

**A 3-D Numerical Study of Flow, Coherent Structures, and
Mechanisms Leading to Scour in a High Curvature
135° Channel Bend With and Without Submerged
Groynes**

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by

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ABSTRACT

This thesis focused on investigating flow, coherent structures, and mechanisms leading to scour around a series of three submerged groynes in a high curvature (radius of curvature (R)/channel width (B) = 1.5) channel bend using a Large Eddy Simulation Numerical (LES) model. Flow was investigated during both an initial and a later stage of scour. The results showed that the groynes appeared effective in keeping the main core of high streamwise velocity away from the outer bank wall in the region where they were installed, although high potential still existed for local scour around the groynes. During the initial stage of scour, horseshoe vortices (HVs) showed the greatest propensity to induce scour immediately upstream of the groyne tips. During the later stage of scour, the HV in front of the first upstream groyne (G1) induced very high mean pressure fluctuations on the outer bank wall. Scour was also of very great concern around the tip of G1 due to severe mean bed pressure fluctuations. Downstream of the groyne field, the presence of a counter-rotating outer bank cell was capable of endangering the stability of the outer bank.

The second focus of this thesis was to investigate flow in a 135° channel bend using both Reynolds Averaged Navier Stokes (RANS) and LES numerical models. The RANS study examined the effects of curvature ratio (R/B), and aspect ratio (B/H , where H is the inlet flow depth), on secondary circulation strength, and bed shear stresses. The study revealed that a decrease in R/B was associated with an increase in secondary circulation strength and peak bed shear stress. A change in B/H also substantially affected cross-stream circulation strength. The LES study was conducted in a 135° ($R/B = 1.5$) bend flume with a fixed bed corresponding to near equilibrium scour conditions, and the results were compared to a similar high curvature 193° bend numerical study. Inner bank vortices and shear layers were

present in both cases although their characteristics were substantially different. Distributions of boundary friction velocities, and turbulence were also quite different for each case.

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1. THESIS OUTLINE

The following is a list of the main chapters included in this thesis, and the journals which they will be, or have been submitted to for publication.

CHAPTER 5: Influence of Channel Aspect Ratio and Curvature on Flow, Secondary Circulation and Bed Shear Stress in a Rectangular Channel Bend.

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Authors: *Shalini Kashyap, George Constantinescu, Talia E. Tokyay, Colin D. Rennie, and Ronald D. Townsend*

CHAPTER 7: Coherent Structures and Scour Mechanisms around Submerged Groynes in a High Curvature Channel Bend using Large Eddy Simulation: Part I, Initial Stage of Scour

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CHAPTER 8: Coherent Structures and Scour Mechanisms around Submerged Groynes in a High Curvature Channel Bend using Large Eddy Simulation: Part II, A Later Stage of Scour

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CHAPTER 9: A Semi-permanent Method for Fixing Sand Beds in Laboratory Flumes

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*Authors: Shalini Kashyap, Benoît Doutreleau, Georges Bou-Botros, Colin D. Rennie, and
Ronald D. Townsend*

2. INTRODUCTION

Erosion and deposition processes occur naturally in alluvial rivers and help to shape their channel form. Most rivers take some type of meandering form which consists of a series of alternating curved reaches with pools at the outer banks, and deposition along the inner banks (Knighton 1988). River bank erosion can eventually lead to channel migration, which can be difficult to predict accurately. For this reason, river erosion and migration can pose substantial risks to existing infrastructures such as roads and bridges years after their construction (Lagasse *et al.* 2004). For example, a bridge that was built on the Hatchie River near Covington, Tennessee in 1936, collapsed in 1989 due to undermining caused by channel bend migration, which led to the death of eight people and the collapse of three roadway spans (Lagasse *et al.* 2004). Bends can also affect river erosion both upstream and downstream of where they are located. This was demonstrated for a bridge constructed across the Cimarron River near Perkins, Oklahoma in 1953. The site chosen for the bridge was assumed to be adequate as it was a straight reach, with bedrock on its south side. However, a bend located one mile upstream of the bridge eventually shifted, leading to severe erosion along the banks near the downstream bridge abutment (García 2008). Rivers can also approach urban areas which are within close proximity to them, and lead to the loss of valuable agricultural land in rural areas. For these reasons, it is often necessary to find ways to prevent or deter river bank erosion.

River bank stabilization techniques commonly include placing riprap or bed mattresses along areas prone to scour (USDA 1996). These methods however, are costly, and do not always present a long term solution. Novel types of groyne structures called ‘stream barbs’ (USDA 2005) are designed specifically to deter bank erosion in river bends. They are linear

structures constructed of rocks, and are usually placed in series along the outer bank of a river bend. They are installed at an angle with the outer bank, such that they point in the upstream direction, which is thought to be most effective for the purpose of preventing outer bank erosion (Prezedwojski *et al.* 1995). Compared to the conventional types of techniques mentioned previously, they are considered to provide a cost-effective, environmentally-friendly long term solution to prevent bank erosion. They also provide additional benefits such as deepening the channel along its thalweg, and improving fish habitat by creating deep scour holes near their toes where fish can rest and feed (Kuhnle *et al.* 2002). Little however, is known about the detailed physics of the flow around groynes in a channel bend, particularly in a high curvature bend (radius of curvature (R)/channel width (B) ≤ 3), where flow patterns are more complex, and levels of scour are often greater. It should be noted, that for the remainder of this thesis, the more common term ‘groyne’ will be used when referring to stream barbs.

As mentioned, flow in a high curvature bend is quite complex. This is due to nonlinear interactions that occur between the secondary circulation cell and the main channel flow, which lead to increases in anisotropy of the cross-stream flow (Blanckaert and de Vriend 2003). These nonlinear interactions also contribute to a flattening of the streamwise velocity profiles (Blanckaert and Graf 2004). Most Reynolds Averaged Navier Stokes (RANS) models which use linear closures, such as the standard $k-\epsilon$ and $k-\omega$ closures, are not able to predict this flattened velocity profile, but rather one that is closer to being logarithmic (Blanckaert and Graf 2004). In high curvature bends the shorter distance measured streamwise along the inner bank compared to the outer bank leads to a potential vortex

distribution of the streamwise velocity in the transverse direction. As a result, starting close to the beginning of the bend reach flow accelerates/decelerates in the inner/outer parts of the cross-section, which causes the core of high streamwise velocity to be located at the inner bank near the entrance to the curved region (Zeng *et al.* 2008). The strength of the curvature induced cross-stream circulation varies along the flume length, and causes gradual advection of the main core of high streamwise velocity towards the outer bank wall (Zeng *et al.* 2008). These factors affect the distribution of velocity within high curvature bends, which can directly impact erosion, as it is the vertical gradient of velocity close to the channel bed that is used to calculate bed shear stress, which is an indicator of scour.

The presence of turbulence, coherent structures, and shear layers within high curvature bends can also impact river erosion (Bathurst *et al.* 1979; Constantinescu *et al.* 2011a, 2011b). As mentioned, nonlinear interactions between the vertical profiles of streamwise and cross-stream velocities increase turbulence levels within the flow (Blanckaert and Graf 2004). The passage of energetic eddies near the channel boundaries and oscillations of cores of large-scale vortices can increase magnitudes of boundary shear stresses above their mean values. Such phenomena cannot usually be detected by lower order numerical models such as typical $k-\epsilon$ and $k-\omega$ time averaged RANS models, but require the use of an eddy-resolving numerical model that can predict both large and small scale flow features in the instantaneous flow field. High mean pressure fluctuations are normally used to indicate areas prone to erosion due to turbulence within their vicinity. Although details of turbulence and flow have previously been investigated for high curvature bends, most of these studies have involved the 193° bend flume at École Polytechnique Fédérale de Lausanne in Switzerland

(Blanckaert 2010; van Balen *et al.* 2010; Constantinescu *et al.* 2011a). Therefore, as will be discussed later, the first part of this thesis will investigate the details of flow, turbulence and coherent structures in a 135° bend using both LES and RANS, in order to gain a better understanding of their characteristics for this flume geometry.

Flow around groynes in a channel bend, which is a major focus of this thesis, is also very complex and challenging to model, as it involves massive separation, highly anisotropic dynamic flow, and both large and small scale eddies. Also, unlike groynes in a straight channel, groynes within a bend interact with the unique helical flow pattern induced by centrifugal forces. To date however, most studies examining groynes have been conducted in a straight channel. These include experimental studies examining scour distributions (Zaghloul 1974; Rajaratnam and Nwachukwu 1983; Kuhnle *et al.* 1999; Elawady 2001), flow patterns (Sukhodolov *et al.* 2002; Uijttewaai 2005; Yossef 2005), and turbulence and exchange processes between the main channel flow and the embayments (Uijttewaai *et al.* 2001; Weitbrecht *et al.* 2002; Zhang *et al.* 2009). Also, extensive numerical modeling has been conducted employing either 2-D or 3-D computationally efficient models such as RANS (Jia and Wang 2000; Tingsanchali and Maheswaran 2000; Bhuiyan *et al.* 2004; Nagata *et al.* 2005; Kuhnle *et al.* 2008; Zhang *et al.* 2009), as well as eddy-resolving techniques such as LES (McCoy 2006; Koken and Constantinescu 2008a; Koken and Constantinescu 2008b). These numerical studies have identified some of the unique features found around groynes including horseshoe vortices, mixing layers, and vertically orientated vortices which can impact scour. Studies involving groynes in a channel bend however, are considerably fewer, and include both experimental/field studies as well as numerical studies.

The experimental/field studies have been mostly aimed towards determining the optimum geometry and configurations for groynes (Prezedwojski *et al.* 1995; Matsuura and Townsend 2004). Numerical work has also revealed important information on the flow patterns and shear stress distributions around groynes (Minor *et al.* 2007a, 2007b; Abad 2008). These studies however, have been limited, and have not been able to resolve the finer details of the coherent structures and turbulence.

This thesis is comprised of two main parts. The first investigates the nature of flow, turbulence and coherent structures within a high curvature ($R/B=1.5$) 135° channel bend, in order to better understand mechanisms leading to erosion within the bend, and how these are influenced by channel geometry. It involves a parameterization study using a 3-D RANS model to examine the influence of curvature ratio (R/B), aspect ratio ($B/\text{channel depth } (H)$) and H/R on secondary circulation strength, large scale flow structures, and bed shear stress distributions. In addition, a 3-D Large Eddy Simulation (LES) numerical model has also been employed to complete a more in-depth analysis of the high curvature 135° bend case with an equilibrium scoured bed. The LES model gives a detailed assessment of turbulence, and large and small scale coherent structures present within the bend, and their relation to bed friction velocities and mean pressure fluctuations. The results from this assessment are compared to the high curvature 193° bend flume study of Constantinescu *et al.* (2011), which used a similar eddy-resolving model called Detached Eddy Simulation (DES) to examine such details. The first part of the thesis aims to gain insight into erosion mechanisms in a 135° bend, such that better techniques may be developed to mitigate such erosion.

The second part of this thesis investigates flow around a series of submerged groynes in the same high curvature 135° bend flume considered above. It employs a 3-D LES model to gain insight into the flow physics, and the role played by the coherent structures in the scouring process around groynes installed along the outer bank of the bend during both the initial (flat bed) and later (deformed bed) stages of scour. The numerical simulations are modeled after a physical groyne experiment conducted at the University of Ottawa at a channel Reynolds number of 60,000, and some of the LES predictions for the deformed bed case are validated with experimental measurements. This is the first time that an eddy-resolving technique has been used to investigate flow around groynes in a channel bend. It is expected that insights gained from the analysis of these LES results will help improve design recommendations and guidelines for groyne installations aimed at protecting channel banks against erosion.

2.1. CHARACTERISTICS OF BENDS WITHIN NATURAL RIVERS AND LABORATORY FLUMES

The link between channel geometry, flow, and erosion patterns in alluvial bends has been recognized for many decades. As previously discussed, curved channels are subject to a unique secondary flow pattern which can redistribute high streamwise velocities closer to the channel boundaries and increase levels of bed shear stresses. The strength of the secondary circulation directly affects the rate at which the core of high streamwise velocity is advected towards the outer bank (Zeng *et al.* 2008). Early laboratory investigations by Rozovskii (1957) proposed that the ratio H/R , where H is the flow depth and R is the radius of curvature, is linearly proportional to the secondary circulation strength. This ratio, was

originally defined as ‘curvature ratio’, and is considered as one of the most important geometric parameters influencing secondary circulation strength.

Field studies have also been able to identify an important link between the ratio R/B , where B is the channel width, and the rate of meander migration. In these studies R/B was adopted to be the new definition of ‘curvature ratio’. Although the reason for this is not clear, it is likely that R/B is more practical to measure in aerial photographs used to analyze meander migration rates, compared to the original ratio H/R . Hickin and Nanson (1975, 1984) and Nanson and Hickin (1986) found that for about 125 natural bends on more than 18 rivers in Canada, meander migration rate peaks between $2 < R/W < 3$. This finding has also generally been confirmed by Begin (1981), de Kramer *et al.* (2000), Hooke (1997), and Howard and Knutson (1984). However, large scatter has been found in this relation between R/B and migration rate. This may be because meander migration rate cannot be determined solely from the parameter R/B . Nanson and Hickin (1986) found that stream power and outer bank sediment size accounted for about 70% of the variance in their data. Blanckaert (2011) also explains that meander migration rate is influenced by the upstream and downstream bends, average flow depth, and bank erodibility and roughness. Blanckaert and de Vriend (2010) developed a nonlinear model which identified R/B and $C_f^{-1}H/B$ (where C_f is the bed friction coefficient, and the entire expression accounts for the shallowness and roughness of the river), to be the dominant control parameters affecting river migration. Typically $C_f^{-1}H/B$ will take on larger values channels when there is a smooth flat bed, and will decrease with increasing roughness.

The curvature ratio, R/B , has also been commonly used to categorize bends as being of high, moderate, or mild curvature. Although the literature does not show a clear consensus for the

range of R/B for each of these categories, Blanckaert (2011) (after Hickin (1977) and Markham and Thorne (1992)) give a range for each based on migration stage. High curvature bends are considered to have $R/B < 2$ to 3, and are defined to be in the termination stage of meander migration. Moderate curvature bends have $2 < R/B < 7$, and are considered to be in a growth stage. Mild curvature bends are considered to have $R/B > 7$, and are in the initiation stage of meander migration. High curvature bends are unique, as not only do they typically exhibit the greatest migration rates, some evidence also suggests that high curvature bends tend to stabilize (Blanckaert 2011). In fact, Blanckaert (2009) explains that saturation of secondary circulation may occur in high curvature bends. This means that there is a point where decreasing R/B will no longer lead to an increase in the strength of secondary circulation. Thorne and Abt (1993) have also reported in their studies that although there tends to be a monotonic increase of velocity at the base of the outer bank of a bend with a decrease in R/B , this velocity appears to reach a maximum which it never exceeds for values of $R/B < 2$.

There are few studies that have investigated the effects of bend angle on erosion patterns over a wide range of angles. Also, the effects are difficult to isolate as bend angle is inevitably linked to changes in other parameters such as bend length. In the field, parameters such as sinuosity, which is the ratio of curved channel length to the straight-line valley length (Knighton 1988), and meander amplitude, which is the distance between two points of maximum curvature measured normal to the straight-line valley length, are more commonly reported compared to bend angle. The bend angle, can be derived directly from sinuosity, by using a Bessel value (Yalin and da Silva 2001) to calculate an initial deflection angle (θ°) at the bend entrance, which may then be converted to a bend angle. An assessment of 42

meandering rivers (minimum sinuosity > 1.2 , average sinuosity = 1.6) from Leopold and Wolman (1960) gives an average bend angle to be 134° , which may be considered to represent a regular meander geometry (see classification scheme of Schumm, 1963, Table 1). This agrees well with the definition given by Kellerhals *et al.* (1976), that a regular meander geometry has a maximum bend angle of 180° , whereas a tortuous meander geometry has a maximum bend angle of greater than 180° . This assessment appears to indicate that river meanders may generally be associated with a fairly high bend angle.

As mentioned, although little is known about the effects of bend angle on erosion patterns, these effects are likely not negligible. An analysis conducted by Kondratiev *et al.* (1982) (as reported by Yalin and da Silva, 2001) on rivers from Europe and the United States, showed that river migration rates vary with bend angle. The study showed that the rate of downstream migration of a meander peaks at about a bend angle of 40° while the outward migration (expansion in the radial direction) rate peaks at about a bend angle of 110° . This finding also agrees with results from computer simulations of Sun *et al.* (1996) which showed downstream migration rates to vary inversely with meander amplitude, and outward expansion rates to vary directly with meander amplitude. This implies that smaller loops primarily migrate downstream, while larger loops migrate outwards (Knighton 1988). An analysis by Thorne and Abt (1993) also appeared to indicate that flow velocities near the outer bank may increase with bank angle and then level off at an angle between 75° to 90° .

Some evidence also exists that the locations of scour pools and point bars may be related to bend angle and/or length. In many meandering rivers a sequence of pools and riffles tend to

form in channels with a heterogeneous bed material size (ranging from 2 to 256 mm) (Knighton 1998). Pools are normally located along the outer bank where scour tends to be greatest, and point bars are located along the inner banks due to sediment deposition, and their locations alternate between opposite sides of the river channel as the outer bank transforms to the inner bank and vice versa. In natural rivers, the spacing of pools is usually regular, and scales with the channel width. Keller and Melhom (1978) showed that on average pools are spaced at about 5.9 times the channel width. Frothingham and Rhoads (2003) studied a meander loop on the Embarras River in Illinois, which had a deflection angle of 110° at the loop entrance, and 90° at the loop exit (equivalent to a bend angle of approximately 180°). This loop contained multiple pools along the outer bank of the bend, rather than pools which alternated between banks. Whiting and Dietrich (1993) found such a pattern of multiple pools along the outer bank to develop in a symmetrical laboratory channel with an initial deflection angle of 100° , and a sinuosity of 2.69. Such a series containing multiple pools, point-bars and riffles have been defined as ‘shingle bars’, and have also been observed in the high amplitude meander flume study of Termini (2009).

Although it appears that shingle bars are normally found in bends of greater amplitude, the mechanisms leading to them are not fully understood (Whiting and Dietrich 1983). It is also difficult to assess how the formation of these bars may be affected by bend angle as opposed to bend length, as the two parameters are interrelated. In order to further investigate the influence of bend angle and/or length on scour pool locations, a number of single bend flume studies with a scoured bed are given in Table 2.1. The locations of the scour pools for each study along the channel length are shown by circles in Figures 2.1 and 2.2. The maximum scour hole location is also distinguished by using an ‘x’ symbol. It can be seen that for bend

angles $\leq 90^\circ$, only one scour pool is present, even when the length of the bend differs. For these bends the scour pool is located very close to the bend exit. For bends with an angle $\geq 120^\circ$, two scour holes are always present, and for the bends with an angle $> 140^\circ$, the maximum scour hole is located upstream of the bend apex. While this analysis may suggest that the locations of scour pools within laboratory flumes are more dependent on bend angle compared to bend length, further analysis would be needed to support such a statement, and a deeper understanding of the mechanisms leading to the development of the scour holes would also be needed.

Table 2.1 Summary of single bend alluvial laboratory experiments with deformed bathymetry

Reference	Description	Bend Angle (°)	Bend Length (m)	Mean Inlet Velocity (m/s)	Width (m)	Discharge (m ³ /s)	R/B	B/H	H/R
Nouh and Townsend (1979)	Clear-water scour, vertical sidewalls	45	0.7069	0.3132	0.30	0.00376	3.00	7.50	0.0444
Nouh and Townsend (1979)	Clear-water scour, vertical sidewalls	60	0.9425	0.3132	0.30	0.00376	3.00	7.50	0.0444
Matsuura (2004)	Clear-water scour, vertical sidewalls	90	1.417	0.2824	0.46	0.0132	1.96	4.53	0.110
Matsuura (2004)	Clear-water scour, vertical sidewalls	90	1.417	0.2824	0.46	0.0101	1.96	6.04	0.080
Barbhuiya and Talukdar (2010)	Live-bed scour, vertical sidewalls	90	3.000	0.3083	0.80	0.0414	2.39	4.79	0.088
Rozovskii (1957)	Live-bed scour, vertical sidewalls	90	7.854	0.3300	2.00	0.0650	2.50	8.89	0.018
Blanckaert and de Vriend (2004)	Clear-water scour, vertical sidewalls	120	4.189	0.3800 (flume avg)	0.40	0.0170	5.00	3.64 (flume avg)	0.055 (flume avg)
Matsuura (2004)	Clear-water scour, vertical sidewalls	135	2.125	0.2824	0.46	0.0132	1.96	4.53	0.11
Matsuura (2004)	Clear-water scour, vertical sidewalls	135	2.125	0.2824	0.46	0.0101	1.96	6.04	0.08
Kashyap (2012)	Clear-water scour, vertical sidewalls	135	3.530	0.3095	1.00	0.0464	3.26	6.67	0.10
Sutmuller and Glerum (1980)	Live-bed scour, vertical sidewalls	180	13.352	0.4800	1.70	0.1714	2.5	8.10	0.049
Blanckaert (2010)	Live-bed scour, vertical sidewalls	193	5.726	0.6100	1.30	0.0890	3.70	11.30	0.070
Dugué et al. (2011)	Clear-water scour, vertical sidewalls	193	5.726	0.3100 (flume avg)	1.30	0.0570	1.31	9.29 (flume avg)	0.082 (flume avg)
Struiksma (1985)	Live-bed scour, test 1	140	29.322	0.3900	1.50	0.0468	8.00	18.75	0.0067
Struiksma (1985)	Live-bed scour, test 2	140	29.322	0.4100	1.50	0.0615	8.00	15.00	0.0083
Struiksma (1985)	Live-bed scour, test 3	140	29.322	0.5400	1.50	0.0737	8.00	16.48	0.0076
Olesen (1985)	Live-bed scour, test 4	140	28.711	0.4400	2.00	0.1188	5.88	14.80	0.0115
Odgaard and Bergs (1988)	Live-bed scour, sloped sidewalls	180	41.186	0.4500	2.44	0.153	5.37	16.27	0.0114

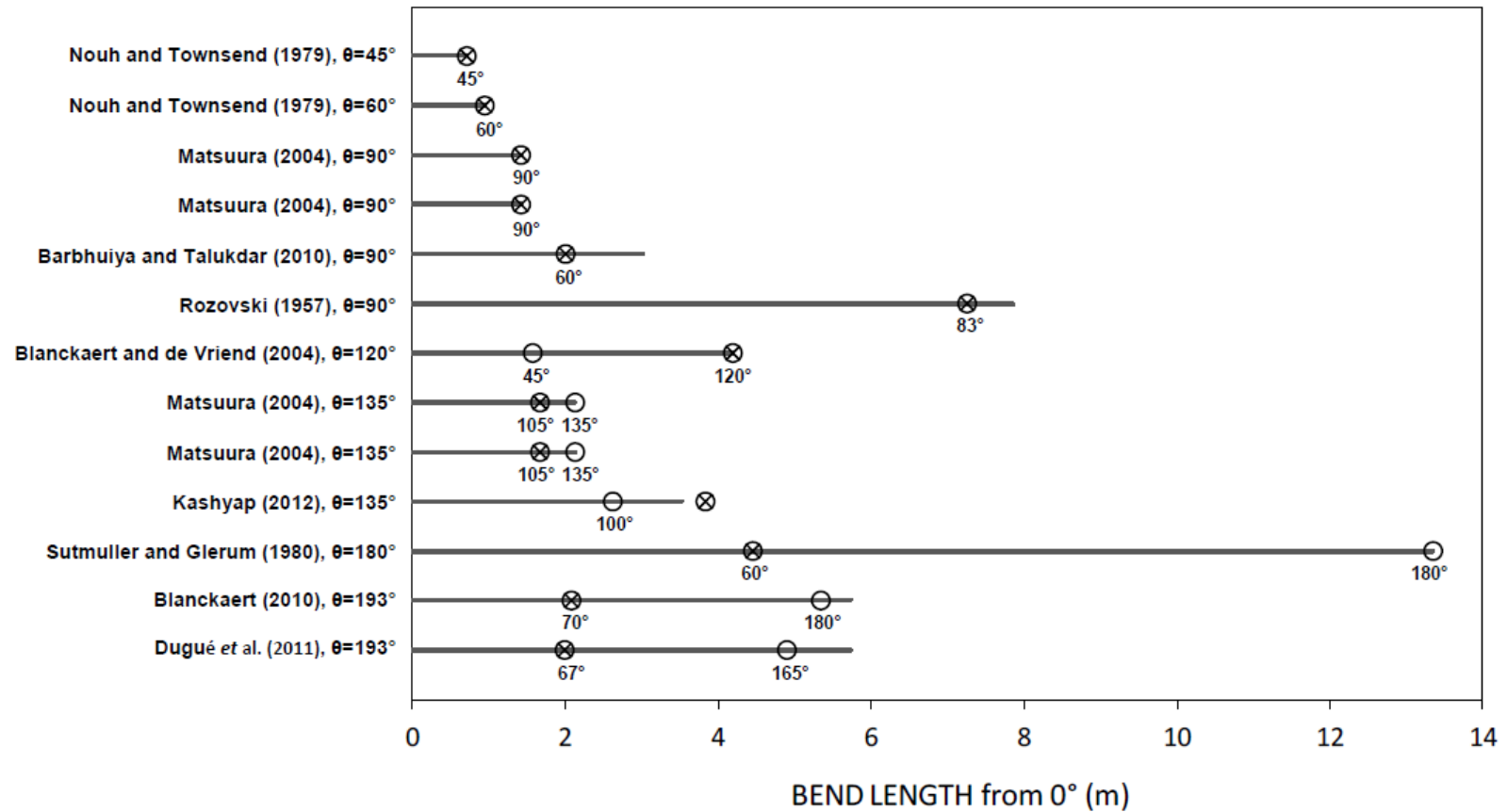


Figure 2.1 Plot of scour pool locations along the length of the bend for various studies (with a bend angle of θ) shown in Table 2.1. The scour pool locations are shown by a circle, and the maximum scour location is given by an 'x' symbol.

