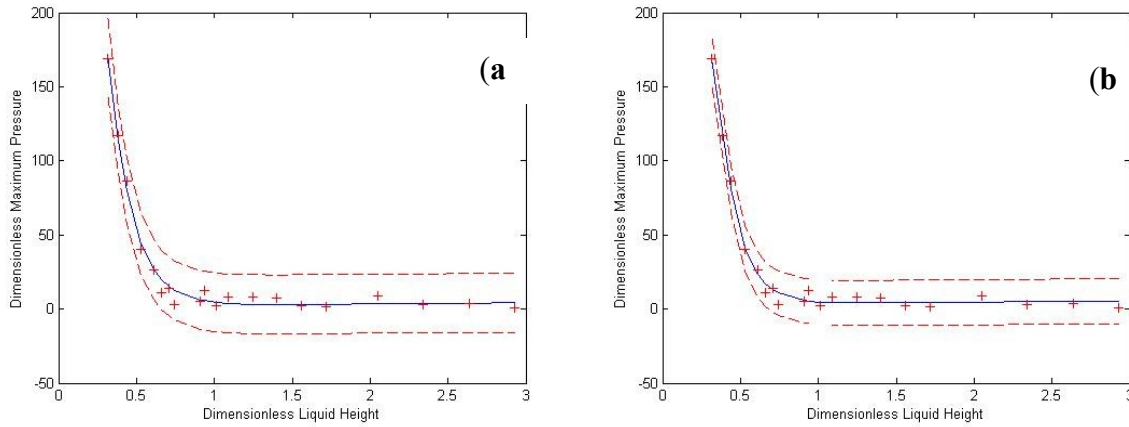


Figure 58: Graph of the proposed equation for dimensionless pressure plotted against dimensionless liquid height with 95% con-fidence bounds for (a) Single-Gene and (b) Multi-Gene modes.

3.4. Sensitivity Analysis

For the sensitivity analysis, a 10% perturbation is applied to an input value of the equation (here, the mean), and the perturbation in the outcome is calculated. The calculations are presented in Equations (48)–(50):

$$h_{dp} = 1.1 \times h_{dm} \quad (48)$$

$$\Delta P_d = \frac{|P_{dp} - P_{dm}|}{P_{dm}} \quad (49)$$

$$S_n = \frac{\Delta P_d}{0.1} \quad (50)$$

where h_{dp} is the 10% perturbed mean dimensionless liquid height, h_{dm} is the actual mean dimensionless liquid height, ΔP_d is the perturbation that appears in the dimensionless pressure due to the 10% perturbation in the dimensionless liquid height, P_{dp} is the change in the value of the dimensionless pressure when the dimensionless liquid height changes, P_{dm} is the value of the dimensionless pressure at mean dimensionless liquid height (h_{dm}) calculated based on Equations

(28) and (29) for Single-Gene and Multi-Gene modes, and S_n is the normal sensitivity of those equations.

This leads to a sensitivity of $S_{n,SG} = 0.258$, or a 25.8% sensitivity for the Single-Gene solution and $S_{n,MG} = 0.116$ or a 11.6% sensitivity for the Multi-Gene solution.

4.4. Conclusions

The purpose of this study was to develop an empirical equation for the maximum pressure at the roofs of liquid storage tanks. To do so, a previously validated OpenFOAM model was used to generate the data. The data included the maximum pressure at the roof. Various tank sizes with different liquid heights were modeled, and harmonic sinusoidal base excitations with resonance frequencies were applied to the tanks. To consider the effect of bi-directional excitation, the tanks were shaken in three different orientations of 0° , 30° , 60° , and 90° . Pressure sensors were distributed on one quarter of the roof, and the maximum pressure at each sensor was recorded.

Using the GP method, a relationship between the dimensionless liquid height and the dimensionless maximum pressure was obtained in both Single-Gene and Multi-Gene modes (Equations (28) and (29)). Using multiple error measures, the two equations were tested, and the results were compared. These results show that the outputs of the equations are in good agreement with the ones obtained by CFD modelling. Uncertainty analyses of the equations were conducted using the Monte Carlo method, leading to reasonable values given that both functions have an ascending shape with a high slope in the beginning of their domains. In addition, the 95% confidence bands for the equation were drawn.

Therefore, it can be concluded that the use of AI techniques combined with CFD is helpful in predicting the maximum pressure at the roof of a base-excited tank. Further investigation on this aspect is currently in progress by the authors.

5. Investigation of effects of seismic excitation of liquid storage tanks on supporting structures – NBC requirements improvement

Background

In chapter 3 the applicability of Navier-Stokes equations in prediction of the liquid behaviour in LSTs subjected to base excitation was demonstrated. In this chapter, those same equations are used in a different numerical method, namely Smoothed Particles Hydrodynamics (SPH), to simulate LSTs subjected to seismic loading. The advantage of the method used in this chapter compared with chapter 3 is simultaneously simulating the liquid and the tank's structure using a combined FEM-SPH model. This combination, although has a slightly higher computational cost, overcomes the issue of tank's wall flexibility and provides more accurate results.

In addition, the ACI350.3 code was investigated for free-board requirements and was shown to need improvements for roof design in chapter 3. In this chapter, base shear calculations based on the National Building Code of Canada (NBC) are compared with numerical results and the code is investigated for providing adequate shear force values for LSTs subjected to ground motion.

Abstract

Liquid storage tanks serve for essential purposes in municipalities and various industries such as the energy sector, food production, and agriculture. Keeping these structures functional after an earthquake event is important as their poor seismic performance can lead to catastrophic environmental damages and economical losses. This study focuses on the effect of base excitations on the supporting structures of rectangular liquid storage tanks and compares the results of numerical simulations using ABAQUS - a structural analysis and simulation software - with the seismic demand requirements of National Building Code of Canada (NBC) in three phases. In the first phase, the feasibility of the study is investigated, and mesh and particle sensitivity analyses are run. In the second phase, various simulations using harmonic base excitations with the Peak Ground Accelerations (PGAs) of two Canadian cities – Ottawa, ON., and Vancouver, BC. – are completed, and the results are compared with the code requirements. In the final phase, four earthquake records are scaled to match the PGAs of those two cities and applied to the tanks. The results are then compared with the code requirements, where it is found that while the NBC very well predicts the total base shear, improvements can be made with regards to shear forces of the individual supports.

5.1. Introduction

Liquid storage tanks (LST's) are lifeline structures used for storage of various materials including: municipal water (e.g., used for drinking or fire-extinguishing purposes), industrial materials that might be toxic or flammable, etc. LSTs are also used in nuclear plants, petroleum factories, and food production. Given the devastating harms caused by poor seismic performance of such structures, their safety and functionality during and after an earthquake event are crucial. There are various types of LST's that differ in mount type (ground-supported, mounted, roof-top, or buried), material (steel or reinforced concrete), and shape (rectangular, square, circular cylindrical, conical, etc.). This variety causes difficulties in having general rules for their design and leads to various study methods on their behavior depending on the type, shape, and material of the tank.

Various analytical, numerical, and experimental studies have been completed in the past. It is critical to note that tanks -unlike building structures- cannot go through ductile energy dissipations, as large values of lateral displacements can adversely affect their serviceability, hence their seismic performance mechanism is not similar to buildings.

There have been efforts to provide analytical solutions to find the seismic response of LST's. Among them, Housner (1963) [15] which is an improved model of his earlier study (Housner 1957) [124] has been adopted -with modifications by design codes such as ACI 350.3 [17] and ASCE7 [125] despite its shortcomings in some cases such as resonance conditions where non-linear waves are created inside the tank (Ghaemmaghami and Kianoush 2010, Isaacson 2010, Moslemi and Kianoush 2012) [22]–[24]. This method divides the liquid into two masses of impulsive and convective, where the impulsive mass is rigidly connected to the tank walls and the convective mass is the sloshing part and is modeled as a mass-spring system. This method, in addition to its simplicity, can provide an accurate estimate of the natural period of the sloshing liquid (Cho and Cho 2007, Jaiswal et al. 2008, Moslemi and Kianoush 2012, Bahreini Toussi et al. 2020) [2], [24], [38], [113].

In a study by Veletsos (1974) [12], it was found that Housner's model was applicable to tanks with rigid structures and the effect of tank flexibility has been neglected. It was found that flexibility does not affect the convective forces, and therefore, Housner's model is applicable for those forces. This was also supported by Ghaemmaghami and Kianoush (2010) [22] which found that flexibility of the tank structure does not affect the sloshing part; hence, Housner's model is applicable.

Haroun (1983) [16] investigated the effect of base excitation on LST's using theoretical analysis and experimental tests in an effort to develop design standards. An analytical solution was proposed based on the anchorage of the tank to the base which can affect the tank behavior. It was found that modal analysis is sufficient for anchored tanks but for the unanchored ones, non-linear analysis was found to be necessary.

Sivý and Musil (2017) [25] investigated the seismic response of liquid storage tanks and provided guidelines for their design. Using the impulsive/convective masses, the base shear can be calculated as follows:

$$V = (m_i + m_w + m_r)S_e(T_{imp}) + m_c S_e(T_{con}) \quad (1)$$

where m_w and m_r are the wall and the roof masses respectively, and $S_e(T_{imp})$ and $S_e(T_{con})$ are spectral accelerations, obtained from the elastic response spectrum.

Malhotra et al. (2000) [26] provided a simple procedure for seismic analysis and design of circular, cylindrical liquid storage tanks. Given that the first impulsive and convective modes account for 85-98% of the total liquid mass, only the first modes were considered in their study. They based their procedure on the studies by Veletsos and Yang (1977), Veletsos (1984), Veletsos et al. (1990) [27]–[29] with modifications. In this model, only the first modes of impulsive and convective masses were considered, but their heights were adjusted to make up for the higher modes. T_{imp} and T_{con} were measured as follows:

$$T_{imp} = C_i \frac{H\sqrt{\rho}}{\sqrt{h/r \times \sqrt{E}}} \quad (2)$$

$$T_{con} = C_c \sqrt{r} \quad (3)$$

where h is the equivalent uniform thickness of the tank wall, ρ the mass density of the liquid, and E the modulus of elasticity of the tank material. The coefficients C_i and C_c are constant values obtained from a Figure suggested in the study.

The results from this method were compared with detailed modal analysis and the calculated base shear from the proposed method was 2-10% higher than the modal analysis, hence conservative with good degree of approximation. However, more detailed studies are required for regions with high seismicity.

The development of computers in recent years has led to increasing popularity of numerical simulations where the volume and structure are broken down into small volumes, elements, or particles and the related equations are solved on those small particles using initial and boundary conditions. Various numerical technics including Finite Element Method (FEM), Finite Volume Method (FVM), Finite Difference Method (FDM), Smoothed Particles Hydrodynamic (SPH) method, and some coupled methods have been used for the analysis of LST's.

Mitra and Sinhamahapatra (2007) [36] studied the sloshing characteristics (e.g. displacement, frequencies, mode shapes) and the hydrodynamic pressure on the walls in rectangular liquid containers. In addition, the use of internal blocks as a wave mitigation technique was investigated. The model was defined by 4-noded quadrilateral elements and Galerkin principle, and the results were compared with the existing analytical solutions. Due to the assumption of small amplitude waves, their analysis was limited to linear problems. The model could be used to find the pressure with a low computational cost. Besides, a computer code was developed to estimate the sloshing characteristics as well as the pressure on the walls. The estimation of sloshing height and wall displacement was found useful for the design of liquid storage tanks.

Cho and Cho (2007) [2] proposed a coupled method by combining the finite element method (for the structure) and the boundary element method (for the liquid at the boundary with the structure) for studying the seismic response of circular cylindrical tanks. A coupled dynamic system was formulated in the time domain that could find the response of the container under seismic excitation, taking the fluid-structure interaction and sloshing of the free surface into account. The results were compared with the ones from Haroun (1983) [16] method and the sloshing height found by this method was much greater than Haroun's, however, the base shear and overturning moment were in good agreement. It was suggested to consider more than one sloshing mode (as suggested by Haroun) so the sloshing height calculation could also be more accurate.

Lee et al. (2007) [37] adopted a coupled FEM to analyze the sloshing in fluid-shell structure interaction where the structure was modelled by 4-Node Mixed Interpolation Tensorial Component (MITC4) shell elements and the analysis of the fluid was done by the Moving Particle Semi-implicit (MPS) method. A semi-implicit time integration scheme and an explicit time integration scheme were proposed for the fluid, and the structure solvers, respectively. The study was done in

a two-dimensional coordinate and the method was found helpful in solving problems related to sloshing.

In a study by Xiong and Xing (2008) [9], a finite element model based on air-water-tank interaction was developed. Four different interactions of liquid-rigid tank, liquid-elastic tank, air-liquid-rigid tank and air-liquid-elastic tank were studied. Natural frequencies and mode shapes of each interaction type were investigated. Harmonic excitations and the El-Centro earthquake record were applied at the base. The study found that presence of air (i.e. air-liquid-tank interactions) increased the natural frequency of the system and reduced the response amplitudes of sloshing and pressure. The effect of elasticity however was dependent on the tank's structural frequency. In a high-frequency tank, elasticity did not have a significant impact on the sloshing characteristics but in large tanks with lower frequencies, the effect of elasticity was found to be more crucial. The authors concluded that entering pressurized air into sealed tanks could reduce the sloshing effects.

Ghaemmaghami et al. (2010) [93] studied two different 3D finite element models for rectangular and cylindrical liquid containers with liquid damping and measuring the impulsive and convective responses separately. Various parameters such as the effect of vertical acceleration combined with the horizontal one, the effect of geometry on sloshing characteristics, and wall flexibility were investigated. The results of the study showed that the ACI code could lead to inaccuracies with the impulsive response of the tank while the convective response had an acceptable agreement. The combination of vertical and horizontal accelerations in either model (i.e. rectangular, or cylindrical tanks) did not have a significant impact on the dynamic behavior. The same finite element model was used by Moslemi et al. (2011) [42] to investigate the seismic response of an elevated water tank mounted on a reinforced concrete shaft. The response time history was obtained using the modal superposition technique. Damping effect of the liquid was also considered. The impulsive and convective masses were analyzed separately as an improvement compared to conventional FEM analyses. The model was able to provide solutions for tanks with complicated geometries (e.g. conical tanks) as well; hence the use of the equivalent cylindrical tank would not be necessary. Base shear and overturning moment were investigated and the effect of wall flexibility and sloshing of the liquid were examined in the analysis. Modal finite element analysis showed a good agreement with Housner's model (Housner, 1963) [15] in terms of the convective and impulsive natural frequencies. Also, it was found that the impulsive and convective modes had different times to get to their respective peak values, which means that sloshing could have either a positive or a negative effect.

Moslemi and Kianoush (2012) [126] studied tall and shallow circular tanks using FEM. Parameters such as aspect ratio (i.e. the ratio between the tank's height and its dimension), the vertical component of an earthquake, the effect of wall flexibility, free surface sloshing, etc. were investigated assuming ideal fluid i.e. incompressible, irrotational, and inviscid with no mean flow. The aspect ratio of the tall tank was three times higher than the shallow one, but the dimensions were chosen such that the two tanks would contain the same amount of liquid. Their results showed that in the shallow tank (with an aspect ratio of about 0.115), regardless of wall flexibility, the vertical ground acceleration could affect the convective hoop force, bending moment and base shear more than the same impulsive components, however, it was generally negligible. In the tall tank (with an aspect ratio of about 0.324), combined vertical and horizontal ground accelerations

showed a significant increase in all impulsive and convective components. The justification for this increase could be the stronger $P-\Delta$ effect in tall tanks. In both shallow and tall tanks, the wall flexibility increased impulsive pressures significantly, while it had minor effects on convective pressures.

Kolukula and Chellapandi (2013) [48] applied a finite element model based on a mixed Eulerian-Lagrangian scheme with the logic that the free surface and the interior nodes have different behavior, where the former behaves as Lagrangian and the latter has an Eulerian behavior. Four-noded iso-parametric elements were used for the analysis. Simulations were conducted using resonance and non-resonance horizontal excitations. The results were compared with the cases of Frandsen (2004) which studied the non-linear FDM analysis on 2D tanks excited by horizontal and vertical harmonic motions separately, and together on a tank with an aspect ratio of 0.5 (i.e. the liquid height was half the tank length) assuming inviscid liquid. A good agreement between the results of the two studies was reported.

Experimental studies have been predominantly used as a validation/verification tool for numerical simulations. Akyildiz and Ünal (2005) [50] performed a series of experiments to study the sloshing of the liquid as well as the pressure distributions at different points in a rectangular tank. A tank with plan dimensions of 920×460 mm and a height of 620 mm was used. To investigate the effect of baffles, the tank was designed to have removable baffles in different directions on walls, roof and bottom. Piezoresistive pressure transducers were installed in different locations on the walls to measure the pressure distribution in the tank. Various sets of experiments with different excitation frequencies and different fill depths were carried out. The results showed that baffles remarkably reduce the motion of the liquid, but there was not enough data to find out the effect of fluid viscosity on pressure, hence more experimental work was necessary.

Panigrahy et al. (2009) [51] conducted a series of experiments to measure the pressure and the free surface in a sloshing tank. A square tank placed on a moving plate driven by a DC motor was used for the experiment. Pressure and displacement of the free surface were measured under different excitation frequencies and fill depths. The focus of the study was to investigate the effect of internal baffles in the tank; hence, experimental tests were carried out with different baffle placements and without them and the results were compared. It was observed that the sloshing of the liquid was a function of several factors including the liquid height (i.e. fill depth), tank size, excitation characteristics (e.g. amplitude and frequency), and liquid characteristics (e.g. density and viscosity). The pressure and sloshing height of the free surface were measured and compared for different cases. A relationship between the wave amplitude and the liquid height was obtained; The pressure on the tank wall was found a function of the excitation period and has a great variation near the free surface rather than deeper in the liquid part. Due to the self-damping property of liquids, for a specific excitation frequency, it was observed that increasing the liquid height decreased the sloshing height. As part of the study, the effect of baffles on the sloshing was investigated and a considerable reduction of sloshing and pressure was observed. Different types of baffles (e.g. blade, ring, vertical, horizontal) were tested and ring baffles were found more effective than other types.

A thorough review of the available studies and the design codes, standards and guidelines shows that the effect of earthquake loading on the support structures of liquid storage tanks with consideration of the liquid sloshing has not been completed before. Also, the effect of earthquake on the seismic response of roof-top liquid containing structures has been neglected in the literature. A roof-top tank can cause complexity in the design of a building structure as it may affect the seismic response of the structure depending on the seismicity of the region, dynamic characteristics of the building, the size and fill depth of the liquid storage tank, etc. The available literature shows a difference in seismic characteristics, and consequently the base shear and overturning moment of tall and shallow liquid containing structures. However, this has not been investigated in roof-top tanks, hence there is a gap and need for further studies on this issue.

The objective of this study is to investigate the effect of earthquake loading on the base shear and shear stresses of steel liquid storage tanks on steel supporting structures. This includes comparing the results of tanks filled with a liquid material and a solid material of equivalent characteristics, evaluating the base shear values against the seismic loading requirements of the National Building Code of Canada (NBC), and analyzing the response of a real-size tank to earthquake records adjusted to the PGAs of Ottawa and Vancouver. The study aims to provide details on how to improve the seismic design of roof-top liquid storage tanks and to fill the gap in the literature on the effect of earthquake on roof-top tank structures.

The current study focuses on the base shear and shear stresses of steel liquid storage tanks on steel supporting structures. An ABAQUS model is developed and after mesh and particle sensitivity analyses, tanks with different sizes and fill depth values are subjected to harmonic and time-history base excitations. Tanks are filled with two different types of materials: a) a liquid material, and b) a solid material with the same characteristics of the liquid (e.g. density). The shear forces at the supporting structure of the tanks are obtained and the results are compared for the two types of materials and the difference is measured. Total base shear is also calculated and compared as per the seismic loading requirements of the National Building Code of Canada (NBC), and recommendations on how to improve the NBC requirements are discussed.

The current study is comprised of three phases. In the first phase, the feasibility of such study is investigated; a tank containing liquid and equivalent solid material is simulated to see whether there is a difference between the two types of material, and also mesh and particle sensitivity analyses are conducted. The second phase focuses on evaluating the base shear values from the NBC and the two types of materials in the tank. In the third phase of the study, a real-size tank previously studied by Kianoush and Ghaemmaghami (2011) [108] is subjected to four earthquake records adjusted to the PGAs of Ottawa, ON. and Vancouver, BC.

This study is organized as follows: in the next section, the methodology of the research is explained, followed by phases 1 to 3 numerical studies. Then results are presented, and a discussion and concluding remarks as well as suggestions for further studies and code improvements are offered.

5.2. Methodology

In this study, the ABAQUS software is used as the numerical modelling application. Four-node linear tetrahedron elements are used for the modelling of the tank and its supporting structures and

a harmonic excitation with resonance frequency is applied at the base. The resonance frequency of the sloshing is measured based on Housner's method which is proven to provide realistic resonance frequencies in several studies (e.g. Cho and Cho 2007, Jaiswal et al. 2008, Moslemi and Kianoush 2012 [2], [38], [126]). The procedure is as follows:

In a rectangular tank with the length equal to $2L$ and water depth h :

$$\omega = \sqrt{k_c/M_c} \quad (4)$$

where ω is the resonance frequency of the sloshing liquid and

$$M_c = M \frac{\tanh 1.7L/h}{1.7L/h} \quad (5)$$

$$k_c = 3 \frac{M_c^2 gh}{M L^2} \quad (6)$$

where M_c is the mass of the convective mode, M is the total liquid mass, L is half the tank length, h is the height of the water inside the tank, k_c is the stiffness of the connecting spring, and g is ground acceleration.

In this paper, the numerical study consists of three phases. In the preliminary phase (i.e. phase 1), the effect of the resonance excitation on the reaction forces of supporting structures of a container partially filled with a liquid material is compared with the same forces for the same tank partially filled with a solid material. The solid material has similar characteristics to the liquid but is modelled as a solid in order to find out the effect of sloshing on the supporting structures.

In the second phase of the study, a larger tank with dimensions closer to real-size is tested against three different frequencies (including the resonance frequency and two other frequencies above and below resonance), however, the amplitudes of the excitations are chosen so that the maximum acceleration of the tank is equal to the Peak Ground Acceleration presented by the NBC for the City of Ottawa, Ontario, Canada. This can be used for comparing the results of the study and the NBC and examine whether NBC's provisions are conservative enough or they require improvements for the roof-top liquid tanks.

In the final phase (i.e., phase 3) a large size tank is subjected to base excitations. The excitations include four earthquake records of 1940 El Centro, 1971 San Fernando earthquake, 1994 Northridge earthquake, and 1995 Kobe earthquake. The earthquake records are adjusted and scaled so that their maximum acceleration is set to the PGAs of Ottawa, ON., and Vancouver, BC. The results for base shear are compared with calculations based on NBC.

5.2.1. Phase 1, Sloshing effects in liquid tanks

In this phase, the focus is to find if there are differences between the seismic response of a rectangular tank containing liquid and solid material (note that the NBC assumes the tank containment as solid).

A tank with the following dimensions is used in this phase of the study:

Length = 750 mm, Width= 300 mm Height= 300 mm, Walls and Roof thickness= 10 mm. The tank is placed over 4 supporting blocks of 50mm × 50 mm × 50 mm. The material used for the tank and its supporting structures is steel with a density of 8050 kg/m³, elasticity modulus of 200 GPa and Poisson's ratio of 0.27.

The depth of the water inside the tank is 250 mm. It has a density of 1000 kg/m³ and dynamic viscosity of 0.001 Pa.s. To observe the effect of sloshing and positive/adverse effects of ignoring the convective part of a liquid inside a tank, water is modelled in two different ways:

- 1) As a liquid material where the mass consists of both convective and impulsive masses: the water is modelled using the SPH method.
- 2) As a solid material where all the liquid mass is considered to be impulsive mass: the liquid is modelled with 8-node linear brick elements.

Mesh and particle sensitivity analyses are also run in this phase to investigate the effect of the mesh size and the number of particles on the reaction forces of the supporting structures. To do so, the mesh size for case #1 and number of particles for case #2 are modified and the effect of such modification on the reaction forces is studied.

5.2.2. Phase 2, NBC requirements for liquid tanks

The focus of this phase is to find the differences between the seismic demands of the tank based on the numerical modelling and the NBC seismic loading requirements in terms of the base shear for specific locations in Canada (i.e. Ottawa and Vancouver in this case). This can help identifying the accuracy or potential shortcomings of the NBC and find a solution for its improvement.

A tank with plan dimensions of 1.5 m × 2.0 m, and a height of 1.2 m filled with water up to 1.0 m is modelled in this phase. The tank has four solid support structures made of the same material as of the tank body (Figure 59). After completion of mesh and sensitivity analyses similar to phase 1, the tank is modelled for the Peak Ground Accelerations (PGA) of Ottawa and Vancouver and is filled with liquid water and the equivalent solid material to measure and compare the shear forces for each of the supports as well as the total base shear.

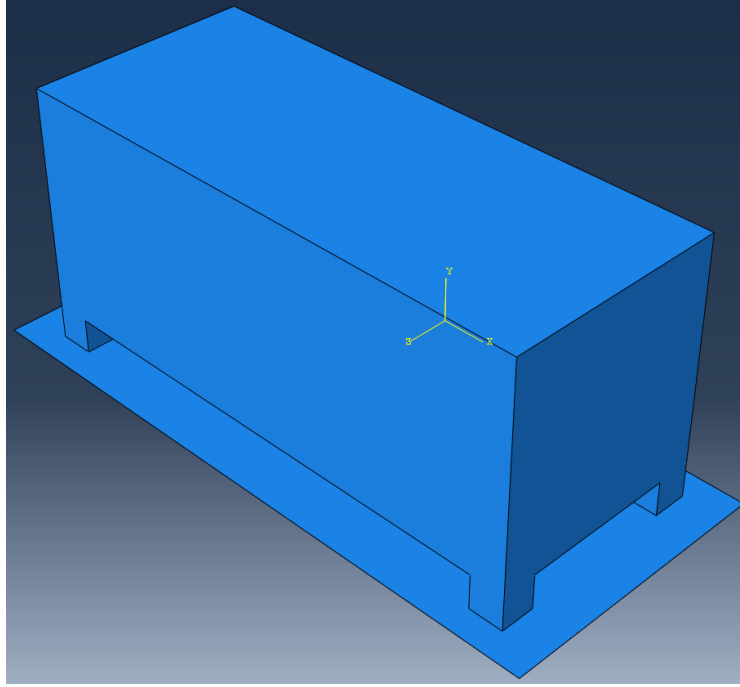


Figure 59: schematic view of the simulated tank

The first step at this phase is to check if the model can accurately capture the correct mass and the fundamental period of the tank structure. To do so, the tank is modelled as empty (without water). Frequency analysis is run through the ABAQUS frequency analyzer tool, and the tank frequency is also measured manually, and the results are compared. To manually measure the frequency, a traction force (S_t) is applied at the top of the tank and the displacement of the tank's top (d_t) is measured. The stiffness and the period of the structure are calculated using the following equations:

$$F_t = L \cdot B \cdot S_t \quad (7)$$

$$k = F_t / d_t \quad (8)$$

$$T = 2\pi \sqrt{k/m} \quad (9)$$

Where F_t is the sum of the traction forces at the top, L and B are the length and width of the structure, k is its stiffness, T is the period and m is the mass of the structure.

Then the same structure undergoes a frequency analysis using the frequency analyzer of the software and the frequency results are compared. The results for manual and automatic mass and period analyses should demonstrate a good agreement between the two.

Once the model is verified for the measurement of the mass and the period of the structure, two separate models are constructed: 1) partially filled with liquid water and 2) partially filled with an equivalent rigid material. Both models are subjected to harmonic sinusoidal excitations with different frequencies with accelerations equal to the Peak Ground Acceleration (PGA) for the cities

of Ottawa and Vancouver as per recommended PGA values in the Appendix C of the NBC 2020 [90]. The amplitude of the excitation is calculated as follows:

$$d(t) = A \cdot \sin \omega t \quad (10)$$

$$a(t) = -A \cdot \omega^2 \sin \omega t \quad (11)$$

$$a_{max} = PGA \quad (12)$$

$$A = PGA / \omega^2 \quad (13)$$

Where $d(t)$ and $a(t)$ are the displacement and acceleration functions, A is the excitation amplitude and ω is the circular frequency of the excitation. The same excitations are applied to the tank partially filled with water as a liquid and the tank partially filled with a solid material similar to water (i.e., with the same density). The base shears are then measured for each case and the results for the liquid and solid materials are compared with the ones from the NBC for the same locations (i.e., Ottawa and Vancouver). Details of the base shear calculation as per the requirements of the NBC are provided in a later section.

It is worth noting that in this phase of the study, two types of frequencies are discussed; 1- Frequency of the structure (i.e. the natural period of the structure) that is calculated manually and also using the numerical model which are compared with each other to examine the accuracy of the model, and 2- The excitation frequency that is the frequency of the harmonic sinusoidal load applied at the base of the structure. This excitation includes three frequencies of above resonance, resonance, and below resonance where the term “resonance” refers to the situation in which the frequency of excitation is equal to the frequency of sloshing. The latter is measured using Housner's simplified method.

5.2.3. Phase 3, NBC Code requirements Vs. numerical results

In this phase, the four earthquake records of 1940 El Centro, 1971 San Fernando earthquake, 1994 Northridge earthquake, and 1995 Kobe earthquake are adjusted to match the PGAs of Ottawa and Vancouver. The results of this phase can examine the conservativeness of the NBC against real-life earthquake records, which contain various frequencies and amplitudes. The procedure for scaling these records is as follows:

- 1) Find the maximum acceleration of each record. This can be a positive or a negative value. For example, San Fernando has a maximum acceleration of +1.219g while for Kobe it is -0.821g.
- 2) Find the PGA values presented for Ottawa and Vancouver by the NBC.
- 3) Multiply the whole record by PGA divided by the absolute value of the maximum acceleration:

$$a_{new} = a_{record} \times \left(\frac{PGA}{|A_{max}|} \right)$$

where a_{new} is the new scaled amplitude, a_{record} is the earthquake recorded amplitude, and $|A_{max}|$ is the absolute value of the maximum acceleration of the recorded earthquake.

The tank used in this phase of the study has plan dimensions of 15 m × 30 m, a height of 15 m, and a thickness of 0.5 m filled up to 12 m with water. The same material and element types for the structure are used and the SPH method is applied for modelling the liquid. The tank is supported on four solid cubic blocks with a 1m dimension.

Base shear for each of the supporting structures as well as the total base shear are captured and compared with calculations based on NBC.

5.2.4. Roof-top Tanks in the NBC

Based on Article 4.1.8.18 of National Building Code of Canada (NBC), the lateral force of non-structural components and equipment are measured based on the following equation:

$$V_P = 0.3F_a S_a(0.2) I_E S_P W_P \quad (14)$$

Where F_a is the Site coefficient as defined in sentence 4.1.8.4(7) equal to $F(0.2)$. This coefficient depends on the soil type and is equal to 1.0 for soil type C, $S_a(0.2)$ is the site spectral response acceleration value at 0.2s, I_E is the importance Factor and is assumed to be 1.0 for this study, S_P is the horizontal force factor for part or portion of a building and its anchorage. It is equal to

$$S_P = C_P A_r A_x / R_P; \max(S_P) = 4.0 \text{ and } \min(S_P) = 0.7 \quad (15)$$

$$A_x = 1 + 2h_x/h_n \quad (16)$$

Where A_x is the height factor, h_x is the height above the base of the x^{th} floor where the component (in this study the liquid storage tank) is located (which is the roof) and h_n is the height above the base of the n^{th} floor of an n -storey building. In this study, since the tank is located at the roof, h_x is equal to h_n , in other words, $A_x = 1 + 2(1) = 3$, C_P is the element or component factor, A_r is the element or component force amplification factor, R_P is the element or component response modification factor.

The values for C_P , A_r , and R_P can be obtained from table 4.1.8.18 of the code (Table 9) as follows:

Table 9: Values of C_P , A_r , and R_P from table 4.1.8.18 of NBC

Machinery, fixtures, equipment, and tanks (including contents)	C_P	A_r	R_P
That are rigid and rigidly connected	1.00	1.00	1.25
That are flexible or flexibly connected	1.00	2.50	2.50

According to Sentence 4.1.8.18.3, for the purpose of applying Sentence (1) for Categories 11 and 12 of Table 4.1.8.18., elements or components shall be assumed to be flexible or flexibly connected unless it can be shown that the fundamental period of the element or component and its connection is less than or equal to 0.06 s, in which case the element or component is classified as being rigid or rigidly connected. In other words, the values of C_P , A_r , and R_P for a roof-top tank are equal to 1.00, 2.50, and 2.50 respectively, unless one can show that the fundamental period of the tank is less than or equal to 0.06s.

This leaves the base shear equation for a normal importance building located on soil class C as follows:

$$V_P = 0.3F_a S_a(0.2)I_E S_P W_P \quad (17)$$

Where $F_a = 1.0$, $I_E = 1.0$, $S_P = 2.4$; hence,

$$V_P = 0.72S_a(0.2)W_P \quad (18)$$

where W_P is the weight of the tank with the water included.

5.3. Results

5.3.1. Phase 1, Sloshing effects in LSTs

5.3.1.1. Mesh and particle sensitivity analyses

Mesh and particle sensitivity analyses are run to find the effect of the mesh size and particle numbers on the reaction forces. The results of this analysis are presented in Figures 60 to 63. The results shows that the case with the solid material is mesh-independent for the nodal reaction forces, meaning that refining the mesh did not lead to significant changes in the reaction forces at the nodes of the base and consequently the base shear, while for the liquid material, the forces start to converge after two steps.

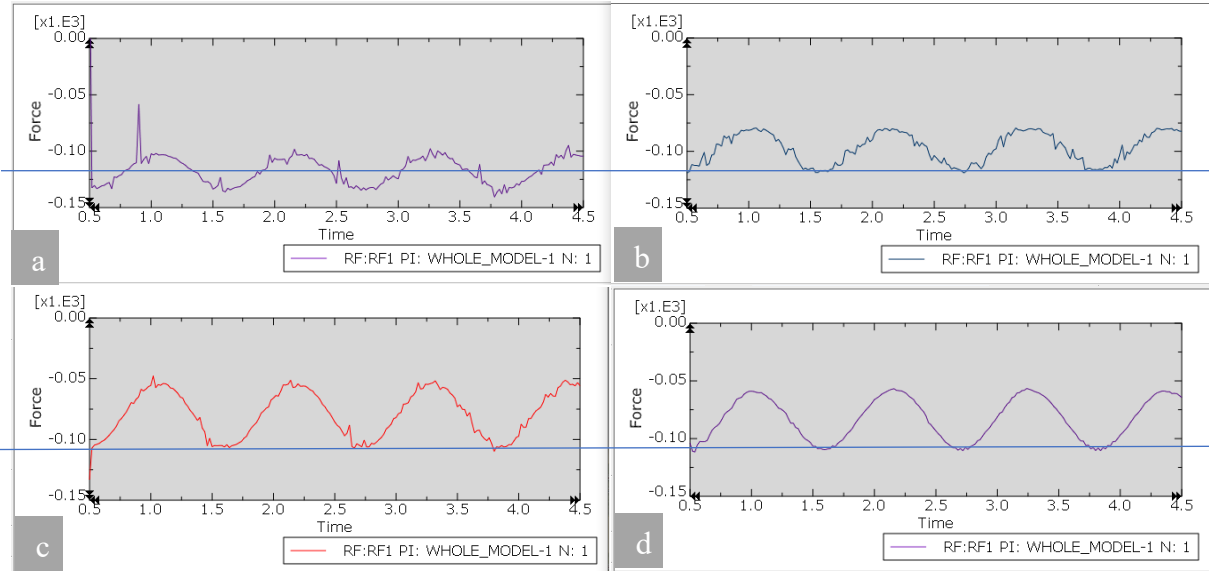
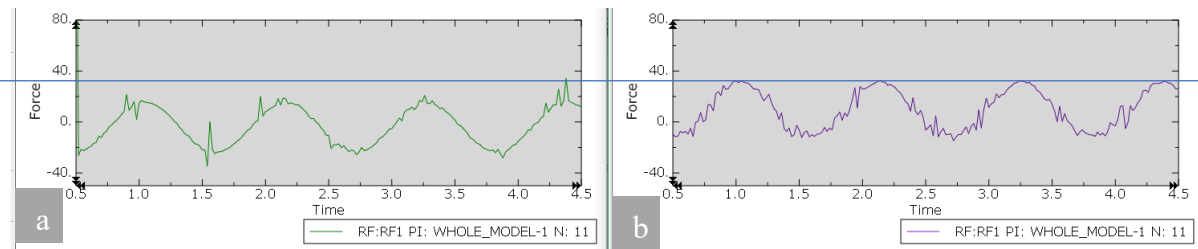


Figure 60: Mesh and particle sensitivity analyses of a nodal reaction force; a) SPH with fewer particles, b) Rigid with a coarse mesh, c) SPH with more particles, d) Rigid with a fine mesh



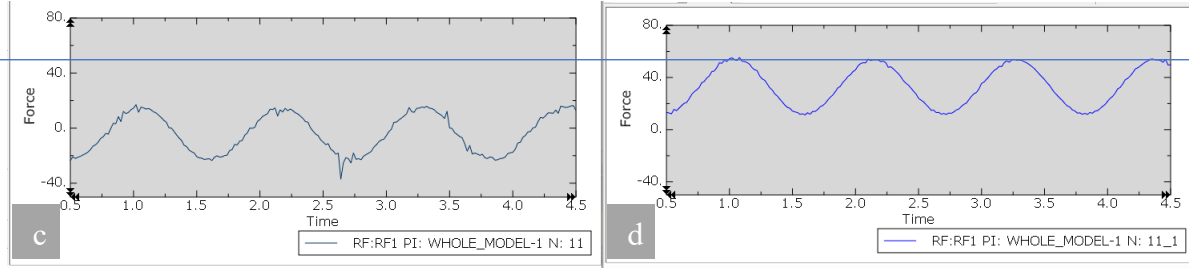


Figure 61: Mesh and particle sensitivity analyses of a nodal reaction force; a) SPH with fewer particles, b) Rigid with a coarse mesh, c) SPH with more particles, d) Rigid with a fine mesh

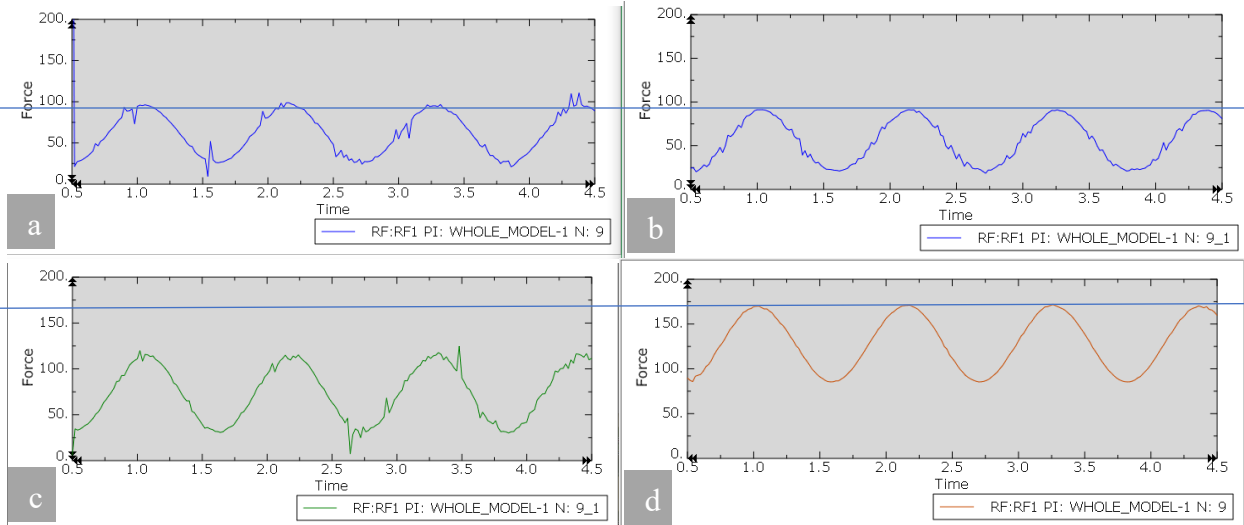


Figure 62: Mesh and particle sensitivity analyses of a nodal reaction force; a) SPH with fewer particles, b) Rigid with a coarse mesh, c) SPH with more particles, d) Rigid with a fine mesh