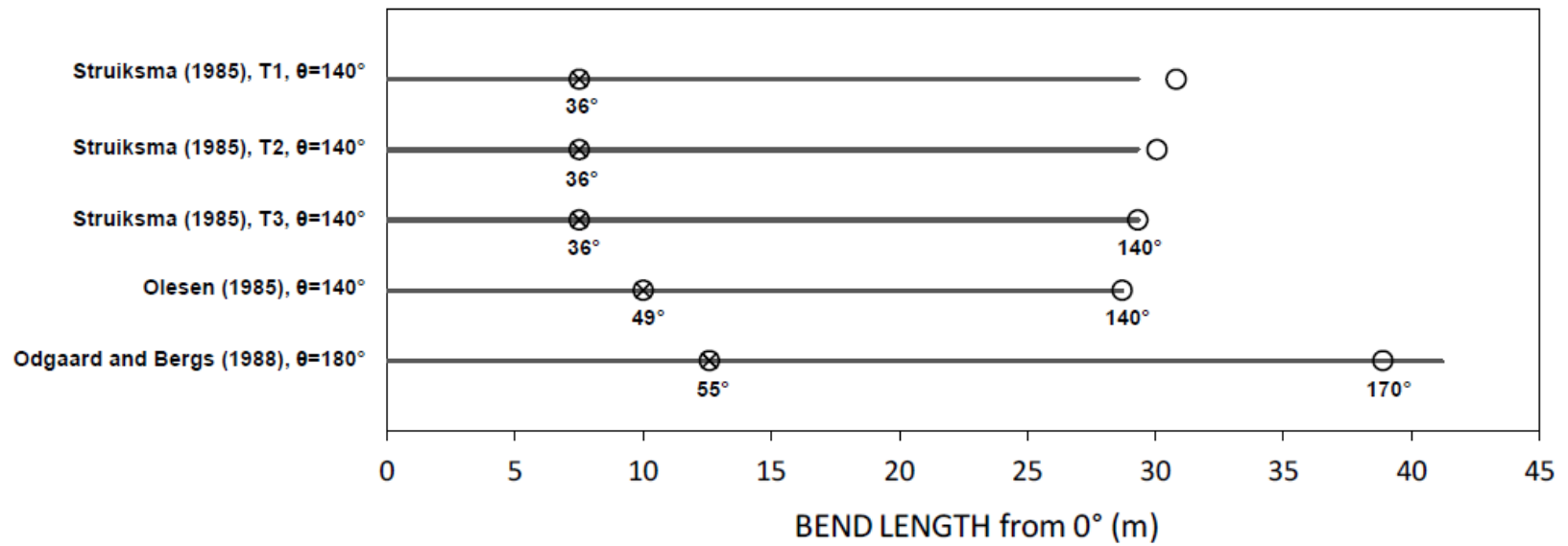


Figure 2.2 Plot of scour pool locations along the length of the bend for various studies (with a bend angle of θ) of longer length as shown in Table 2.1. The scour pool locations are shown by a circle, and the maximum scour location is given by an 'x' symbol.

The effects of discharge and sediment type also play important roles in shaping the form of a natural river, but may often be overlooked, and/or difficult to assess in laboratory studies. Knighton (1988) explains that the width of a channel is about proportional to the square root of the discharge. Also, since Leopold and Wolman (1957, 1960) established that meander wavelength is approximately 10 to 14 times the channel width, it follows that meander wavelength should also be related to channel discharge. Schumm (1967) used a multiple regression technique to relate meander wavelength to discharge and material properties at the channel boundaries. These relations showed that as channel boundaries become more cohesive (i.e. a higher percentage of clay) the meander wavelength should be less. Usually, channels which are more cohesive tend to be narrow and deep. This is important, as channels which are narrow and deep ($B/H < 10$) tend to have flow which is more 3-dimensional, and thus velocity redistribution by secondary circulation becomes a process of leading order, whereas in shallow wide rivers, with $B/H > 50$, the effects of secondary circulation on velocity redistribution are almost negligible (Blanckaert 2011).

2.2. IDEALIZATIONS OF THE BEND STUDIES

This thesis considers flow and mechanisms leading to scour in idealistic channel bends with rigid vertical sidewalls, and a constant radius of curvature. Although such an investigation helps to isolate the effects of curvature on secondary circulation, turbulence, and bed shear stresses in the absence of complexities present in natural rivers, it is also important to understand how such results may differ from those expected in natural rivers. Some of the idealizations made in the present study, and their effects on the results are discussed below.

2.2.1. Smooth Vertical Sidewalls

The sidewalls in the bend experiments conducted in this thesis were made of Plexiglas, and thus for the numerical studies, the sidewalls were assumed to be smooth, non-erodible, and vertical. In a natural channel, it is expected that the banks should be slightly sloped, and that the natural channel shape for a straight river should be close to trapezoidal, whereas for a meandering channel it should be closer to triangular (Ye and McCorquodale 1998). The erodibility and shape of natural river banks however, may depend on many factors such as bank material composition, soil compaction and moisture, vegetation, and variability of discharge (Knighton 1988).

Many field and laboratory investigations of flow in channels of medium and high curvature have reported the presence of a weak cell of secondary circulation close to the free surface of the outer bank, rotating in the directions opposite to that of the main channel helical flow cell (Bathurst *et al.*, 1979; Thorne and Hey, 1979; Blanckaert and de Vriend, 2004; Blanckaert, 2011). While some studies have shown that this cell was not found in natural rivers where the outer bank slope was mild or shelving, Blanckaert (2011) showed that this cell may exist even when the banks are mild or shelving, but that its size and strength are enhanced when the banks are close to vertical, and when the bank roughness is greater. On the other hand, the same study did not show any appreciable change in the strength of the main helical flow cell when the bank walls were sloped as opposed to vertical.

2.2.2. Constant Radius of Curvature

The bend flumes examined in this study experience a very abrupt change in curvature at the junction of the bend entrance and the straight inflow section, and the bend exit and the straight outflow section. Such an abrupt change in curvature is not normally seen in natural

meandering rivers. Its effect in the present study is to cause rapid acceleration of high velocity flow towards the inner bank at the bend entrance. It can also lead to a rapid increase in turbulence production at the bend entrance (Blanckaert 2009). In natural meanders, there is a more gradual change in curvature, and the presence of high streamwise velocity near the inner bank may often be the result of the outer bank transitioning to the inner bank near the meander crossover point.

In natural rivers, the effect of gradual variations in curvature may be that the flow never reaches a fully developed state, which is characteristic of an infinite bend where no streamwise gradients occur for the hydraulic parameters (Blanckaert 2011). In other words, in fully developed bend flow, we would expect the core of high streamwise velocity to always be located along the outer bank. Flow and bathymetry however, adjust slowly to changes in curvature, and therefore in a natural river, there may be a spatial lag between the location of maximum velocity excess (velocity excess is defined in Blanckaert, 2011, and is often used to predict meander migration), and the local curvature (Blanckaert 2011). Another effect of varying curvature is that a decrease in curvature could cause high streamwise velocities to prematurely move to the outer bank and lead to scour. This may make predicting the locations of outer bank erosion to be more challenging if the analytical model does not account for varying curvature.

2.2.3. Variable Discharge and Scour Conditions

In natural rivers, discharges are variable, and usually much greater than those used in laboratory channels. Although there is some consensus that discharge plays an important role in shaping channel morphology, controversy exists as to which discharge plays the most important role (Knighton 1988). In addition, when sediment transport is present, it rarely

occurs under clearwater scour conditions (which were the conditions for the experiments in this thesis), and therefore moving bedforms such as ripples and dunes tend to be common in natural rivers. Although some studies suggest that the dominant bed features are similar under both live-bed and clearwater scour conditions (Roca *et al.* 2007; Fazli *et al.* 2009), the presence of moving dunes under live-bed scour conditions have been shown to alter secondary flow patterns (Abad and Garcia 2009), although their effects on meander migration are not entirely clear.

In the experiments conducted for this thesis, equilibrium scour was only reached for the bed, as the sidewalls were non-erodible and rigid. In natural channels however, the banks and bed should erode simultaneously. As the planform of the meander changes, the equilibrium scour patterns at the bed should also change. Therefore, a 'true' equilibrium may not occur until the meander reach stabilizes, which realistically could take decades to occur, or may never happen.

3. OBJECTIVES

3.1. PRIMARY OBJECTIVE

The primary objective of this thesis is to use a 3-D Large Eddy Simulation (LES) numerical model to investigate the characteristics of coherent structures and mechanisms leading to scour around a series of three submerged groynes in a high curvature 135° channel bend. The study will investigate flow over a fixed bed during two stages of scour. The first case corresponds to the initial stage of scour, when the sediment bed is flat, and the second case corresponds to a later stage of scour, which is close to the final stages of scour when the sediment bed has substantially deformed. Selected validation of the LES cases will be completed using measurements taken from identical physical experiments conducted specifically for this purpose.

3.2. SECONDARY OBJECTIVES

1. To use 3-D LES and RANS models to better understand the nature of flow and mechanisms leading to scour in a 135° channel bend without groynes during different stages of scour. Again, the RANS and LES models are validated using experimental laboratory data collected specifically for this purpose. These studies will also investigate the influence of flume geometry on secondary circulation strength, flow structures and boundary shear stresses.
2. To develop a method for hardening sand beds in laboratory flumes made of Plexiglas, that is gentle enough to be removed from the flume without causing damage, yet is durable enough to be used for several days under flowing water.

4. MOTIVATION/NOVELTY

4.1. MOTIVATION

1. Groynes present a viable and cost-effective environmentally-friendly alternative for deterring scour along the outer banks of river bends. Unlike many conventional bank stabilization techniques which work mostly to increase the erosion resistance of banks, groynes potentially provide a longer term solution by deflecting flow away from the banks. However, they are often subject to variable performance, particularly in channels of high curvature. Therefore an improved understanding is needed of mechanisms leading to scour around groynes in a channel bend, in order to improve guidelines for their design.
2. Currently, existing studies which have investigated flow around groyne-like structures in a channel bend include either experimental/field studies (Beckstead 1978; Prezedwojski *et al.* 1995; Matsuura and Townsend 2004; USDA 2005), or lower order numerical studies involving models such as Reynolds Averaged Navier Stokes (RANS) (Minor *et al.* 2007a, and Minor *et al.* 2007b; Abad *et al.* 2008). However, such investigations are usually not resolved enough to reveal the fine details of both large and small scale coherent structures within the flow. For this reason, an eddy-resolving numerical technique is required to better understand mechanisms leading to scour around groynes in a channel bend.
3. The groyne case being considered in this thesis should be of high practical interest from a design point of view. This is because it involves groynes performing under extreme conditions. Submerged groynes correspond to flood conditions when erosion is normally

greatest, and the three dimensionality of the flow is greatly enhanced. Also, the case of flow in a high curvature bend is considerably more complex compared to flow in a milder curvature bend.

4. There is currently a need for a more in-depth understanding of flow structures, turbulence, and mechanisms leading to scour in high curvature bends of different geometries. Most existing studies involve the 193° bend flume at École Polytechnique Fédérale de Lausanne in Switzerland.

4.2. NOVELTY

The novelty of each chapter of the thesis is described below.

1. CHAPTER 5: This is the first study to complete a comprehensive investigation of the effects of curvature ratio and aspect ratio on flow structures, secondary circulation, and bed shear stress distributions in a 135° bend using a RANS numerical model. For the first time, the variation in the strength of the secondary circulation along the flume length is quantitatively assessed for a wide range of curvature ratios and aspect ratios.
2. CHAPTER 6: This is the first study to employ an LES numerical model to study flow in a high curvature 135° bend. The impacts of turbulence, streamwise orientated vortices, and flow on erosion are examined. Also, for the first time, the variation in the strength of the cross-stream circulation for a high curvature 135° bend has been shown using LES.
3. CHAPTER 7: This is the first study to use an eddy-resolving numerical model to study flow and mechanisms leading to scour around a series of submerged groynes in a

channel bend during the initial stages of scour. For the first time, the detailed characteristics of the main coherent structures present around groynes are revealed.

4. CHAPTER 8: This is the first study to use an eddy-resolving numerical model to study flow and mechanisms leading to scour around a series of submerged groynes in a channel bend during a later stage of scour, when the channel bed is deformed. The characteristics of the main coherent structures present around groynes in a channel bend are examined.
5. CHAPTER 9: A new bed hardening technique is developed to fix sand beds for laboratory flumes. This new technique is able to withstand appreciable bed shear stress under continuous underwater testing for 2 days, which currently has not been reported for other non-permanent and semi-permanent techniques.

CHAPTER 5: INFLUENCE OF CHANNEL ASPECT RATIO AND CURVATURE ON FLOW, SECONDARY CIRCULATION AND BED SHEAR STRESS IN A RECTANGULAR CHANNEL BEND

5.1. ABSTRACT

Flow within alluvial channel bends is significantly affected by channel geometry including curvature ratio (bend radius/channel width, R/B) and aspect ratio (channel width/flow depth, B/H). High curvature bends ($R/B \leq 3$) can experience substantially more erosion than milder curvature bends. In this study, a 3-D Reynolds-Averaged Navier-Stokes (RANS) model is employed to investigate the effects of R/B and B/H on flow in a 135° bend. Experimental measurements have been used to validate the results from the RANS model for the high curvature base cases with a flat bed (FB) and equilibrium deformed bed (DB). Five curvature ratios (1.5, 3, 5, 8, and 10) and four aspect ratios (5.00, 6.67, 9.09, and 12.50) were investigated. Results showed that a decrease in R/B for the FB cases resulted in a substantial increase in the circulation strength of the large main channel secondary flow cell, an increase in the maximum bed shear stress, and an increase in the contribution of the cross-stream component towards the total (magnitude of) bed shear stress. R/B and B/H also affected the structure of the cross-stream flow. The main cell of cross-stream circulation split into two clockwise-rotating cells at low R/B values, and at high R/B values, a secondary counter-clockwise rotating cell was found along the outer bank wall. At lower B/H values, the main cell split into two clockwise-rotating cells. This study shows that the position and size of regions of high bed shear stress, and thus the capacity of the flow to entrain sediment, all depend strongly on bend curvature.

5.2. INTRODUCTION

Flow within a channel bend is subject to a unique helical flow pattern that is induced by centrifugal forces, which cause surface flows with higher velocities to move faster towards the outer bank compared to deeper flows. As velocities decrease near the outer bank wall, a super elevation of the water surface develops, causing the water surface to be sloped in the radial direction. As a result, a radial pressure gradient is present, which is constant over the depth at a specific point along the radius. At the bed, the forces from the radial pressure gradient cause flow to be deflected towards the inner bank (Julien 2002). Although this helical flow pattern has been known for over a century (Thomson 1887), there is still much to understand about flow in bends. Over the years, many studies have tried to quantify the influence of R/B , B/H , and H/R on secondary flow strength, and distributions of bed shear stresses and velocities within bends. Early studies established H/R (equal to $(H/B)*(B/R)$) to be the main parameter affecting secondary flow strength (Rozovskii 1957; Engelund 1974; and Zimmerman 1977). Through field studies, Hickin (1978) found that circulation induced by secondary flow increases with decreasing R/B . Several studies have also found bend migration rate to be a function of R/B . For example, Hickin and Nanson (1984) found that bend migration rate increases with decreasing R/B until $R/B \approx 2$, at which point it starts to decrease. More recently, Blanckaert (2011) and Ottevanger *et al.* (2011) have investigated the effects of R/B and $C_f^{-1}H/B$ (where C_f is the bed friction coefficient) on bend flow through the use of nonlinear 1-D analytical models. Such models were found to perform relatively well, not only for mildly curved bends, but also for high curvature bends.

In high curvature (sharp) bends, the main flow and secondary circulation interact to give rise to a path of maximum velocity that begins at the inner bank, near the entrance of the curved

reach, and crosses to the outer bank after the bend apex (Dietrich 1987). The mechanisms leading to this redistribution of flow velocity within a high curvature bend have been discussed in several studies (e.g., see Blanckaert, 2010, Zeng *et al.*, 2008a). First, at the bend entrance, a streamwise pressure gradient develops over the channel width due to a tilting of the water surface. This causes flow to accelerate/decelerate in the inner/outer parts of the bend. This phenomenon, known as a potential-vortex effect (Blanckaert and de Vriend 2005), forces the core of high streamwise velocity to move towards the inner bend close to the entrance of the curved reach. Second, within the bend, this core of high velocity is slowly advected towards the outer bank by the cross-stream circulation. The presence of a counter-rotating outer bank cell is also a common feature of most bend flows, especially during the initial stages of scour and deposition (Bathurst *et al.* 1979; Blanckaert and de Vriend 2004; and Blanckaert 2010). Thirdly, the presence of a deformed bed can also complicate the process of advection by cross-stream circulation. For example, Dietrich and Smith (1983) described ‘shoaling’ of the secondary flow over the inner bank point bar, where flow is directed towards the outer bank throughout the depth. At the same time, according to Chezy’s law, higher velocities are attracted to greater flow depths, and thus flow is ‘topographically steered’ (Dietrich and Smith 1983) towards the thalweg once the bathymetry becomes strongly deformed. Finally, at the bend exit, the streamwise pressure gradient disappears causing flow to accelerate/decelerate suddenly towards the outer/inner banks.

Various types of numerical models have been employed to elucidate details of flow within bends and meandering channels (see Zeng *et al.*, 2008a for a review). Odgaard (1986a,b;

1989a,b) developed a simplified 2-D flow and sediment transport model based on conservation of mass and momentum, and a stability criterion for sediments. Yeh and Kennedy (1993a,b) developed a 2-D depth-averaged model which accounted in an approximate way for the vertical flow structure using additional moment-of-momentum equations. These models have produced accurate predictions for flow in mild to moderately curved bends, but have not been as successful in bends of higher curvature. 3-D numerical Reynolds Averaged Navier Stokes (RANS) models have also been employed to investigate the details of flow and sediment transport in medium and high curvature bends. R  ther and Olsen (2005) [$R/B = 3.4$], Khosronejad *et al.* (2007) [$R/B = 3.0$], Minor *et al.* (2007) [$R/B = 2.0$], Zeng *et al.* (2008a) [$R/B = 1.3$] and Zeng *et al.* (2008b, 2010) [$R/B \sim 4$] have investigated the use of isotropic RANS models. Although these studies have lead to an increased knowledge of flow in high curvature bends, they have not been able to reproduce some finer details such as the presence of a secondary counter- rotating outer bank cell, which has been observed in some experiments.

A higher-order turbulence model or closure such as a RANS model with a Reynolds Stress Model (RSM) closure or Large Eddy Simulation (LES) is generally required to predict flow features such as the counter-rotating outer bank cell, whose formation is driven primarily by turbulence anisotropy (van Balen *et al.* 2010; Constantinescu *et al.* 2011). Van Balen *et al.* (2010) have shown that LES was able to successfully predict this outer bank cell in a high curvature bend, while an isotropic RANS model was not. LES-type approaches are, however, computationally very expensive and difficult to employ in a parameterization study. Therefore, this study has employed a 3-D RANS model with a second order RSM

turbulence closure to assess how varying both R/B and/or B/H influences flow structures, secondary flow strength, and bed shear stress distributions within a 135° bend.

5.3. METHODOLOGY

This study focused on analyzing results from a series of numerical simulations in a 135° bend in which the parameters R/B and B/H were varied. The setup of the numerical simulations was based on three high curvature ($R/B=1.5$) flume experiments conducted at the University of Ottawa, which in this study are referred to as ‘base cases’. Data collected from these experiments were used to validate results from the corresponding numerical simulations. Throughout this chapter both the numerical simulations and experiments are categorized into two series of runs, R1 and R2. The primary difference between the two is that R1 was run with a sediment size (D_{50})=1.100mm, which for the numerical simulations corresponded to a roughness factor (k_s) of 1.100mm, and R2 was run with $D_{50}=0.689$ mm, which for the numerical simulations corresponded to $k_s=0.689$ mm. The simulations were conducted with either a deformed sediment bed, corresponding to equilibrium scour conditions in the experiment, or with a flat bed, corresponding to the initial sand bed in the experiment, before the start of erosion. In this chapter the same nomenclature is used when referring to both the numerical simulations and experiments, namely: R denotes ‘Run’, C denotes ‘curvature ratio’, H denotes ‘inlet water depth in cm’, FB denotes a ‘flat bed’, and DB denotes a ‘deformed bed’. For example, R1C1.5H20DB refers to a case belonging to run 1, with a curvature ratio of 1.5, an inlet channel water depth of 20cm, and a deformed bed. The three experiments conducted were R1C1.5H20DB, R2C1.5H15DB, and R2C1.5H15FB. In total, twelve numerical simulations were completed with R/B ranging from 1.5 to 10 and B/H ranging from 5.00 to 12.50. The parameters for both the experiments and the numerical simulations are summarized in Table 5.1.

5.3.1. Experimental Methods

The three experiments, R1C1.5H20DB, R2C1.5H15DB, and R2C1.5H15FB, were conducted in a 135° bend flume ($R/B = 1.5$) with a 12.2m straight entrance section, a 3.6m curved section, and a 2.4m straight exit section. (see Jamieson *et al.*, 2010, and Post, 2007, for further flume details). All experiments were run under clear water scour conditions, such that the entry channel bed friction velocity (u^*) was less than the Shields critical bed friction velocity (u^*_{cr}) (Rouse 1939) for the given sediment size. For the DB cases, velocity measurements were taken after the bed profile reached equilibrium. The FB case was run with a fixed bed using a bed hardening technique described in Kashyap *et al.* (2010) [see Chapter 9]. This technique did not seem to appreciably alter k_s , at least not within the precision of the k_s estimation. R1C1.5H20DB was run using a constant discharge (Q) = 0.0788m³/s, a $D_{50} = 1.100$ mm, and a bed slope of 0.0004. R2C1.5H15DB was run with a constant $Q = 0.0464$ m³/s, a $D_{50} = 0.689$ mm, and a bed slope of zero. R2C1.5H15FB also used a constant $Q = 0.0464$ m³/s, and a bed slope of zero.

Velocity measurements were taken for all three experiments using Nortek[®] Vectrino Acoustic Doppler Velocimeters (ADV). These ADVs had a measurement accuracy of $\pm 0.5\%$ of the measured velocity ± 1 mm/s (Nortek 2011). Each ADV measured four velocity components, streamwise, cross-stream, vertical, and a second vertical velocity measurement to compute error. All velocity components were measured relative to the flume walls, at a sampling frequency of 200Hz, for a period of two minutes. Probe alignment errors were precisely checked and corrected for using methods described in Post (2007). Errors in alignment ranged from 2.194° to 2.654°, and were corrected for in each specific ADV using

post processing computer code. Post processing of the data also removed mean velocities with low correlations ($<70\%$), and low signal to noise ratios (<10). Apparent outliers (“spikes”) in single ping velocities, with values that exceeded four standard deviations from the mean, had errors in vertical velocities greater than 0.1 m/s , or had accelerations $>1.5 \times (\text{gravitational acceleration})$, were corrected for by using a value interpolated between the previous and subsequent instantaneous velocity value. The accuracy of all raw data appeared good, with all correlations being greater than 69.5% , and all signal to noise ratios being greater than 11.

For R1C1.5H20DB (R2C1.5H15DB and R2H1.5H15FB) the velocity profiles were measured at the center of five equal 20cm intervals (six equal 16.67 cm intervals) across the 1m flume width. The ADV transducers were submerged at least 5mm below the water surface, and the sample volume was 4.5 to 5.5cm below the transducer. Thus, the first sample volume for each vertical profile was located 5 to 6cm below the water surface. For R1C1.5H20DB the number of vertical measurements varied with flow depth. Measurements were taken at 5, 10, 20, 40, 70, 100, 140, 180, and 220mm above the bed or until the transducer was no longer fully submerged. For R2C1.5H15DB, measurements were taken at 1cm intervals which increased to a maximum of 2cm close to the water surface. For R2C1.5H15FB, the measurement points were located at least 1cm above the bed, to a maximum of 10cm. Water discharge was measured using a V-notch weir installed in the flume exit tank and an ultrasonic flow-meter connected to the discharge piping. These discharges were also validated by calculating Q from the ADV measurements in the straight inlet section. Bathymetry measurements were taken with a Leica DistoTM pro4a laser

altimeter which has an accuracy of ± 0.0015 m. For R1C1.5H20DB (R2C1.5H15DB), a total of 2772 (14,408) bathymetry measurements were taken within 28 (147) transverse sections, with a spacing of 1cm between each point in the section along the 1m flume width. Further details on the measurement techniques are given in Jamieson *et al.* (2010) and in Post (2007).

5.3.2. Numerical Methods

A steady finite-volume 3-D RANS viscous solver with a standard RSM closure was used to perform the simulations. The RSM model is preferred to isotropic $k-\varepsilon$ and $k-w$ closure models that have been previously used in RANS investigations of flow in curved channels because it can account for turbulence anisotropy. The options chosen for the RSM model available in Fluent (Fluent Inc. 2006) were a linear model for the pressure-strain term, non-equilibrium wall functions and the default model constants of $C_\mu=0.09$, $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, and $C_{1PS}=1.8$.

The inflow boundary condition was set 10m downstream (2.2m upstream) of the experimental inlet (beginning of the curved reach). In this section the flow was not yet affected by the presence of the curved reach of the flume. Separate preliminary RANS simulations were run to create the fully developed inlet velocity profiles. These preliminary simulations were conducted in straight channels (2m length, 1m width, and a depth equal to the value H given in Table 5.1) using the same constant discharge as the simulations conducted in the curved channels (Table 5.1). The streamwise velocities, turbulent kinetic

energy, and rate of turbulent dissipation generated from these straight channel simulations were used to specify the inlet boundary condition for curved channel simulations.

The bed was fixed in the RANS simulations, and for the DB cases the deformed bed face was created from bathymetry measurements taken at the end of the experiments. The bathymetry measurements were interpolated onto an equal interval 200x200 (425x300) grid for R1C1.5H20DB (R2C1.5H15DB). The interpolated surfaces showed mean absolute biases of 0.001m (0.002m) for R1C1.5H20DB (R2C1.5H15DB). Values of k_s were set equal to the D_{50} values given in Table 5.1. For the simulations conducted without a corresponding experiment, a k_s value of 1.100(0.698)mm was used for all cases of R1(R2). This choice of k_s value may have been somewhat conservative as D_{50} is considered to be a lower bound estimate for flow resistance due to particle size (Millar 1999). The mesh spacing was fine enough at the bed to resolve much of the form roughness, although for R2C1.5H15DB, the ripples were smoothed slightly (by less than 1mm) in order to help convergence. All solid boundaries were modeled as ‘no-slip’ surfaces. A zero shear ‘rigid–lid’ approximation was used to specify the conditions at the free surface, and this boundary condition was set to symmetric. The estimations of water superelevation (E) for the cases R1C1.5H20FB and R2C1.5H15FB using Equation 5.1 (Bridge 1992) were 10.5mm and 6.5mm, respectively.

$$E = \frac{B\overline{U}^2}{gR} \quad (5.1)$$

These values represented 5.3% and 4.3% of the channel flow depth for cases R1C1.5H20FB and R2C1.5H15FB, respectively. From the pressure difference predicted at the free surface in the RANS simulations it was estimated that the water superelevations would have been 11.8mm and 7.5mm for R1C1.5H20FB and R2C1.5H15FB, respectively. These expected

superelevations are a small percentage of the flow depth, and thus, although the rigid-lid assumption may have slightly affected the secondary flow strength, it is expected that the results should be sufficiently reliable (McGuirk and Rodi 1978). The rigid-lid assumption has also previously been applied with reasonable accuracy for similar values of superelevation and R/B in the curved bend studies of Khosronejad *et al.* (2007) and Zeng *et al.* (2008a; 2010). It is generally accepted that as long as the Froude number remains smaller than 0.5, approximations associated with the use of a rigid lid assumption to calculate flow in open channels using RANS and LES based models are acceptable (e.g., see discussion and additional references in Rodi, 1997, Kirkil *et al.*, 2008, as well as the study of flow in a curved bend by Zeng *et al.*, 2006 who directly compared results obtained using a movable mesh with those obtained using the rigid lid approximation).

Structured meshes with hexahedral elements containing approximately 700 000 nodes (ranging from 500 000 to 3.4 million nodes) were used to perform the simulations. An example of the mesh generated on the bottom surface for case R1C1.5H20DB is shown in Figure 5.1. The meshes were created using Gambit software and a quad mapping technique. The non-dimensional mesh spacing at the bed and wall boundaries is defined in terms of non-dimensional wall units y^+ which equals $(Re)(u^*/U)(\Delta y/H)$, where Re is the Reynolds number, U is the main channel mean velocity, u^* is the main channel bed shear velocity, and Δy is the dimensional grid spacing. In all cases, y^+ was less than 5 in the wall normal direction at the lateral walls and bed. At the surface y^+ reached a maximum of 800.

The solutions were checked to be grid independent. A test simulation was conducted for case R1C1.5H20FB, where the number of mesh nodes was increased from 666 250 to 1.5 million (see Figures 5.18d and 5.18e). Little change was found in the results. The average (maximum) change in velocity magnitude was 0.2% (3.7%), based on a random sampling of 10,000 points within the curved reach. All simulations were run on eight processors of a PC cluster for at least 48 hours, after which time the solutions were found to be converged.

5.3.3. Analytical Methods

The cross-stream circulation magnitude (Γ) associated with a streamwise orientated vortex (SOV) was calculated in cross-sections that were perpendicular to the axis of the SOV. The 2-D streamwise vorticity (ω_s) within a plane was calculated as $(\delta w / \delta y_R) - (\delta v / \delta z)$, where w is the vertical velocity, y_R is the cross-stream direction perpendicular to the flume walls, v is the cross-stream velocity, and z is the vertical direction. Positive ω_s rotates in the clockwise direction when facing in the downstream direction, and negative ω_s rotates in the counter-clockwise direction. Γ equals $|\omega_s|$ integrated over the cross-sectional area of the SOV. In particular, Γ_+ is the total positive circulation calculated by integrating ω_s over regions with $\omega_s > 0$. For the DB cases, bed shear stress magnitudes (τ_M) were calculated from the streamwise, cross-stream, and vertical components, whereas for the FB cases they were calculated from the streamwise and cross-stream components only. The components of τ_M were calculated directly in the Fluent software, using non-equilibrium wall functions.

5.4. RESULTS AND DISCUSSION

The equilibrium bathymetries for cases R1C1.5H20DB and R2C1.5H15DB (Figure 5.2) were qualitatively very similar. For R1C1.5H20DB (R2C1.5H15DB) the maximum scour was -0.25m (-0.19 m) and the maximum deposition was +0.14m (+0.10m), measured from the initial bed level. For both cases, the maximum point of scour occurred at the outer bank, just downstream of 135°, and the maximum deposition occurred along the inner bank between 100° and 120°. In both cases the main thalweg of scour was located close to the inner bank at the entrance to the curved reach (0°), and it gradually deepened as it moved towards the outer bank near the exit of the curved reach (135°).

5.4.1. Experimental Validation

The agreements between experimental measurements and numerical results were fairly good. Scatter plots for simulated versus measured velocity magnitudes (Figure 5.3) showed that 82.1%, 88.9%, and 94.2% of simulated velocities were within 15% of the measured velocities for cases R1C1.5H20DB, R2C1.5H15DB, and R2C1.5H15FB, respectively. For the DB cases (Figures 5.3a and 5.3b), errors greater than 15% were mostly observed very close to the bed, in the deepest part of the scour hole near the outer bank between 120° and 135°+0.64m (see also discussion of Figure 5.6 for case R1C1.5H20DB). Nevertheless, good overall agreement was seen for the flow patterns and velocities in this part of the channel, and throughout the straight exit reach. For case R2C1.5H15FB there was a small cluster of points in Figure 5.3c where the errors for the RANS predictions were greater than 15% (Figure 5.3). These points were located very close to the bed. It was found that small variations in the elevation of the fixed bed in the experiment resulted in the bed being a fraction of a centimeter (<5mm) above the zero reference height in some locations. This

caused measurements for these points to be slightly closer to the bed than corresponding numerical points. This resulted in greater errors, due to the high vertical gradient of streamwise velocity near the bed.

Figure 5.4 shows contour plots comparing the RANS predictions with the experimental measurements in the 30° cross-section (105° cross-section) for case R1C1.5H20DB (R2C1.5H15FB). The predicted and measured streamline patterns in the 30° cross-section for case R1C1.5H20DB show that the core of the main cross-stream circulation cell is situated close to the center of the channel thalweg, although it is offset slightly towards the inner side of the bend. Moreover, the predicted distributions of streamwise and cross-stream velocity contours, in the region where velocity measurements are available, show good qualitative agreement with the experiment.

The distributions of streamwise velocity and 2-D streamlines in the 105° cross-section for the RANS simulation of case R2C1.5H15FB (Figure 5.4e) suggest that the main recirculation cell has split into two clockwise-rotating cells. The core of the cell situated close to the inner wall is also located within a region of high streamwise velocity. Though velocity measurements were not available sufficiently close to the inner wall to clearly confirm the presence of this eddy in the experiment, the streamline patterns and cross-stream velocities close to the free surface suggest that such an eddy was also present in the experiment. The presence of streamwise oriented cells near the inner bank has been previously observed in high curvature bends with flat beds in the LES studies of van Balen *et al.* (2010) and Kashyap *et al.* (2011). In contrast, such inner-bank cells have not been

observed in milder curvature bends (Blanckaert and de Vriend 2004). This suggests that the reorganization of the main recirculation cell into two clockwise-rotating cells is likely a characteristic of high-curvature bends. This inner bank cell is present within the shear layer which is typically generated in bends of high curvature, due to large differences in the streamwise velocities in the transverse direction close to the inner bend. Also, the model predicts a sharper velocity gradient at the outer bank than was observed in the experiment, where measurements suggest the presence of a weak counter-rotating cell near the free surface.

5.4.2. Flow in a High curvature Bend and Influence of Aspect Ratio

To better understand the mechanisms leading to flow redistribution in the DB cases, where ‘topographic steering’ effects play an important role, the distributions of non-dimensional streamwise unit discharge, $q/(Q/B)$ for cases R1C1.5H20DB and R2C1.5H15DB are examined in Figure 5.5. Streamwise unit discharge is equal to the depth-averaged streamwise velocity multiplied by the local flow depth. For both cases, the distributions are similar, and the region of high streamwise unit discharge follows the channel thalweg, and gradually moves from the inner bank near 0° to the outer bank as the end of the curved reach is approached. The unit discharge along the thalweg represents about 50% of the flow moving across the channel width even though it occupies approximately only one third of its width. Along the inner bank wall, the streamwise unit discharge is almost zero through most of the curved reach, although flow does not separate at the inner bank. The effects of topographic steering for these cases is to promote further scour along the thalweg, while reducing the likelihood of scour over the point bar near the inner bank. The effects of topographic steering were much stronger for the high curvature 193° bend case of

Constantinescu *et al.* (2011), where it caused a dramatic shift of the main channel core of high streamwise velocity to the outer bank just downstream of 0° . In the present study, the core does not reach the outer bank until close to the bend exit.

On re-examination of the bathymetry plots of Figure 5.2, two elongated regions of deep scour can be seen along the outer bank, separated by a small elevated ridge starting at 120° . The results from both the simulations and experiments suggest that at 120° , the main circulation cell (M1) is splitting (not shown) into two clockwise-rotating circulation cells (M1 and M2) which can be seen immediately downstream, in the 135° section shown in Figure 5.6 for case R1C1.5H20DB. The locations of the core centers for M1 and M2 are superimposed on the bathymetry plots in Figure 5.2. In the simulation results, both the cores of M1 and M2 run parallel to the edges of the two elongated regions of deep scour. M1 is the main cell of cross-stream motion. It appears to form near 0° close to the inner bank. Its core center then gradually moves towards the channel center. M2 seems to form slightly downstream of the bend entrance close to the outer bank. It is much weaker than M1. It remains very small, and almost negligible, until close to 120° . Past this section, M2 increases rapidly in size and strength, such that the size and circulation of M1 and M2 become comparable at 135° (see the streamline patterns and streamwise vorticity distributions at the 135° cross-section in Figure 5.6, and circulation throughout the domain in Figure 5.7). The plots of the depth averaged streamwise velocity (Figures 5.8a and 5.8b) show that downstream of the 90° cross section, a region of lower streamwise velocity is found between M1 and M2. The majority of the flow moves along the outer bank with M2. The flow structures for case R2C1.5H15DB are similar, except that the two clockwise-rotating cells of

cross-stream circulation are slightly smaller and are situated closer to the bed at most locations within the channel.

The presence of the two clockwise-rotating cells, M1 and M2, aligned with the two elongated regions of large scour near the bend exit (Figure 5.2), suggests that the main cells of cross-stream circulation within a high curvature bend influence both the distributions of scour and streamwise velocity past the initial stages of scour. Most previous studies of flow in curved channels with deformed beds have focussed on the characteristics of the main circulation cell, M1. Since the size and circulation of M2 become comparable to those of M1 near the bend exit (Figure 5.7), it is likely that M2 plays an important role in the transfer of momentum near and downstream of 135° . The circulation of the two clockwise-rotating cells is high enough to push some of the high streamwise-velocity fluid away from the deeper outer bank area (Figure 5.6). This is the main reason why streamwise velocity levels remain high in the center of the channel, downstream of 120° (Figures 5.6 and 5.8). The distributions of Γ_+ for the high curvature bend cases (R1C1.5H20DB, R2C1.5H20DB) in Figure 5.7 agree well with those observed in previous high curvature bend studies (van Balen *et al.* 2010; Zeng *et al.* 2008a). In all these cases there was a rapid increase in Γ_+ upstream of the bend apex, followed by a more gradual decay. The magnitude of Γ_+ is important, as the outward transport of streamwise momentum is strongly dependent on this variable which controls the nonlinear interactions between the streamwise and cross-stream (radial) velocities in regions of high channel curvature (Zeng *et al.* 2008a).

To further investigate the relationship between the main circulation cells and scour patterns, the distributions of the bed shear stresses are examined in Figures 5.9 and 5.10 for the DB cases. Similar to the streamwise unit discharge, the region of high bed shear stress magnitude, τ_M , starts close to the inner bank at the bend entrance and gradually moves towards the outer bank. A zone of low τ_M is present very close to the inner bank throughout much of the bend and the exit reach. Within the bend, the cores of M1 and M2 are situated over regions of high τ_M (Figures 5.9a and 5.10a). Downstream of the bend exit, a region of low τ_M is situated in the vicinity of M2. This is because the center of the core of M2 is located very close to the bed, and high streamwise velocities are typically advected around the boundary of a circulation cell. Thus the core of M2 may be located too close to the bed to advect high streamwise velocities directly beneath it. Still, the cross-stream velocities induced by M2 result in significant local amplification of the cross-stream component of bed shear stress, τ_R (see Figures 5.9b and 5.10b which show the relative cross-stream bed shear stress τ_R/τ_M). Generally, τ_R/τ_M decays rapidly in the straight exit reach except for in the small region situated beneath M2. It should be noted that the streamwise component of bed shear stress remains dominant within the bend. The most obvious effect of the channel aspect ratio on bed shear stress distributions, as seen in Figures 5.9 and 5.10, is the lower values of τ_R/τ_M within the bend for case R2C1.5H15DB, which has a lower channel depth. The parameter τ_R/τ_M characterizes the strength of the secondary flow in the near-bed region.

Comparison of the distributions of τ_M/τ_0 and τ_R/τ_M in the deformed bed cases shows that even for high curvature bends, the streamwise velocities make a larger contribution to τ_M compared to the cross-stream velocities. Note that τ_0 is the mean value of bed shear stress in

the straight inflow reach. The fact that a band of high τ_M is located below M1 in Figures 5.9a and 5.10a can largely be explained by topographic steering. Furthermore, the appearance of a second band of relatively high τ_M along the outer bank downstream of section 60° (Figures 5.9a and 5.10a) is likely associated with the presence of M2. Within the curved region, high τ_M values coincide with the locations of streamwise oriented vortical cells, and lower τ_M values generally occur in between these cells, as long as the cells are able to advect streamwise velocities below them. Just upstream of the bend exit, a band of very low streamwise velocity (Figure 5.8) is present between M1 and M2 near the surface (Figure 5.6). The cells M1 and M2 appear to be acting as mechanisms controlling the distribution of high streamwise velocities. It should also be noted that for the DB cases, gravitational forces and flow direction relative to the bed slope must also be considered to evaluate local entrainment over a deformed surface, as they alter the local value of critical bed shear stress (Zeng *et al.* 2008a). Such effects on the critical bed shear stress have not been evaluated for this present study.

The deviation angle, $\theta = \arcsin(\tau_R/\tau_M)$, is defined as the angle the near-bed streamlines make with a line tangent to the channel centerline at that point. It was found from Figures 5.9b and 5.10b that most values of θ within the curved reach of the channel range from 24° to 37° for case R1C1.5H20DB, and from 20° to 33° for case R2C1.5H15DB. This is consistent with the fact that Γ_+ is lower for case R2C1.5H15DB (Figure 5.7).

To better understand the effects of B/H on the flow and erosion, flat bed simulations were conducted for R1 with B/H between 5.00 and 12.50 for selected cases of R/B between 1.5

and 10. The simulation results showed substantial changes in the magnitude of peak Γ_+ among the different cases (Figure 5.11). For the high curvature cases with $R/B=1.5$, there was about a 65% increase in the peak value of Γ_+ when B/H was decreased by 2.5 times. For the milder curvature cases ($R/B=8$), the magnitudes of Γ_+ within the bend were considerably less compared to the high curvature cases. However, the peak value of Γ_+ increased by about 67% when B/H was decreased by 2.5 times. Interestingly, in the cases with $R/B=8$, the streamwise position where the peak value of Γ_+ was predicted, moved from close to the bend entrance for $B/H=5$ to the bend exit for $B/H>9$.

As observed for case R2C1.5H15FB (Figure 5.4e), the simulation results for case R1C1.5H20FB (Figure 5.18d) also show the presence of two clockwise-rotating cells, V1 and M1, where V1 is located close to the inner bank, and M1 is the main cell of cross-stream circulation. The locations of the core centers of V1 and M1 are shown in the bed shear stress plots in Figure 5.12. As already discussed, the inner bend cell, V1, is considered to be a characteristic of flow in high curvature bends with a flat bed. An increase (decrease) in B/H (H) from 5 (0.20) to 12.5 (0.08) induces the formation of an additional clockwise-rotating cell, M12, near the outer bank for case R1C1.5H8FB (Figure 5.18a). This change in B/H however, has minimal effects on the locations of the main circulation cell and the inner bank cell, as seen in Figures 5.12 and 5.13. For the mild curvature case of R1C8H20FB (Figure 5.18b), only one main clockwise-rotating circulation cell, M1, is present. Its location is shown in the bed shear stress plots of Figure 5.14. Similar to the high curvature bend cases, an increase of B/H leads to the formation of an additional clockwise rotating cell, M12, as

shown in Figure 5.15 for the case R1C8H8FB. The location of the main circulation cell does not change as a result of the increase in B/H .

The increase (decrease) of B/H (H) from 5 (0.20) to 12.5 (0.08) in the simulations with $R/B=1.5$ does not have a substantial effect on the distributions of bed shear stress magnitude (e.g., see Figures 5.12a and 5.13a). However, for case R1C1.5H20FB (Figure 5.12a) the maximum value of τ_M/τ_0 occurs downstream of the bend exit, while for case R1C1.5H8FB (Figure 5.13b) the maximum value occurs within the bend close to the inner bank. Differences in the magnitudes of τ_M/τ_0 within the bend however, are less than 10%, although, the values of τ_R/τ_M are about 40% less for case R1C1.5H8FB (see Figures 5.12b and 5.13b). The presence of the clockwise rotating cell M11 causes a slight amplification of τ_R/τ_M along the outer bank. Meanwhile, for both cases with $R/B=8$, the maximum value of τ_M/τ_0 occurs downstream of the bend exit close to the outer bank (Figures 5.14a and 5.15a).

A main finding related to the influence of B/H on the distribution of bed shear stress (τ_M/τ_0) in high curvature bends ($R/B=1.5$) is that the location of the maximum τ_M/τ_0 switches from the outer bank, near the bend exit for the high B/H values to the inner bank, near the bend entrance for the low B/H values. This change in the location of the peak τ_M/τ_0 did not occur when varying B/H for the milder curvature bend ($R/B=8$). One possible explanation could be that the decrease in cross-stream circulation (Γ^+) corresponding to a decrease in H , may reduce the rate at which the streamwise velocity is advected by cross-stream circulation, causing a greater proportion of higher streamwise velocities to remain closer to the inner bank. It is interesting that Hickin (1978) reported a similar finding for studies conducted on

the Squamish River, but he found a shift in maximum velocity occurred with a variation of R/B not B/H . This may indicate that perhaps it is the parameter H/R (the product of $B/R * H/B$) that is causing this change. He found that decreasing R/B below 3.0 caused the location of maximum velocity to shift to the inner bank, resulting in higher bed shear stresses over the point bar at the inner bank. Of course, the results of Hickin (1978) were for deformed bed cases while this present parametric study is conducted for flat beds.

5.4.3. Influence of Curvature Ratio

In this section the influence of curvature ratio, R/B for a 135° bend, is investigated for the flat-bed cases, with respect to the base case R1C1.5H20FB.

The first major difference found between flow in the high curvature bend ($R/B=1.5$) and that in the milder curvature bends ($R/B>3$) for the FB simulations is in the distributions of depth-averaged streamwise velocity or, equivalently, streamwise unit discharge, as flow depth is constant for the FB cases. For the high curvature bend, this plot (see Figure 5.16a for $R/B=1.5$). shows that core of high streamwise velocity is situated close to the inner bank near the bend entrance, and then gradually moves towards the outer bank. In contrast, for the milder curvature bends, the core of high streamwise velocity is located close to the outer bank throughout most of the bend (see Figure 5.16b for $R/B=8$). This unique distribution of depth-averaged streamwise velocity within a high curvature channel bend seen in this study has also been observed in previous bend studies (Blanckaert and de Vriend 2005; Khosronejad *et al.* 2007; and Zeng *et al.* 2008a). By comparing the distribution of streamwise unit discharge between the FB and DB cases with $R/B=1.5$ (Figs 5.5a and 5.16a) one can see the effect of topographic steering in the case with a deformed bed. The

maximum unit discharge for case FB is about 20% less than that predicted for case DB. The core of high unit discharge is located closer to the inner bank for case FB. Also, the region of very low unit discharge near the inner bank observed in case DB is absent in case FB.

A second important difference between the bends of high and milder curvature is that two clockwise-rotating cells of cross-stream circulation are present in the high curvature bends (M1 and V1 in Figures 5.4e and 5.18d for $R/B=1.5$), whereas only one main cell (M1 in Figures 5.18b and 5.18c for $R/B=8$ and 5, respectively) is present in the bends with $R/B>3$. For the high curvature cases the narrow inner-bank cell, V1, remains in the vicinity of the inner bank and its core contains fairly high streamwise velocity fluid (see Figure 5.18d). The presence of V1 at the inner bend is due to the fact that streamwise flow entering the high curvature bend cannot adjust fast enough to the shape/position of the inner bank. Consequently, a shear layer forms at the inner bank for the high curvature bend. This cell induces ejections of a tongue of opposite-sign vorticity from the attached boundary layer forming at the inner bank. The presence of V1 is also important, as it can affect the distributions of velocities and bed shear stresses on the inner side of the channel where its coherence is significant. For the milder curvature bends, the axis of M1 is situated close to the channel centerline in the downstream part of the bend region and inside the exit reach. However, as R/B decreases the axis of M1 shifts towards the outer wall in the upstream part of the curved reach.

Inspection of Figures 5.18b, 5.18c, and 5.18d helps in clarifying the effects of R/B on the distributions of velocity and streamwise vorticity in the 135° cross section, where curvature-

induced effects are important. A second counter-clockwise rotating cell of cross-stream circulation, C1, is present near the outer bank in the simulations with $R/B \geq 8$ (e.g., case R1C8H20FB, Figure 5.18b). C1 extends along the entire length of the outer bank within the bend reach (not shown). The velocity plot of Figure 5.18b shows that C1 reduces the streamwise velocity gradient at the outer bank very close to the free surface, which protects the outer bank near the free surface from erosion. Still, the circulation of C1, which peaks near the 105° section, remains much lower than that of M1. The effect of decreasing R/B is an increase in streamwise vorticity levels (Figures 5.18b, 5.18c, and 5.18d), and thus of the circulation associated with the main cell of cross-stream motion (Figure 5.19a). As R/B decreases, the top boundary of the region of high streamwise vorticity associated with M1 moves away from the bed. These distributions of streamwise velocity and vorticity seem to show that streamwise cells of cross-stream circulation play an important role in redistributing streamwise momentum within the bend, and their characteristics are a function of channel curvature. The velocity plot of Figure 5.18d shows that the highest velocities are concentrated around the two clockwise-rotating cells V1 and M1, and are lower in the surrounding flow and at the boundary between the two cells. Therefore, it is reasonable to believe that V1 and M1 are affecting the distribution of the core of high streamwise velocity, and streamwise momentum is likely being exchanged between the two cells. For example, moving downstream from the bend apex, the values of high streamwise velocity around V1 start to decrease, while at the same time those around M1 increase (not shown).

The plot in Figure 5.19a shows that the total circulation associated with the clockwise rotating cells is a strong function of the channel curvature for $R/B < 8$. In particular, the peak

value of the circulation, Γ_+ , increases by about three times as R/B decreases from 8 to 1.5 (Figure 5.19b). For $1.5 < R/B < 10$ shown in Figure 5.19b for the simulations with $H=0.2$ m, the peak value of Γ_+ follows the best fit power law: $0.83(R/B)^{-0.682}$, which shows that the relation between the peak value of Γ_+ and R/B is not linear. Figure 5.19a also shows that as R/B decreases the cross section where the peak value of Γ_+ occurs is situated farther downstream. For example, the peak value of Γ_+ occurs at 75° for $R/B=1.5$, at 40° for $R/B=5$, and at 30° for $R/B=8$. In the high curvature bend simulations with a flat bed, Γ_+ increases rapidly to reach its peak value around 75° . A more gradual decay is observed in the downstream part of the curved reach. For the mild curvature cases ($R/B > 8$), Γ_+ reaches a plateau-like region a short distance downstream of the cross-section where the peak value is observed.

Figure 5.19a also shows that for case R1C1.5H20FB the $k-\varepsilon$ turbulence model slightly underpredicts the magnitude of peak Γ_+ compared to the RSM turbulence closure. In Figure 5.18f, it can be seen that the $k-\varepsilon$ model shows a different distribution of streamwise vorticity in the 135° cross section compared to the one predicted by the RSM closure (Figure 5.18d). The fact that the distribution of the streamwise velocity in the cross section is more uniform suggests the $k-\varepsilon$ model is more dissipative and thus less accurate than the RSM turbulence closure.

The increase in the overall levels of Γ_+ along the bend and the peak values of Γ_+ (Figure 5.19b) with decreasing R/B is expected because the strength of the secondary flow increases with channel curvature. Although this trend of secondary circulation has been reported

previously (e.g. Hickin 1978), we believe that this is one of the first studies to quantitatively assess distributions of Γ_+ for a large range of R/B . The distributions of Γ_+ (Figure 5.19a) are also affected by bend length, since bend length will increase with an increase in R/B . Also noticeable, is the fact that Γ_+ reaches an almost constant level during its decay in the milder curvature bends, and that the beginning of this region moves upstream as R/B increases. It appears that for a sufficiently long bend, an equilibrium region forms where the generation and decay of streamwise circulation are in balance. Also, the distributions of Γ_+ for the FB and DB cases are similar (Figures 5.11 and 5.19a).

We next compare distributions of τ_M between the FB and DB cases (Figures 5.9a and 5.12a). The main difference is that for the FB case (Figure 5.12a) the band of high τ_M is closer to the inner bank over most of the bend reach. The high shear stresses at the inner bank are associated with the presence of V1. The cross-stream component, τ_R , contributes substantially to the total bed stresses in case FB over most of the bend region, except for the region situated close to the outer bank. For case FB, the peak values of τ_R/τ_M are observed in the first half of the bend reach. Also, the size of the region where $\tau_R/\tau_M > 0.35$ is larger for case FB (compare Figures 5.12b and 5.9b).

Next, the influence of R/B on distributions of bed shear stresses is considered. Figure 5.12a shows that for case R1C1.5H20FB, Shields' critical stress, τ_c (corresponding to $D_{50}=1.1\text{mm}$), is exceeded over the whole channel width near the exit of the curved reach, and occupies most of the width inside the downstream straight reach. As R/B is increased to 5 (Figure 5.17a), τ_M does not exceed τ_c in any region situated close to the inner bank. As R/B is

increased further, the width of the region where $\tau_M/\tau_c > 1$ reduces. For example, for $R/B=8$ (Figure 5.14a) the region with $\tau_M/\tau_c > 1$, is situated entirely within the outer bank side of the channel. The maximum value of τ_M along the outer bank for $R/B=5$ ($R/B=8$) is about 25% (30%) lower compared to that for $R/B=1.5$. The distributions of τ_R/τ_M in Figures 5.17b and 5.14b show that the cross-stream bed shear stress contribution to the total stress in the bends of relatively low curvature peaks along the channel centerline, below the center of the main cell M1. The peak values of θ below M1 for $R/B=5$ ($R/B=8$) range from 14° to 19° (11° to 14°). These values are more than two times lower than peak θ values predicted for $R/B=1.5$.

For the FB cases with $H=20\text{cm}$, the maximum value of bed shear stress, τ_M , occurs near the outer bank wall at the start of the straight exit for all values of R/B . The fact that peak values of τ_M increase with decreasing R/B is expected (Zeng *et al.*, 2008b) and may be explained by the fact that more of the high-speed flow entering the bend cannot follow the inner bank, but is diverted towards the outer bank as R/B decreases. The increase in cross-stream circulation with decreasing R/B may also play a role in distributing τ_M , as it increases the rate at which streamwise velocities are advected towards the outer bank. One must note however, that Blanckaert (2009) suggests that saturation of circulation may occur at some point in a high curvature bend, when increasing R/B will no longer lead to an increase in cross-stream circulation. Related to this observation, Hickin and Nanson (1984) have also reported that the migration rate of bends can decrease for $R/B < 2$.