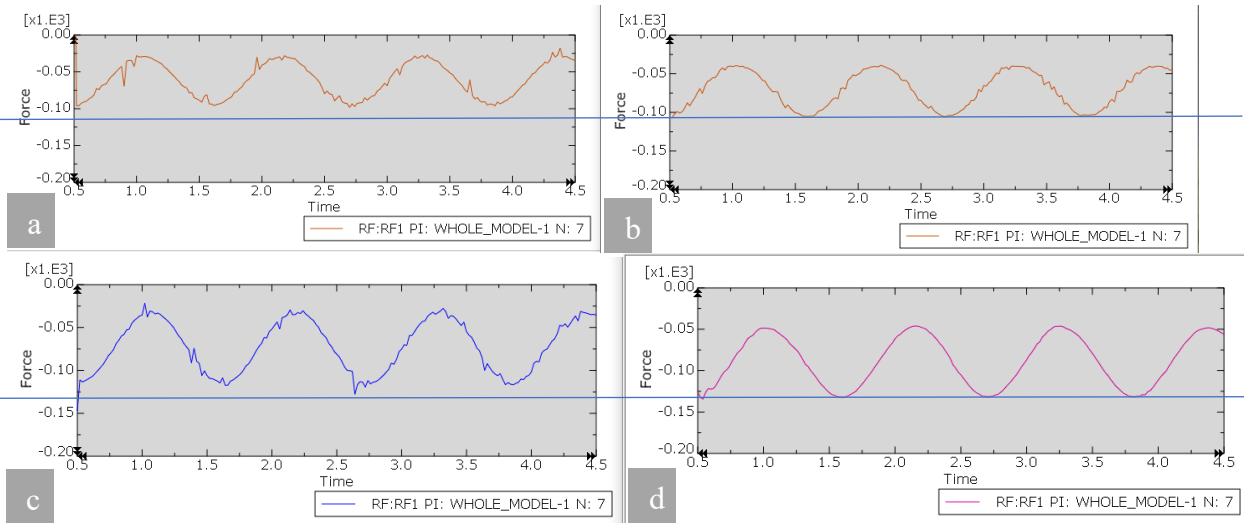


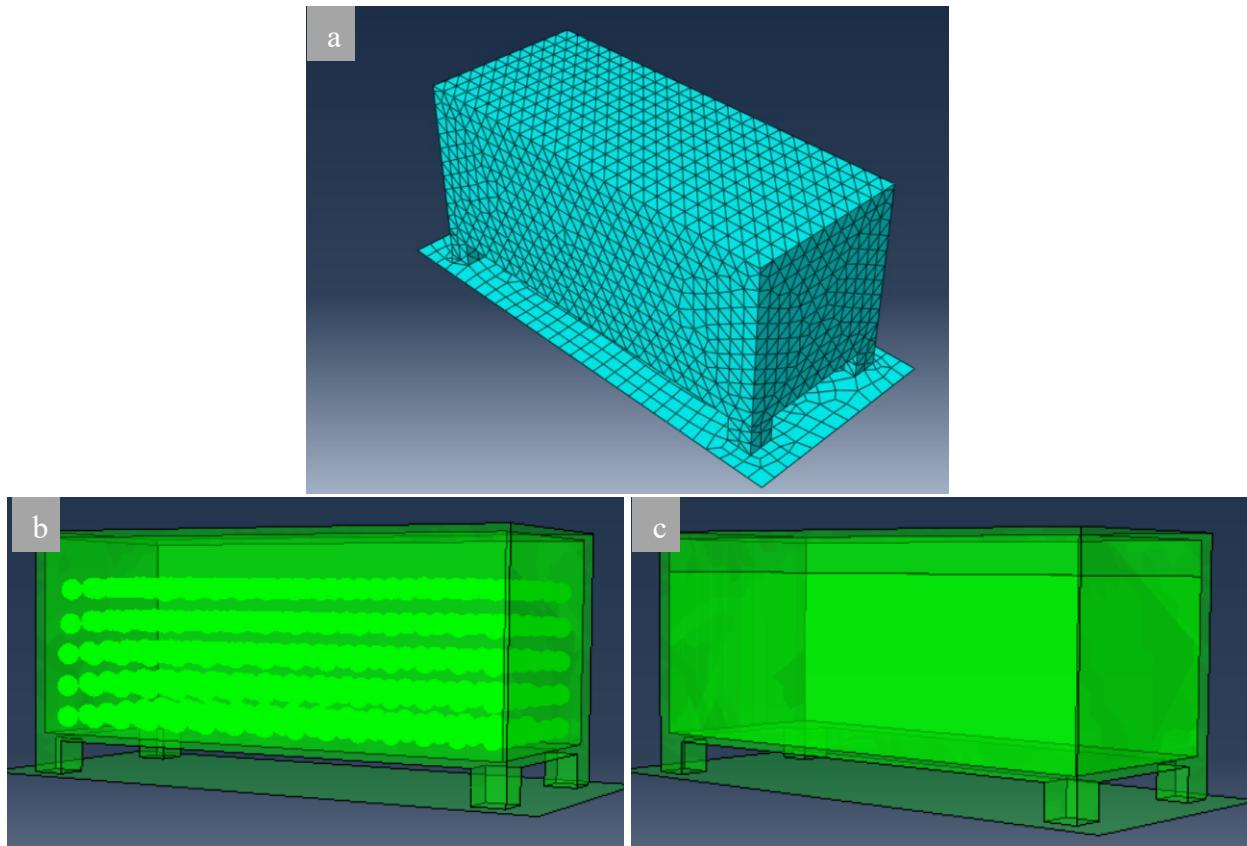
Figure 63: Mesh and particle sensitivity analyses of a nodal reaction force; a) SPH with fewer particles, b) Rigid with a coarse mesh, c) SPH with more particles, d) Rigid with a fine mesh

5.3.1.2. Comparison of Tank seismic response filled with solid and liquid materials

Reaction forces at different points of the base of the supporting structures in the excitation direction (namely X direction) are compared for Solid and SPH methods (Figure 64). The graphs presented in Figure 65 are nodal reaction forces at the base of the support structures. They only show the

lateral force at those specific points and do not represent the total shear force of the supporting structure. The graphs show that when the model is changed to SPH, there is an increase of 10-30 percent in the reaction forces captured at the base points.

Preliminary results from phase 1 show that there is a significant gap between the solid material assumption - presented by the NBC - and the liquid material. Therefore, the study deemed feasible to proceed to phase 2 with a larger tank so that the gap between the assumptions by the code and the results from numerical models could be determined more precisely.



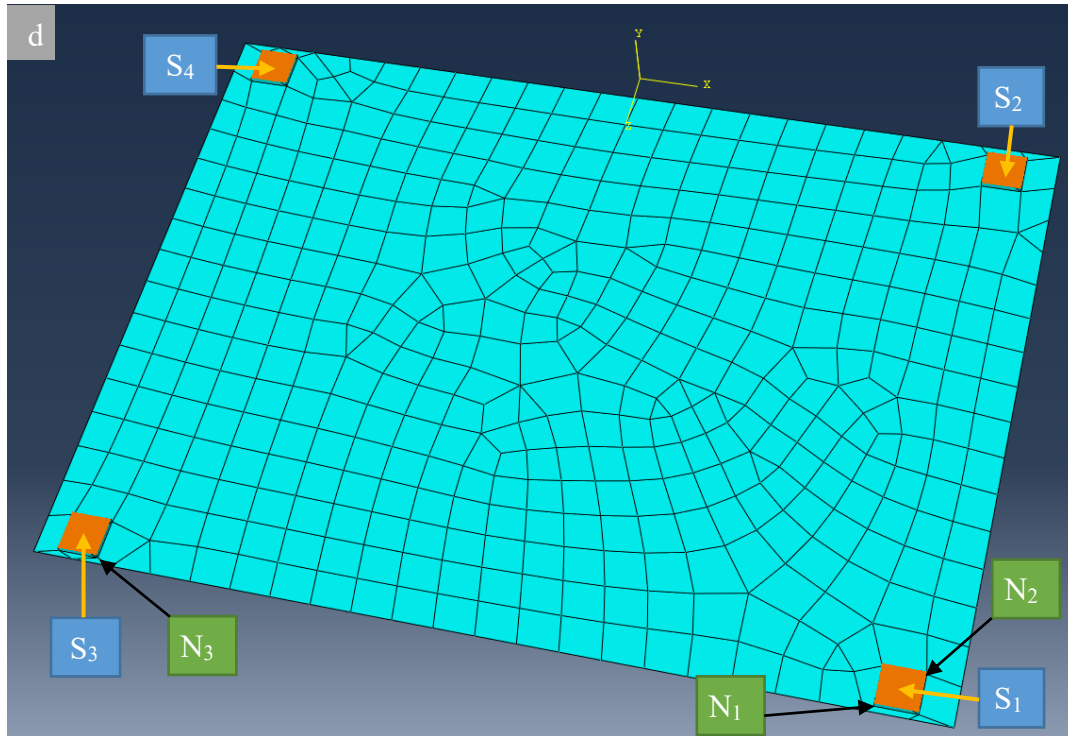


Figure 64: a) Structure mesh, b) SPH model, c) Solid material model, d) Base of the tank; demonstrating supports $S1-S4$, and nodes $N1-N3$

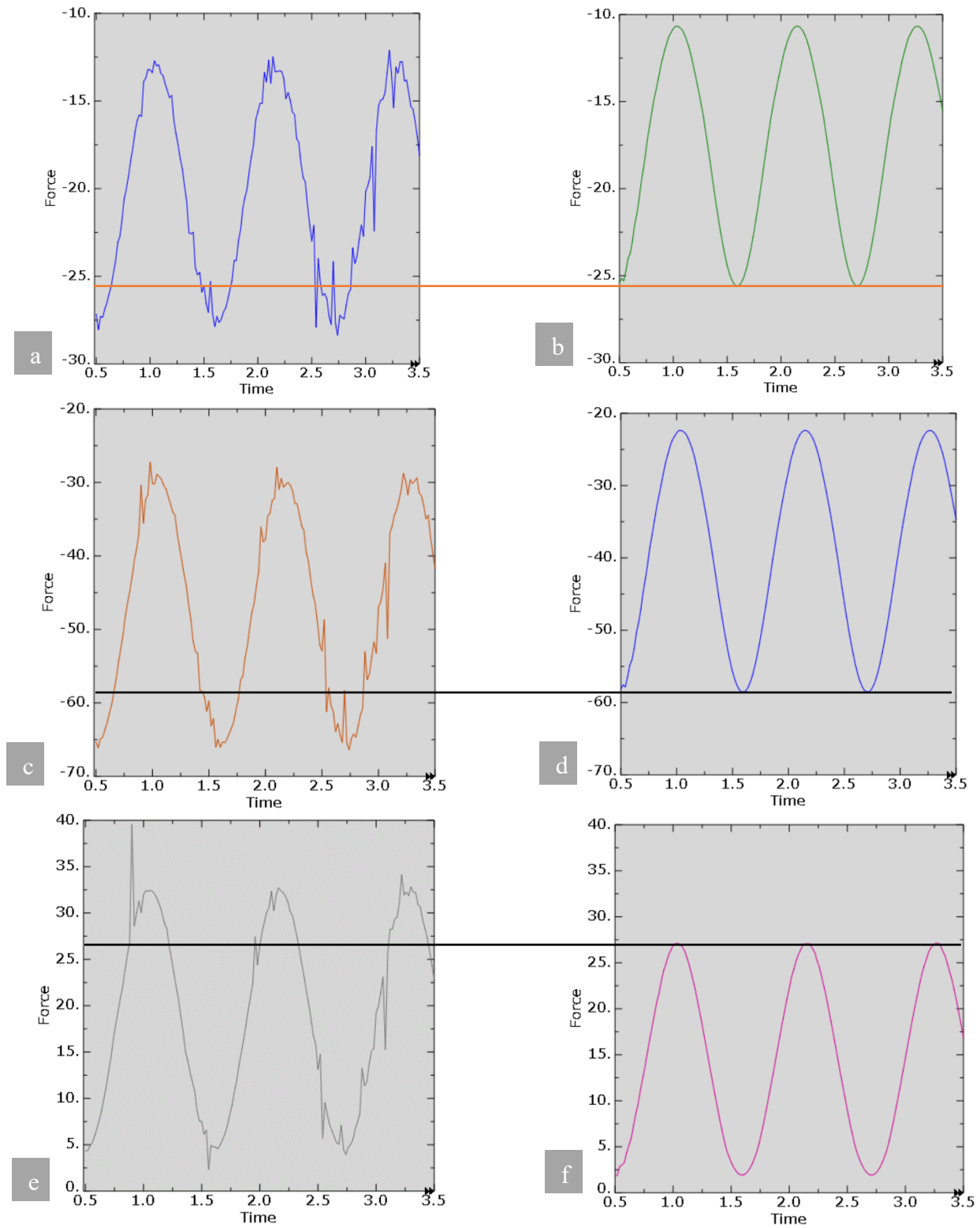


Figure 65: Comparison of nodal reaction forces using liquid (SPH) and solid materials: a) N1 SPH, b) N1 solid, c) N2 SPH, d) N2 solid, e) N3 SPH, f) N3 solid

5.3.2. Phase 2, NBC requirements for liquid tanks

This phase consists of two sections, i) mass and frequency analyses, and ii) liquid-solid-NBC comparison. In the first part, the mass and frequency of the structure are measured both manually and using the software and the results are compared. In the second part, the results of the harmonic excitations are compared with NBC for the city of Ottawa, Ontario, Canada.

5.3.2.1. Mass and frequency analyses

In this section, the mass and frequency of the tank structure are measured using the ABAQUS software and compared with manual calculations to determine the accuracy of the model. The results from the software are obtained using the frequency analysis tool and are as follows:

Total mass (structure and water) = 7488.2 kg

Structure mass without water = 4488.2 kg

Mass of the water part = 3000 kg

Deducting the mass of the rigid base leads to the pure mass of the structure as follows:

Pure mass of the tank structure excluding supports = 4488.2 – 850.08 = 3638.12 kg

Circular frequency of the 1st mode of vibration obtained from the model = 185.53 cycles/s

Using this circular frequency, the period of the structure is measured as follows:

$$T_{software} = \frac{1}{f} = \frac{1}{185.53} = 0.0054 \text{ s}$$

$$\omega_{software} = 2\pi f = 1165.7 \text{ rad/s}$$

For the manual calculation, a constant traction force of 10 kN/m² is applied to the roof of the tank for two seconds and the displacement of the top is obtained from the software, which is equal to 10×10^{-6} m. The force and the displacement are then used to measure the stiffness, and consequently the structure's period and frequency. The calculations are as follows:

$$F_t = L.B.S_t = 2.06 \times 1.56 \times 10000 = 32136 \text{ N}$$

$$k = F_t / d_t = \frac{32136}{10 \times 10^{-6}} = 3213600000 \text{ N/m}$$

$$\omega_{manual} = \sqrt{k/m} = \sqrt{\frac{3213600000}{3638.12}} = 939.85 \text{ rad/s}$$

$$T_{manual} = 2\pi \sqrt{m/k} = 2\pi \sqrt{\frac{3638.12}{3213600000}} = 0.0067 \text{ s}$$

It is observed that there is a 19% difference between the calculated period and the period obtained from the model. The same difference occurs for the frequency as well. This difference can be a result of the methods used for calculations and the effect of higher modes on the manual calculations and other contributing factors, however, this difference is within a reasonable range.

5.3.2.2. Comparison of liquid material, solid material, and the code

Now that the model's accuracy is found reasonable, a comparison between the results of simulations for liquid material, the equivalent solid material and the base shear obtained from the NBC are presented and compared for Ottawa, Ontario and Vancouver, British Colombia, Canada.

Ottawa, Ontario

The PGA provided by NBC for the city of Ottawa is 0.281g where g is the ground acceleration, equal to 9.81 m/s² and hence, the PGA is equal to 2.757 m/s². Three harmonic loadings with different frequencies, but the same accelerations equal to the PGA are applied to the tank partially filled with water and the equivalent solid material. The base shear for each support structure and the total base shear are measured. The base shear based on the NBC equation is also calculated and compared with the results from the software. The results are as follows.

Using the NBC, the base shear for the roof-top tank located on the site class C is calculated by the following equation:

$$V_P = 0.3F_a S_a(0.2)I_E S_P W_P \text{ where } F_a = 1.0, I_E = 1.0, S_P = 2.4 \text{ and hence,}$$

$$V_P = 0.72S_a(0.2)W_P$$

For the city of Ottawa $S_a(0.2)$ is equal to 0.439g, hence $V_P = 0.316W_P$.

For the tank in this case, $W_P = 7488.2 \times 9.81 = 73459.2 \text{ N}$

Hence, $V_P = 0.316W_P = 0.316 \times 73459.2 = 23213.1 \text{ N}$

For a single support structure, the base shear would be $V_s = \frac{23213.1}{4} = 5803.3 \text{ N}$

The graphs in Figures 66-68 present the comparison between the above-calculated base shear (i.e. NBC) and the base shears predicted by the numerical modelling.

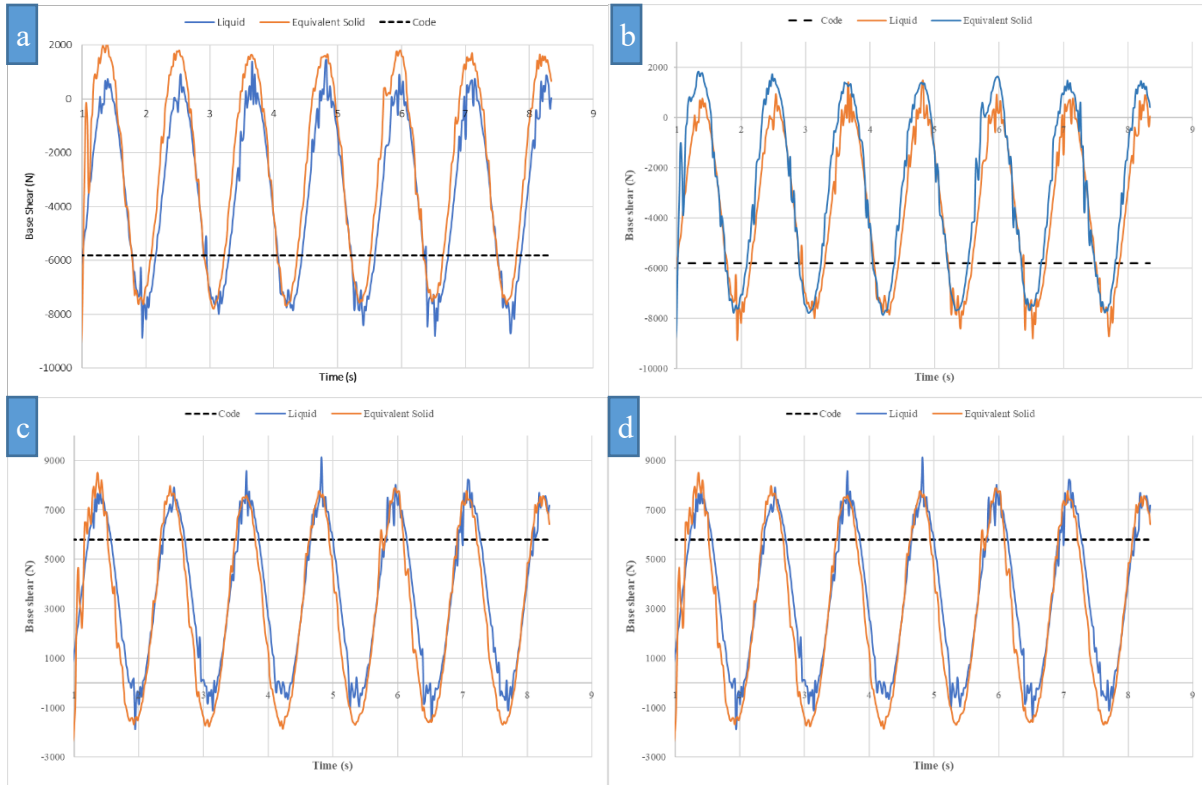


Figure 66: : Base shear for individual supports excited by above resonance frequency, Ottawa: a) Support S1, b) Support S2, c) Support S3, d) Support S4

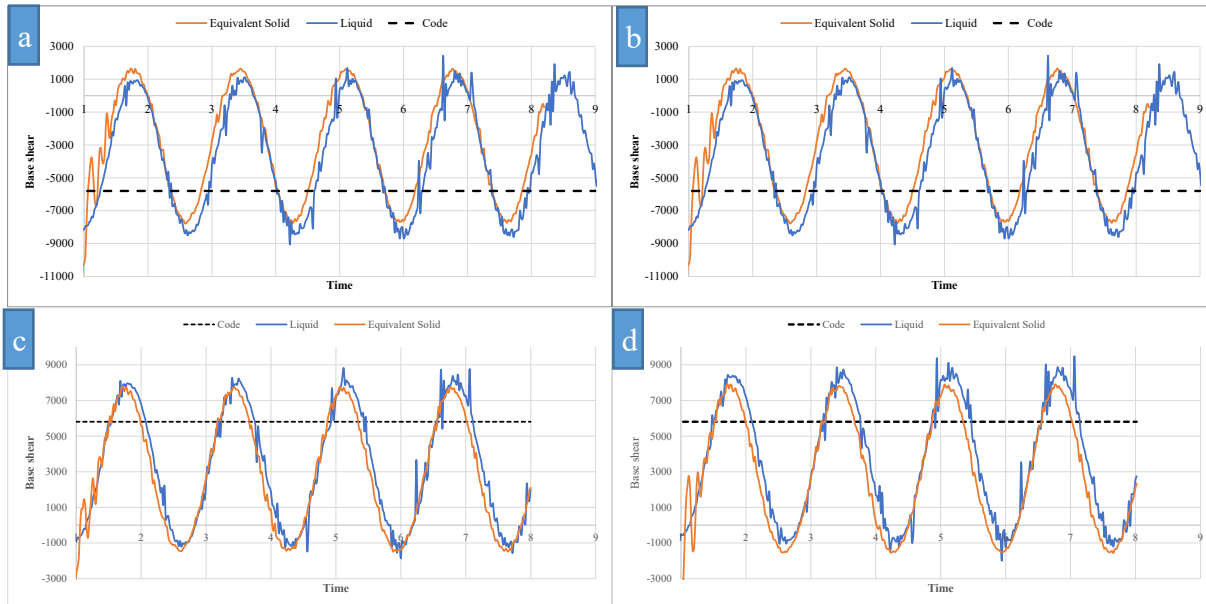


Figure 67: Base shear for individual supports excited by resonance frequency, Ottawa: a) Support S1, b) Support S2, c) Support S3, d) Support S4

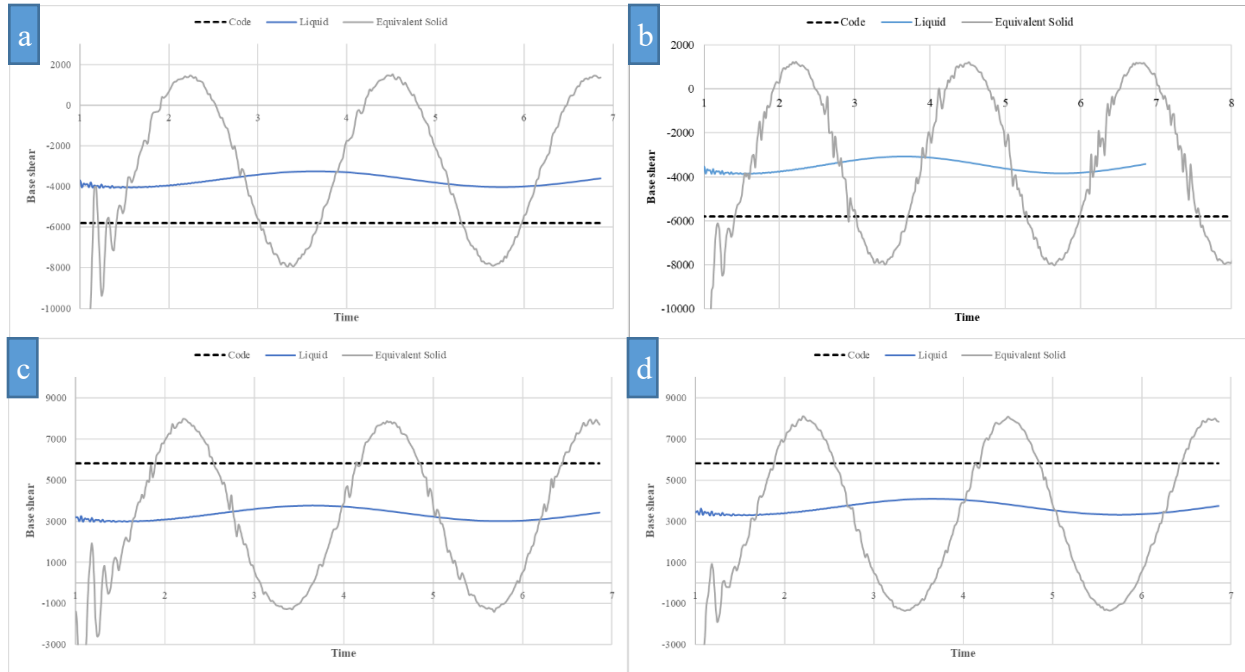


Figure 68: Base shear for individual supports excited by below resonance frequency, Ottawa: a) Support S1, b) Support S2, c) Support S3, d) Support S4

The total base shear for the liquid, equivalent solid, and the code are also compared. The comparison is demonstrated in Figures 69-71. It can be seen that in all cases, the code can precisely capture the total base shear.