5.5. COMPARISON WITH SELECTED ANALYTICAL MODELS

It is important to understand how the results presented here compare with some previous studies which have investigated the influence of R/B , B/H and H/R on secondary flow, and streamwise velocity distributions within channel bends. As mentioned, the deviation angle (θ) is defined as the angle the near-bed streamlines make with a line tangent to the channel centerline at that point, and it is expected to increase with an increase in helical flow strength. Rozovskii (1957) found H/R to be the main factor affecting the value of θ , and developed the simplified analytical model $\tan(\theta) = C(H/R) = \tau_R / \tau_S$, where C is a constant. Rozovskii determined that $C=11$ provided a good fit for most data tested in his study, although slightly different values of C have been determined by others (Engelund 1974 [$C=7$]; Zimmerman 1977 [$C=5$]). Figure 5.20a shows the ranges of $\tan(\theta)$ within the bend obtained from the present study for all FB cases as a function of H/R , and compares these values to the predictions given by the analytical models of Rozovskii (1957) and Zimmerman (1977). In all cases there is a trend of increasing $\tan(\theta)$ with increasing H/R . The Rozovskii model only appears to show a good fit for low H/R values and for the low curvature bend ($R=8$). While the Zimmerman model appears to show a better fit, the predictions fall at the extreme ends of the data range for lower and higher values of H/R , suggesting that the actual trend may not be linear.

Velocity excess, ΔU , is the main parameter used in most one-dimensional analytical models to predict meander migration (e.g., see Hickin and Nanson, 1984, Ikeda et al., 1981, Odgaard, 1989a). It is defined as the difference between the maximum depth-averaged value of the streamwise velocity near the outer bank and the cross-sectional averaged velocity, U . Blanckaert and de Vriend (2010) provide a more detailed discussion of the main types of

meander models. In such reduced-order models, the velocity excess is mainly due to the secondary flow whose strength is proportional to channel curvature. The secondary flow strength and its capacity to induce erosion can be parameterized as a function of B/R and H/B . Once ΔU is estimated, the streamwise velocity near the outer bank in simplified 1-D models can be approximated as $U + \Delta U$. The outer bank velocity is then used to estimate the shear stress at the outer bank, which may also involve using a correction factor (Ottevanger *et al.* 2011). This stress controls the migration rate.

Following Ottevanger *et al.* (2011), the variation of the non-dimensional velocity excess $\Delta U/U$ as a function of B/R is plotted in Figure 5.20b for different values of H/B ($H/B=0.2$ and 0.08). While values of $\Delta U/U$ will vary along the length of the flume, it is customary to estimate values just upstream of the bend exit where the flow should be closer to being fully developed (K. Blanckaert, personal communication, September 2011). The values of $\Delta U/U$ in the 130° cross section situated close to the exit from the bend reach are compared to those given by the 1-D model proposed by Blanckaert (2011). The 1-D model assumes that $\Delta U/U$ is taken for a very long bend where flow is fully developed, and therefore is independent of the streamwise location along the bend. For low curvature channels (very small B/R), the secondary flow strength increases with channel curvature. This leads to an increase of $\Delta U/U$ with increasing B/R . However, past a certain threshold value of B/R , $\Delta U/U$ starts decreasing with increasing B/R . For increasing channel aspect ratio H/B , the 1-D model predicts that the maximum of $\Delta U/U$ occurs for lower values of B/R .

As explained by Ottevanger et al. (2011), for large values of B/R , the interaction of the primary and secondary flow leads to a change in the streamwise velocity profile over the depth in the central part of the cross section (see also Zeng et al., 2008a). The maximum velocity occurs below the free surface. The vertical gradient of the streamwise velocity becomes nearly independent of B/R . In fact, a slight increase of the velocity gradient is expected as B/R increases further. This induces a decay in the secondary flow strength, which reduces the outward transport of momentum in the cross section and thus $\Delta U/U$.

For both values of H (20cm and 8cm) in Figure 5.20, RANS predicts velocity excess to be close to the value given by the simplified 1-D model of Blanckaert (2011). In particular, it confirms the reduction of $\Delta U/U$ with B/R for $B/R > 0.1$ and the increase of $\Delta U/U$ with the increase in H/B at a fixed value of B/R as found by Ottevanger et al. (2011). One should stress that the 3-D RANS model accounts for many of the processes neglected in 1-D analytical models. Ottevanger *et al.* (2011) presented a similar comparison between the velocity excess predicted by the 1-D model and that inferred from 3-D LES of axisymmetric (infinitely-long) fully-developed flow in curved channels of constant curvature. The level of agreement was similar. The present results based on 3-D RANS simulations serve as further validation of the 1-D analytical model. It is worth noting, however, that with increasing bend sharpness ($B/R > 0.1$) a decrease in velocity excess was observed, while also observing a monotonic increase in secondary circulation (Figure 5.19a). It should also be noted that in these cases velocity excess was calculated upstream of the bend exit, whereas maximum shear stress normally occurs in the straight channel downstream of the bend exit.

5.6. SUMMARY AND CONCLUSIONS

In this study, the influence of aspect ratio (B/H) and curvature (R/B) on secondary circulation within a 135° channel bend was investigated through a series of Reynolds-Averaged Navier Stokes (RANS) numerical simulations with a second order Reynolds Stress Model (RSM) turbulence closure. The capability of the RANS model to predict flow structures was assessed based on validation with data from experiments conducted in a laboratory flume for the high curvature ($R/B=1.5$) base cases. For the equilibrium scour cases, the results for two aspect ratios ($B/H=5.00$ and 6.67) were compared. For the initial scour cases (flat bed simulations) a parametric study was conducted which involved three aspect ratios ($B/H=5.00$, 9.09 , and 12.50) and a total of five curvature ratios ($R/B=1.5$, 3 , 5 , 8 and 10). Relations between the secondary circulation cells and the distributions of velocities and bed shear stresses were elucidated, in order to understand how these cells impacted erosion at a given stage of scour. The main findings from this study are summarized below.

1. Varying the bend curvature ratio (R/B) substantially affected distributions of depth-averaged streamwise velocity (or unit discharge) within the bend (Figure 5.16). The greatest difference occurred at around $R/B=3$, which is the threshold generally used to differentiate between high and moderate curvature bends. This confirms that the potential-vortex effect described in previous studies is much greater for high curvature bends (Blanckaert and de Vriend 2005; Zeng *et al.* 2008a). As had been seen in previous studies, for high curvature bends with a flat bed the core of high streamwise velocity was located very close to the inner bank near the bend entrance, whereas for the milder curvature channels ($R/B>3$), the core of high streamwise velocity did not reach the inner

bank, but was located at the outer bank side of the channel throughout most of the channel.

2. A change in aspect ratio (B/H) (at constant flume width) substantially affected the strength of the main channel secondary flow cell. Although a decrease in aspect ratio led to an increase in bed shear stress magnitude, these changes were less than 10% for the ranges of B/H considered. For the high curvature bend case, a decrease in H by a factor of 2.5 (with B and R kept constant) caused the location of maximum bed shear stress to move from the outer bank, downstream of the bend exit, to the inner bank, close to the bend entrance. In the shallower channel simulations ($H=0.08\text{m}$), the main channel flow cell split into two clockwise-rotating cells regardless of the channel curvature. The smaller clockwise-rotating cell present along the outer bank maintained its coherence through the downstream straight reach.
3. Bed shear stress distributions substantially changed with curvature ratio, and were closely related to distributions of depth-averaged streamwise velocities. For the high curvature flat bed cases ($R/B \leq 3$), the region of highest bed shear stress was located near the inner bank close to the bend entrance, and gradually moved towards the outer bank. For the high curvature flat bed cases, the Shields critical bed shear stress value was exceeded both close to the inner bank and the outer bank. However, for the milder curvature flat bed cases ($R/B > 3$), the Shields critical bed shear stress value was only exceeded along the outer bank, and was never exceeded at the inner bank. Moreover, the peak bed shear stress value in the bend increased by about 70% as R/B decreased from 8

to 1.5. These differences in bed shear stress distributions may have obvious consequences on how scour and deposition regions develop within channels of high or low curvature.

4. Multiple clockwise-rotating streamwise-orientated circulation cells were found within the flow for the high curvature bends ($R/B \leq 3$) with $H \geq 0.11$. By contrast, only one main circulation cell was present for the milder curvature bends ($R/B > 3$) with $H > 0.11$, which is consistent with experiments and simulations of bends of moderate curvature with a similar aspect ratio (Zeng *et al.* 2008b). The circulation cells within the high curvature bends appeared to influence the distribution of streamwise velocity. High streamwise velocities were found around these cells. Bed shear stress magnitudes were usually greater beneath these cells within the bend, while they tended to be lower in the region between these cells.
5. A decrease in channel curvature ratio (R/B) was associated with an increase of cross-stream circulation strength. Similarly, with respect to the streamwise direction for the velocity streamlines near the bed, the angle of deviation increased with decreasing curvature ratio, and increasing H/R . For example, the contribution of the cross-stream component of the bed shear stress to the bed shear stress magnitude increased from a maximum of about 15% for $R/B=8$ to more than 60% for $R/B=1.5$. A larger angle of deviation was associated with stronger helical flow. These findings confirm similar trends found previously by Hickin (1978), Rozovskii (1954), and Zimmerman (1977).

6. The 3-D RANS simulations allowed for quantification of the increase of the cross-stream circulation along the bend as a result of increased curvature (lower R/B). The higher curvature channels were characterized by a faster decay of circulation past the section where the peak total cross-stream circulation occurred. The location along the bend length at which the peak circulation occurred was found to increase with channel curvature (e.g., from 30° to about 75° as R/B was varied from 8 to 1.5). For the milder curvature bends ($R/B > 8$) it was also found that, beyond the location where the peak total cross-stream circulation occurred, the circulation reaches a constant equilibrium level until the straight exit section was reached. It is likely that both these effects are related to the channel length, since the bend length increases with increasing curvature ratio.
7. The aim of this study was to provide insight into the effects of secondary flow strength and streamwise oriented vortices on the redistribution of bed shear stress in a high curvature bend, and how these compare to milder curvature bends. While this study suggested that flow structures may impact the rate of transfer of momentum across the channel, and the distribution of bed shear stresses, further investigation would be needed to understand how these observations could extend on, or be incorporated into existing analytical channel meander models.

5.7. ACKNOWLEDGEMENT

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5.8. NOTATION

B = channel width (m)

D_{50} = median sediment size (mm)

E = water superelevation at apex of bend (m)

g = gravitational acceleration (m/s^2)

H = water depth in the inlet section (m)

k_s = bed roughness (m)

q = streamwise unit discharge (m^2/s)

Q = discharge (m^3/s)

R = radius of curvature at channel centerline (m)

Re = main channel Reynolds number = UH/ν

T = temperature ($^{\circ}\text{C}$)

u = streamwise velocity relative to the channel centerline (m/s)

U = mean velocity in the inlet section (m/s)

$\bar{U}$ = depth averaged velocity (m/s)

u^* = bed shear velocity (m/s)

u_{cr}^* = critical bed shear velocity (m/s)

v = cross-stream velocity relative to the channel (m/s)

w = vertical velocity (m/s)

y_R = cross-stream direction perpendicular to the flume walls (m)

z = vertical distance from initial bed level (m)

- θ = angle of deviation ($^{\circ}$)
- τ_c = Shields' critical stress for sediment entrainment (N/m^2)
- τ_M = bed shear stress magnitude (N/m^2)
- τ_0 = average bed shear stress at the inlet section (N/m^2)
- τ_R = cross-stream bed shear stress (N/m^2)
- τ_S = streamwise bed shear stress (N/m^2)
- ν = kinematic fluid viscosity (m^2/s)
- Γ = non dimensional cross-stream circulation magnitude
- Γ_+ = total positive non dimensional cross-stream circulation
- ω_s = streamwise vorticity = $(\delta w / \delta y_R) - (\delta v / \delta z)$ ($1/\text{s}$)

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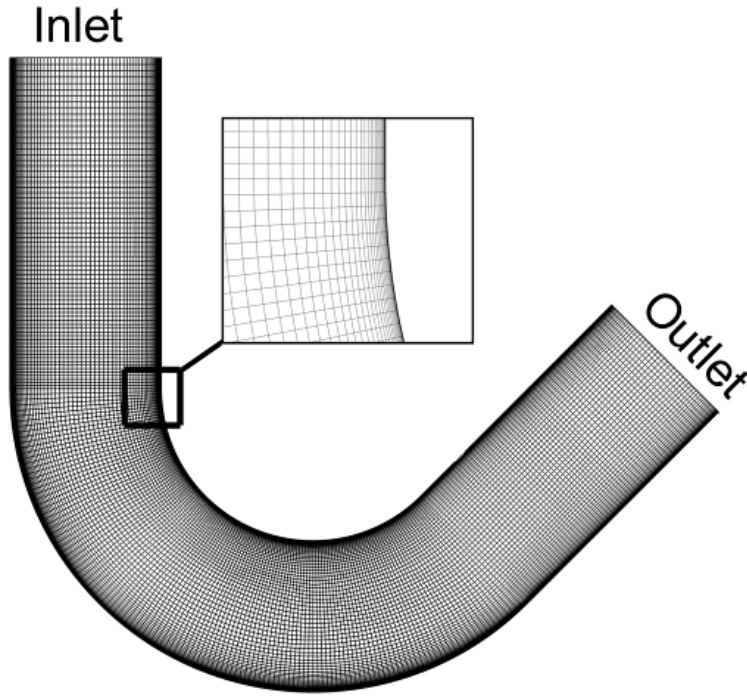


Figure 5.1 Structured mesh at the bed for case R1C1.5H20DB, with a close-up view of the mesh near the inner bend wall.

Table 5.1 Parameters for all cases. Note that physical experiments were only conducted for cases R1C1.5H20DB, R2C1.5H15DB, and R2C1.5H15FB.

	Re	Q	U	u^*	u^*_{cr}	B	H	R/B	B/H	D_{50}	Max T
		[m ³ /s]	[m/s]	[m/s]	[m/s]	[m]	[m]			[mm]	[°C]
R1C1.5H20DB	86,026	0.0788	0.3940	0.0250	0.0260	1	0.20	1.5	5.00	1.100	24
R2C1.5H15DB	61,324	0.0464	0.3095	0.0175	0.0195	1	0.15	1.5	6.67	0.698	33
R1C1.5H20FB	86,026	0.0788	0.3940	-	-	1	0.20	1.5	5.00	-	-
R2C1.5H15FB	61,324	0.0464	0.3095	0.0175	-	1	0.15	1.5	6.67	-	33
R1C3H20FB	86,026	0.0788	0.3940	-	-	1	0.20	3.0	5.00	-	-
R1C5H20FB	86,026	0.0788	0.3940	-	-	1	0.20	5.0	5.00	-	-
R1C8H20FB	86,026	0.0788	0.3940	-	-	1	0.20	8.0	5.00	-	-
R1C10H20FB	86,026	0.0788	0.3940	-	-	1	0.20	10.0	5.00	-	-
R1C1.5H11FB	43,460	0.0398	0.3619	-	-	1	0.11	1.5	9.09	-	-
R1C1.5H8FB	30,000	0.0275	0.3435	-	-	1	0.08	1.5	12.50	-	-
R1C8H11FB	43,460	0.0398	0.3619	-	-	1	0.11	8.0	9.09	-	-
R1C8H8FB	30,000	0.0275	0.3435	-	-	1	0.08	8.0	12.50	-	-

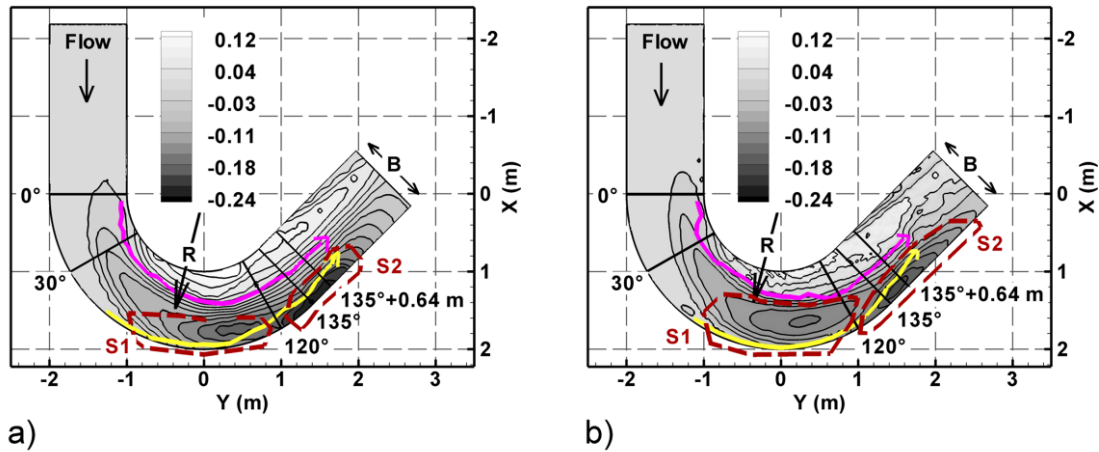


Figure 5.2 Contours show channel bathymetry, $z(m)$, for cases a) R1C1.5H20DB and b) R2C1.5H15DB. The location of the core center for the main clockwise-rotating cell (M1) is shown by a pink line, and for the clockwise-rotating cell (M2) is shown by a yellow line. The extent of the two regions of deep scour S1, and S2 are shown within the red dashed lines. z is measured from the initial flat bed level in meters and + (-) values refer to deposition (scour).

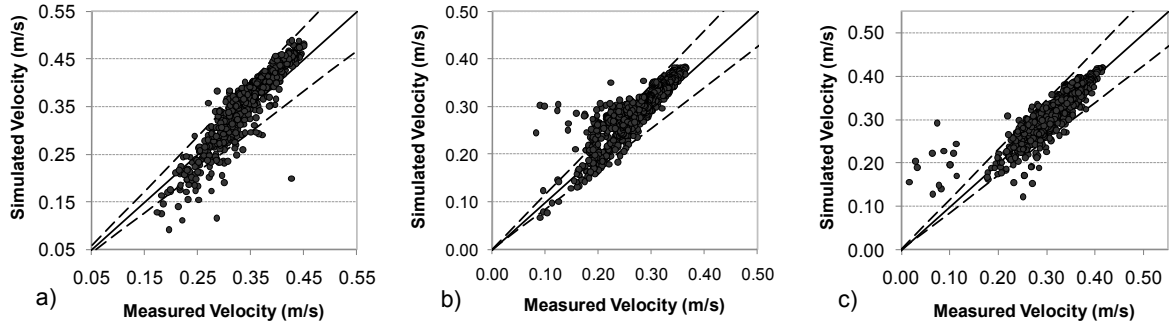


Figure. 5.3 Simulated versus measured velocity magnitudes for cases a) R1C1.5H20DB, b) R2C1.5H15DB, and c) R2C1.5H15FB. The dashed lines represent errors of $\pm 15\%$ of the measured values.

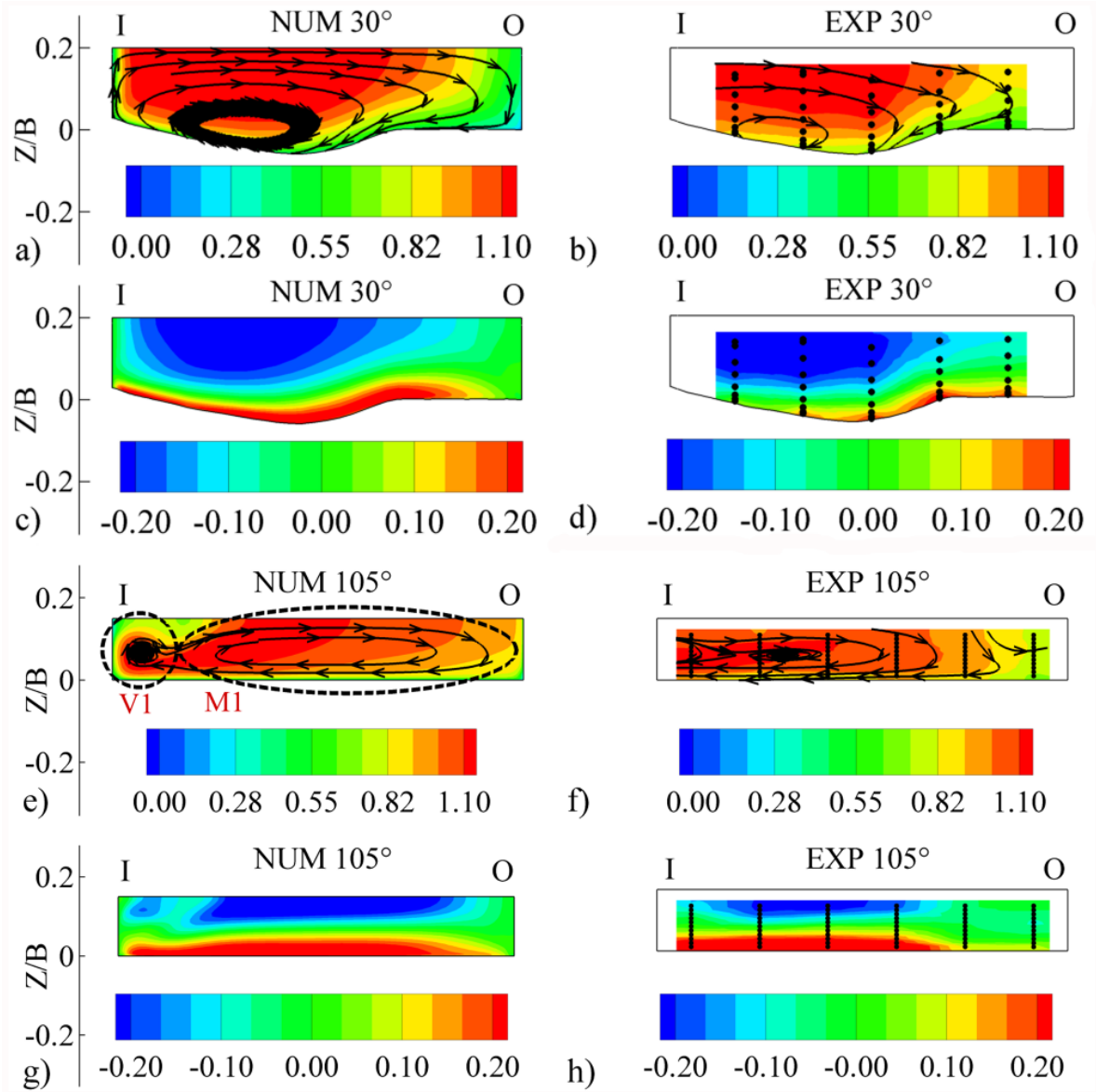


Figure 5.4 Comparisons of simulated (left) and measured (right) non-dimensional velocities for case R1C1.5H20DB in the 30° cross section (frames a-d) and for case R2C1.5H15FB in the 105° cross section (frames e-h). Streamwise velocity (u/U) contours and 2-D streamlines are shown in frames a, b, e and f. Cross-stream velocity (v/U) contours are shown in frames c, d, g and h. Experimental contours and streamlines in the frames are obtained from interpolation of the experimental measurements points shown by the black dots. The inner bend is labeled 'I', while the outer bend is labeled 'O'.

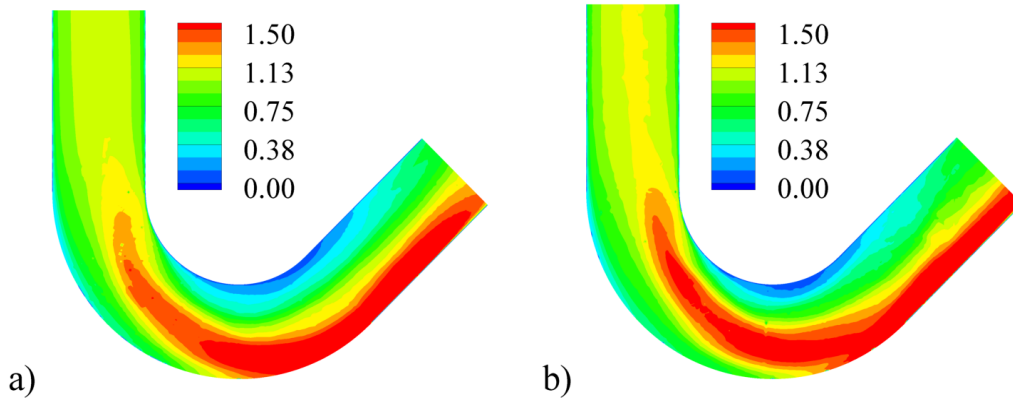


Figure 5.5 Distributions of non-dimensional streamwise unit discharge, $q/(Q/B)$, calculated from the RANS simulations for cases a) R1C1.5H20DB and b) R2C1.5H15DB.

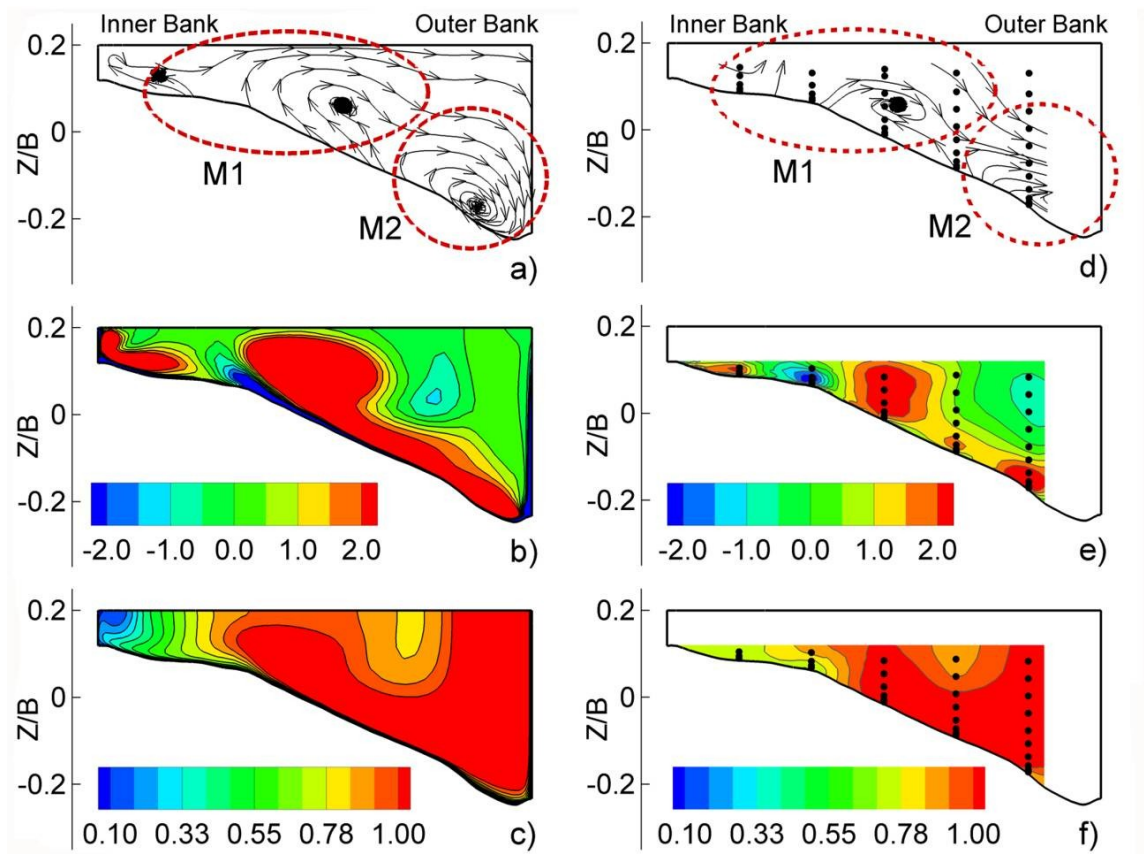


Figure 5.6 Comparison of 2-D streamline patterns (top), streamwise vorticity, $\omega_s(B/U)$, (middle) and, streamwise velocity, u/U , (bottom) in the simulation (left) and experiment (right) for the 135° cross section of case R1C1.5H20DB. Experimental contours and streamlines in the frames are obtained from interpolation of the experimental measurements points shown by the black dots.

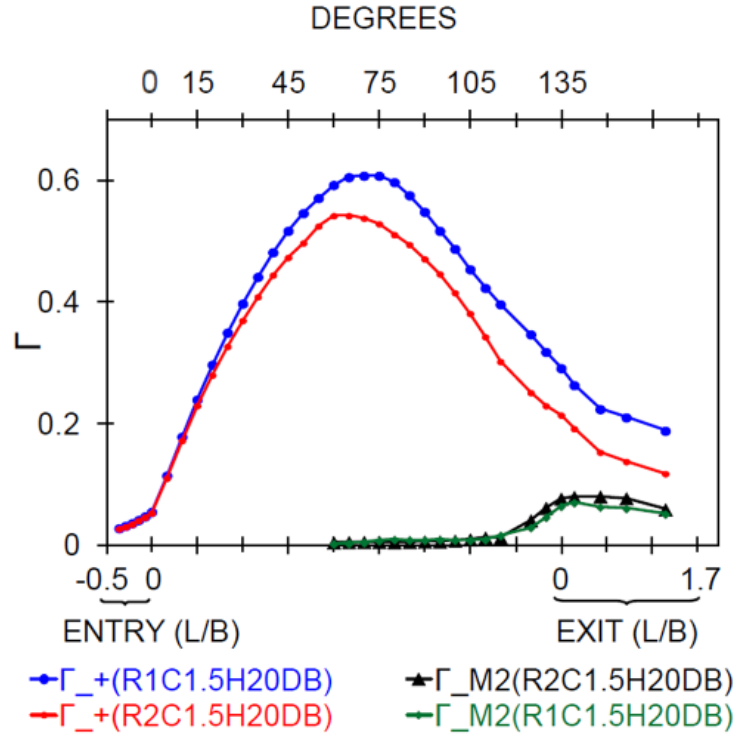


Figure 5.7 Streamwise variation of non-dimensional (positive) circulation associated with the clockwise-rotating cells M1 and M2 (Γ_+), and with cell M2 (Γ_{M2}) for deformed bed cases R1C1.5H20DB and R2C1.5H15DB. Γ is non-dimensionalized by the mean velocity (U) and channel width (B) given in Table 5.1.

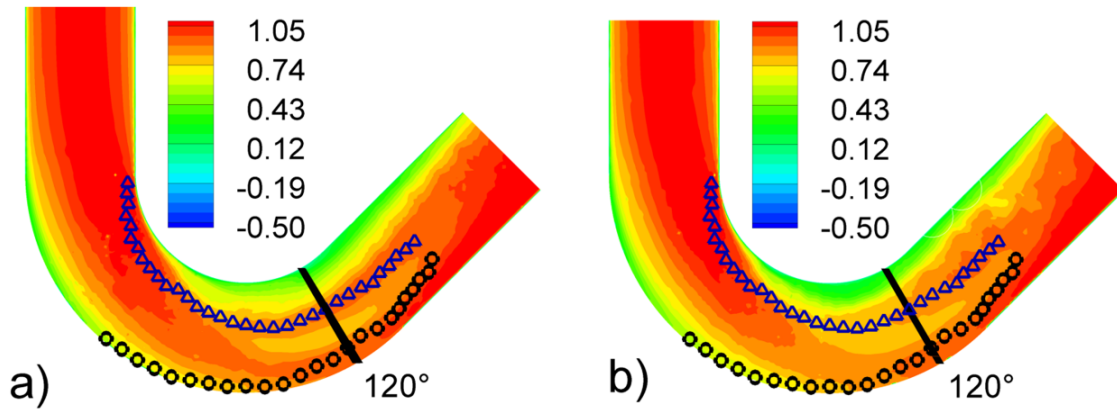


Figure 5.8 Depth averaged streamwise velocity (u/U) for cases a) R1C1.5H20DB and b) R2C1.5H15DB. The locations of the core centers of the clockwise-rotating cells M1 and M2 (see Figure 5.6) are shown using blue triangles and black squares, respectively.

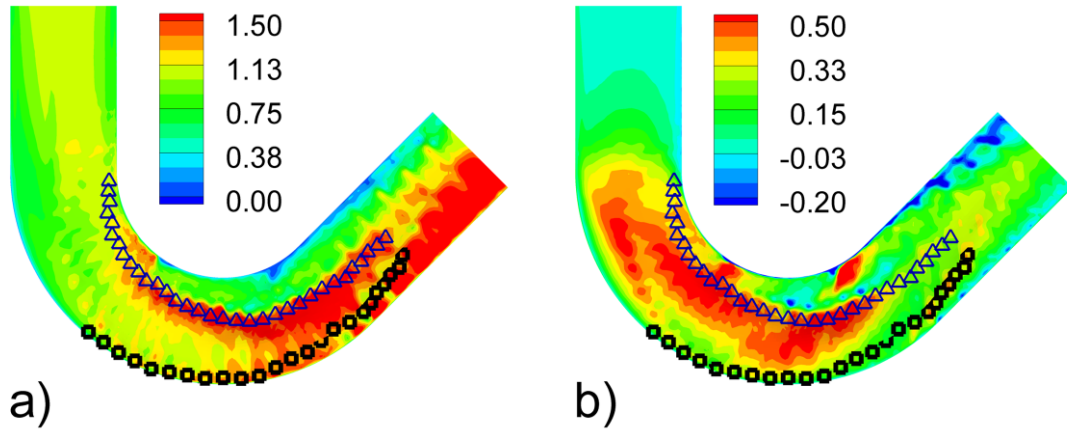


Figure 5.9 Bed shear stress distributions for case R1C1.5H20DB. a) Bed shear stress magnitude, τ_M/τ_0 , and b) cross-stream bed shear stress divided by bed shear stress magnitude, τ_R/τ_M . The locations of the core centers of the clockwise-rotating cells M1 and M2 (see Figure 5.6) are shown using blue triangles and black squares, respectively. τ_0 is the average bed shear stress at the inlet section.

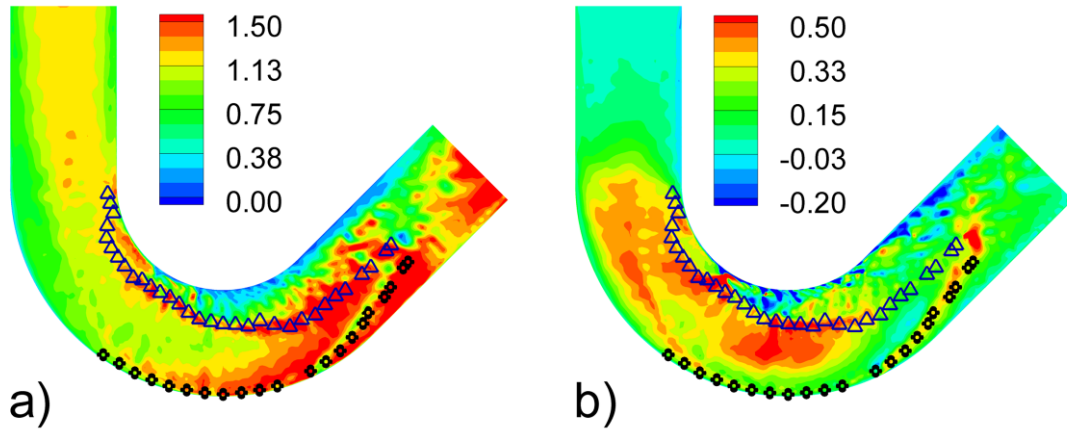


Figure 5.10 Bed shear stress distributions for case R2C1.5H15DB. a) Bed shear stress magnitude, τ_M/τ_0 , and b) cross-stream bed shear stress divided by bed shear stress magnitude, τ_R/τ_M . The locations of the core centers of the clockwise-rotating cells M1 and M2 are shown using blue triangles and black squares, respectively. τ_0 is the average bed shear stress at the inlet section.

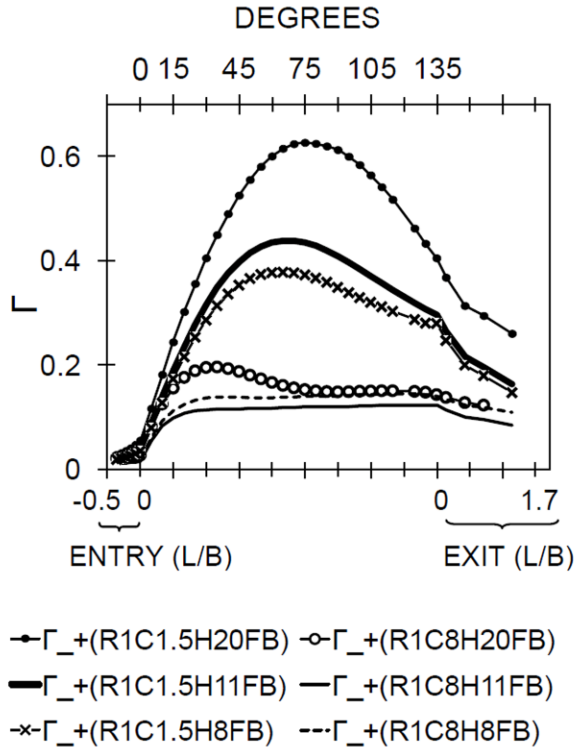


Figure 5.11 Streamwise variation of the non-dimensional total positive cross-stream circulation associated with the clockwise-rotating cells (Γ_+) for R1C1.5 and R1C8 flat bed cases with varying B/H . Γ is non-dimensionalized by the mean velocity (U) and channel width (B) given in Table 5.1.

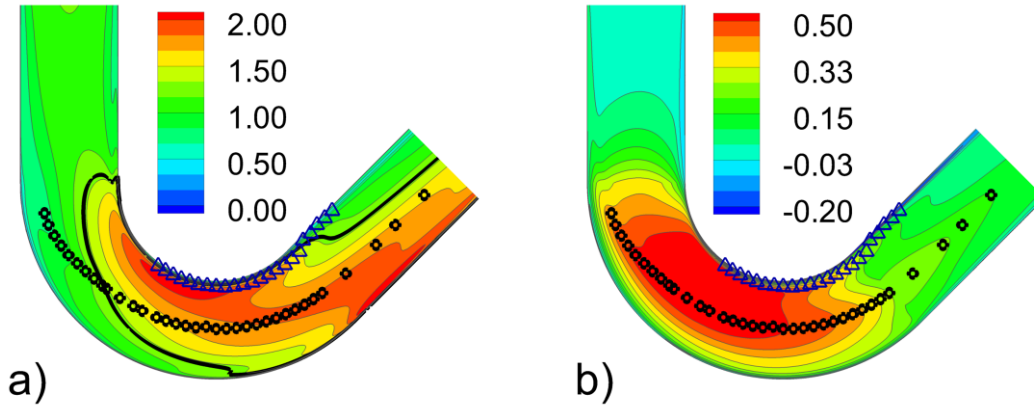


Figure 5.12 Bed shear stress distributions for case R1C1.5H20FB. a) Bed shear stress magnitude, τ_M/τ_0 , and b) cross-stream bed shear stress divided by bed shear stress magnitude, τ_R/τ_M . The locations of the core centers of the clockwise-rotating cells M1 and V1 (see Figure 5.18d) are shown using black squares and blue triangles, respectively. τ_0 is the average bed shear stress at the inlet section. The black line in frame a) corresponds to Shields' critical stress, τ_c/τ_0 ($=1.29$ for $D_{50}=1.1$ mm).

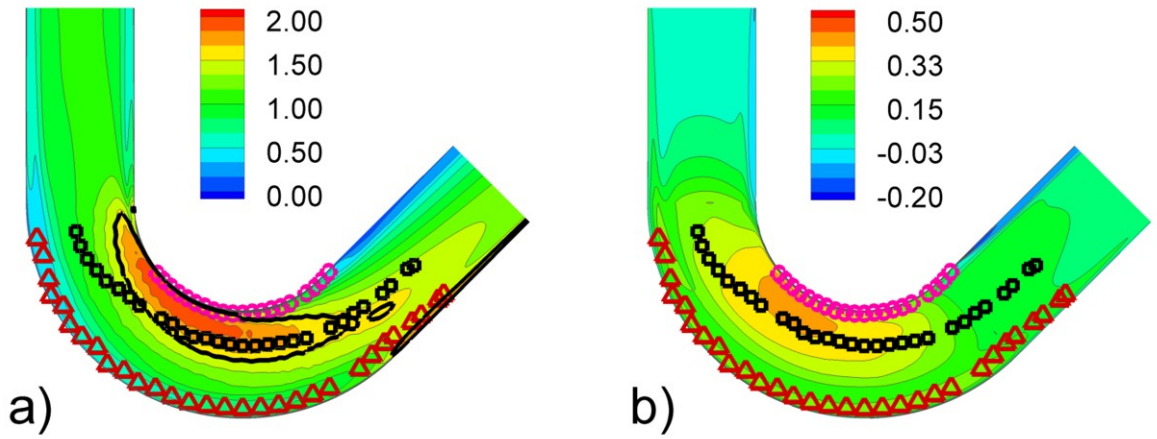


Figure 5.13 Bed shear stress distributions for case R1C1.5H8FB. a) Bed shear stress magnitude, τ_M/τ_0 , and b) cross-stream bed shear stress divided by bed shear stress magnitude, τ_R/τ_M . The locations of the core centers of the clockwise-rotating cells V1, M11, and M12 (see Figure 5.18a) are shown using pink circles, black squares, and red triangles, respectively. τ_0 is the average bed shear stress at the inlet section. The black line in frame a) corresponds to Shields' critical stress, τ_c/τ_0 ($=1.53$ for $D_{50}=1.1$ mm).

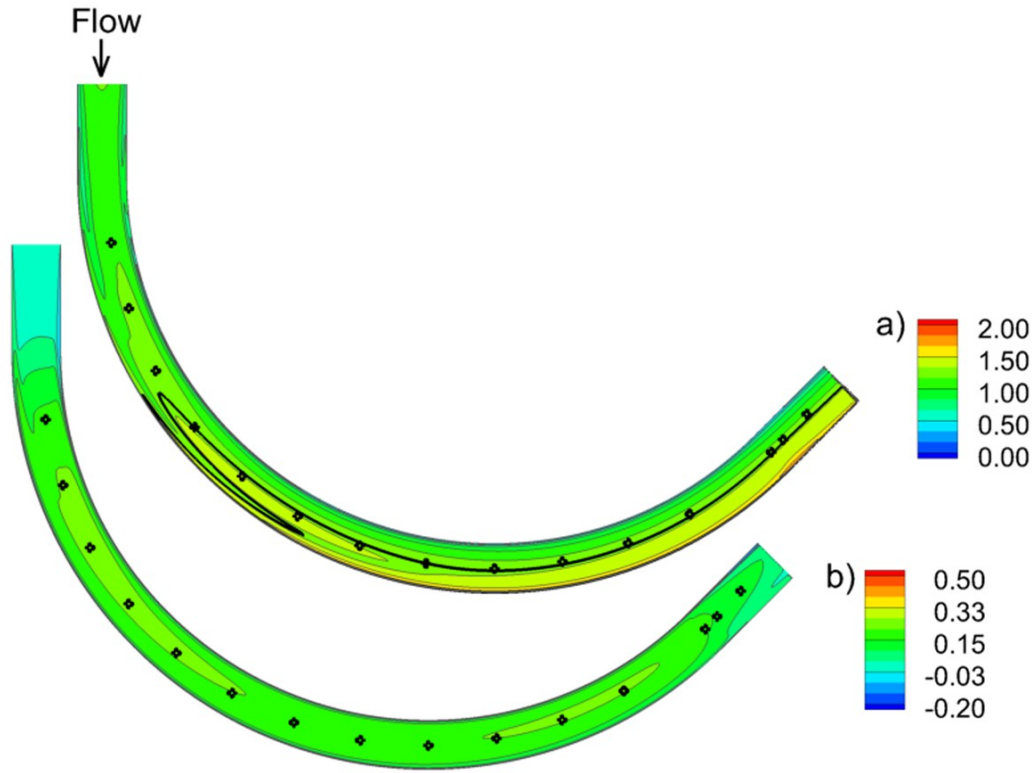


Figure 5.14 Bed shear stress distributions for case R1C8H20FB. a) Bed shear stress magnitude, τ_M/τ_0 , and b) cross-stream bed shear stress divided by bed shear stress magnitude, τ_R/τ_M . τ_0 is the average bed shear stress at the inlet section. The location of the core center of the clockwise-rotating cells M1 (see Figure 5.18b) is shown using black squares. The black line in frame a) corresponds to Shields' critical stress, τ_c/τ_0 ($=1.29$ for $D_{50}=1.1$ mm).

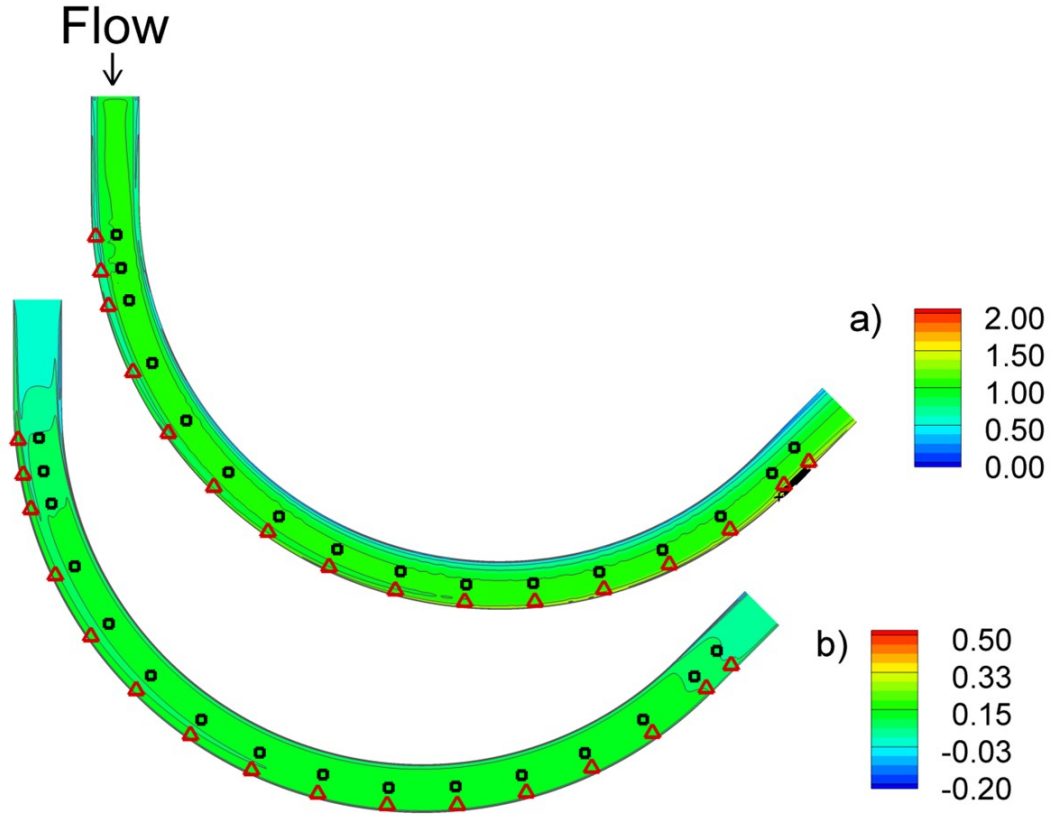


Figure 5.15 Bed shear stress distributions for case R1C8H8FB. a) Bed shear stress magnitude, τ_M/τ_0 , and b) cross-stream bed shear stress divided by bed shear stress magnitude, τ_R/τ_M . τ_0 is the average bed shear stress at the inlet section. The locations of the core centers of the clockwise-rotating cells M11 and M12 (see Figure 5.18a) are shown using black squares and red triangles, respectively. The black line in frame a) corresponds to Shields' critical stress, τ_c/τ_0 ($=1.53$ for $D_{50}=1.1$ mm).

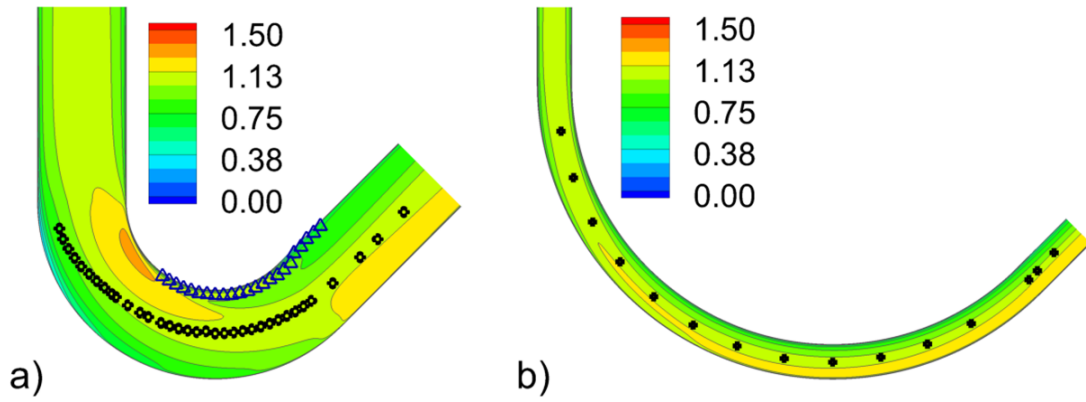


Figure 5.16 Distributions of non-dimensional streamwise unit discharge, $q/(Q/B)$, for cases a) R1C1.5H20FB and b) R1C8H20FB. The locations of the core centers for the clockwise-rotating cells M1 and V1 (see Figure 5.18d) are shown using black squares and blue triangles, respectively. Note that the scales for the two frames are different, as both channels have the same width.

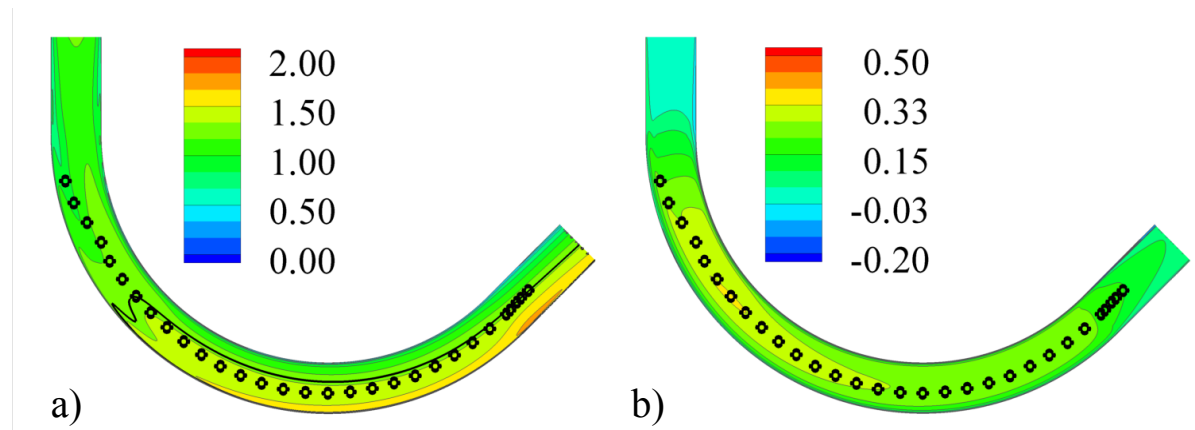


Figure 5.17 Bed shear stress distributions for case R1C5H20FB. a) Bed shear stress magnitude, τ_M/τ_0 , and b) cross-stream bed shear stress divided by bed shear stress magnitude, τ_R/τ_M . The location of the core center for the clockwise-rotating cell M1 (see Figure 18c) is shown using black squares. τ_0 is the average bed shear stress at the inlet section. The black line in frame a) corresponds to Shields' critical stress, τ_c/τ_0 ($=1.29$ for $D_{50}=1.1$ mm).

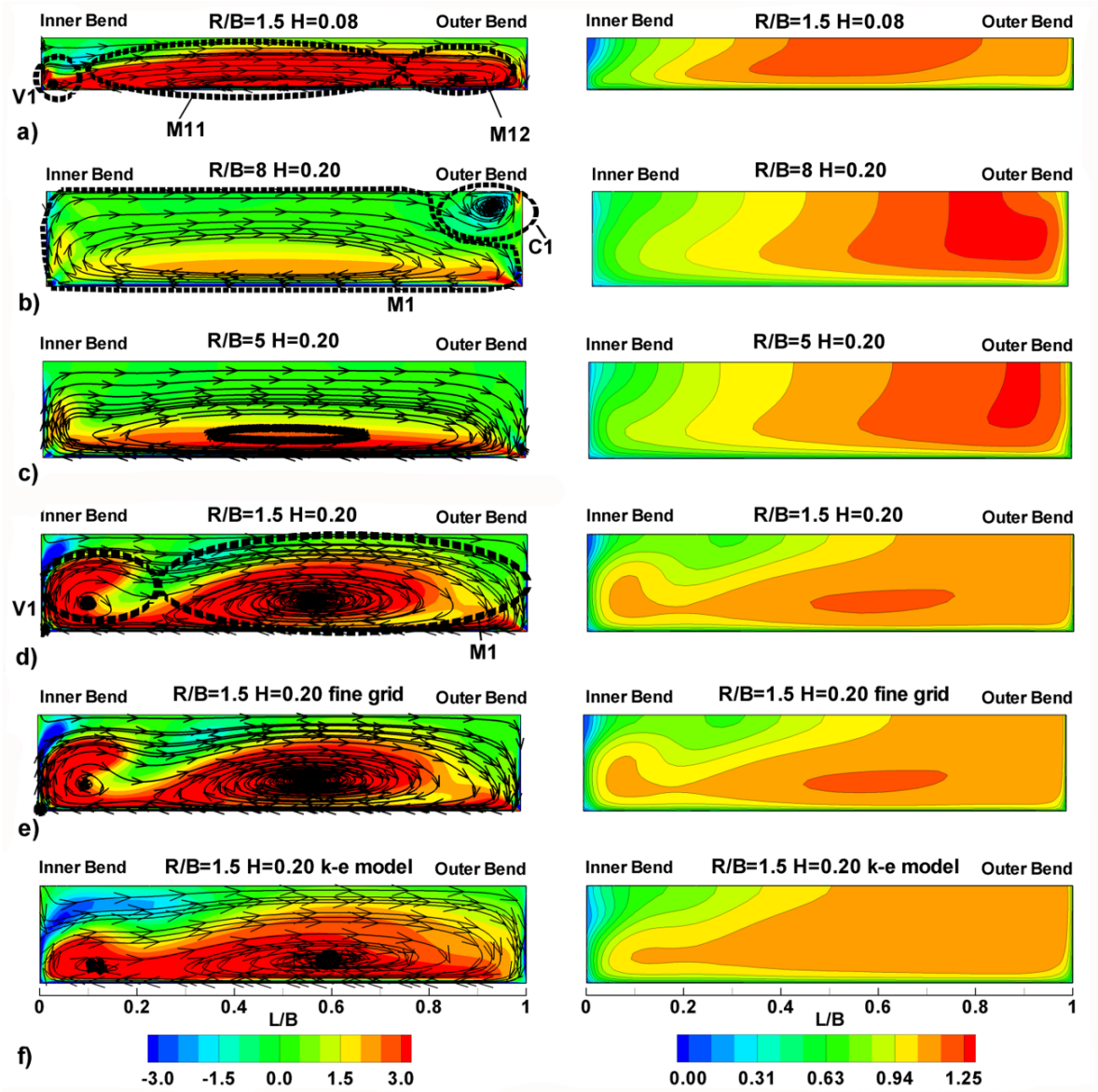


Figure 5.18 Comparison of 2-D streamline patterns and streamwise vorticity, $\omega_s(B/U)$, (left) and streamwise velocity, u/U , (right) in the 135° cross-section for cases a) R1C1.5H8FB, b) R1C8H20FB, c) R1C5H20FB, d) R1C1.5H20FB, e) R1C1.5H20FB calculated on a fine mesh, and f) R1C1.5H20FB calculated using the $k-\varepsilon$ model. Notice the presence of a counter-clockwise rotating outer bank cell, C1, and a clockwise-rotating cell M1 in a), two clockwise-rotating cells M1 and V1 in c), and three clockwise rotating cells V1, M11 and M12 in f).