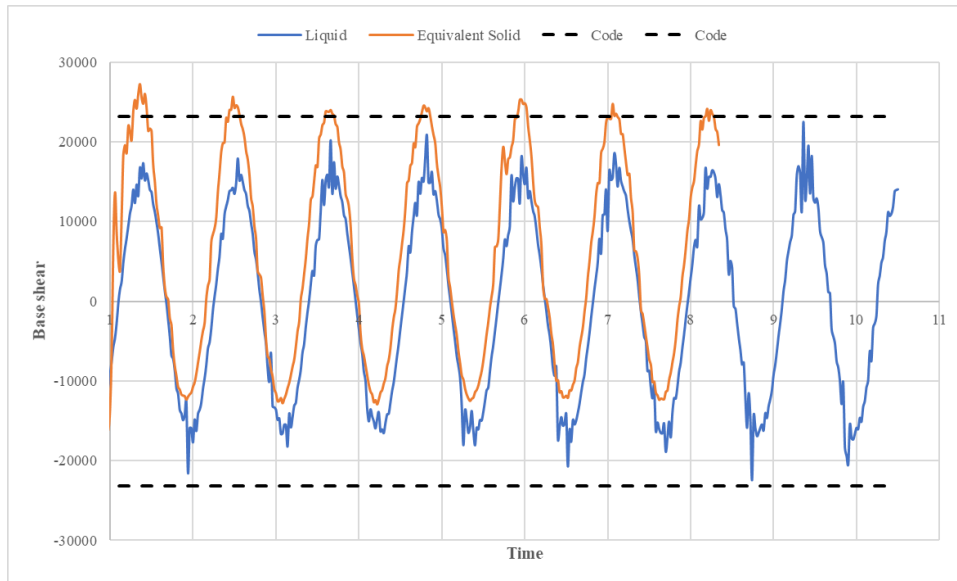


Figure 69: Total base shear (algebraic sum of individual base shears), Above resonance frequency, Ottawa

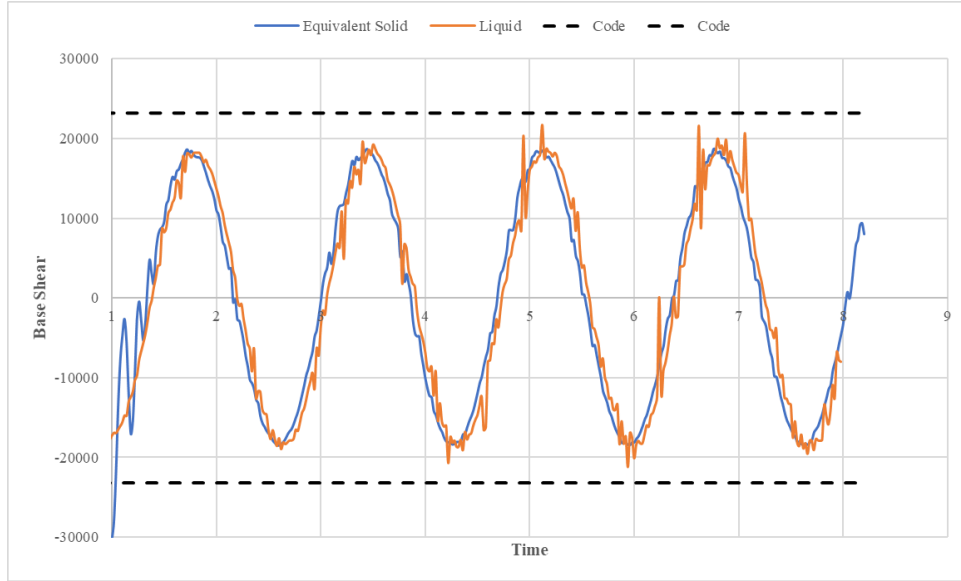


Figure 70: Total base shear (algebraic sum of individual base shears), Resonance frequency, Ottawa

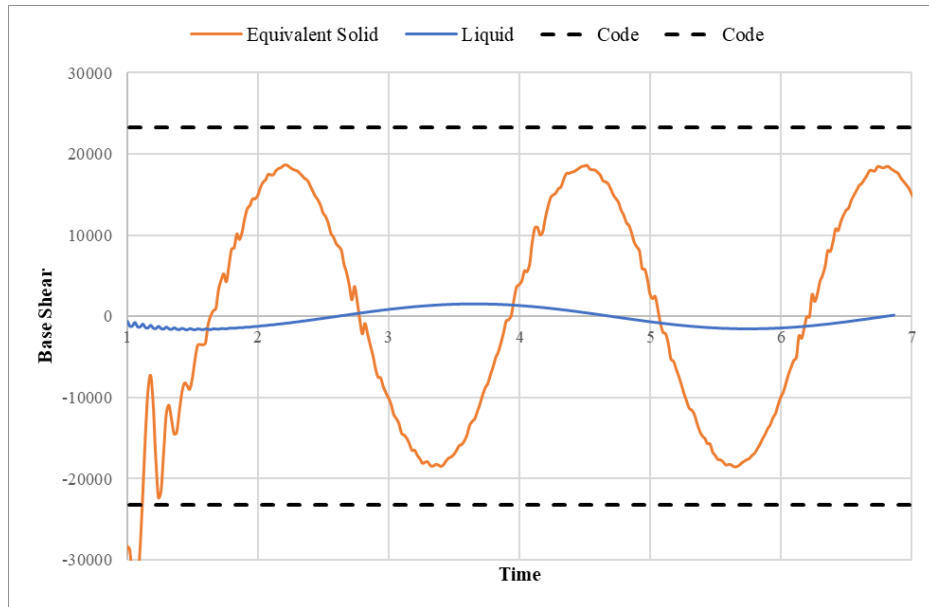


Figure 71: Total base shear (algebraic sum of individual base shears), Below resonance frequency, Ottawa

Vancouver, British Columbia

The same methodology is used for the city of Vancouver. The PGA for this city is 0.369g, or 3.62 m/s² which is applied to the tank using the model. The base shear for a roof-top tank calculated based on the code for this city is

$$V_P = 0.72S_a(0.2)W_P$$

Where $S_a(0.2)$ is equal to 0.848g, hence $V_P = 0.611W_P$.

$$W_P = 7488.2 \times 9.81 = 73459.2 \text{ N},$$

Hence, $V_p = 0.611W_p = 0.611 \times 73459.2 = 44883.6 \text{ N}$

For a single support structure, the base shear would be $V_s = \frac{44883.6}{4} = 11220.1$

The results are presented in figures 72-74.

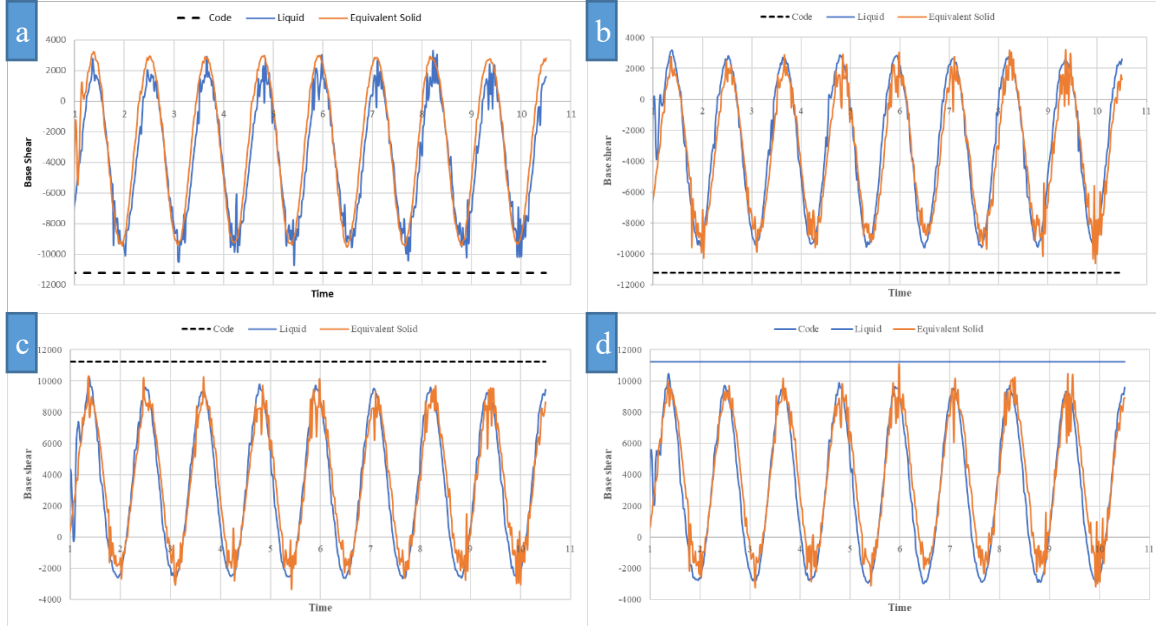


Figure 72: Base shear for individual supports excited by above resonance frequency, Vancouver: a) Support S1, b) Support S2, c) Support S3, d) Support S4

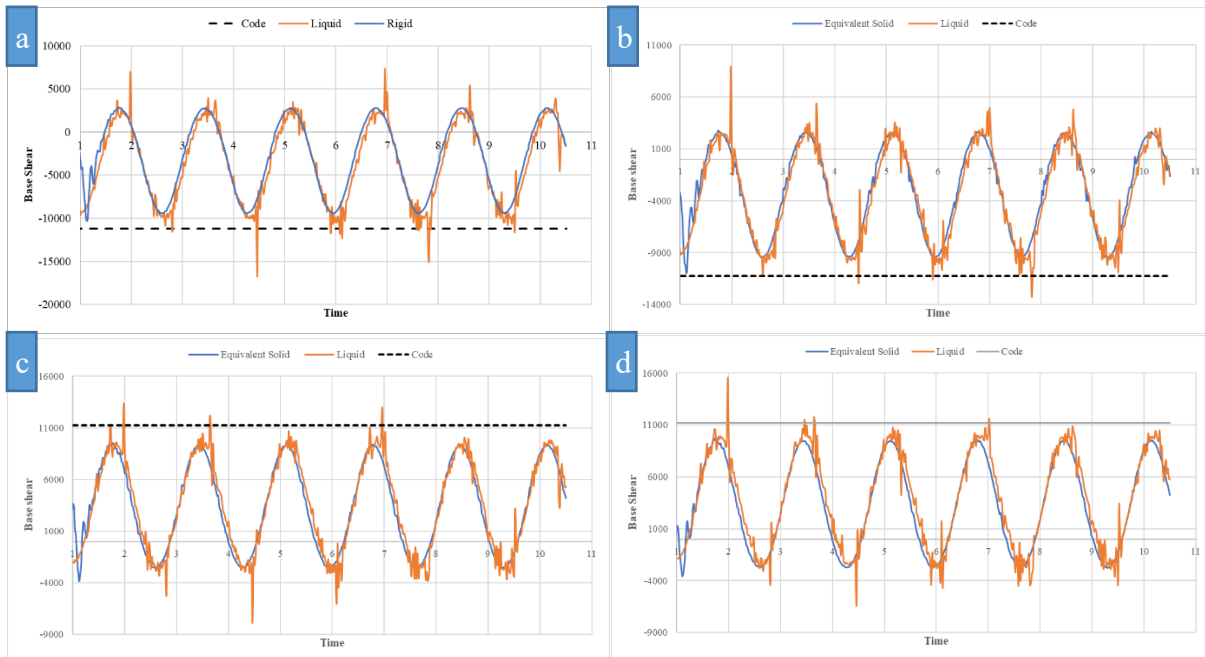


Figure 73: Base shear for individual supports excited by resonance frequency, Vancouver: a) Support S1, b) Support S2, c) Support S3, d) Support S4

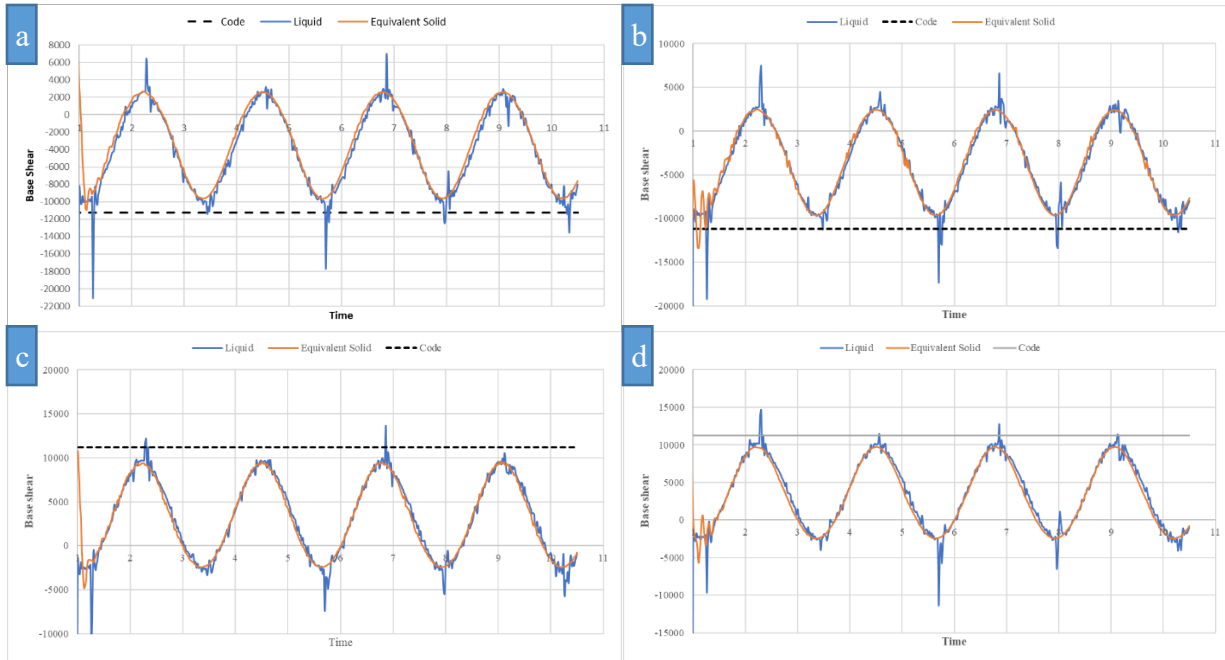


Figure 74: Base shear for individual supports excited by below resonance frequency, Vancouver: a) Support S1, b) Support S2, C) Support S3, D) Support S4

The comparison of total base shear for the liquid, equivalent solid, and the code are compared and presented in Figures 75-77. Similar to Ottawa, it can be seen that in all cases, the code can precisely capture the total base shear.

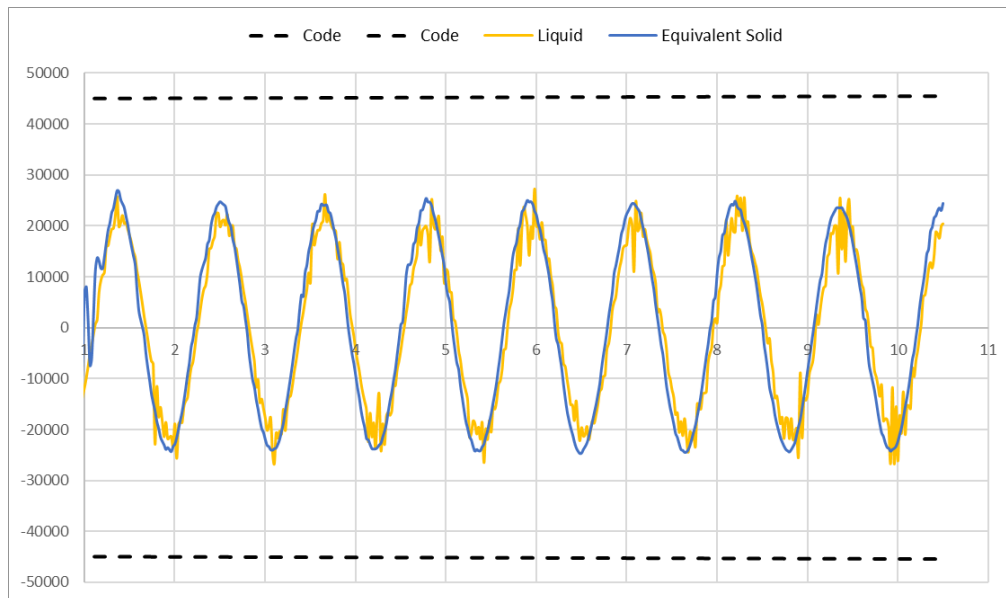


Figure 75: Total base shear (algebraic sum of individual base shears), Above resonance frequency, Vancouver

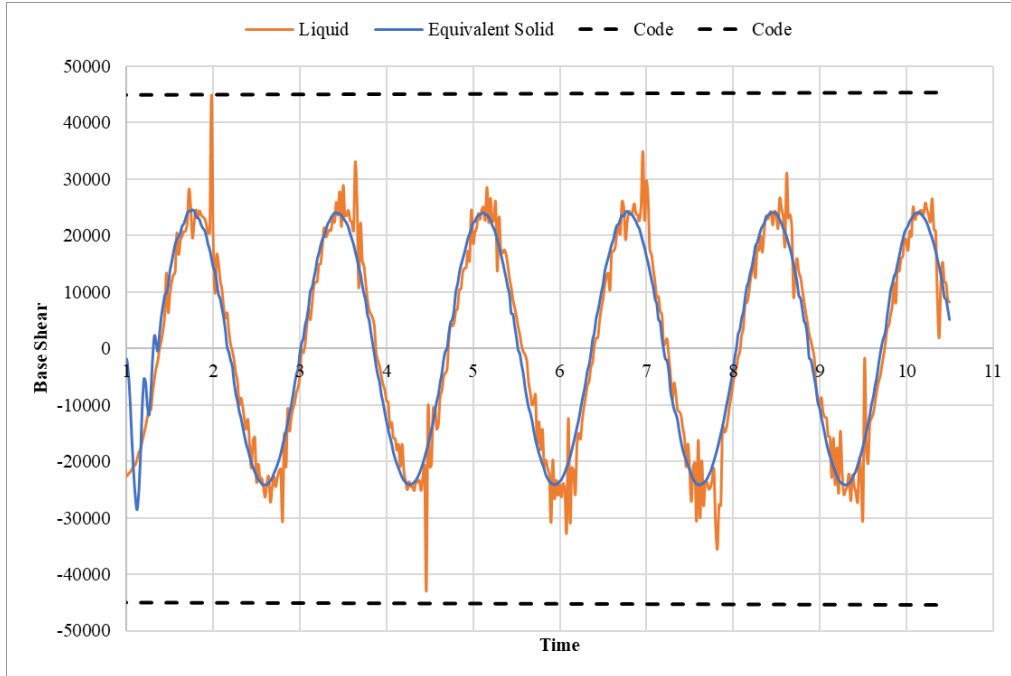


Figure 76: Total base shear (algebraic sum of individual base shears), Resonance Frequency, Vancouver

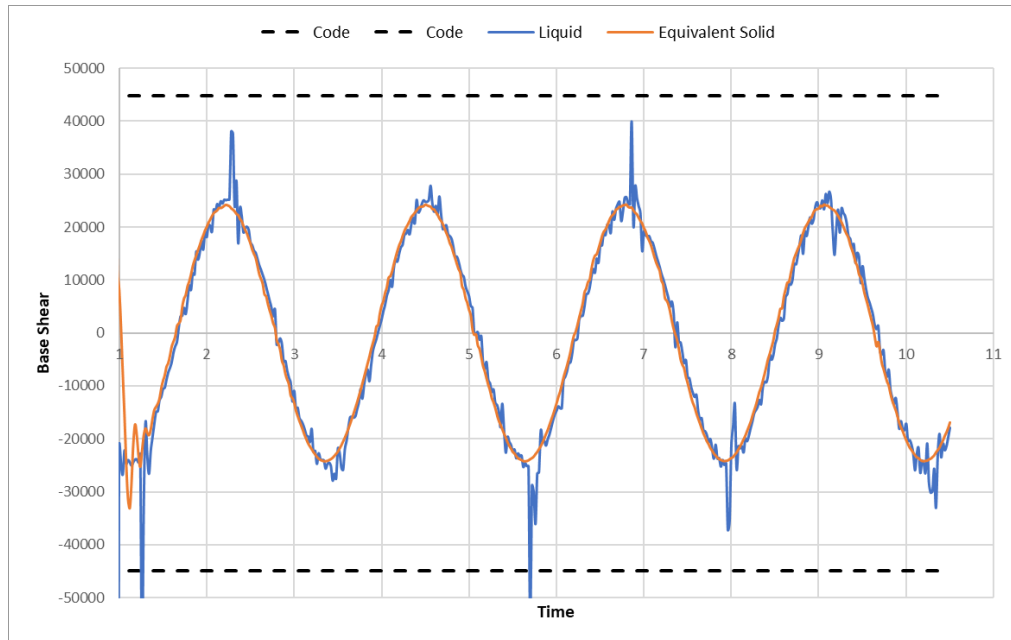


Figure 77: Total base shear (algebraic sum of individual base shears), Below resonance frequency, Vancouver

5.3.3. Phase 3, NBC Code requirements Vs. numerical results

A total of eight simulations are completed in this phase. Four earthquake records, namely 1940 El Centro, 1971 San Fernando earthquake, 1994 Northridge earthquake, and 1995 Kobe, adjusted to PGAs of Ottawa, ON., and Vancouver, BC. are applied to the base of a tank with plan dimensions of 15×30m and height of 15m with liquid filled up to 12m (i.e., 80% fill depth). The base shear for each support as well as total base shear of the tank are measured and compared with the results provided by NBC.

According to the NBC, the base shear for a tank with the above-mentioned dimensions located on the roof of a building situated in an area with site class C in Ottawa, ON. is calculated as

$$W_p = 14947300 \times 9.81 = 146633013 \text{ N}$$

$$\text{Hence, } V_p = 0.316W_p = 0.316 \times 146633013 = 46336032 \text{ N, or } 46336 \text{ kN}$$

$$\text{For a single support structure, the base shear would be } V_s = \frac{46336}{4} = 11584 \text{ kN}$$

And for Vancouver, BC.:

$$V_p = 0.611W_p = 0.611 \times 146633013 = 89592771 \text{ N, or } 89593 \text{ kN}$$

$$\text{For a single support structure, the base shear would be } V_s = \frac{89593}{4} = 22398 \text{ kN}$$

Figures 78 through 93 present comparisons between the code and numerical models for the two cities.

Ottawa, Ontario

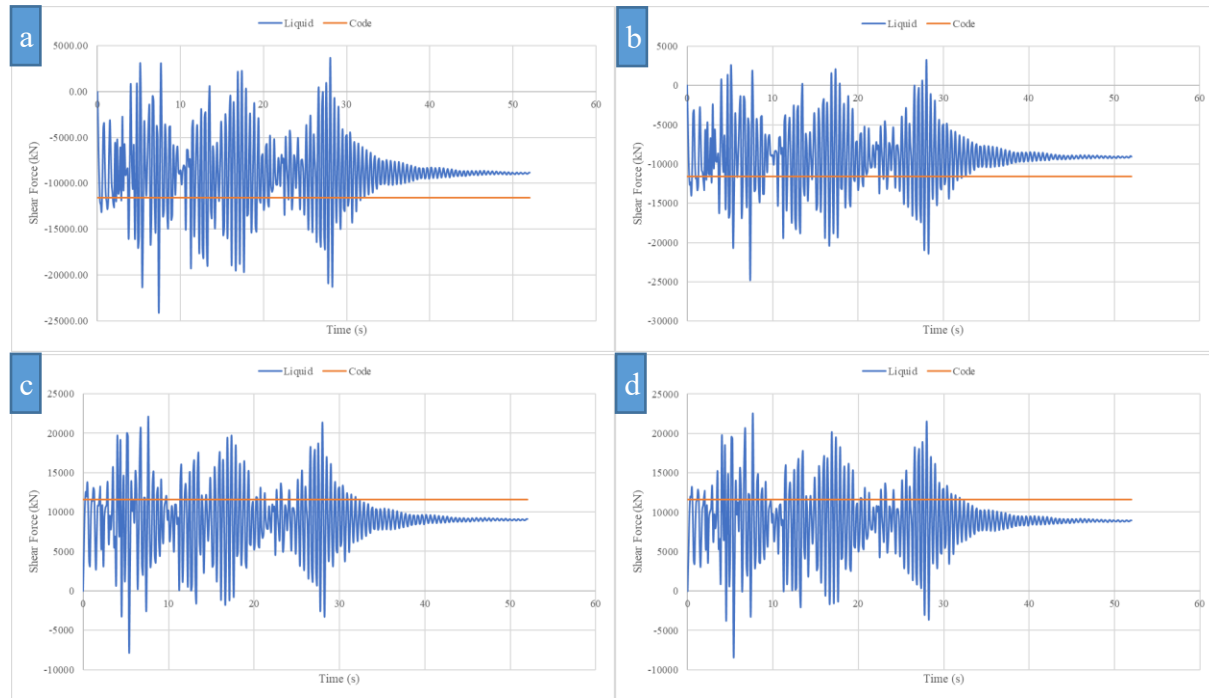


Figure 78: Shear Force for individual supports excited by El-Centro earthquake adjusted to Ottawa's PGA: a) Support S1, b) Support S2, C) Support S3, D) Support S4

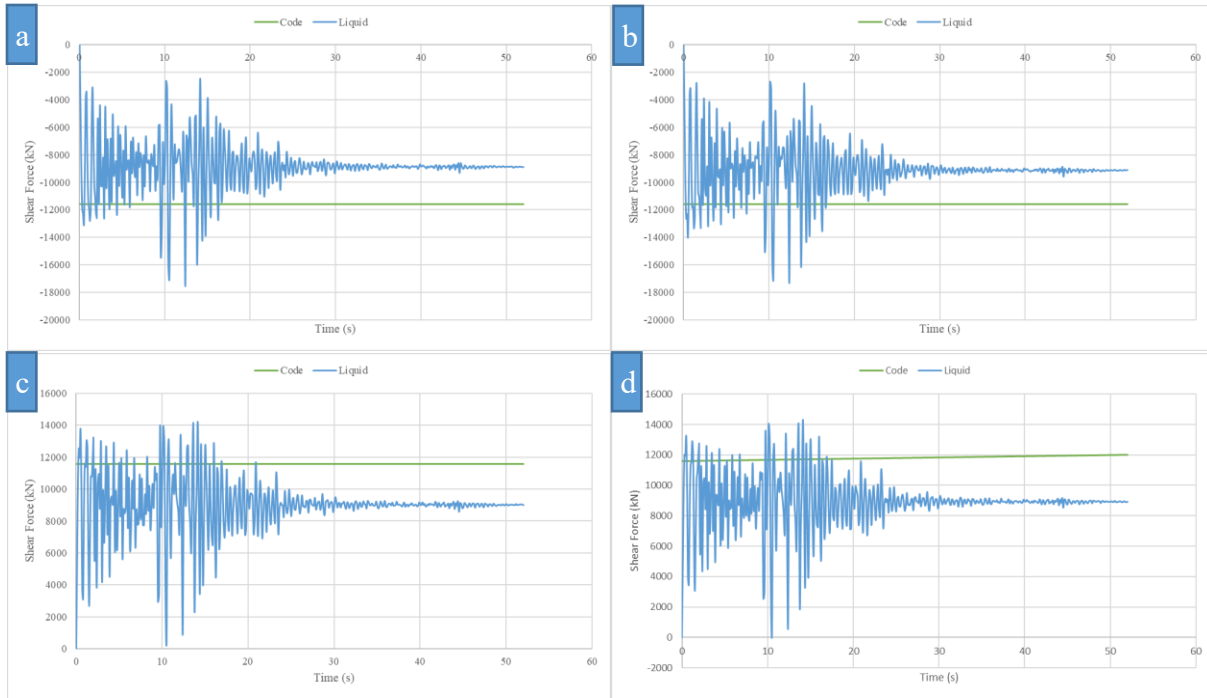


Figure 79: Shear Force for individual supports excited by Kobe earthquake adjusted to Ottawa's PGA: a) Support S1, b) Support S2, C) Support S3, D) Support S4

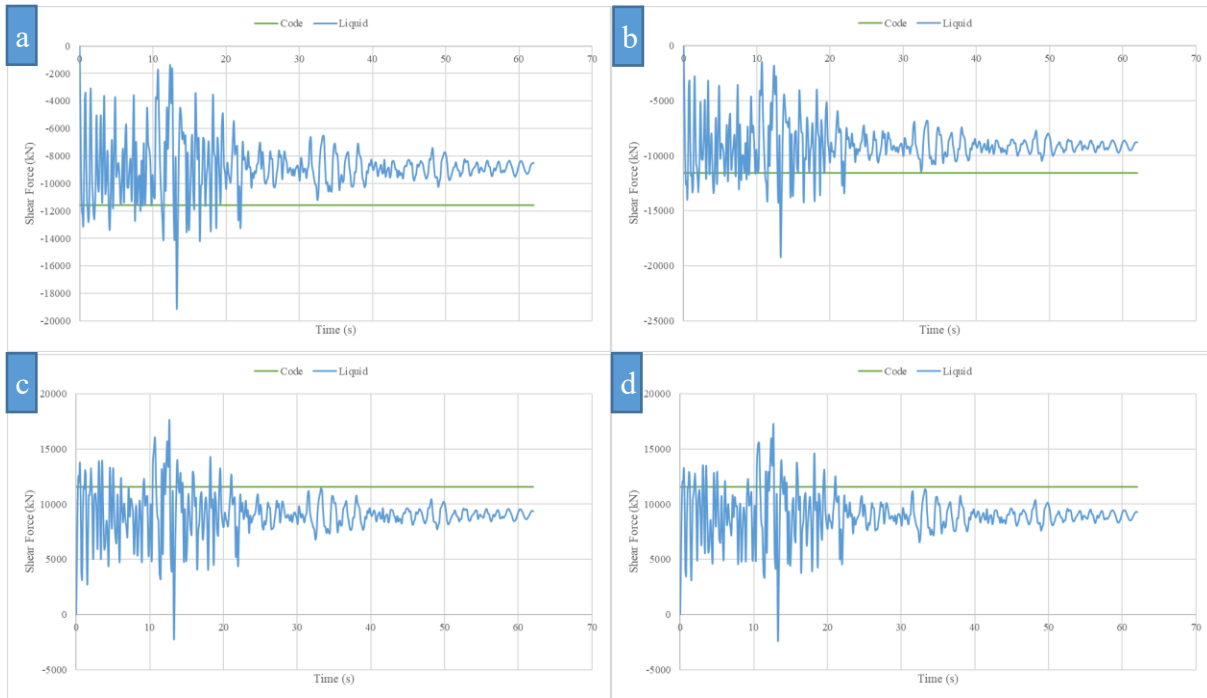


Figure 80: Shear Force for individual supports excited by Northridge earthquake adjusted to Ottawa's PGA: a) Support S1, b) Support S2, C) Support S3, D) Support S4

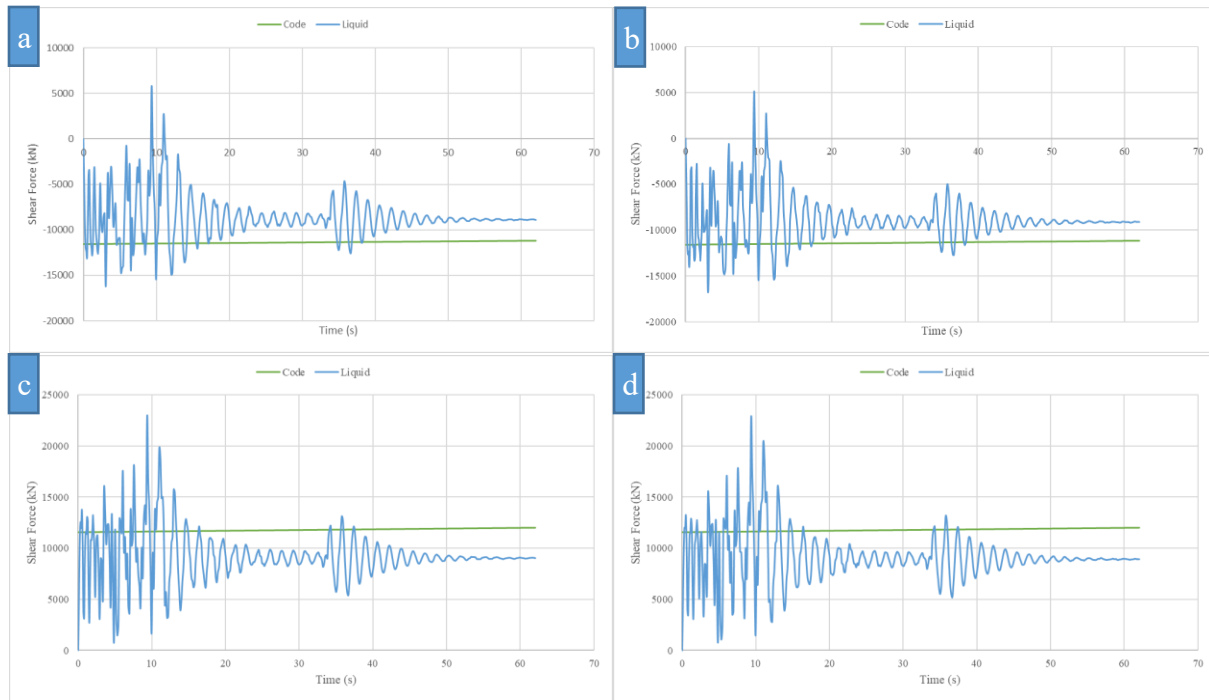


Figure 81: Shear Force for individual supports excited by San Fernando earthquake adjusted to Ottawa's PGA: a) Support S1, b) Support S2, C) Support S3, D) Support S4

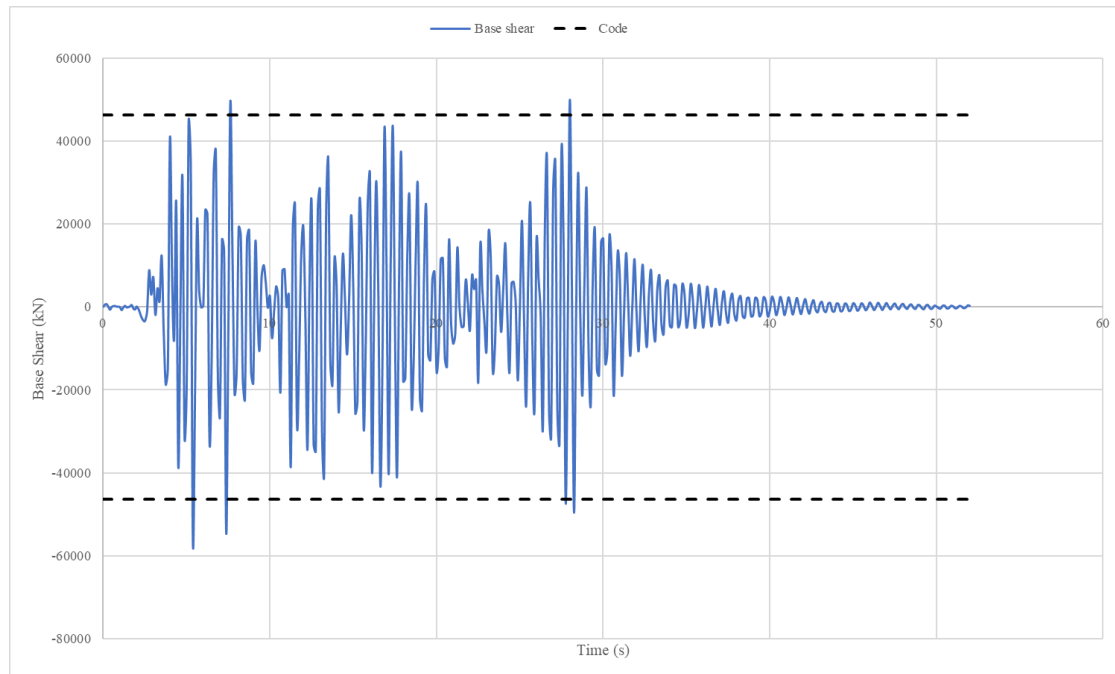


Figure 82: Total base shear for the tank excited by El-Centro earthquake adjusted to Ottawa's PGA

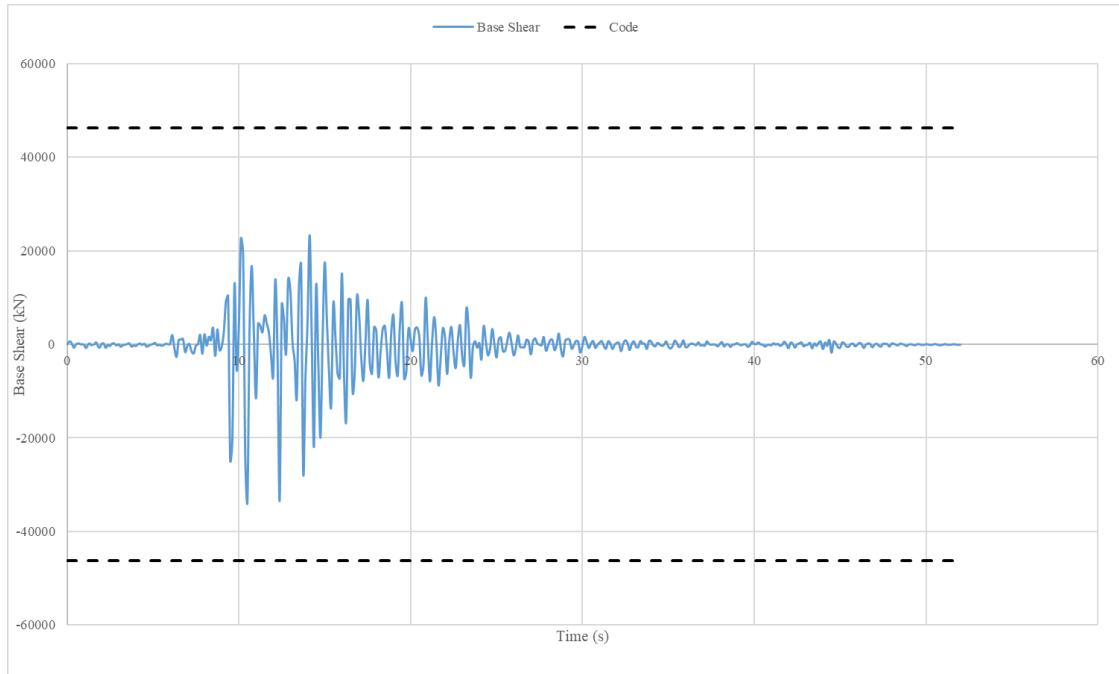


Figure 83: Total base shear for the tank excited by Kobe earthquake adjusted to Ottawa's PGA

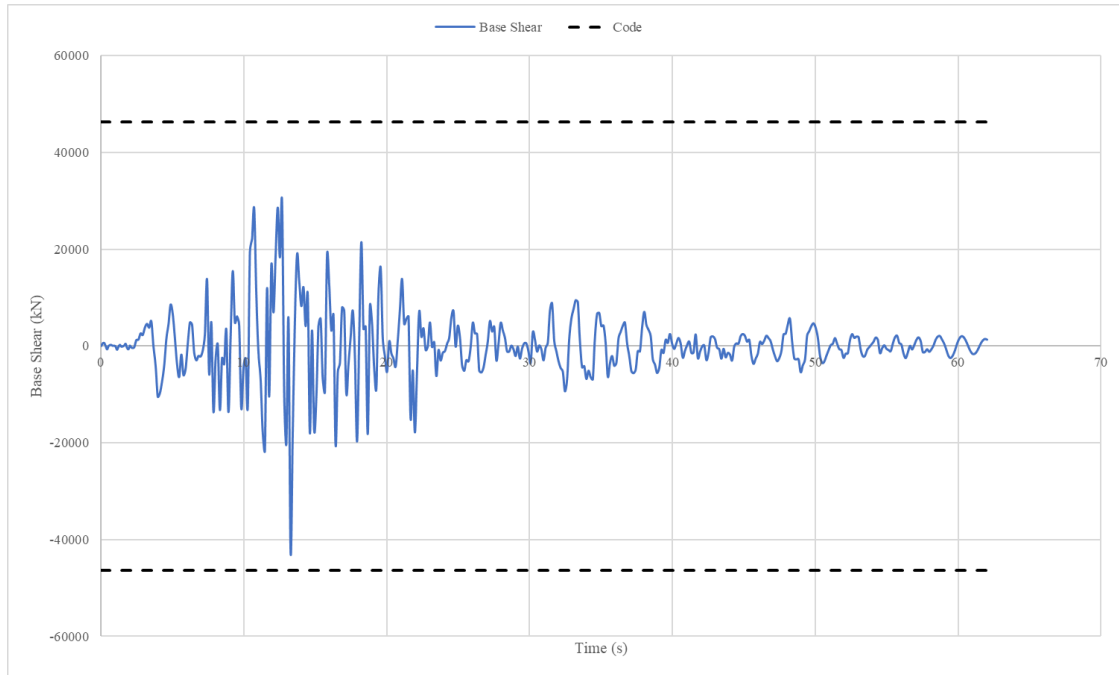


Figure 84: Total base shear for the tank excited by Northridge earthquake adjusted to Ottawa's PGA