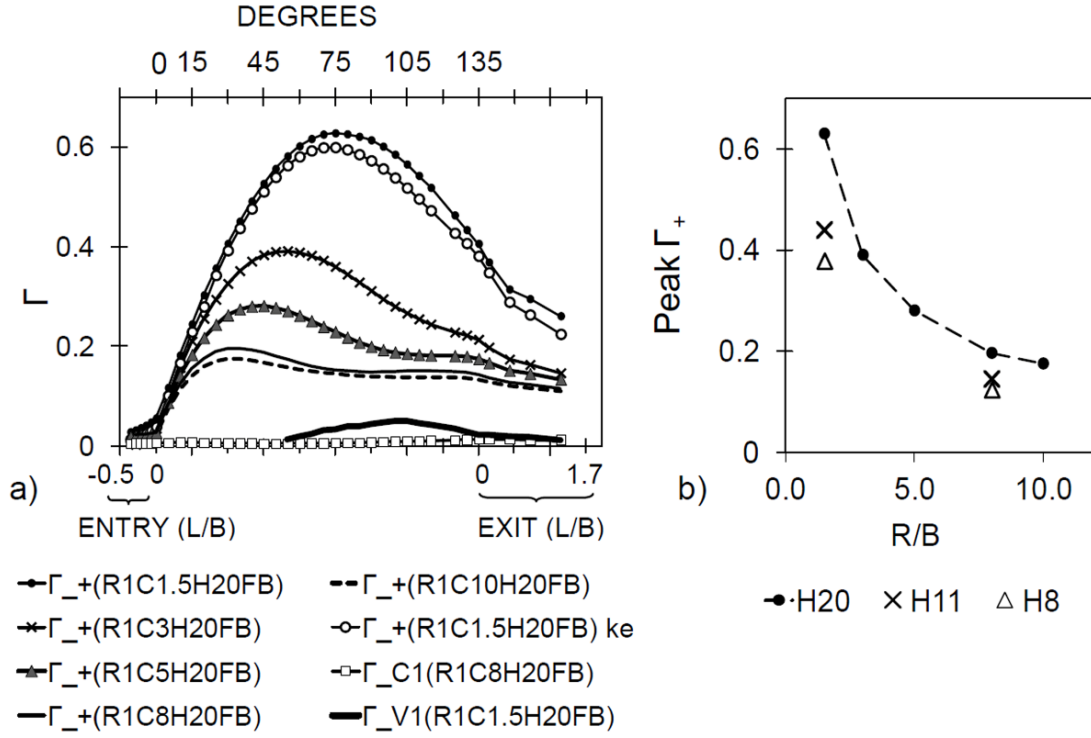


Figure 5.19 Streamwise variation of the non-dimensional (positive) circulation associated with the clockwise-rotating cells (Γ_+) for the R1 FB cases with varying R/B . Results obtained using the $k-\varepsilon$ model to simulate case R1C1.5H20FB are also included in frame a. Also shown are the non-dimensional magnitudes of the circulation for the counter-clockwise rotating cell, C1, present in case R1C8H20FB and of the clockwise-rotating cell, V1, present in case R1C1.5H20FB (see Figure 5.18). Frame b shows the variation of the peak value of Γ_+ with the curvature ratio, R/B , for various values of B/H for the FB cases. Γ is non-dimensionalized by the mean velocity (U) and channel width (B) given in Table 5.1.

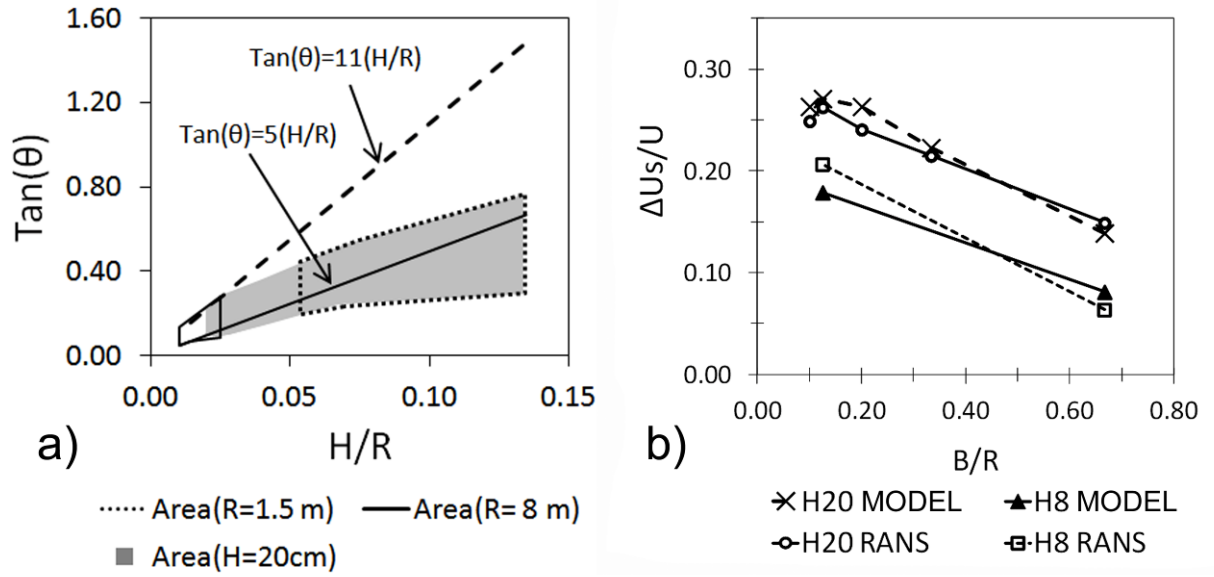


Figure 5.20 a) The areas in the legend indicate ranges of $\tan(\theta)$ for a given value of R or H for all FB cases as a function of H/R . The functions $\tan(\theta)=11(H/R)$ and $\tan(\theta)=5(H/R)$ are shown using solid and dashed lines, respectively. b) Velocity excess ($\Delta U_s/U$) in the 130° cross section for various values of B/R and H/B for the R1 FB cases. RANS refers to values extracted directly from the RANS simulation results, and MODEL refers to values calculated using the analytical model of Blanckaert (2011).

CHAPTER 6: HYDRODYNAMIC PROCESSES AND SEDIMENT EROSION MECHANISMS IN AN OPEN CHANNEL BEND OF STRONG CURVATURE WITH DEFORMED BATHYMETRY

6.1. ABSTRACT

High curvature (radius of curvature (R)/channel width (B) ≤ 3) river channels often experience substantial levels of erosion due to complex flow patterns that are not fully understood. This study aims to gain insight into the details of these flow patterns and the mechanisms leading to the development of channel morphology in a high curvature ($R/B=1.5$) 135° rectangular channel bend during the final stages of scour, when the bed profile is close to the equilibrium one. It employs a highly resolved Large Eddy Simulation (LES) numerical model to analyze the flow, which is better able to resolve the details of turbulence and coherent structures compared to typical time-averaged models. The impacts of flume geometry were assessed by comparing these results to those of a similar high curvature ($R/B=1.35$) 193° bend flume study, which used a Detached Eddy Simulation (DES) model. Both channels had deep outer bank scour holes located near the exit of the curved reach, but the very strong effects of topographic steering for the 193° bend contributed towards the formation of a second deeper outer bank scour hole upstream of the bend apex. Topographic steering effects also induced important quantitative and qualitative differences in the vortical and turbulence structure within the open channel for the two cases. The position and extent of the shear layers forming between regions containing high streamwise velocity and slower moving fluid or separated flow differed between the two cases. While streamwise oriented vortical (SOV) cells formed at the inner bank for both cases, the flow did not separate at the inner bank for the 135° bend. The results for both

cases showed that for bends of high curvature, bank erosion can also be of concern along the inner bank. Also, besides the large main channel cell of cross-stream circulation, the secondary flow close to the outer bank of the 135° bend was characterized by the presence of a secondary counter-rotating SOV cell near the free surface which extended far into the straight outflow reach. No secondary outer bank cell was observed for the 193° bend. While for both cases outer bank shear stress was strongly amplified near the exit of the curved reach, the largest values were recorded near the free surface for the 193° bend, in which the outer bank was not protected by a secondary SOV cell, and at mid-depth levels for the 135° bend. Such information is important for understanding bank erosion mechanisms, bank protection design, and calibration of simplified models for outer bank migration.

6.2. INTRODUCTION

In nature, the majority of rivers tend to have some type of meandering form. Straight rivers are relatively rare, and tend to occur only on slopes $\sim > 10\%$ (Church 1992; Rosgen 1994). In river bends, secondary cross-stream circulation of the flow is induced by centrifugal forces, which cause surface flows with higher velocities to move faster towards the outer bank compared to deeper flows. As velocities decrease near the outer bank wall, a superelevation of the water surface develops at the outer bank, causing the water surface to be sloped in the radial direction. As a result, a radial pressure gradient is present, which is constant over the depth at a specific point along the radius. At the bed, the forces from the radial pressure gradient and the radial bed shear stress cause flow to be deflected towards the inner bank (Julien 2002). This forms the basis for what is known as secondary circulation in river bends.

This secondary circulation plays an important role in the distribution of velocities and bed shear stresses within a bend. It influences the transport of streamwise momentum, which causes advection of the core of high streamwise velocity towards the outer bank (Zeng *et al.* 2008a; Blanckaert and de Vriend 2004). Locally, it can also increase levels of velocity near the bed and banks. This is important as an increase in the vertical gradient of velocity close to the bed will increase the levels of bed shear stress which can lead to scour (Blanckaert *et al.* 2008; Zeng *et al.* 2008a; Kashyap *et al.* 2012).

Flow within high curvature (sharp) bends (radius of curvature (R)/channel width (B) ≤ 3) is quite complex. Unlike bends of milder curvature, high curvature bends show a nonlinear interaction between the cross-stream circulation and the main channel flow. Blanckaert and de Vriend (2003) and Blanckaert and Graf (2004) discuss that the evolution of cross-stream circulation depends on interactions between the vertical profiles of streamwise and cross-stream velocities. Zeng *et al.* (2008a) investigated the variation of cross-stream circulation along the flume length of a sharp 193° bend using a 3-D Reynolds Averaged Navier Stokes (RANS) numerical model and experimental measurements. The investigation showed that although the RANS model slightly underpredicted peak circulation magnitude by about 10%, it supported the theory that in sharp bends, a complex interaction occurs between cross-stream circulation and downstream velocity.

In addition to advection by cross-stream circulation, other mechanisms leading to redistribution of velocity within a sharp bend have been discussed previously by Zeng *et al.* (2008a) and Blanckaert (2010). At the bend entrance a streamwise pressure gradient

develops over the channel width which causes flow to accelerate/decelerate in the inner/outer parts of the bend. This causes the core of high streamwise velocity to move towards the inner bank at the bend entrance. Also, as scour and deposition occur, flow becomes ‘topographically steered’ towards the channel thalweg (Dietrich and Smith 1983). For example, as sediment deposits along the inner bank of a bend, the flow moves away from the inner bank, towards deeper areas of the channel. As this occurs, high streamwise velocities also redistribute according to Chezy’s law (García 2008) that higher velocities are attracted to greater flow depths. Topographic steering may complicate the process of the transport of streamwise momentum through advection. Finally, at the bend exit, the streamwise pressure gradient over the channel width weakens, causing flow to accelerate/decelerate suddenly towards the outer/inner banks.

Flow structures have also been investigated for their effects on the distribution of velocity within a channel bend. The presence of a counter-clockwise rotating outer bank cell which forms close to the free surface has been identified in both sharp and milder curvature bends (Rozovskii 1957; Bathurst *et al.* 1979; Thorne and Hey 1979; Blanckaert and de Vriend 2004; Blanckaert 2010; van Balen *et al.* 2010). Blanckaert and Graf (2004) suggest that this cell may serve to protect the outer bank from erosion, by keeping the core of high streamwise velocity away from the outer bank. Bathurst *et al.* (1979) however, are of the opinion that this cell may endanger the stability of the outer bank by advecting high momentum fluid towards the base of the outer bank.

Until recently, detailed investigations of the unique flow structures existing within a sharp channel bend have been limited. This may be because previous investigations have mostly involved experimental studies, 2-D numerical models, and lower resolution 3-D numerical models such as Reynolds Averaged Navier Stokes (RANS) models (Blanckaert and de Vriend 2004; Rüther and Olsen 2005; Khosronejad *et al.* 2007; Minor *et al.* 2007; Odgaard 1989a,b; Yeh and Kennedy 1993a,b). While experimental studies provide accurate information, measurements are usually not sufficiently resolved to show 3-D flow structures. RANS models may predict some of the main flow structures present, but they have difficulties in resolving finer details (van Balen *et al.* 2010; Constantinescu *et al.* 2011b; Kashyap *et al.* 2009; Kashyap *et al.* 2012 [see Chapter 5]). A higher order eddy-resolving numerical model such as Large Eddy Simulation (LES) or a hybrid RANS-LES approach such as Detached Eddy Simulation (DES) is required for accurate 3-D resolution of flow structures.

Recent studies involving LES and DES have provided insight into some of the finer details of fluid structures unique to flow in high curvature bends. Shear layers (SLs) have been observed close to the inner bank wall slightly downstream of the bend entrance during both the initial stage of scour (i.e., flat bed) (Kashyap *et al.* 2011; van Balen *et al.* 2010), and the final stage of scour (i.e., deformed bed) (Constantinescu *et al.* 2011b; Kang *et al.* 2011). These SLs form due to a high gradient of streamwise velocity that develops in the cross-stream direction near the inner bank, as fluid inertia prevents the flow from following the very high curvature at the inner bank wall. Consequently, shear layers develop between the relatively low-velocity fluid near the inner bank and the higher velocity fluid in the bulk

flow towards the centre of the channel. Constantinescu *et al.* (2011b) and Kashyap *et al.* (2010, 2011) have shown that strong streamwise orientated vortices (SOVs) are found near these SLs which can cause scour at the inner bank wall due to an amplification of wall shear stresses and pressure fluctuations. Constantinescu *et al.* (2011b) also used a DES model to investigate the influence of SOVs on boundary shear stresses and turbulence within the main channel of a high curvature bend.

The present study investigates flow in a 135° bend during the final stages of scour, and compares results to those obtained in the DES study of Constantinescu *et al.* (2011b) conducted in a 193° high curvature bend during the final stages of scour. Previously, Kashyap *et al.* (2011) investigated flow patterns in the same 135° bend during the initial stages of scour using LES. Van Balen *et al.* (2010) also investigated flow patterns during initial scour conditions in the 193° bend using experiments, LES, and RANS. The results from these studies revealed that during initial scour conditions, both bends showed similar velocity distributions where the core of high streamwise velocity was close to the inner bank near the bend entrance, and gradually moved to the outer bank as it approached the bend exit. As will be shown in this study, velocity distributions and flow patterns for the two bends change considerably during the final stages of scour due to the presence of a deformed bed. The objective of this study is to use LES to gain new insight into the flow structures and patterns present during the final stages of scour and their influences on distributions of velocity, bed shear stress, turbulence, and mean pressure fluctuations. Unlike DES, LES directly calculates eddies at the scale of the grid size close to the boundary layer, and therefore may reveal greater details of coherent structures. All SOVs generated in the

deformed bed sharp bend flow are considered, including the main secondary circulation cell, flow structures generated between the inner wall and the inner wall SL, and the outer bank cell. The streamwise variation of cross-stream circulation of these flow structures is also quantified for the first time. The overall goal of this study is to gain a better understanding of mechanisms leading to the development of equilibrium scour patterns and how they may be influenced by channel geometry.

6.3. METHODS

6.3.1. LES Numerical Solver

The LES solver used to simulate flow for the 135° bend was developed by Mahesh *et al.* (2004). It employs a finite volume method to solve the 3-D spatially filtered Navier Stokes equation for the flow field given by Equation 6.1 in tensor notation, on a hybrid unstructured grid.

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = \frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j}, \frac{\partial \overline{u_i}}{\partial x_i} = 0 \quad (6.1)$$

Here the overbar denotes spatial filtering, $\partial \tau_{ij} = \overline{u_i u_j} - \overline{u_i} \overline{u_j} = 2\nu_t \overline{S_{ij}}$ are the subgrid stresses, ν_t is the turbulent eddy viscosity, $\overline{S_{ij}}$ is the deformation tensor and ν is the kinematic viscosity. This LES is used to solve both the mean and the time-resolved instantaneous flow field on a fixed grid, and does not simulate sediment transport. The methods have been developed to be non-dissipative such that they conserve both first order quantities such as momentum, and second order quantities, such as kinetic energy. The code has been shown to

be robust in complex geometries with unstructured grids and high Reynolds numbers (Mahesh *et al.* 2004; McCoy *et al.* 2007).

The code is a parallel message passing interface (MPI) solver that uses a collocated finite-volume scheme. In the predictor-corrector formulation the Cartesian velocity components are defined at the center of the cell and the face-normal velocities are treated as independent variables. The fractional step algorithm is second order accurate in both space and time. All the operators in the code, including the convective terms, are discretized using central schemes. The numerical scheme used to solve the Navier-Stokes equations discretely conserves energy. This increases the robustness of the numerical algorithm with the use of numerical dissipation which is essential for accurate LES. Time discretization is achieved using a Crank Nicholson scheme for the convective and viscous operators in the momentum (predictor step) equations. The resulting system of equations due to the implicit time discretization, is solved using a successive over-relaxation (SOR) method. The pressure equations are solved using a conjugate gradient method with preconditioning. No wall functions are used, and the governing equations are integrated through the viscous sub-layer. A constant Smagorinsky SGS model is used to solve for the subgrid stresses in Equation 6.1 in order to avoid instabilities due to the complex domain geometry and the high Reynolds number involved. The constant Smagorinsky model solves for the turbulent eddy viscosity (ν_t) using Equations 6.2 to 6.4.

$$\nu_t = C_s \Delta \left| \bar{\mathbf{S}} \right| \quad (6.2)$$

$$|\bar{S}| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}} \quad (6.3)$$

$$\bar{S}_{ij} = \frac{1}{2} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (6.4)$$

Here, C_s is the Smagorinsky constant which for this study is 0.08, and Δ is the characteristic subgrid-scale length (grid size).

6.3.2. DES Numerical Solver

The full details of the DES solver employed for the 193° bend simulation are given in Constantinescu *et al.* (2011b) and Constantinescu and Squires (2004). It uses a RANS model near the solid boundaries, and an LES model away from the boundaries. A Spalart-Allmaras RANS model is employed which does not use wall functions. The LES solver is the same as the one described in the previous section. However, it uses a model parameter that is qualitatively more similar to the dynamic version of the Smagorinsky model.

6.3.3. Setup of Simulations

The numerical domain, flow conditions, and geometry for the 135° bend case were modelled after a physical experiment conducted at the University of Ottawa. The experiment was run in a high curvature flume with vertical sidewalls containing sediment with a median diameter (d_{50}) = 0.689 mm. The flow was run until the equilibrium scour stage was reached under clear water scour conditions. The bathymetry collected during the equilibrium scour stage was used in the LES fixed bed simulation. The main experimental flow parameters used in the simulation are given in Table 6.1. The bed shear velocity (u^*) in the straight inlet channel was below the Shields critical value and the simulation was run under hydraulically

smooth conditions. A plan view of the computational domain is given in Figure 6.1a. In order to save computational cost, the inlet for the numerical model was set 10 m downstream of the actual experimental inlet. The initial mean water depth (H) in the experiment was 0.15 m, and was used as the length scale for non-dimensionalizing the flow and geometric variables in the simulation. The mean inlet velocity (U) was used as the velocity scale. The modelled flume contained a straight inlet section of length $L_1=14.55H$, a curvature ratio $(R/B) = 1.5$, and a straight exit section of length $L_2=27H$. The flume width (B) = $6.67H$.

The inflow velocity profiles were obtained from a preliminary RANS simulation with a Reynolds Stress Model (RSM) turbulence closure, which was conducted at a Reynolds number of 60,000. Zero mean turbulent velocity fluctuations obtained from a preliminary LES simulation in a periodic channel were superimposed on the mean velocity profiles. The constant flow discharge (Q) was $6.67U/H^2$. The free surface was modelled using a symmetric boundary condition, assuming a rigid lid approximation, which is considered acceptable (see discussion in Zeng *et al.*, 2008a) due to the low (<0.3) Froude number (Table 6.1). Khosronejad *et al.* (2007) also showed a rigid lid approximation is adequate when the change in water surface elevation is small compared to the water depth. For this study the superelevation was estimated to be less than 5% of the flow depth. A convective outflow boundary condition was set at the end of the straight exit section to help reduce numerical noise and distortions. All solid boundaries of the channel were treated as non-slip smooth surfaces.

The grid was a hybrid unstructured mesh containing only hexahedral cells. It consisted of a total of about 3.4 million cells (554 x 160 x 38 points in the streamwise, transverse, and vertical directions). The grid size ranged from a non dimensional size of $(\Delta n/H) \sim 0.001$, or $y^+ < 3$ closest to the bed and lateral walls, to $(\Delta n/H) \sim 0.1$ at the surface, or about $y^+ \sim 300$, where $y^+ = 1 = (\text{Re})(u^*/U)(\Delta n/H) = u^* \Delta n/\nu$. The simulation was run in parallel on 22 processors. The time step in the simulation was $0.01H/U$ which allowed resolving the time scales associated with the energetic structures in the flow at a channel Reynolds number of 60,000. Statistics were collected after the flow reached a statistically steady state, a process that took about $200H/U$. 100 instantaneous solutions spaced at a non-dimensional time interval of $H/U = 0.5$ were used to calculate the mean flow statistics.

The flume geometry used for the 193° DES simulation conducted by Constantinescu *et al.* (2011b) is shown in Figure 6.2a. This simulation was modeled after the mobile bed experiment *M89*, described in Blanckaert (2002) and further details of the simulation setup are given in Constantinescu *et al.* (2011b). The bend had $R=1.7\text{m}$ and $B=1.3\text{m}$. For the simulation, the inlet was situated 9m upstream of the bend entrance (section D00), and the outlet was 5m downstream of the bend exit (section D193). The inflow boundary condition corresponded to fully developed turbulent inflow. The outflow was set to a free convective outflow condition. The fixed bed and flume walls were set to no-slip conditions, and an equivalent total bed roughness of 0.037m was used for the fixed bed. The free surface was set to a rigid lid condition, with the free surface elevations set to values measured in the experiment. Although the experiment was run under live bed scour conditions, the DES simulation had a fixed bed, and used bathymetry obtained during the equilibrium stage of a live-bed scour experiment. The equilibrium scour bathymetry in the 193° channel is

considered similar for both clearwater and live-bed scour conditions, as two similar loci of scour occur along the outer bank under both conditions (compare Figure 6.2 herein with Figure 3a of Dugue *et al.* 2011). The DES mesh had 12 million cells (1820 x 192 x 35 points in the streamwise, spanwise, and vertical directions). The mesh spacing at the boundaries was $y^+=1$, and wall functions were not used. The full details of the numerical setup are given in Constantinescu *et al.* (2011b), and the main experimental flow parameters used for the simulation are given in Table 6.1. The results for the simulation are presented here in non-dimensional form, using a length scale of $H=0.115\text{m}$, and a velocity scale of $U=0.61\text{m/s}$.

6.4. VALIDATION OF THE NUMERICAL MODEL

General validation of the LES code is discussed in this section, as well as specific validation for the 135° bend case. The LES code has been previously validated for internal and external flows of various complexities using Laser Doppler Velocimetry (LDV) or PIV (Particle Image Velocimetry) experimental data, or by using highly-resolved numerical simulations with spectral codes. In particular, the code has been validated for isotropic turbulence, turbulent channel flow, flow past cylinders and jet flows (Mahesh *et al.* 2004; Muppidi and Mahesh 2005). It has also been validated for flows in hydraulic and river engineering applications where large-scale coherent structures play a dominant role in determining momentum and mass exchange processes. Such investigations were reported by McCoy *et al.* (2008) for flow in open channels containing a series of groynes, and by Tokyay and Constantinescu (2006) for flow in water pump intakes. For all of these investigations, the channel Reynolds number was between 10^4 and 10^5 , which is the range in which most laboratory experiments of flow in curved open channel are conducted. The LES studies of Koken and Constantinescu (2008a, 2008b) and Kirkil *et al.* (2008) are also particularly

relevant to the current study as they involve flow in open channels with obstructions and complex bathymetry. Also, as mentioned previously, the 193° deformed bed bend case being considered in this study was previously validated by Constantinescu *et al.* (2011b).