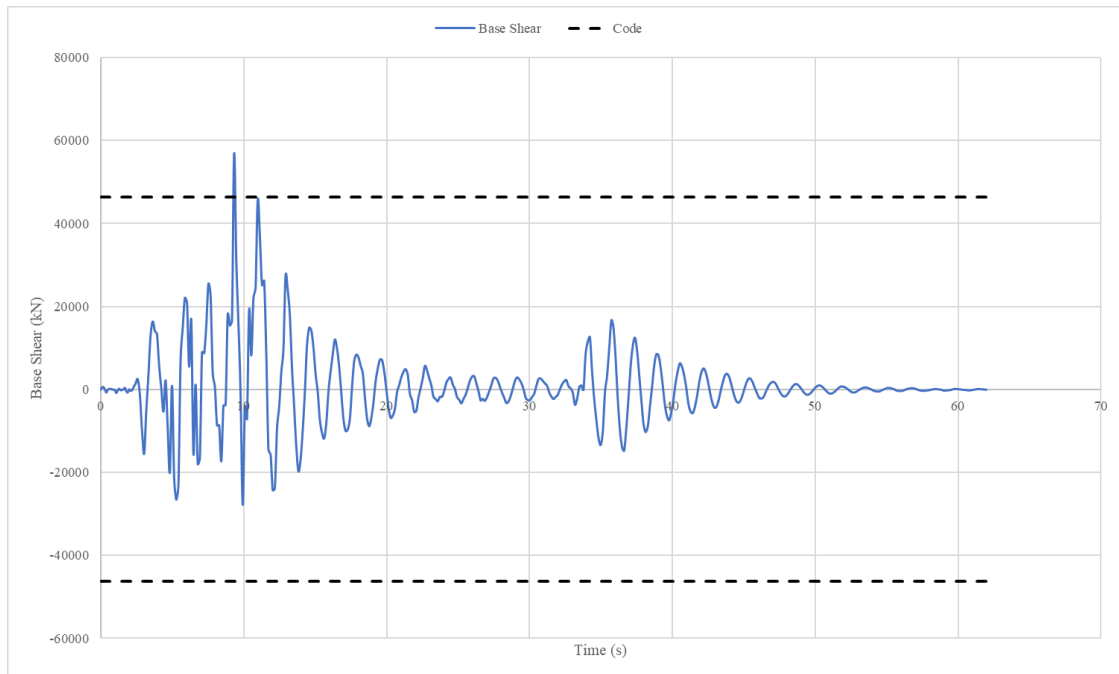


Figure 85: Total base shear for the tank excited by San Fernando earthquake adjusted to Ottawa's PGA

Vancouver, British Columbia

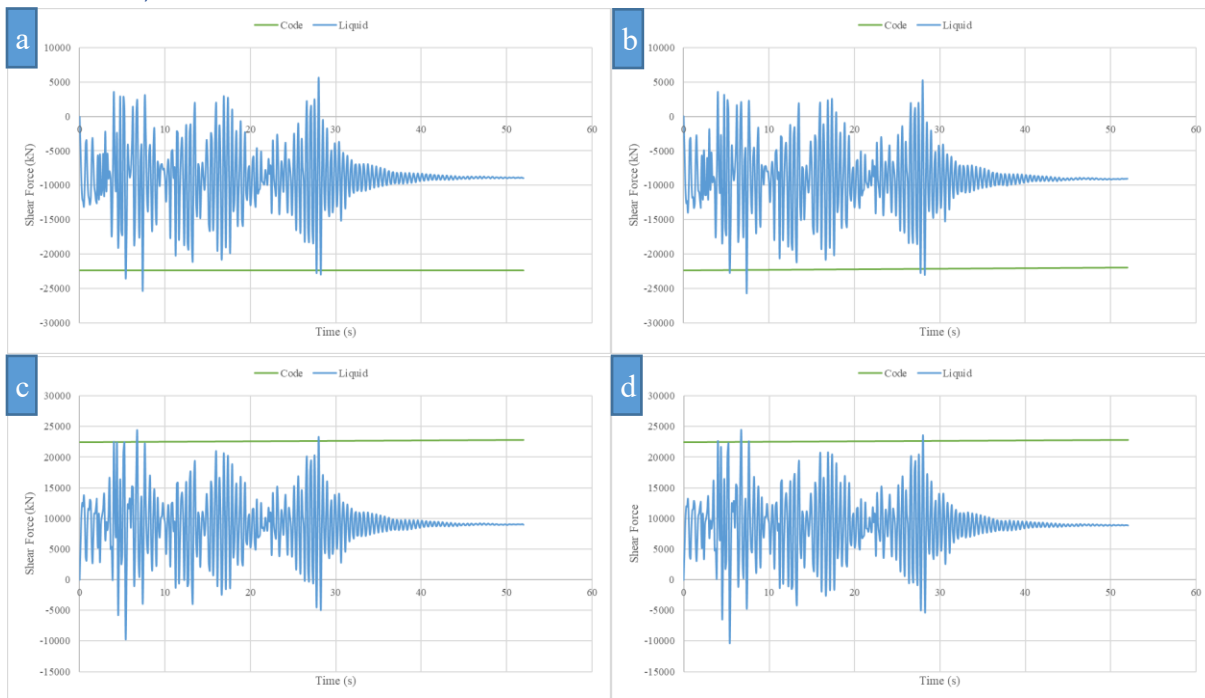


Figure 86: Shear Force for individual supports excited by El-Centro earthquake adjusted to Vancouver's PGA: a) Support S1, b) Support S2, c) Support S3, d) Support S4

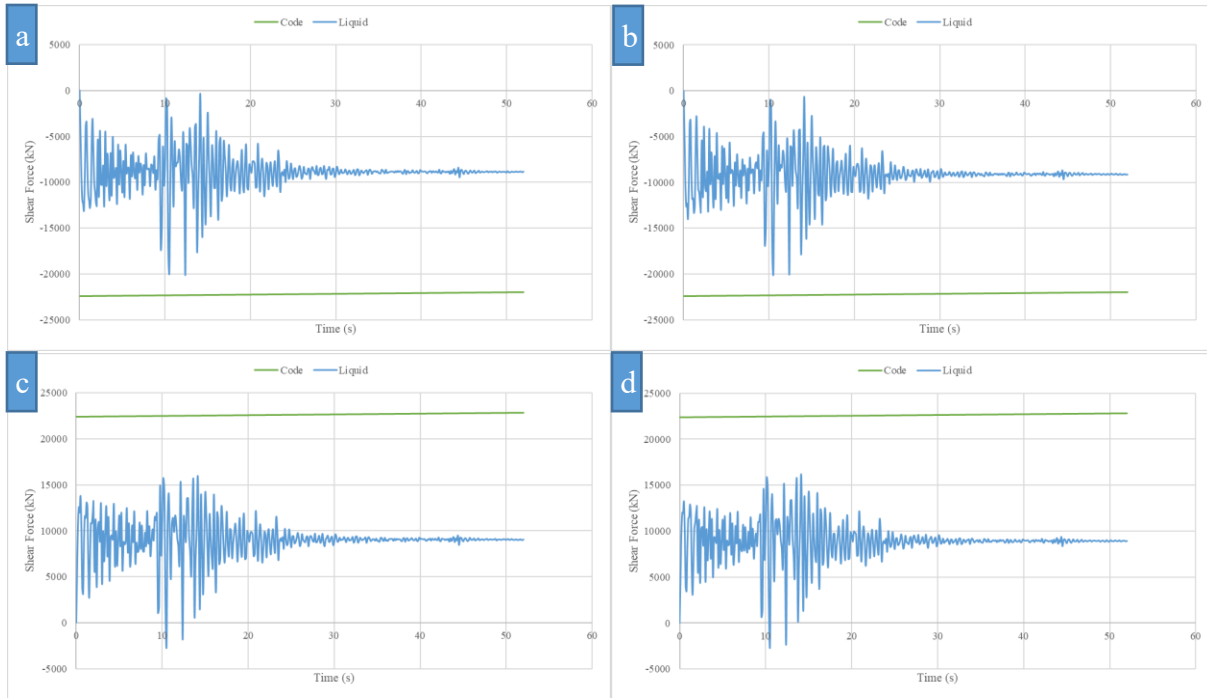


Figure 87: Shear Force for individual supports excited by Kobe earthquake adjusted to Vancouver's PGA: a) Support S1, b) Support S2, C) Support S3, D) Support S4

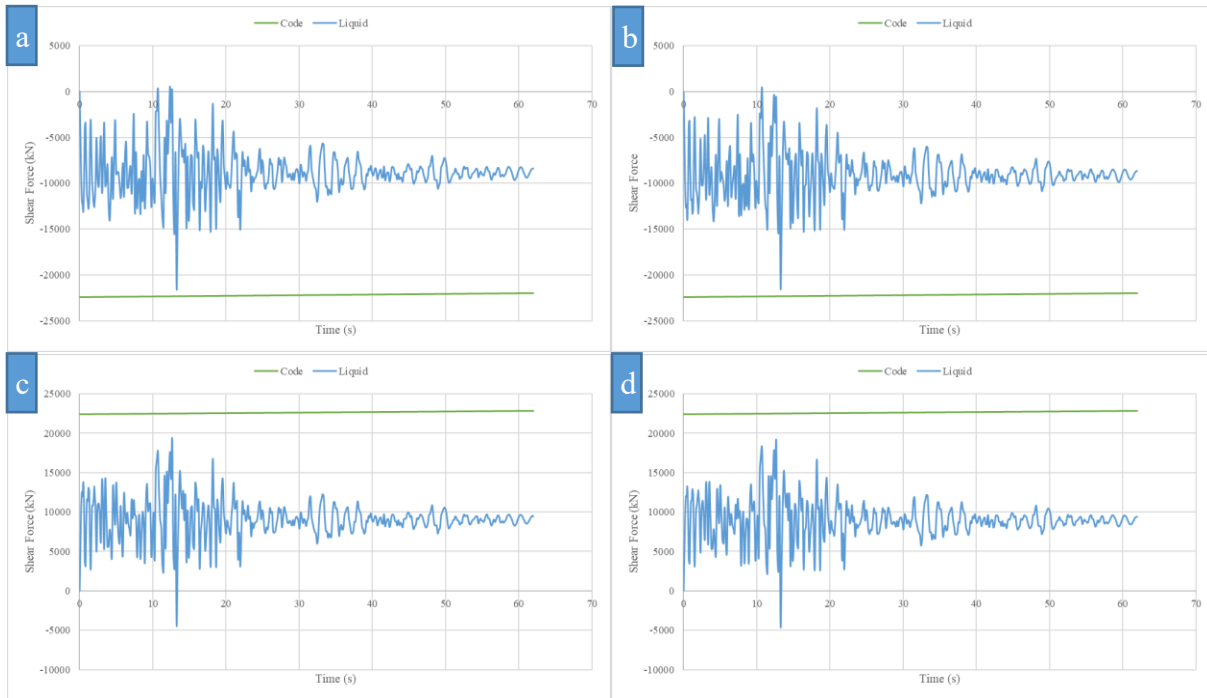


Figure 88: Shear Force for individual supports excited by Northridge earthquake adjusted to Vancouver's PGA: a) Support S1, b) Support S2, C) Support S3, D) Support S4

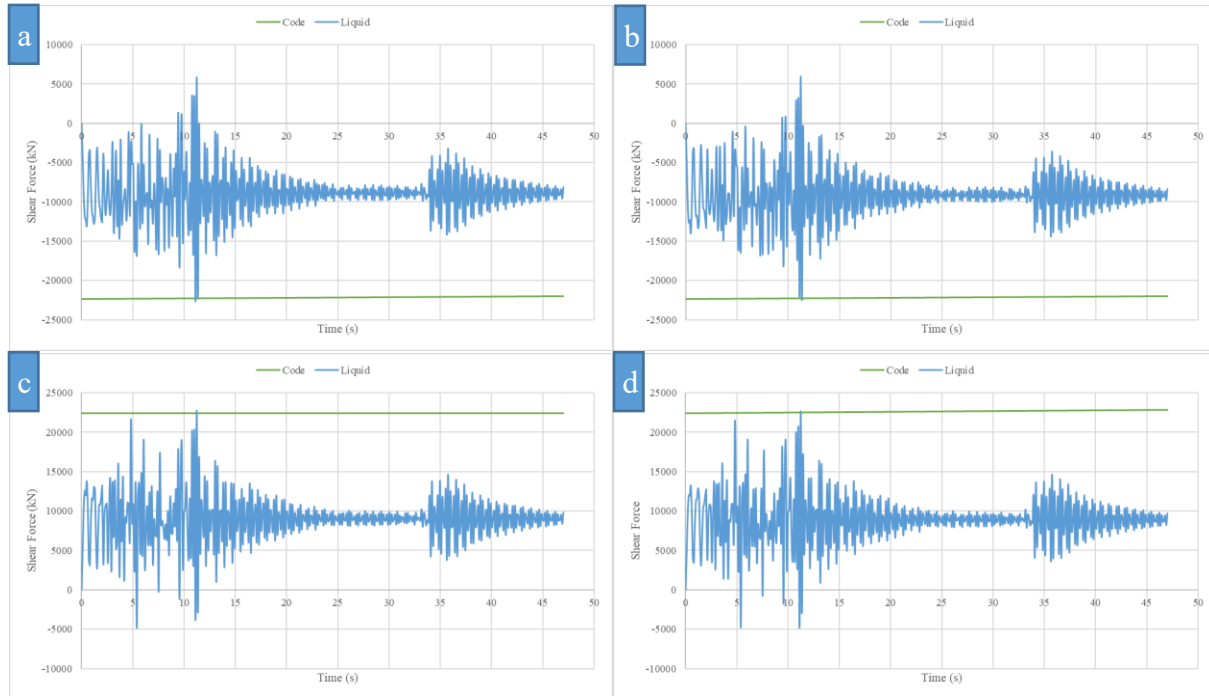


Figure 89: Shear Force for individual supports excited by San Fernando earthquake adjusted to Vancouver's PGA: a) Support S1, b) Support S2, C) Support S3, D) Support S4

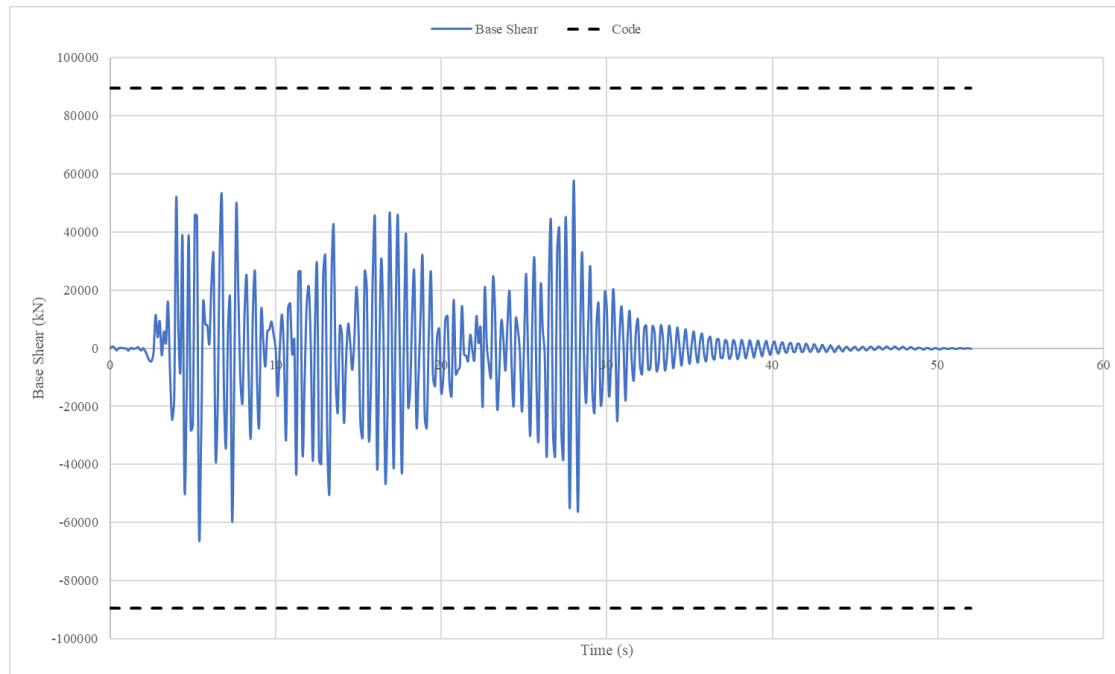


Figure 90: Total base shear for the tank excited by El-Centro earthquake adjusted to Vancouver's PGA

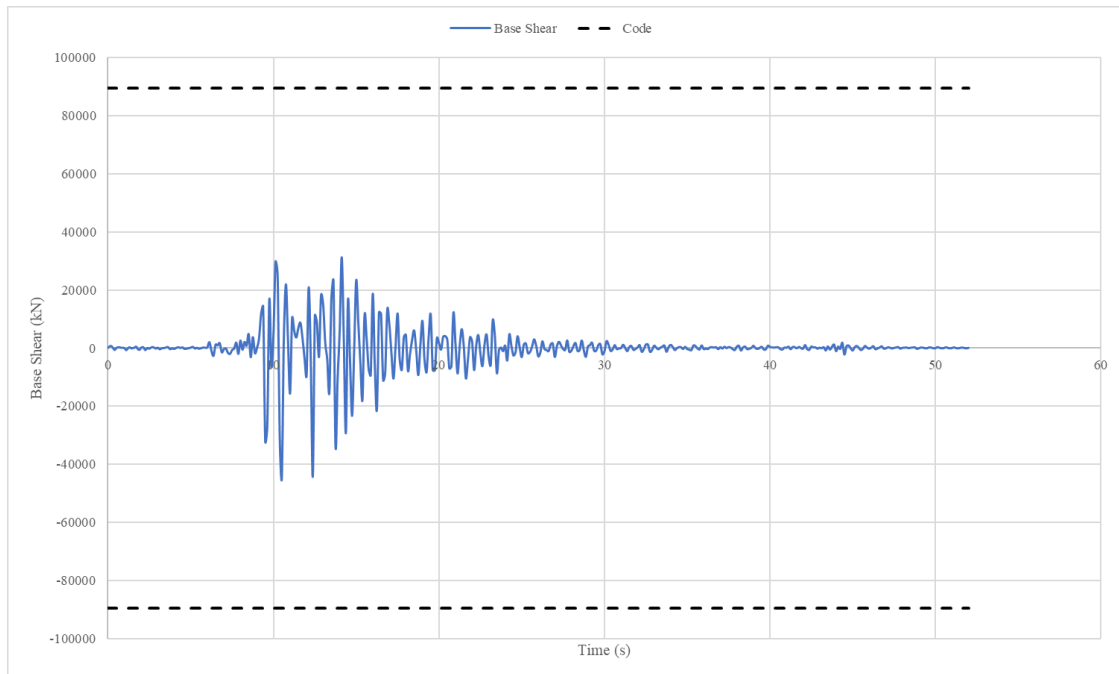


Figure 91: Total base shear for the tank excited by Kobe earthquake adjusted to Vancouver's PGA

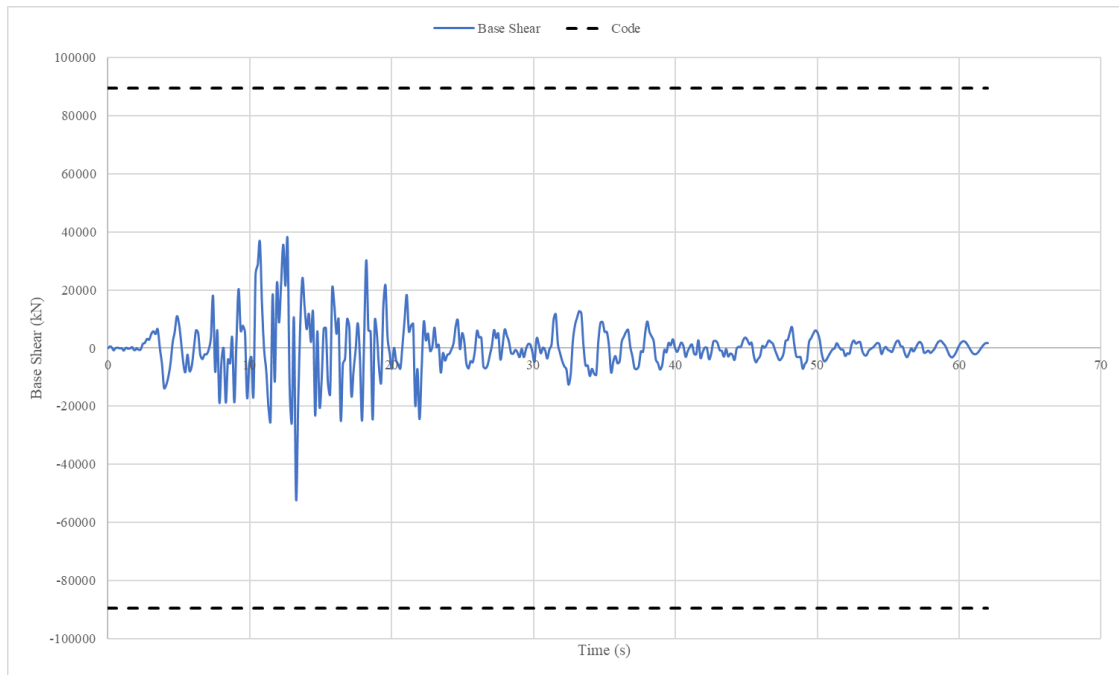


Figure 92: Total base shear for the tank excited by Northridge earthquake adjusted to Vancouver's PGA

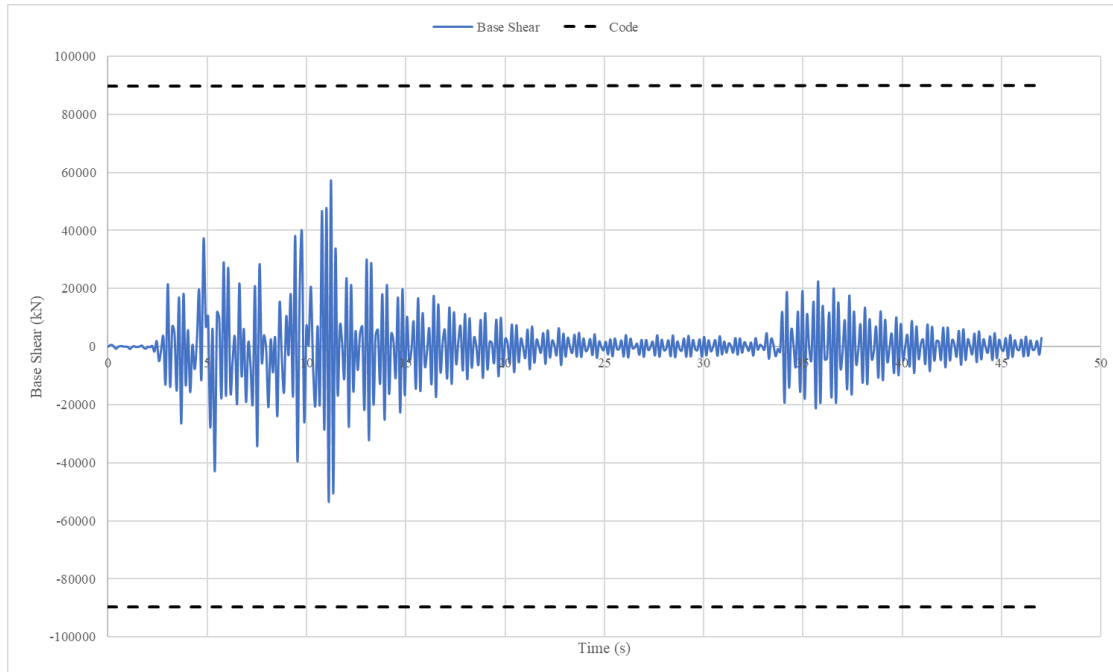


Figure 93: Total base shear for the tank excited by San Fernando earthquake adjusted to Vancouver's PGA

5.4. Discussion

In this study, the shear forces at the base of a water tank subjected to harmonic base excitations are investigated using numerical modelling. The study is composed of three phases. In the initial phase, a feasibility study is completed to determine whether the presence of a liquid material inside the tank can affect the base shear in comparison with a solid material. In the second phase of the study, a more thorough analysis is conducted. The reliability of the model is tested using frequency and mass analyses, and the model is run with the PGA's provided for the two Canadian cities of Ottawa and Vancouver and the results are compared with the formula provided by the NBC. In the final phase, a large tank is subjected to scaled earthquake records representing the PGAs of two Canadian cities of Ottawa and Vancouver and the results are examined against the code.

The results of the initial phase of the study demonstrate that the presence of a liquid material instead of a solid material (i.e., the default assumption of the NBC) inside the tank can increase the nodal shear forces by up to forty percent. It is worth noting that this forty percent increase is for this particular tank dimensions and can be higher or lower with other tank dimensions. It is also found that the model is not entirely mesh-independent, however, the base shear converged with the first mesh refinement, therefore, the model's sensitivity to mesh is very low.

To validate the model in the second phase of the study, the frequency of the structure is measured using numerical modelling as well as manual calculations. The results show that the model is reasonably accurate in predicting these values and can be used for the study.

The occurrence of resonance condition (i.e., when the excitation frequency approaches the sloshing frequency) is possible during an earthquake, depending on the size of the tank, the frequency of the earthquake, and height of the building on top of which the tank is located, hence the proper design of the support structures for this condition is crucial for keeping the tank functional. To

examine the effect of resonance on the base shear of the tank, three different excitations are applied at the base of the tank, including the resonance condition, above resonance, and below resonance frequencies. The excitation amplitude for each frequency is chosen so that the maximum acceleration would match the PGA provided by NBC for the cities of Ottawa and Vancouver.

National Building Code of Canada (NBC) provides a formula for finding the base shear of the support structures of non-structural components. This formula does not consider sloshing of water inside the container as a contributing factor, which can lead to failure of the support structures of liquid containers. The results of this study show that NBC despite well predicting the total base shear, may come short for measuring the base shear for individual supports. In other words, the algebraic sum of the base shears for all the support structures using the numerical model are in line with the values provided by the NBC, however, when the NBC value is divided by the number of supports, there is an underestimation of thirty to fifty percent compared with the liquid material. The reason for this discrepancy is during a harmonic base excitation, two of the supports are being pulled (i.e., have a negative value) while the other two are being pushed (i.e., have a positive value) due to the sloshing effects. When combined, these reactions (i.e., the negative and positive values) are summed up and partially cancel each other out. Therefore, despite accurately measuring the total base shear, the NBC underestimates the shear force value for each of the individual supports.

The results of the final phase in which earthquake records are applied to the tank also demonstrate the same issue, namely underestimating the shear force for individual supports while accurately predicting the total base shear of the tank. Especially, for the city of Ottawa (i.e., a city with moderate seismicity) this phenomenon is observed for all the earthquake records, while for the city of Vancouver (i.e., a high seismicity location) it is seen in two of the four earthquake excitations. This could be due to more conservative standards for Vancouver compared to Ottawa.

It is worth noting that this study is limited to applying PGA as the maximum acceleration at the base of the tank, while a more accurate approach is using the Peak Floor Acceleration (PFA). Compared to PGA, PFA has a higher value, and hence, the shear force found in this part of the study can even increase further if PFA was used. However, calculating the PFA requires more information about the building and its properties such as number of floors, floor heights, Seismic Force Resisting System (SFRS), ductility, etc., which is out of the scope of the current study.

5.5. Conclusion

In this study, the effect of earthquake on the support structures of liquid storage tanks with respect to their base shear is investigated using ABAQUS numerical modelling. Three tank sizes are studied in the three phases of this research study. In the first phase, a feasibility analysis and a mesh sensitivity analysis are completed using a smaller tank dimension. It is found that the presence of liquid material inside the tank compared to an equivalent solid material can increase the shear forces by up to forty percent. In the second phase, reliability of the model and its accuracy are investigated on a larger tank size. Once the model is validated, harmonic base excitations using the PGA's of two Canadian cities (Ottawa, Ontario and Vancouver, British Columbia) are applied and the results are compared with the provisions of the National Building Code of Canada. Three different frequencies including resonance conditions where the excitation frequency is close to the natural frequency of the sloshing liquid are used. It is found that while the code can very well

capture the total base shear in all cases, the shear forces at each individual support can be higher than the code's prediction by a factor of up to thirty percent, regardless of the location and frequency. In the final phase, a large tank is subjected to earthquake records scaled to the two Canadian cities and the results are compared with the code. The results are consistent with the previous phases, demonstrating conservative prediction of the total base shear by the code while under-predicting shear forces for individual supports.

This inconsistency in predictions by the code can be due to the simultaneous compression and tension that occur in the support structures where two of them are in tension mode and the other two are in compression mode, so when combined they cancel out each other and the total base shear falls within the code limits. It is also worth noting that the NBC does not treat the liquid in a container as such, in other words, it is treated as a solid material with no convective mass. This assumption ignores the sloshing effects of the liquid inside the tank, which can affect reaction forces and base shears.

It is suggested for future studies to consider the PFA instead of the PGA for various building sizes/types and use different combinations of support structures so a more thorough conclusion with regards to the roof-top water tanks using the NBC code can be reached.

6. Summary and Conclusion

This study was comprised of three major parts regarding LSTs under seismic loading: numerical studies using the OpenFOAM, Artificial Intelligence, and numerical simulations using the ABAQUS. The results of each component were further used for the next component.

In the first part of the study (i.e., OpenFOAM), simulations were used to validate the numerical model using experimental data generated in previous studies by the author and others. Both qualitative and quantitative methods were used to ensure the validity of the model. This process ensured that the numerical model is able to accurately simulate the behavior of the LST in question, which is crucial for the subsequent simulations. In this process, Navier-Stokes equations were shown to be applicable in modelling the behaviour of LSTs subjected to base excitation. Once the numerical model was validated, more simulations were completed using different excitations such as earthquake and harmonic loads. These simulations were used to obtain hydrodynamic pressures at various locations in an LST subjected to base excitations. In addition, the liquid sloshing height for different tank sizes with various fill depths were compared with the free-board provided by the ACI350.3-20. The results of these comparisons showed that the code underestimates the sloshing heights when the tank is subjected to resonance conditions. This indicates that the current standards and guidelines for the seismic design of LSTs may not be sufficient to ensure the safety and reliability of these structures during earthquakes. The results from this part of the study provided insights into the behavior of liquids in LSTs during earthquake events which can help identify areas where improvements in standards and guidelines may be necessary to ensure the safety and reliability of these crucial infrastructures. In addition, the validated model can be used to generate data for the second part of the study.

After obtaining appropriate data from the numerical simulations, AI techniques, namely Genetic Programming (GP) and Multi-Gene Genetic Programming (MGGP), were applied to help find formulae for the prediction of maximum hydrodynamic pressures at the roof of tanks subjected to ground motion. These techniques were used to analyze the data and identify patterns and relationships that can be used to predict the behavior of the tank under different conditions. The goal was to develop a formula that can be used to predict the maximum hydrodynamic pressure at the roof of the tank based on known parameters such as the tank size, fill depth, and the intensity of the seismic excitation. As part of the analysis, a relationship between the dimensionless liquid height and the dimensionless maximum pressure was obtained. Multiple error measurements and complexity analyses were applied to the results of the GP and MGGP models. These analyses were used to evaluate the accuracy and simplicity of the models. The results of the analyses showed that while the GP model provided a simpler answer, the MGGP model had a more accurate response. However, both methods demonstrated relatively low errors and acceptable results. This part of the study also presented a proof of concept in terms of applicability of AI methods and in particular Genetic Programming and MGGP in prediction of forces and pressures in LSTs subjected to base excitation. Once enough data is gathered through numerical modelling and experimental tests, more reliable predictive models can be generated. That predictive model can then replace the need for time-consuming and computationally expensive simulations and analyses, and be used for new design codes, standards, and guidelines.

The focus of the ABAQUS component of the study was on the tank's structure and the base shear at the supports. The goal was to evaluate the behavior of the tank and its supporting structures during seismic excitation and identify areas where improvements may be necessary. The applicability of Navier-Stokes equations in LSTs subjected to seismic loads was demonstrated in the first part of the study, hence they were used for this part with the SPH method. In order to validate the model, mass and frequency analyses were conducted comparing the results from simulations and manual calculations. Once the model was validated, various simulations were conducted to generate adequate data for comparison with the National Building Code of Canada (NBC). The results of these simulations were used to evaluate the performance of the tank and its supporting structures and to compare the results with the NBC. The goal was to determine whether the code is conservative in predicting the base shear pressures for the supporting structures of LSTs subjected to base excitation. The preliminary results showed that despite well predicting the total base shear, the NBC does not adequately predict individual base shears for the supporting structures of LSTs subjected to base excitation.

The results of this study can be used in the development and improvement of design codes and standards for LSTs subjected to seismic loading. The findings of the study can be used to improve the design and safety of these structures, which are crucial for the storage and transportation of liquids in various industries. The first component of the study, the OpenFOAM studies, can be used to improve provisions on the acceptable freeboard of roofless tanks which are common in industry. The results of these simulations can be used to evaluate the behavior of the tank and its contents during seismic excitation and to determine the minimum freeboard required to ensure the safety and integrity of the tank. The second component of the study, the AI application, can help in the development of guidelines for the design of roofs of LSTs. The current ACI code does not address this issue appropriately and only mentions the need for proper design when adequate freeboard is not provided. The results of the AI analysis can be used to develop guidelines for the design of roofs that take into account the specific characteristics of the tank and the water it contains. The third component of the study, the ABAQUS study, is also useful for improving the NBC. The current code considers the material inside the tank to be solid and does not consider the individual supports of LSTs, whether they are located at the roof or on the ground. The results of the ABAQUS study can be used to evaluate the behavior of the tank and its supports during seismic excitation and to identify areas where the code may be improved to ensure the safety and reliability of these structures.

Recommendations for future studies

- Conduct more experimental studies: While numerical simulations provide valuable insights into the behavior of LSTs during seismic excitation, experimental studies are also important. They can be used to validate the simulation results or to generate additional data that can be used to improve the models.
- Study the behavior of other types of liquids: The behavior of different types of liquids can vary significantly and conducting studies that focus on the specific characteristics of different liquids can provide additional insights. This could include studying the behavior of liquids with different densities, viscosities, and surface tensions.

- Investigate the behavior of different types of tank structures: Different types of tank structures can have different seismic behaviors, and therefore it is important to conduct studies that focus on the specific characteristics of different types of tank structures, such as cylindrical, rectangular, and spheroidal tanks.
- Consider the effect of flexibility of the tank structure in experimental and numerical studies.
- Study the behavior of tanks with different support conditions: The behavior of tanks with different support conditions such as ground-supported and rooftop tanks can vary significantly, hence, it is important to conduct studies that focus on the specific characteristics of different support conditions.
- Study the effect of the tank environment: The effect of the tank environment such as temperature, pressure, and surrounding soil conditions can have a significant impact on the behavior of LSTs during seismic excitation. it can be helpful to consider the effect of the tank environment in future studies.
- Consider evaluating the effect of coupled modeling of the deformation of the building and rooftop tanks both experimentally and numerically.
- Coupling the commercial software (i.e., ABAQUS) with the open-source (i.e., OpenFOAM) where the OpenFOAM is used to generate data and the hydrodynamic pressures are transferred into the ABAQUS software, the structure is analyzed and the results are transferred back into OpenFOAM, continuing this cycle until the difference between two iterations are within an acceptable margin.

References

- [1] <http://www.earthquakescanada.nrcan.gc.ca/info-gen/magfreq-en.php>
- [2] K.-H. Cho and S.-Y. Cho, "Seismic response of cylindrical steel tanks considering fluid-structure interaction," *Steel Struct.*, vol. 7, no. 2, pp. 147–152, 2007.
- [3] S. Zama, H. Nishi, K. Hatayama, M. Yamada, and H. Yoshihara, "On Damage of Oil Storage Tanks due to the 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0), Japan," p. 10.
- [4] K. V. Steinbrugge and R. Flores A., "The Chilean earthquakes of May, 1960: A structural engineering viewpoint," *Bull. Seismol. Soc. Am.*, vol. 53, no. 2, pp. 225–307, Feb. 1963, doi: 10.1785/BSSA0530020225.
- [5] T. W. Cooper and T. P. Wachholz, "Optimizing post-earthquake lifeline system reliability," in *Proceedings of the 5th US conference on lifeline earthquake engineering*. ASCE, 1999, pp. 878–86.
- [6] S. Soroushnia, Sh. T. Tafreshi, F. Omidinasab, N. Beheshtian, and S. Soroushnia, "Seismic Performance of RC Elevated Water Tanks with Frame Staging and Exhibition Damage Pattern," *Procedia Eng.*, vol. 14, pp. 3076–3087, 2011, doi: 10.1016/j.proeng.2011.07.387.
- [7] H. A. Afan, A. El-shafie, W. H. M. W. Mohtar, and Z. M. Yaseen, "Past, present and prospect of an Artificial Intelligence (AI) based model for sediment transport prediction," *J. Hydrol.*, vol. 541, pp. 902–913, 2016.
- [8] OpenCFD, "OpenFOAM." OpenCFD Ltd.: Bracknell, UK, 2014.
- [9] Y. P. Xiong and J. T. Xing, "Transient Dynamic Responses of an Integrated Air-Liquid-Elastic Tank Interaction System Subject to Earthquake Excitations," in *Volume 4: Fluid-Structure Interaction*, Chicago, Illinois, USA: ASMEDE, Jan. 2008, pp. 421–430. doi: 10.1115/PVP2008-61815.
- [10] Abaqus, G, "Abaqus 6.11." Dassault Systemes Simulia Corporation, Providence, RI, USA, 2011.
- [11] C.-H. Wu, B.-F. Chen, and T.-K. Hung, "Hydrodynamic forces induced by transient sloshing in a 3D rectangular tank due to oblique horizontal excitation," *Comput. Math. Appl.*, vol. 65, no. 8, pp. 1163–1186, Apr. 2013, doi: 10.1016/j.camwa.2013.02.012.
- [12] A. S. Veletsos, "Seismic effects in flexible liquid storage tanks," in *Proceedings of the 5th world conference on earthquake engineering*, Bulletin of the Seismological Society of America McLean, VA, USA, 1974, pp. 630–639.
- [13] K. P. Murphy, *Probabilistic machine learning: an introduction*. MIT press, 2022.
- [14] G. W. Housner, "Dynamic pressures on accelerated fluid containers," *Bull. Seismol. Soc. Am.*, vol. 47, no. 1, pp. 15–35, 1957.
- [15] G. W. Housner, "The dynamic behavior of water tanks," *Bull. Seismol. Soc. Am.*, vol. 53, no. 2, pp. 381–387, 1963.
- [16] M. A. Haroun, "Vibration studies and tests of liquid storage tanks," *Earthq. Eng. Struct. Dyn.*, vol. 11, no. 2, pp. 179–206, Mar. 1983, doi: 10.1002/eqe.4290110204.
- [17] ACI 350.3, "Seismic Design of Liquid-Containing Concrete Structures and Commentary (ACI 350.3-6)," *Am. Concr. Inst. Farmington Hills MI USA*, p. 67, 2006.
- [18] A. S. of C. Engineers, "Minimum design loads and associated criteria for buildings and other structures," American Society of Civil Engineers, 2017.
- [19] P. Code, "Eurocode 8: Design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings," *Bruss. Eur. Comm. Stand.*, 2005.
- [20] "2009-Final-including-Figures2.pdf."
- [21] O. R. Jaiswal, D. C. Rai, and S. K. Jain, "Review of Seismic Codes on Liquid-Containing Tanks," *Earthq. Spectra*, vol. 23, no. 1, pp. 239–260, Feb. 2007, doi: 10.1193/1.2428341.

- [22] A. R. Ghaemmaghami and M. R. Kianoush, "Effect of Wall Flexibility on Dynamic Response of Concrete Rectangular Liquid Storage Tanks under Horizontal and Vertical Ground Motions," *J. Struct. Eng.*, vol. 136, no. 4, pp. 441–451, Apr. 2010, doi: 10.1061/(ASCE)ST.1943-541X.0000123.
- [23] M. Isaacson, "Earthquake-induced hydrodynamic forces on reservoir roofs," *Can. J. Civ. Eng.*, vol. 37, no. 8, pp. 1107–1115, Aug. 2010, doi: 10.1139/L10-049.
- [24] M. Moslemi and M. R. Kianoush, "Parametric study on dynamic behavior of cylindrical ground-supported tanks," *Eng. Struct.*, vol. 42, pp. 214–230, Sep. 2012, doi: 10.1016/j.engstruct.2012.04.026.
- [25] M. Sivy and M. Musil, "Procedure for seismic analysis of liquid storage tanks using fem approach and analytical models," in *Advances in Mechanism Design II*, Springer, 2017, pp. 213–219.
- [26] P. K. Malhotra, T. Wenk, and M. Wieland, "Simple procedure for seismic analysis of liquid-storage tanks," *Struct. Eng. Int.*, vol. 10, no. 3, pp. 197–201, 2000.
- [27] A. S. Veletsos and J. Y. Yang, "Earthquake Response of Liquid Storage," *Tech. Counc. Lifeline Earthq. Eng. ASCE*, pp. 255–365, 1977.
- [28] A. S. Veletsos, "Seismic response and design of liquid storage tanks," *Guidel. Seism. Des. Oil Gas Pipeline Syst.*, pp. 255–370, 1984.
- [29] A. S. Veletsos, P. Shivakumar, Y. Tang, and H. T. Tang, "Seismic response of anchored steel tanks," in *Proceedings of the Third Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping (Gupta, AK Ed.)*, North Carolina State University, 1990, pp. 2–15.
- [30] C. KURIHARA, Y. MASUKO, and A. SAKURAI, "Sloshing impact pressures of roofed liquid storage tanks," *Doboku Gakkai Ronbunshu*, vol. 1991, no. 432, pp. 51–58, 1991.
- [31] P. K. Malhotra, "Sloshing loads in liquid-storage tanks with insufficient freeboard," *Earthq. Spectra*, vol. 21, no. 4, pp. 1185–1192, 2005.
- [32] P. K. Malhotra, "Earthquake induced sloshing in tanks with insufficient freeboard," *Struct. Eng. Int.*, vol. 16, no. 3, pp. 222–225, 2006.
- [33] M. A. Goudarzi, S. R. Sabbagh-Yazdi, and W. Marx, "Seismic analysis of hydrodynamic sloshing force on storage tank roofs," *Earthq. Spectra*, vol. 26, no. 1, pp. 131–152, 2010.
- [34] S. Koshizuka and Y. Oka, "Moving-particle semi-implicit method for fragmentation of incompressible fluid," *Nucl. Sci. Eng.*, vol. 123, no. 3, pp. 421–434, 1996.
- [35] V. Sriram, S. A. Sannasiraj, and V. Sundar, "Numerical simulation of 2D sloshing waves due to horizontal and vertical random excitation," *Appl. Ocean Res.*, vol. 28, no. 1, pp. 19–32, Feb. 2006, doi: 10.1016/j.apor.2006.01.002.
- [36] S. Mitra and K. P. Sinhamahapatra, "Slosh dynamics of liquid-filled containers with submerged components using pressure-based finite element method," *J. Sound Vib.*, vol. 304, no. 1–2, pp. 361–381, Jul. 2007, doi: 10.1016/j.jsv.2007.03.014.
- [37] C. J. K. Lee, H. Noguchi, and S. Koshizuka, "Fluid-shell structure interaction analysis by coupled particle and finite element method," *Comput. Struct.*, vol. 85, no. 11–14, pp. 688–697, Jun. 2007, doi: 10.1016/j.compstruc.2007.01.019.
- [38] O. R. Jaiswal, S. Kulkarni, and P. Pathak, "A study on sloshing frequencies of fluid-tank system," in *Proceedings of the 14th World Conference on Earthquake Engineering*, 2008, pp. 12–17.
- [39] D. Liu and P. Lin, "A numerical study of three-dimensional liquid sloshing in tanks," *J. Comput. Phys.*, vol. 227, no. 8, pp. 3921–3939, Apr. 2008, doi: 10.1016/j.jcp.2007.12.006.