6.4.1. Validation for the 135° bend case

6.4.1.1. Experimental setup

The LES results for the 135° bend case with a deformed bed were validated with data from a flume experiment conducted at the University of Ottawa. The 135° bend flume had a 12.2m straight entrance section, a 3.6m curved section, and a 2.4m straight exit section. The channel side walls were vertical, and $R=1.5\text{m}$, and $B=1\text{m}$ (see Jamieson *et al.*, 2010, and Post, 2007, for further flume details). The bottom of the flume was filled to a depth of approximately 30cm with a sediment having a mean particle size $d_{50}=0.689\text{mm}$. The experiment was run under steady clear water scour conditions with $Q=0.0464\text{m}^3/\text{s}$ for 167 hrs until equilibrium scour was reached. The bed slope was zero, and the initial water depth (H) was a constant of 0.15m. Velocity measurements were taken using Nortek® Vectrino Acoustic Doppler Velocimeters (ADV). These ADVs had a measurement accuracy of $\pm 0.5\%$ of the measured velocity $\pm 1\text{mm/s}$ (Nortek 2011). Each ADV measured four velocity components, streamwise (u_x), cross-stream (u_C), vertical (u_Z), and a second vertical velocity measurement to compute error. All velocity components were measured relative to the flume walls, at a sampling frequency of 200Hz, for a period of two minutes. Probe alignment errors were precisely checked and corrected for using methods described in Post (2007). Errors in alignment ranged from 2.194° to 2.654°, and were corrected for in each specific ADV using post processing computer code. Post processing of the data also removed mean velocities with low correlations ($<70\%$), and low signal to noise ratios (<10). Apparent outliers

(“spikes”) in single ping velocities, with values that exceeded four standard deviations from the mean, had errors in vertical velocities greater than 0.1 m/s, or had accelerations $>1.5 \times (\text{gravitational acceleration})$, were corrected for by using a value interpolated between the previous and subsequent instantaneous velocity values. The accuracy of all raw data appeared good, with all correlations being greater than 69.5%, and all signal to noise ratios greater than 11.

Velocity profiles were measured at the center of six equal 16.67 cm intervals across the 1m flume width. The ADV transducers were submerged at least 5mm below the water surface, and the sample volume was 4.5 to 5.5cm below the transducer. Thus, the first sample volume for each vertical profile was located 5 to 6cm below the water surface. The number of vertical measurements varied with the flow depth and were taken at 1cm intervals which increased to a maximum of 2cm close to the water surface. Water discharges were measured using a V-notch weir installed in the flume exit tank and were validated by calculating Q from the ADV measurements in the straight inlet section. Bathymetry measurements were taken with a Leica DistoTM pro4a laser altimeter which had an accuracy of ± 0.0015 m.

6.4.1.2. RANS Simulation

A second simulation was also completed using a steady finite-volume RANS model with an RSM turbulence closure for the same 135° deformed bed case (Figure 6.1a). Fluent (Fluent Inc. 2006) was the software of choice. The flow parameters were the same as those given in Table 6.1 for the 135° bend LES simulation. The surface was set to a rigid lid symmetric boundary condition, and the outlet was set to a free convective outflow. The bed was fixed, and used bathymetry obtained during equilibrium scour conditions of the experiment to

create the deformed bed surface. A roughness value (k_s) of 0.698mm was used at the bed, and wall functions were used to treat velocity profiles near the bed. The mesh consisted of an unstructured grid with hexahedral elements and 704 480 nodes (37 in the vertical x 160 in the transverse x 119 in the longitudinal directions), with a mesh spacing of $y^+ < 3.5$ at the walls and bed. Further details on the RANS setup can be found in Kashyap (2012, Chapter 5).

6.4.1.3. Validation Results

Flow patterns and velocity distributions predicted by both the LES and RANS for the 135° deformed bed case were very similar to those found in the experiment. 2-D sectional plots of streamwise velocity (u_x/U), cross-stream velocity (u_y/U), vertical velocity (u_z/U) and streamlines are shown in Figures 6.3 to 6.5 for sections D10, D115, and D125. The LES appeared to predict flow structures better than RANS. In particular, the LES was able to predict the presence of the counter-rotating outer bank cell in sections D115 and D125 which has been previously seen in field, numerical, and experimental bend studies of various geometries (Bathurst *et al.* 1979; van Balen *et al.* 2010; Blanckaert and de Vriend 2004; Kashyap *et al.* 2012). The RANS model did not predict this cell, even though the 2-D experimental streamline plots (Figures 6.4 and 6.5) showed strong evidence of its presence. Comparisons of streamwise velocity profiles are also shown in frame e) of Figures 6.3 to 6.5. Both RANS and LES show a flattening of the streamwise velocity profiles in sections D115 and D125, compared to section D10. Blanckaert and Graf (2004) describe that this type of flattening is characteristic of flow in sharp bends, and is due to nonlinear interactions between the cross-stream circulation and the main channel flow. Generally, the agreement

between simulated and measured velocity profiles appears to be reasonable and the predictions from the LES improve for the downstream sections.

Although the sectional plots seem to show that flow patterns predicted by the LES agree better with the experimental results compared to RANS, the LES had a greater tendency to over predict or under predict velocity magnitudes compared to RANS. This can be seen in the scatter plots showing simulated versus measured velocity magnitudes in Figures 6.6a and 6.6b for the LES and RANS results, respectively. The greatest errors for LES occurred in the deepest scour hole near section D135 where LES over predicted velocity magnitudes, and also along the inner bank between sections D45 to D85, where the LES tended to under predict velocity magnitudes. Error statistics for the scatter plots in Figure 6.6 are given in Table 6.2. The mean absolute velocity error (ϵ_a) is defined as the average absolute difference between the measured and simulated velocities, and is about 37% greater for the LES compared to the RANS results (Table 6.2). For both models however, this error seemed reasonable, as it was less than 13% of the mean incoming velocity U . The root mean square error (ϵ_{rms}) is equal to $(1/n(\sum(\text{velocity difference})^2))^{-1/2}$, where n is the sample size. The ϵ_{rms} was greater for both models compared to ϵ_a since ϵ_{rms} gives greater weighting to errors of greater magnitude. The ϵ_{rms} was 36% greater for LES compared to RANS. The discrepancy ratio (d) is the simulated velocity magnitude over the measured velocity magnitude. Although the RANS results generally showed a greater percentage of the data had a value of d closer to 1, more than 85% of the velocity magnitudes for both LES and RANS were within $0.75 < d < 1.33$. Errors for the LES were greater than RANS, likely because the locations and sizes of the observed flow structures differed slightly between the LES and

experiment. We emphasize, however, that the LES successfully reproduced the main features of circulation cells suggested by the experimental data to be present in the flow. Furthermore, the LES provided sufficient information to fully characterize these cells, which was not possible with the experimental data alone.

6.5. RESULTS AND DISCUSSION

6.5.1. Equilibrium bathymetry

Before investigating the flow characteristics, it is important to first compare the main features of the equilibrium bathymetry for both the 135° and 193° bend cases. This is because once the pool and point bar develop inside the curved open channel, topographic steering effects play an important role in redistributing streamwise velocities and can affect the formation, position and coherence of SOV cells and regions of high turbulence (e.g., shear layers). Topographic steering effects can also promote flow separation along the inner bank.

For the 135° bend case (Figure. 6.1b), scour starts close to the inner bank near section D00. In the downstream direction the maximum scour increases monotonically and moves closer to the outer bank. The flow depth reaches a peak value of about $1.8H$ in section D100 at about $1/3B$ from the outer bank. Severe scour then occurs again in the immediate vicinity of the outer bank between sections D120 and D135+ $10H$, with a maximum flow depth of $2.3H$ occurring at about $2H$ (0.30 m) downstream of section D135. The point bar starts near section D30 and remains attached to the inner bank until the end of the curved reach. The minimum flow depth is around $0.3H$ in the immediate vicinity of the inner bank, and the position of maximum deposition moves away from the inner bank downstream of section

D135. Meanwhile, the minimum flow depth increases in the exit section such that it is larger than $0.8H$ past section D135+21.2*H*.

For the 193° case (Figure. 6.2b), scour develops in the outer half of the channel downstream of section D00. The flow depth along the outer bank reaches a maximum of about $3.2H$ between sections D60 and D90, before reducing to a value of about $2.2H$ in sections D120 and D150. Scour then increases again upon approaching the bend exit, and the flow reaches a depth of about $2.6H$ in section D180. Downstream of section P2.0, which is situated 2.0m ($18H$) from the end of the curved reach, scour decays in the outer part of the channel. In this region the bed is close to being flat and the flow depth is about $1.0H$. Meanwhile, some moderate scour is observed at the inner half of the channel downstream of section P1.5. Two main regions of sediment deposition form along the inner bank between sections D30 and D100 and sections D180 and P1.0. The minimum flow depth between sections D60 to P0.5 is between $0.1H$ - $0.2H$.

In summary, the main differences between the two cases are that: 1) The most severe scour at the outer bank occurs in the upstream half of the curved reach for the 193° bend ($3.2H$) and close to the exit from the curved reach for the 135° bend ($2.3H$); 2) The point bar is wider in the 193° bend. The amount of sediment deposited close to the inner bank past the end of the curved reach in the 135° case is relatively small compared to the 193° case; and 3) Overall, both scour and deposition are more severe for the 193° bend.

6.5.2. 3-D flow and large-scale coherent structures

Q criterion (Hunt *et al.* 1988) is used to visualize the large-scale coherent structures and eddies in the flow and their relative position with respect to the channel bed and banks in Figures 6.7 and 6.8. The variable Q is the second invariant of the velocity gradient tensor ($Q = -0.5(\delta u_i/\delta x_j)(\delta u_i/\delta x_j)$). Being able to identify regions occupied by strongly coherent eddies is important because, as will be shown later, energetic eddies close to a boundary surface can induce substantial increases in boundary shear stresses and/or turbulence intensities, which can significantly enhance the capability of the flow to induce erosion.

In the 135° case, the main cell of cross-stream circulation, V1, extends as a well defined vortex from the entrance into the curved reach until close to section D110. Its core is situated within the inner half of the section in the upstream part of the curved reach, and the central part of the cross section inside the downstream part of the curved reach. This is different from what was observed experimentally and numerically for the 193° case (see Figure 6.4 in Constantinescu *et al.*, 2011b) where the main cell was located very close to the outer bank at all streamwise locations within the curved reach. Both cases however show that the main cell approximately follows the deepest part of the bathymetry within the curved reach. Thus, topographic steering effects control the position of the main cell during the later stages of scour and deposition, after well-defined pool and bar structures have developed within the bend.

The flow structure close to the inner bank is significantly more complex for the 135° case compared to the 193° case. For the 135° case, besides two (co-rotating) SOV cells (V2 and V3), which contain streamwise vorticity of the same sign as the main cell V1, a large

counter-rotating SOV cell, V4, is also present (Figures 6.7 and 6.8). V2 and V3 move quickly away from the inner bank and their cores are situated close to the free surface, V4 remains in the immediate vicinity of the inner bank and, at some sections, extends over the whole flow depth. For the 135° case, the counter-rotating SOV (V4) modifies the local distribution of streamwise and transverse velocities and thus the capacity of the flow to erode the channel boundaries close to the inner bank. This is in contrast to the 193° bend where a co-rotating SOV altered the distribution of velocities close to the inner bank (see discussion of Figure 16 in Constantinescu *et al.*, 2011b).

Important qualitative differences can also be observed in the straight outflow reach. The larger extent and relative depth of the pool within this reach for the 135° case seems to promote the formation and/or growth of the large co-rotating SOV, V6, within the deeper part of the bathymetry, starting around section D100 (Figure 6.7). The vertical extent of this SOV is limited by the presence of a large counter-rotating secondary cell (V5) close to the free surface at the outer bank. Though V5 only appears in section D90 in Figure 6.8, this secondary cell is present between sections D45 to D135+18H, and can be seen by 2-D streamline patterns in Figure 6.12. The reason for its absence in Figure 6.8 is due to the relatively large value of Q used to represent the coherent structures. Both the experiment and simulations showed that a secondary outer bank cell did not form near the free surface for the 193° case. Thus, a comparison of these two cases gives a better understanding of the differences in the flow structures and their effects on the capacity of the flow to induce bank erosion. Previous experimental and numerical studies have provided detailed discussions of the effects of the counter-rotating outer bank secondary cell on the flow in high curvature

bends with a flat bed (Blanckaert and de Vriend 2004; van Balen *et al.* 2010). Such cells have also been observed in field studies where there is a large pool near the outer bank (Bathurst *et al.* 1979). Unfortunately, field studies do not allow a detailed characterization of flow structures and/or estimation of bank shear stresses at all flow depths, which is needed to understand to what extent, and regions over which the secondary cell protects the outer bank from erosion, or to the contrary, endangers bank stability (Bathurst *et al.* 1979).

The effects of the large-scale coherent structures on the mean flow and turbulence statistics is analyzed next based on distributions of 2-D streamlines, streamwise velocity, vertical vorticity and turbulent kinetic energy (TKE) at the free surface and in a horizontal plane situated at $0.5H$ below the free surface (Figure 6.9). The most important qualitative difference between the two bend cases is the absence of flow separation in horizontal planes for the 135° case. By contrast, large recirculation regions are present in the 193° case, behind the shallowest parts of the inner bank point bar (Figure 6.3 in Constantinescu *et al.*, 2011b). Strong separated shear layers (SSL) are also present bordering the recirculation eddies. The presence or absence of flow separation along the inner bank for these cases is mainly a topographic steering effect related to bathymetry features close to the inner bank.

Despite the absence of flow separation for the 135° case, several regions of high magnitude vertical vorticity are observed in Figure 6.9c. Similar to the 193° case, the main sheet of vertical vorticity forming near section D30, which extends past the entrance into the straight outflow reach, is due to the fact that the core of high streamwise momentum fluid does not lose streamwise momentum and gain transverse momentum fast enough to follow the

surface of the high-curvature inner bank. As a result, a region of high mean shear develops at the boundary between the core of high streamwise velocity and slower fluid moving over the point bar. Though the mechanism responsible for the formation of this SL is the same for the two bend cases, the streamwise extent and shape of the SLs are quite different. For the 135° bend case, the SL extends a much greater distance in the downstream direction, and its axis is well aligned with the outer bank past section D90. For the 193° case, the main SL does not extend a great distance along the flume length, but extends quite a distance across the flume width, and reaches close to the outer bank near the free surface. The strongly energetic eddies convected within the SL were shown by Constantinescu *et al.* (2011b) to locally amplify the capacity of the flow to erode the outer bank near the free surface. As shown in the distribution of instantaneous vertical vorticity in Figure 6.10a, though such energetic eddies are also convected within the main SL in the 135° bend and, at times these eddies approach the outer bank (e.g., around section D100), they never really contact the outer bank wall. The main reason for this is that the secondary counter-rotating outer bank cell, visible as a region of mostly negative vertical vorticity in Figure 6.10a, protects the outer bank near the free surface. The other SLs of positive and negative vertical vorticity seen in Figure 6.9c between the main SL and the inner bank are associated with regions located between the SOVs (V1, V2, V3, and V4).

The SOVs near the inner bank (V2, V3, and V4) also appear to influence the distribution of streamwise velocity between V1 and the inner bank wall. The intrusion of low streamwise velocity fluid near the free surface between sections D30 and D60 (Figures 6.9 and 6.12) is associated with the core of V3 that also transports low streamwise velocity fluid. This patch

of low streamwise velocity is visible in the plane $z=-0.5H$ of Figure 6.9. However, at distances larger than $0.3D$ from the free surface, the main region of low streamwise velocity is located closer to the inner bank and coincides with the core of V4. Finally, the region of low streamwise velocity close to the outer bank in Figure 6.9b is much larger than the thickness of the attached boundary layer upstream of the curved reach. What appears as a thick boundary layer between sections D00 and D90 at the free surface, and sections D00 and D60 at $z=-0.5H$ (Figure 6.9), is actually a region of relatively low streamwise velocity where fairly energetic eddies are convected (Figure 6.10a). Its presence is likely due to several reasons. First, the core of high streamwise velocity moves towards the inner bank near section D00, which reduces the transverse gradient of streamwise velocity at the outer bank. Second, the counter-rotating outer bank cell (V5) helps to prevent high streamwise velocities from reaching the outer bank wall downstream of section D45. Finally, mean pressure levels increase from the inner to the outer bank, causing the outer bank boundary layer to form in an area with an adverse pressure gradient (Figure 6.10b).

The high amplification of TKE in Figure 6.9d near the free surface close to the central region of the channel downstream of section D60 is due to energetic eddies in the main SL which form due to a Kelvin-Helmholtz (KH) type of instability. The coherence of these eddies is greatest close to the free surface. The other region of high TKE, closer to the inner bank, is due to production by mean shear associated with a high streamwise velocity gradient in the transverse direction near the cores of V2, V3 and V4. The increase of the TKE within these SLs (up to $0.03U^2$) is more than one order of magnitude greater compared to levels in the straight inflow reach.

6.5.3. Depth averaged flow

The distributions of non-dimensional streamwise unit discharge (q_s), or equivalently streamwise depth averaged flow, are shown in Figure 6.11 for both bend cases. The values for q_s are calculated from the depth-averaged streamwise velocity multiplied by the local flow depth, and are important in understanding the distribution of flow across the channel width. As will be discussed in greater detail later, q_s also gives insight into effects of topographic steering, which are of particular importance when the bed is deformed. It is also the main variable that determines patterns of bed entrainment for depth-averaged 2-D numerical models that are able to predict sediment transport.

The main differences in the distributions of q_s between the two cases (Figure 6.11) are primarily due to differences in equilibrium bathymetries. For the 135° bend (Figure 6.11a), the majority of flow follows the channel thalweg, and represents more than 50% of the flow across the channel width, even though it occupies less than one third of the width. For the 193° bend (Figure 6.11b), the majority of the flow moves along the outer bank region where scour is deepest. The presence of a wide inner bank point bar, and the rapid development of the transverse bed slope, cause flow to move rapidly towards the outer bank for the 193° case. The region of high q_s for the 193° bend extends from the outer bank wall by about one third of the channel width. Two regions of flow recirculation can be seen along the inner bank in Figure 6.11b where q_s is negative. These regions decrease the channel width through which positive q_s can flow. The result is that values of q_s increase over the deepest parts of the bathymetry along the outer bank in order to maintain a constant discharge through the channel. In the sections where the widths of the recirculation regions are greatest, peak

values of q_s are about three times greater than in the straight inflow reach. For the 135° bend, the distribution of q_s is qualitatively closer to what would be observed in medium curvature bends, and the scour develops more gradually within the curved reach. In particular, near the entrance into the curved reach, the largest values of q_s are observed closer to the inner bank, which is consistent with a potential flow distribution of streamwise velocity in the transverse direction (Rozovskii 1957). Gradually, curvature effects push the core of high q_s towards the outer bank. Both cases are good examples of sharp bends that contain developed pool-point bar structures where bathymetry and curvature-induced cross-stream circulation play dominant roles in controlling the distribution of q_s .

6.5.4. Curvature and topographic steering effects on streamwise velocity, secondary flow and turbulence

The effects of bend curvature and topographic steering on secondary circulation, turbulence levels, and mean flow patterns can be better understood by investigating distributions of streamwise vorticity, streamwise velocity, and TKE. Γ represents the secondary circulation strength magnitude of a cell of cross-stream motion induced by channel curvature. Γ is calculated in a plane cut perpendicular to the longitudinal axis of the SOV, and is the magnitude of the streamwise vorticity integrated over the cell cross-sectional area. The streamwise variation of Γ for the main SOV cells within the 135° bend is shown in Figure 6.13, and helps in understanding where the effects of the SOVs on mean flow and boundary shear stresses can be greatest. It must be noted however, that maximum levels of Γ may not always directly coincide with maximum levels of bed shear stress. This is because the size of the SOVs and their distance to the bed must also be considered in order to determine their ability to affect the gradient of velocity close to the bed. As it is sometimes difficult to

identify a clear boundary between the cores of V2, V3, and the main cell V1, the total circulation of the main channel cell (Γ_+) is calculated in Figure 6.13 by including contributions from V1, V2, and V3. Γ_+ affects the rate at which streamwise momentum and velocity are advected across the flume width (Zeng *et al.* 2008a). In Figure 6.13, Γ_+ increases rapidly past 0° and peaks at around 60° . By comparison, the peak value of the circulation associated with the main cell in the 193° bend occurs at around 90° (van Balen *et al.* 2010). In both test cases, the circulation decreases gradually within the remaining part of the curved reach. This evolution of cross-stream circulation in high curvature bends has primarily been attributed to the interaction between the vertical profiles of the streamwise and cross-stream velocities (Blanckaert and de Vriend 2003). Distributions of Γ for the SOVs in these cases, and their effects on distributions of velocity will be referred to and discussed in more detail in the following paragraphs.

For the 135° bend case, bed deformations start close to the inner bank near section D00. In section D30 (Figure 6.12), the center of the core of the main cell, V1, is situated over the deepest part of the section. By section D60, both the main channel cell V1, and the main core of high streamwise velocity have moved away from the inner bank due to the development of the inner bank point bar. In agreement with previous experimental and numerical studies of flow in medium- and high-curvature channels (Bathurst *et al.* 1979; Ferguson *et al.* 2003; Roca *et al.* 2009; Kang and Sotiropoulos 2011), the smaller region of maximum streamwise velocity between sections D60 to D120 is not observed at or just beneath the free surface, but rather, closer to the bed. Also, the distribution of high streamwise velocity within this region is somewhat complex and skewed, and is not always

uniform over the entire flow depth. This is mainly due to the presence of the SOV cells that redistribute streamwise velocity across the thalweg. The patch of concentrated high negative values of streamwise vorticity and low streamwise velocity close to the inner bank in Figure 6.12 (section D60) is associated with V4, which occupies the whole channel depth. In this section, a slight dip in the bathymetry can be seen below V4 due to high levels of Γ_{V4} , which cause erosion at the bed. The secondary counter-rotating outer bank cell, V5, is already present in section D60 and is contained within the thick boundary layer forming at the outer bank. Its circulation is too low to have any noticeable effect on the distribution of streamwise velocity close to the outer bank in this section. Downstream of section D135 the core of high u_ξ extends from the bed to the free surface and the distribution of streamwise velocity is fairly uniform in the vertical direction. The lines of constant streamwise velocity in sections D135 and D135+2.8H (Figure 6.15) diverge away from the outer bank near the free surface. This is due to the presence of V5 that protects the bank close to the free surface. At the same time however, peak values within the core of high streamwise velocity are located very close to the outer bank in section D135+2.8H. This is due to convection of high-streamwise-velocity fluid by the combined action of V5 and V6 towards the outer bank wall at about half bank-depth levels. This supports the observation of Bathurst *et al.* (1979) that advection of high momentum fluid towards the base of the outer bank by the outer bank cell can endanger bank stability.

It is also important to consider regions where TKE levels are high within the bend, as these may lead to high mean pressure fluctuations at the channel bed and banks. As had been seen in Figure 6.9d, very high levels of TKE are present along the outer bank immediately

downstream of section D00. As already discussed, these high levels occur in a region of relatively low streamwise velocity ($u_{\xi}/U < 0.5$) where large scale energetic eddies are induced. Section D30 in Figure 6.14 shows that TKE levels within this region are elevated by about 15 times compared to the surrounding flow. Figure 6.14, section D60 shows that high levels of TKE are also present within the SL forming in between V4 and V2 that are rotating in opposite directions. Relatively high TKE values are also observed in this section within the main SL close to the free surface that borders the core of high u_{ξ} . While the TKE values within the core of V4 are only slightly larger than TKE levels in the straight entrance channel, a small region of high TKE is also present near the inner bank due to the high circulation of V4 that induces large cross-stream velocities near the inner bank. This suggests that V4 may have the capacity to induce high shear stresses at the inner wall. The fact that the TKE remains low within the core of V4 means that this SOV cell is not subject to large-scale oscillations in the instantaneous flow fields, and does not transport large scale turbulence similar to the SLs. In section D120 (Figure 6.14), the region of very high TKE in the central region of the section close to the free surface coincides with the main SL.

6.5.5. Mechanisms controlling bed and bank erosion during the later stages of the scour and deposition process. Role of large-scale coherent structures

The distribution of non-dimensional mean bed shear stress, τ/τ_0 , where τ_0 is the mean value of bed shear stress in the straight inflow reach, reveals where scour may occur during the later stages of erosion in the 135° bend (Figure 6.15a). Overall, a good correlation exists between regions with high q_s (Figure 6.11a), and regions with high values of τ/τ_0 (Figure 6.15a). The correlation is even greater if one considers only the streamwise component of bed shear stress (Figure 6.16a), which is calculated from the streamwise velocity gradient

close to the bed. The reason why the distributions of the two quantities are not exactly the same is due to the nonuniformity of the streamwise velocity over the depth, which is caused by curvature and topographic steering effects. In particular, the streamwise component of τ/τ_0 is amplified in regions where cross-stream cells with high streamwise vorticity and streamwise velocity are located closer to the bed. This occurs between sections D60 to D120 (Figure 6.12). Also, regions where the streamwise vorticity is high at the bed beneath the cores of V1 and V6 (Figure 6.12) are also regions where the transverse component of τ/τ_0 is high (Figure 6.16b). In comparison, q_s is calculated from the depth averaged values of streamwise velocity, rather than local values of velocity close to the bed.

For the 135° bend, maximum values of τ/τ_0 are about 4 (Figure 6.15a), whereas for the 193° bend they are about 6. One reason for the greater levels of τ/τ_0 in the 193° bend may be that scour depths are deeper, leading to higher levels of both q_s and streamwise velocities in the regions of deeper scour. Another reason is that for the 193° bend, scour develops under live bed scour conditions as opposed to clear water scour conditions, and thus levels of excess velocity should be greater. However, the extent of the region where $\tau/\tau_0 > 2$, is comparatively greater for the 135° case, and covers much of the central part of the curved reach past section D30. The significant decrease in τ/τ_0 in the downstream part of the curved reach for the 193° case is related to the movement of high streamwise velocities away from the bed. Meanwhile, the contribution of the cross-stream component of bed shear stress to the total bed shear stress magnitude inside the curved reach is up to around 50% for both cases, although this contribution is slightly greater at the entrance into the curved reach for the 135° case (Figure 6.16b).

The elongated streak of relatively high cross-stream bed shear stress close to the inner bank between sections D30 and D90 is induced by V4 (Figure 6.16b). As already discussed, V4 transports low streamwise momentum fluid and its cross-stream circulation is relatively high especially between sections D45 and D90 (Figure 6.13). Examination of the two components of τ/τ_0 confirms that the transverse component is the primary contributor ($\approx 80\%$) to the total shear stress magnitude at the bed in the region situated beneath V4. The other elongated streak of high τ/τ_0 situated inside the straight outflow reach is induced by V6 (Figure 6.12). This SOV moves away from the outer bank towards the shallower region past section D120 (e.g., see Figure 6.8, and 2-D streamline patterns in Figure 6.14). The main role of this SOV cell, as far as morphodynamics is concerned, is to entrain sediment particles from the deeper parts of the pool and to push them against the transverse slope of the scour hole while these particles move downstream. Its cross-stream circulation is large enough to induce a significant transverse component of τ/τ_0 (around 30% of the total bed shear stress). The presence of a large counter-rotating secondary cell (V5) close to the surface for the 135° bend favors the confinement of V6 towards the deeper regions and limits the growth of its core. As a result, its sediment entrainment potential is larger compared to bends where a main cell with equivalent cross-stream circulation occupies most of the flow depth close to the outer bank.