- [40] Y. G. Chen, K. Djidjeli, and W. G. Price, "Numerical simulation of liquid sloshing phenomena in partially filled containers," *Comput. Fluids*, vol. 38, no. 4, pp. 830–842, Apr. 2009, doi: 10.1016/j.compfluid.2008.09.003.
- [41] D. H. Kang and Y. B. Lee, "Summary report of sloshing model test for rectangular model," *Daewoo Shipbuild. Mar. Eng. Co Ltd South Korea*, no. 001, 2005.
- [42] M. Moslemi, M. R. Kianoush, and W. Pogorzelski, "Seismic response of liquid-filled elevated tanks," *Eng. Struct.*, vol. 33, no. 6, pp. 2074–2084, Jun. 2011, doi: 10.1016/j.engstruct.2011.02.048.
- [43] C. W. Hirt and B. D. Nichols, "Volume of fluid (VOF) method for the dynamics of free boundaries," *J. Comput. Phys.*, vol. 39, no. 1, pp. 201–225, Jan. 1981, doi: 10.1016/0021-9991(81)90145-5.
- [44] P. Ming and W. Duan, "Numerical simulation of sloshing in rectangular tank with VOF based on unstructured grids," *J. Hydrodyn.*, vol. 22, no. 6, pp. 856–864, 2010.
- [45] C.-H. Wu and B.-F. Chen, "Transient Response of Sloshing Fluid in a Three-Dimensional Tank," *J. Mar. Sci. Technol.*, vol. 20, no. 1, p. 12, 2012.
- [46] Y. Kim, "Numerical simulation of sloshing flows with impact load," *Appl. Ocean Res.*, vol. 23, no. 1, pp. 53–62, 2001.
- [47] J. B. Frandsen, "Sloshing motions in excited tanks," *J. Comput. Phys.*, vol. 196, no. 1, pp. 53–87, May 2004, doi: 10.1016/j.jcp.2003.10.031.
- [48] S. S. Kolukula and P. Chellapandi, "Nonlinear Finite Element Analysis of Sloshing," *Adv. Numer. Anal.*, vol. 2013, pp. 1–10, Feb. 2013, doi: 10.1155/2013/571528.
- [49] F. Gui and S. Jiang, "Numerical simulation of liquid sloshing problem under resonant excitation," *Adv. Mech. Eng.*, vol. 6, p. 834657, 2014.
- [50] H. Akyildiz and E. Ünal, "Experimental investigation of pressure distribution on a rectangular tank due to the liquid sloshing," *Ocean Eng.*, vol. 32, no. 11–12, pp. 1503–1516, Aug. 2005, doi: 10.1016/j.oceaneng.2004.11.006.
- [51] P. K. Panigrahy, U. K. Saha, and D. Maity, "Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks," *Ocean Eng.*, vol. 36, no. 3–4, pp. 213–222, Mar. 2009, doi: 10.1016/j.oceaneng.2008.11.002.
- [52] T. C. Su, Y. K. Lou, J. E. Flipse, and T. J. Bridges, "A numerical analysis of large amplitude liquid sloshing in baffled containers," *Ocean Eng. Program Tex. AM Univ. Coll. Stn. Tex. USA Rep. No MARD-940-82046*, 1982.
- [53] V. Armenio and M. La Rocca, "On the analysis of sloshing of water in rectangular containers: numerical study and experimental validation," *Ocean Eng.*, vol. 23, no. 8, pp. 705–739, 1996.
- [54] M. Eswaran, U. K. Saha, and D. Maity, "Effect of baffles on a partially filled cubic tank: Numerical simulation and experimental validation," *Comput. Struct.*, vol. 87, no. 3–4, pp. 198–205, Feb. 2009, doi: 10.1016/j.compstruc.2008.10.008.
- [55] C. Zhao, J. Chen, J. Wang, N. Yu, and Q. Xu, "Seismic mitigation performance and optimization design of NPP water tank with internal ring baffles under earthquake loads," *Nucl. Eng. Des.*, vol. 318, pp. 182–201, 2017.
- [56] T. Nasar and S. A. Sannasiraj, "Sloshing dynamics and performance of porous baffle arrangements in a barge carrying liquid tank," *Ocean Eng.*, vol. 183, pp. 24–39, 2019.
- [57] M. Hosseini, M. A. Goudarzi, and A. Soroor, "Reduction of seismic sloshing in floating roof liquid storage tanks by using a Suspended Annular Baffle (SAB)," *J. Fluids Struct.*, vol. 71, pp. 40–55, 2017.

- [58] M. Ghalandari, S. Bornassi, S. Shamshirband, A. Mosavi, and K. W. Chau, "Investigation of submerged structures' flexibility on sloshing frequency using a boundary element method and finite element analysis," *Eng. Appl. Comput. Fluid Mech.*, vol. 13, no. 1, pp. 519–528, 2019.
- [59] P. K. Malhotra, "Method for seismic base isolation of liquid-storage tanks," *J. Struct. Eng.*, vol. 123, no. 1, pp. 113–116, 1997.
- [60] H. R. Vosoughifar and M. A. Naderi, "Numerical analysis of the base-isolated rectangular storage tanks under bi-directional seismic excitation," *Br. J. Math. Comput. Sci.*, vol. 4, no. 21, p. 3054, 2014.
- [61] H. Luo, R. Zhang, and D. Weng, "Mitigation of liquid sloshing in storage tanks by using a hybrid control method," *Soil Dyn. Earthq. Eng.*, vol. 90, pp. 183–195, 2016.
- [62] V. R. Panchal and D. P. Soni, "Seismic behaviour of isolated fluid storage tanks: A-state-of-the-art review," *KSCE J. Civ. Eng.*, vol. 18, no. 4, pp. 1097–1104, 2014.
- [63] H. N. Phan, F. Paolacci, D. Corritore, B. Akbas, E. Uckan, and J. J. Shen, "Seismic vulnerability mitigation of liquefied gas tanks using concave sliding bearings," *Bull. Earthq. Eng.*, vol. 14, no. 11, pp. 3283–3299, 2016.
- [64] A. G. Ivakhnenko and G. A. Ivakhnenko, "The review of problems solvable by algorithms of the group method of data handling (GMDH)," *Pattern Recognit. Image Anal. Cc Raspoznavaniye Obraz. Anal. Izobr.*, vol. 5, pp. 527–535, 1995.
- [65] R. Mohammadpour, A. Ghani, and H. M. Azamathullah, "Estimating time to equilibrium scour at long abutment by using genetic programming," *Parameters*, vol. 50, p. 50, 2011.
- [66] H. M. Azamathulla, "Development of GEP-based functional relationship for sediment transport in tropical rivers," *Neural Comput. Appl.*, vol. 24, no. 2, pp. 271–276, 2014.
- [67] Z. He, X. Wen, H. Liu, and J. Du, "A comparative study of artificial neural network, adaptive neuro fuzzy inference system and support vector machine for forecasting river flow in the semiarid mountain region," *J. Hydrol.*, vol. 509, pp. 379–386, 2014.
- [68] S. Lallahem, J. Mania, A. Hani, and Y. Najjar, "On the use of neural networks to evaluate groundwater levels in fractured media," *J. Hydrol.*, vol. 307, no. 1–4, pp. 92–111, 2005.
- [69] I. N. Daliakopoulos, P. Coulibaly, and I. K. Tsanis, "Groundwater level forecasting using artificial neural networks," *J. Hydrol.*, vol. 309, no. 1–4, pp. 229–240, 2005.
- [70] M. Mirzavand, B. Khoshnevisan, S. Shamshirband, O. Kisi, R. Ahmad, and S. Akib, "Evaluating groundwater level fluctuation by support vector regression and neuro-fuzzy methods: a comparative study," *Nat. Hazards*, vol. 1, no. 1, pp. 1–15, 2015.
- [71] R. Mohammadpour, S. Shaharuddin, C. K. Chang, N. A. Zakaria, A. A. Ghani, and N. W. Chan, "Prediction of water quality index in constructed wetlands using support vector machine," *Environ. Sci. Pollut. Res.*, vol. 22, no. 8, pp. 6208–6219, 2015.
- [72] N. Deshpande, S. Londhe, and S. Kulkarni, "Modeling compressive strength of recycled aggregate concrete by Artificial Neural Network, Model Tree and Non-linear Regression," *Int. J. Sustain. Built Environ.*, vol. 3, no. 2, pp. 187–198, 2014.
- [73] W.-Y. Loh, "Classification and regression trees," *Wiley Interdiscip. Rev. Data Min. Knowl. Discov.*, vol. 1, no. 1, pp. 14–23, 2011.
- [74] A. Garg, A. Garg, and K. Tai, "A multi-gene genetic programming model for estimating stress-dependent soil water retention curves," *Comput. Geosci.*, vol. 18, no. 1, pp. 45–56, 2014.
- [75] A. M. Sattar and B. Gharabaghi, "Gene expression models for prediction of longitudinal dispersion coefficient in streams," *J. Hydrol.*, vol. 524, pp. 587–596, 2015.
- [76] C. Ferreira, "Gene expression programming: a new adaptive algorithm for solving problems," *ArXiv Prepr. Cs0102027*, 2001.

- [77] A. Sattar, B. Gharabaghi, and E. A. McBean, "Prediction of timing of watermain failure using gene expression models," *Water Resour. Manag.*, vol. 30, no. 5, pp. 1635–1651, 2016.
- [78] H. M. Azamathulla, "Gene expression programming for prediction of scour depth downstream of sills," *J. Hydrol.*, vol. 460, pp. 156–159, 2012.
- [79] C. Chinnarasri and D. Kositgittiwong, "Laboratory study of maximum scour depth downstream of sills," in *Proceedings of the Institution of Civil Engineers-Water Management*, Thomas Telford Ltd, 2008, pp. 267–275.
- [80] M. Najafzadeh, M. Rezaie Balf, and E. Rashedi, "Prediction of maximum scour depth around piers with debris accumulation using EPR, MT, and GEP models," *J. Hydroinformatics*, vol. 18, no. 5, pp. 867–884, 2016.
- [81] A. Gholami, H. Bonakdari, M. Zeynoddin, I. Ebtehaj, B. Gharabaghi, and S. R. Khodashenas, "Reliable method of determining stable threshold channel shape using experimental and gene expression programming techniques," *Neural Comput. Appl.*, vol. 31, no. 10, pp. 5799–5817, 2019.
- [82] Z. S. Khozani, H. Bonakdari, and I. Ebtehaj, "An analysis of shear stress distribution in circular channels with sediment deposition based on Gene Expression Programming," *Int. J. Sediment Res.*, vol. 32, no. 4, pp. 575–584, 2017.
- [83] A. H. Gandomi and A. H. Alavi, "A new multi-gene genetic programming approach to nonlinear system modeling. Part I: materials and structural engineering problems," *Neural Comput. Appl.*, vol. 21, no. 1, pp. 171–187, 2012.
- [84] H. Kaydani, A. Mohebbi, and M. Eftekhari, "Permeability estimation in heterogeneous oil reservoirs by multi-gene genetic programming algorithm," *J. Pet. Sci. Eng.*, vol. 123, pp. 201–206, 2014.
- [85] M. J. S. Safari and A. D. Mehr, "Multigene genetic programming for sediment transport modeling in sewers for conditions of non-deposition with a bed deposit," *Int. J. Sediment Res.*, vol. 33, no. 3, pp. 262–270, 2018.
- [86] A. Danandeh Mehr and V. Nourani, "Season algorithm-multigene genetic programming: a new approach for rainfall-runoff modelling," *Water Resour. Manag.*, vol. 32, no. 8, pp. 2665–2679, 2018.
- [87] A. H. Gandomi, G. J. Yun, and A. H. Alavi, "An evolutionary approach for modeling of shear strength of RC deep beams," *Mater. Struct.*, vol. 46, no. 12, pp. 2109–2119, 2013.
- [88] A. H. Gandomi, A. H. Alavi, S. Kazemi, and M. Gandomi, "Formulation of shear strength of slender RC beams using gene expression programming, part I: Without shear reinforcement," *Autom. Constr.*, vol. 42, pp. 112–121, 2014.
- [89] A. Zahiri, A. A. Dehghani, and H. M. Azamathulla, "Application of gene-expression programming in hydraulic engineering," in *Handbook of genetic programming applications*, Springer, 2015, pp. 71–97.
- [90] Canadian Commission on Building and Fire Codes, *National Building Code of Canada*. National Research Council of Canada, 2015.
- [91] "Natural Resources Canada-NRCAN." <http://www.earthquakescanada.nrcan.gc.ca/info-gen/magfreq-en.php>
- [92] H. Mirzabozorg, M. A. Hariri-Ardebili, and R. Nateghi, "Free surface sloshing effect on dynamic response of rectangular storage tanks," *Am. J. Fluid Dyn.*, vol. 2, no. 4, pp. 23–30, 2012.
- [93] A. R. Ghaemmaghami, M. Moslemi, and R. Kianoush, "DYNAMIC BEHAVIOUR OF CONCRETE LIQUID TANKS UNDER HORIZONTAL AND VERTICAL GROUND MOTIONS USING FINITE ELEMENT METHOD," p. 9.

- [94] M. K. Minoglou, G. D. Hatzigeorgiou, and G. A. Papagiannopoulos, "Heuristic optimization of cylindrical thin-walled steel tanks under seismic loads," *Thin-Walled Struct.*, vol. 64, pp. 50–59, Mar. 2013, doi: 10.1016/j.tws.2012.12.009.
- [95] F. D. Konstandakopoulou and G. D. Hatzigeorgiou, "Water and wastewater steel tanks under multiple earthquakes," *Soil Dyn. Earthq. Eng.*, vol. 100, pp. 445–453, Sep. 2017, doi: 10.1016/j.soildyn.2017.06.026.
- [96] Y. Li, R. Zhu, G. Miao, and F. A. N. Ju, "Simulation of tank sloshing based on OpenFOAM and coupling with ship motions in time domain," *J. Hydrodyn. Ser B*, vol. 24, no. 3, pp. 450–457, 2012.
- [97] D. Burkacki, M. Wojcik, and R. Jankowski, "Numerical investigation on behaviour of cylindrical steel tanks during mining tremors and moderate earthquakes," *Earthq. Struct.*, vol. 18, no. 1, pp. 97–111, 2020.
- [98] M. R. Shekari, "On the numerical assessment of the resonant sloshing responses in 3D multi baffled partially liquid-filled steel cylindrical tanks shaken by long-period ground motions," *Soil Dyn. Earthq. Eng.*, vol. 129, p. 105712, Feb. 2020, doi: 10.1016/j.soildyn.2019.105712.
- [99] P. K. Panigrahy, "Development of a test setup to study the sloshing behavior of liquids in baffled tanks," *M Tech Thesis Dep. Mech. Eng. IIT Guwahati India*, 2006.
- [100] P. K. Panigrahy, U. K. Saha, D. Maity, and S. Sharma, "Wall pressures on a square tank due to liquid sloshing," in *Proceedings of 3rd international (& 33rd national) conference on fluid mechanics and fluid power, December*, 2006, pp. 7–9.
- [101] T. Ikeda, R. A. Ibrahim, Y. Harata, and T. Kuriyama, "Nonlinear liquid sloshing in a square tank subjected to obliquely horizontal excitation," *J. Fluid Mech.*, vol. 700, pp. 304–328, Jun. 2012, doi: 10.1017/jfm.2012.133.
- [102] C.-H. Wu, O. M. Faltinsen, and B.-F. Chen, "Analysis on shift of nature modes of liquid sloshing in a 3D tank subjected to oblique horizontal ground motions with damping devices," *Adv. Mech. Eng.*, vol. 5, p. 627124, 2013.
- [103] O. M. Faltinsen and A. N. Timokha, "Resonant three-dimensional nonlinear sloshing in a square-base basin. Part 4. Oblique forcing and linear viscous damping," *J. Fluid Mech.*, vol. 822, pp. 139–169, Jul. 2017, doi: 10.1017/jfm.2017.263.
- [104] A. P. I. Standard, "Welded tanks for oil storage," *Am. Pet. Inst.*, vol. 1220, 2013.
- [105] J. M. Spritzer and S. Guzey, "Review of API 650 Annex E: Design of large steel welded aboveground storage tanks excited by seismic loads," *Thin-Walled Struct.*, vol. 112, pp. 41–65, Mar. 2017, doi: 10.1016/j.tws.2016.11.013.
- [106] New Zealand Society of Earthquake Engineering (NZSEE), "Seismic Design of Storage Tanks: 2009, Recommendations of a NZSEE Study Group on Seismic Design of Storage Tanks." Nov. 2009. Accessed: Apr. 18, 2022. [Online]. Available: <https://www.nzsee.org.nz/wp-content/uploads/2019/05/2009-Final-including-Figures2.pdf>
- [107] A. I. O. Japan, "Design Recommendation for Storage Tanks and Their Supports with Emphasis on Seismic Design," *AIJ Archit. Inst. Jpn. AIJ Jpn.*, 2010.
- [108] M. R. Kianoush and A. R. Ghaemmaghami, "The effect of earthquake frequency content on the seismic behavior of concrete rectangular liquid tanks using the finite element method incorporating soil–structure interaction," *Eng. Struct.*, vol. 33, no. 7, pp. 2186–2200, Jul. 2011, doi: 10.1016/j.engstruct.2011.03.009.
- [109] Chopra, A.K., *Dynamics of Structures: Theory and Applications to Earthquake Engineering*. Prentice Hall Inc.: Upper Saddle River, NJ, USA, 1995.

- [110] H. K. Gildeh, *Numerical modeling of thermal/saline discharges in coastal waters*. University of Ottawa (Canada), 2013.
- [111] A. Barakati, "Numerical modelling of liquid containing structure under dynamic loading," Université d'Ottawa/University of Ottawa, 2015.
- [112] A. Ab. Ghani and H. M. Azamathulla, "Development of GEP-based functional relationship for sediment transport in tropical rivers," *Neural Comput. Appl.*, vol. 24, pp. 271–276, 2014.
- [113] I. Bahreini Toussi, R. Kianoush, and A. Mohammadian, "Numerical and Experimental Investigation of Rectangular Liquid-Containing Structures under Seismic Excitation," *Infrastructures*, vol. 6, no. 1, p. 1, Dec. 2020, doi: 10.3390/infrastructures6010001.
- [114] F. C. Bartlett, "Cambridge University Press; Cambridge, UK: 1932," *Rememb. Sch.*
- [115] C. J. Greenshields, *OpenFOAM—The OpenFOAM Foundation—User Guide*. 2018.
- [116] J. R. Koza, "Evolution of subsumption using genetic programming," in *Proceedings of the first European conference on artificial life*, MIT Press Cambridge, MA, USA, 1992, pp. 110–119.
- [117] D. S. Pandey, I. Pan, S. Das, J. J. Leahy, and W. Kwapinski, "Multi-gene genetic programming based predictive models for municipal solid waste gasification in a fluidized bed gasifier," *Bioresour. Technol.*, vol. 179, pp. 524–533, 2015.
- [118] D. P. Searson, D. E. Leahy, and M. J. Willis, "GPTIPS: An open source genetic programming toolbox for multigene symbolic regression," presented at the International MultiConference of Engineers and Computer Scientists, Hong Kong, Hong Kong, Mar. 2010, pp. 77–80.
- [119] H. Bonakdari, H. Moeeni, I. Ebtehaj, M. Zeynoddin, A. Mahoammadian, and B. Gharabaghi, "New insights into soil temperature time series modeling: linear or nonlinear?," *Theor. Appl. Climatol.*, vol. 135, pp. 1157–1177, 2019.
- [120] H. Azimi, H. Bonakdari, I. Ebtehaj, B. Gharabaghi, and F. Khoshbin, "Evolutionary design of generalized group method of data handling-type neural network for estimating the hydraulic jump roller length," *Acta Mech.*, vol. 229, pp. 1197–1214, 2018.
- [121] T. Bengtsson and J. E. Cavanaugh, "An improved Akaike information criterion for state-space model selection," *Comput. Stat. Data Anal.*, vol. 50, no. 10, pp. 2635–2654, 2006.
- [122] A. H. Gandomi and D. A. Roke, "Assessment of artificial neural network and genetic programming as predictive tools," *Adv. Eng. Softw.*, vol. 88, pp. 63–72, 2015.
- [123] K. D. Dolan, L. Yang, and C. P. Trampel, "Nonlinear regression technique to estimate kinetic parameters and confidence intervals in unsteady-state conduction-heated foods," *J. Food Eng.*, vol. 80, no. 2, pp. 581–593, 2007.
- [124] G. W. Housner, "Dynamic pressures on accelerated fluid containers," *Bull. Seismol. Soc. Am.*, vol. 47, no. 1, pp. 15–35, 1957.
- [125] ASCE 7, "Minimum design loads for buildings and other structures. ASCE Standard ASCE/SEI 7-10," American Society of Civil Engineers Reston, VA, 2010.
- [126] M. Moslemi and M. R. Kianoush, "Parametric study on dynamic behavior of cylindrical ground-supported tanks," *Eng. Struct.*, vol. 42, pp. 214–230, 2012.