The large erosion potential of some of the SOV cells is also confirmed by the shear stress distribution at the inner bank between sections D15 and D70 where $\tau/\tau_0 > 1.25$ (Figure 6.17a). A comparison of the distributions of the vertical component of τ/τ_0 (Figure 6.18) and total

shear stress (Figure 6.17a) at the inner bank indicates that the vertical component provides the main contribution to the total boundary shear stress. This finding is consistent with the fact that the SOV cells forming at the inner bank contain low streamwise velocity and high circulation fluid. The vertical component is oriented towards the free surface between sections D15 and D45 and towards the bed between sections D45 and D70 (Figure 6.18). This is because the amplification of τ/τ_0 at the inner bank is first due to V2 and then due to V4 that rotates in the opposite direction. Thus, erosion at the inner bank is mostly driven by the SOV cells rather than being induced by the presence of the core of high streamwise velocity. The only region where streamwise velocity is responsible for the amplification of the shear stress at the inner bank is around section D00. However, the magnitude of τ/τ_0 around section D00 is smaller than in the downstream direction, where the cores of V2 and V4 are situated close to the inner bank. One should also notice that over these regions peak values of τ/τ_0 are comparable to those observed at the outer bank (Figure 6.17b). Thus, in the case of sharply curved bends, bank erosion is a problem that is not confined to the outer bank.

The main region of high shear stress ($\tau/\tau_0 > 1.25$) on the outer bank wall occurs between sections D100 and D135+3H for the 135° case (Figure 6.17b), and between sections D120 and P2.0 for the 193° case. In both cases the amplification of τ/τ_0 is due mainly to the movement of the core of high u_ξ values close to the outer bank. This is confirmed by the fact that in both cases the vertical component of the total shear stress (not shown) is much smaller than the streamwise component at all streamwise locations. For the 135° case, peak values of τ/τ_0 at the outer bank are located quite below the free surface, and are at a depth

generally situated close to the boundary between V6 and V5. By contrast, peak values of τ/τ_0 within the corresponding region of high bank shear stress were always situated at or very close to the free surface for the 193° case. This is because close to the free surface the secondary counter-rotating outer bank cell for the 135° case protects the outer bank against erosion. However, at mid-depth level the two vortices (V5 and V6) gradually push high streamwise velocities closer to the outer bank downstream of section D100 (see streamwise velocity distributions in sections D120 to D135+2.8H of Figure 6.12). In this way they increase the wall shear stresses around the mid-depth level, even though the direct erosion potential of both V5 and V6 is small. This highlights the complex effect of curvature on flow structures near the outer bank wall. Finally, the region of high τ/τ_0 near the bottom of the outer bank wall past section D135+4H is due to the reduction in the thickness of the boundary layer close to the junction line between the bed and the outer bank (Figure 6.17b).

The passage of energetic eddies near the channel boundaries and/or the random oscillations of the cores of the large-scale vortices situated near these boundaries can substantially increase the magnitudes of shear stresses above their mean values. Thus, the potential for bed and bank erosion may be greater in regions of high turbulence intensity. The distributions of mean pressure fluctuations, $\overline{p'^2}/\rho^2 U^4$, at the bed (Figure 6.19a) and at the two banks (Figure 6.20) helps to identify these regions for the 135° bend. As mentioned, the boundary layer at the outer bank of the curved reach develops into a region subject to a large adverse pressure gradient within the upstream half of the bend (Figure 6.10b) which induces highly-energetic turbulent eddies and causes an increase in the boundary layer width (Figure 6.10a). Peak values of $\overline{p'^2}/\rho^2 U^4$ within this region are predicted just downstream of section

D00 (Figure 6.19) and are due to the sudden change in curvature between the straight inflow reach and the curved reach. One expects the amplification of turbulence at the entrance into the region of high channel curvature to be smaller in natural channels where the change in curvature takes place gradually. Some of the eddies generated in the attached boundary layer get away from the outer bank surface past the formation region, but because of the high curvature of the outer bank, approach its surface again between sections D70 and D100 (Figure 6.20b). This explains the variation of $\overline{p'^2}/\rho^2 U^4$ along the outer bank in Figure 6.20b. A similar region of severe amplification of mean pressure fluctuations on the outer bank wall was observed around section D90 for the 193° case (see Figure 6.20 in Constantinescu *et al.*, 2011b).

The large amplification of mean pressure fluctuations on the inner bank wall between sections D60 and D100 observed in Figure 6.20a is due to the presence of V2 and V4 in the immediate vicinity of the bank wall. The random temporal variations in the coherence of these vortices, and the distance between their cores and the bank surface generate ejections of patches of vorticity from the attached boundary layer. The end effect is an amplification of pressure and boundary shear stress fluctuations on the inner bank. The same mechanism is responsible for the streak of high $\overline{p'^2}/\rho^2 U^4$ forming between sections D60 and D90 on the bed below the core of V4 near the inner bank (Figure 6.19a). Additionally, elongated regions of high $\overline{p'^2}/\rho^2 U^4$ are observed in Figure. 19 around the boundary between the regions of high and low streamwise unit discharge on the outer side of the channel (Figure 6.11a). Regions of high mean shear (e.g., shear layers) generate turbulent eddies due to the growth of the Kelvin Helmholtz (KH) instabilities, especially away from the bed surface (Figure 6.10a). At

times, some of these eddies can penetrate very close to the bed to significantly increase the local value of bed shear stress. This happens more in some regions compared to others because of the local mean flow pattern than can favor or impede the occurrence of such events depending on the local shape of the bathymetry.

6.6. SUMMARY AND CONCLUSIONS

The data generated from an LES model for a 135° open channel bend with $R/B=1.5$ was used to gain insight into the flow, turbulent structures, and sediment entrainment mechanisms for sharply curved bends with natural bathymetry corresponding to equilibrium scour conditions. The results were compared to those generated using a DES model for a 193° open channel bend with $R/B=1.3$ and equilibrium bathymetry (Constantinescu *et al.* 2011b). The study revealed that bend geometry seems to substantially influence the characteristics of flow structures, flow patterns, turbulence, and scour distributions in a sharp bend. Overall, for the 193° bend, both scour and deposition were more severe, and flow and scour patterns were more complex. Some of the main observations from this study are given below.

1. For both cases, topographic steering affected both the distributions of flow and streamwise velocity, as well as the size and position of the SOVs. For both cases, the location of the main channel SOV tended to coincide with the channel thalweg. Also, strong SOV cells formed along the inner bank between the main SL and the region of slower moving fluid near the inner bank. This SL was characterized by large values of both vorticity, and TKE, whose local production was driven by mean horizontal shear. The results suggest that the presence of strongly coherent SOV cells, and SLs at the inner

bank are a general characteristic of flow in open channel bends when the ratio R/B is sufficiently small (e.g., $R/B < 3$).

2. An important qualitative difference in the flow structures between the two cases was also observed along the outer bank. For the 135° bend a counter-rotating SOV cell was located near the free surface at the outer bank starting at section D45, and extending a considerable distance into the straight exit reach. Such an outer bank cell was not present in the corresponding 193° case with a deformed bed, but has previously been observed in experimental and numerical studies conducted for the same 193° bend with a flat bed (van Balen *et al.* 2010), as well as in field studies of natural river reaches (Bathurst *et al.* 1977; Thorne and Hey 1979; de Vriend and Geldof 1983). Most observations of this type of secondary outer bank cell in controlled laboratory experiments have come from test cases with a flat bed in which the cell extends almost the entire flow depth in regions where its circulation is greatest. This type of situation however, is not very realistic as severe scour normally occurs in regions of high cross-stream circulation, where deep scour is normally present, and the flow depth is usually much greater than the size of this circulation cell.
3. While in both cases the wall shear stress at the outer bank was strongly amplified near the exit of the curved reach, the largest values were recorded near the free surface for the 193° bend, in which the outer bank was not protected by a secondary cell, and at mid-depth levels for the 135° bend, in which the outer bank was protected by a secondary cell. Over the upstream half of the 135° bend, the outer bank cell contained lower

streamwise momentum fluid compared to the surrounding flow. Over this region, the outer bank cell decreased outer bank shear stress close to the free surface. However, past the middle of the curved reach, high outer bank shear stress was observed at mid-depth between the lower cell (V5) and the upper outer bank counter-rotating cell (V6). This region of high outer wall shear stress overlapped with the lower part of the counter-rotating secondary cell, since this cell seemed to be advecting high streamwise velocities to this region. This supports the observation of Bathurst *et al.* (1979) that the outer bank cell can endanger bank stability by advecting high-momentum fluid towards the outer bank.

4. SOVs were found to increase levels of the streamwise component of boundary shear stress by advecting high streamwise velocities towards the channel banks and bed. They were also found to increase cross-stream bed shear stress levels below them due to their secondary circulation. For the sharply curved bends being considered, the cross-stream component accounted for up to 50% of the total bed shear stress magnitude within the bend. The ability of the SOVs to increase bed shear stress also depended on the proximity of the cell to the bed. Kashyap (2012, Chapter 5) have also found similar results for SOVs in the same 135° bend at both initial and equilibrium scour conditions using a 3-D RANS model.
5. Regions of flow separation along the inner bank for the 193° case decreased the channel width through which the main flow could pass. As a result, streamwise unit discharge and streamwise velocities increased within the outer half of the cross-sections cutting

through the recirculation eddy (e.g., first between sections D60 and D120 and then between sections P0.5 and P2.0 for the 193° case). Downstream of the first recirculation eddy, the flow expanded, causing high streamwise velocities to move towards the inner bank, and a reduction in bed shear stress at the bed near the outer bank. It was seen for the 135° case, which had no flow separation at the inner bank, that a closer correlation was observed between the regions of high flow depth and high bed shear stress.

6. For bends of mild to low curvature, erosion is known to be most problematic along the outer bank. This study shows that for bends of high curvature, very high shear stresses can also be present on the inner bank. The results for the 135° case show that SOV cells close to the inner bank can locally amplify inner bank shear stresses to levels comparable to those at the outer bank. The vertical component primarily contributes to the higher shear stress levels at the inner bank is the vertical one. This is consistent with the fact that the SOV cells are generally regions of high streamwise vorticity and low streamwise velocity.

Ultimately, the information collected from such eddy resolving simulations can be used to identify critical regions where the river reach should be protected against erosion. Because of their lower computational cost, depth-integrated 2-D models, based on shallow flow equations, are still the most popular approach used to predict flow, sediment transport and morphodynamics in natural streams. However, information from 3-D eddy resolving simulations can be used in calibrating 2-D models to improve their predictive abilities in regions of high curvature (e.g., see discussion in Vasquez *et al.*, 2005, and Zeng *et al.*,

2008b). One of the most popular and effective ways to protect river banks against excessive bed and bank erosion in regions of high channel curvature is by installing groynes. Although detailed experimental methods and LES have already been completed to study flow and turbulence structures in channels containing groyne fields, these studies are limited to the simplified case of a straight channel (e.g., see detailed literature review in McCoy *et al.*, 2008). However, in practical field applications, groynes are usually installed in regions of high channel curvature where the potential for outer bank erosion is high. The present LES model is being modified to study the effects of placing a series of groynes along the outer bank of high-curvature channel bends.

6.7. NOTATION

B = channel width (m)

d = discrepancy ratio

d_{avg} = minimum discrepancy ratio

d_{min} = minimum discrepancy ratio

d_{max} = maximum discrepancy ratio

d_{50} = median sediment size (mm)

Fr = non-dimensional Froude number = $(Ug/H)^{1/2}$

g = gravitational acceleration (m/s^2)

H = initial water depth (m)

k = kinetic energy (m^2/s^2) = $0.5(\langle (u_1')^2 \rangle + (u_2')^2 + (u_3')^2)$

k_s = roughness value (mm)

L_ζ = streamwise distance measured along the channel sidewall (m)

- p = pressure (N/m^2)
- p' = pressure fluctuations (N/m^2)
- q_s = non-dimensional streamwise unit discharge
- Q = discharge (m^3/s)
- r^2_{adj} = adjusted coefficient of determination
- R = radius of curvature at channel centerline (m)
- Re = main channel Reynolds number = UH/ν
- Re^* = main channel particle Reynolds number = u^*d_{50}/ν
- t = time (s)
- u_C = cross-stream velocity perpendicular to the channel centerline (m/s)
- $u_{i,j,k}'$ = fluctuating component of velocity, i, j , and k represent directions in Cartesian co-ordinate system x, y , and z , respectively (m/s)
- u_Z = vertical velocity (m/s)
- u_ξ = streamwise velocity relative to the channel centerline (m/s)
- U = mean velocity in the inlet section (m/s)
- u^* = bed shear velocity (m/s)
- u_0^* = inlet channel bed shear velocity (m/s)
- u_{cr}^* = critical bed shear velocity (m/s)
- $x_{i,j,k}$ = distance, i, j , and k represent directions in Cartesian co-ordinate system x, y , and z , respectively (m/s)
- y^+ = non-dimensional mesh spacing at the boundary = $(Re)(u^*/U)(\Delta n/H)$
- z = vertical distance from initial bed level (m)

- Δn = dimensional mesh spacing at the boundary (m)
- ε_a = mean absolute velocity error
- ε_{rms} = root mean square velocity error
- ρ = water density (kg/m³)
- τ = shear stress magnitude (N/m²)
- τ_0 = average bed shear stress at the inlet section (N/m²)
- ν = kinematic fluid viscosity (m²/s)
- Γ = non-dimensional cross-stream circulation strength
- Γ_+ = total positive non-dimensional cross-stream circulation strength
- ω_ξ = streamwise vorticity = $(du_\xi/dy)-(du_c/dx)$ (1/s)
- ω_z = vertical vorticity = $(dw/dy)-(du_c/dz)$ (1/s)

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Table 6.1 Flow parameters for the 135° bend flume experiment

Case	U (m/s)	H (m)	u_0^* (m/s)	u_{cr}^* (m/s)	d_{50} (mm)	Re^* (u^*d_{50}/ν)	Re (UH/ν)	Fr (Ug/H) ^{1/2}
135°	0.310	0.150	0.0152	0.0197	0.689	13.8	60,000	0.255

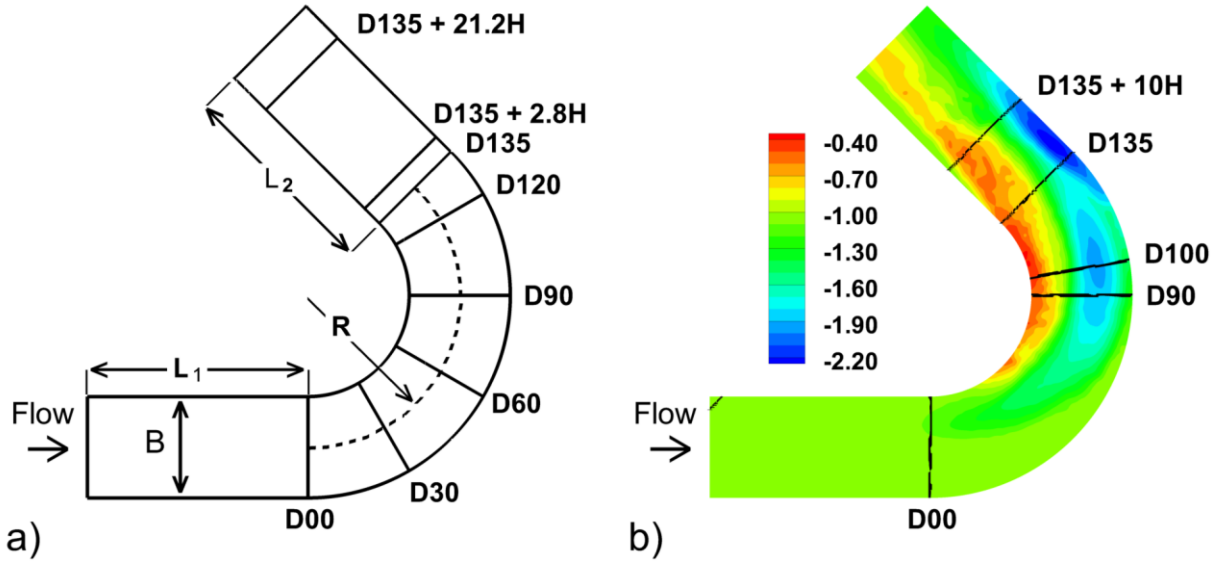


Figure 6.1 a) Sketch of the part of the flume in which the 135° bend experiment with a mobile bed was conducted. The dashed line shows the flume centerline. b) Bathymetry at equilibrium scour conditions. The bed elevation (z/H) is measured with respect to the mean position of the free surface ($z/H=0$) in the straight inlet section.

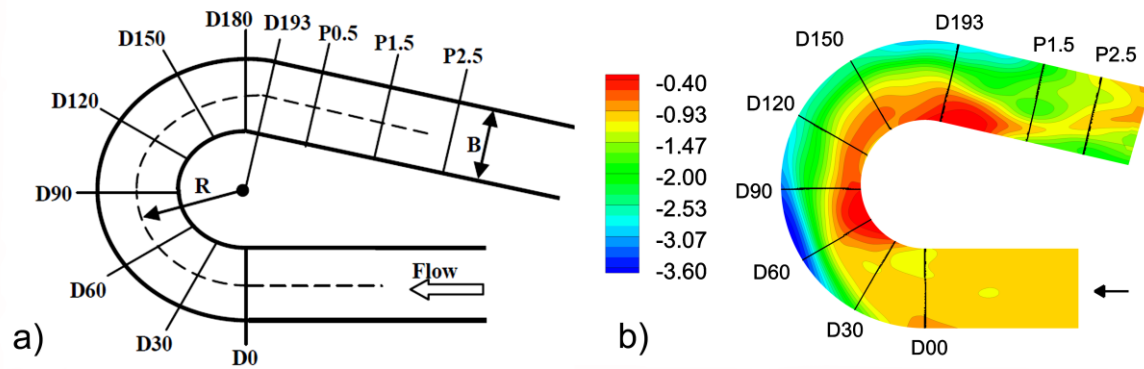


Figure 6.2 a) Sketch of the part of the flume in which the 193° bend experiment with a mobile bed (Blanckaert, 2002) was conducted. The dashed line shows the flume centerline. b) Bathymetry at equilibrium scour conditions. The bed elevation (z/H) is measured with respect to the mean position of the free surface ($z/H=0$) in the straight inlet section (Constantinescu *et al.* 2011b).

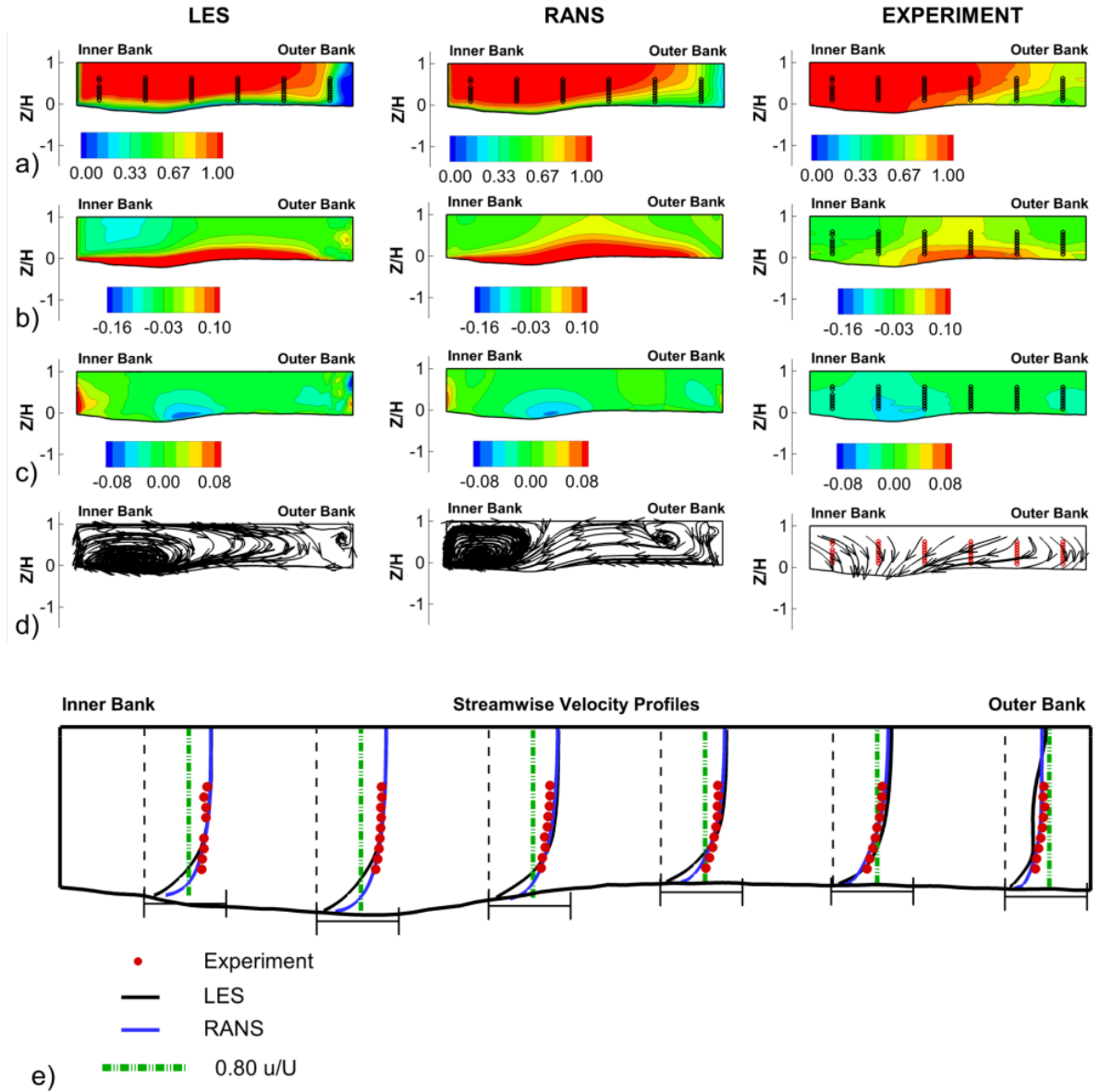


Figure 6.3 Contour plots for section D10 of a) streamwise velocity (u_{ξ}/U), b) cross-stream velocity (u_c/U), c) vertical velocity (u_z/U), and d) 2-D streamlines for (left) LES, (center) RANS, and (right) experiment. Measurement locations are shown by black circles. f) Vertical profiles of streamwise velocity (u_{ξ}/U) values for (red dot) experiment, (black line) LES, and (blue line) RANS. Dashed vertical line shows the location of $u_{\xi}/U=0$, and dashed green vertical line shows $u_{\xi}/U=0.80$.

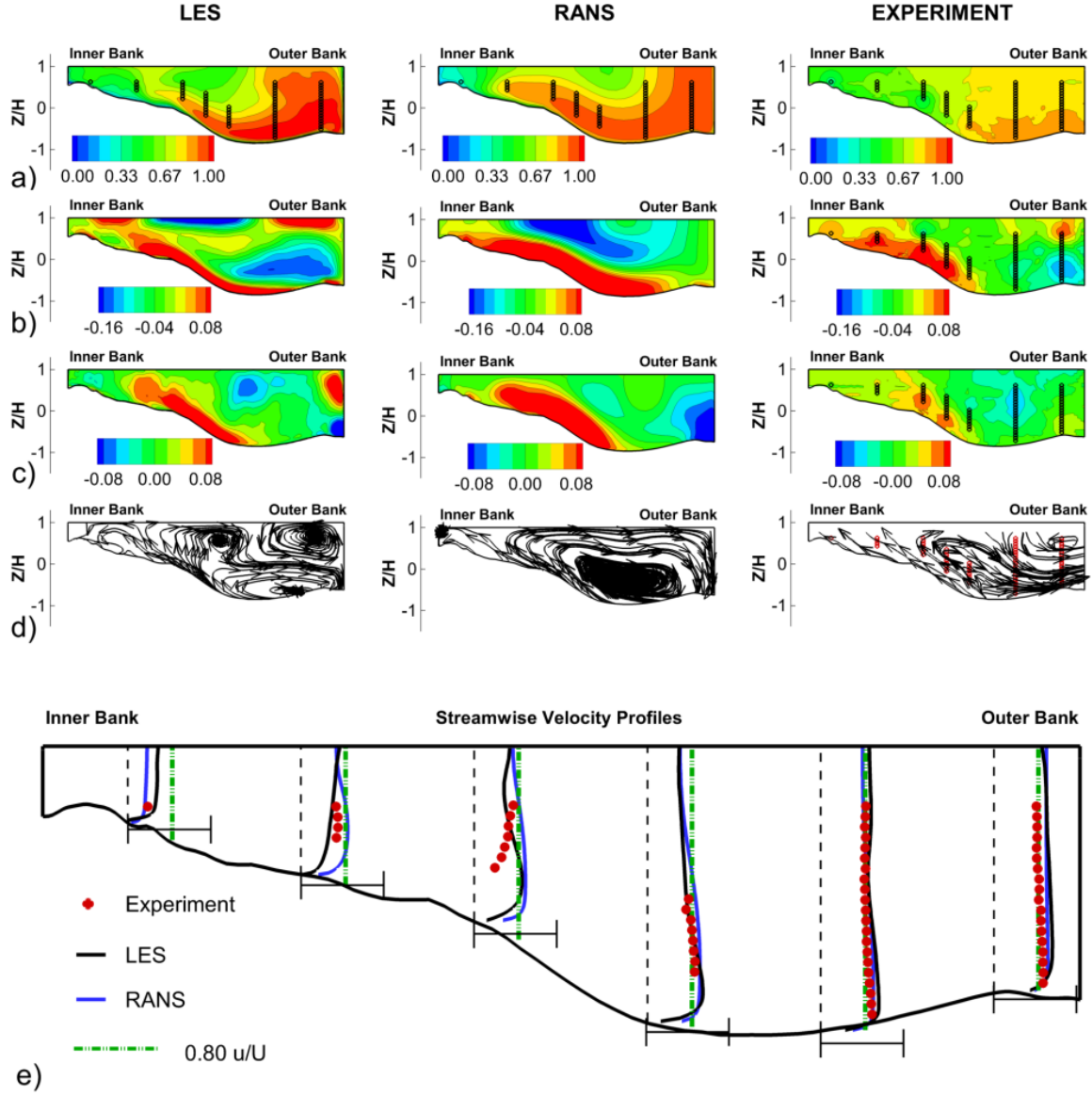


Figure 6.4 Contour plots for section D115 of a) streamwise velocity (u_x/U), b) cross-stream velocity (u_y/U), c) vertical velocity (u_z/U), and d) 2-D streamlines for (left) LES, (center) RANS, and (right) experiment. Measurement locations are shown by black circles. e) Vertical profiles of streamwise velocity (u_x/U) values for (red dot) experiment, (black line) LES, and (blue line) RANS. Dashed black vertical line shows the location of $u_x/U=0$, and dashed green vertical line shows $u_x/U=0.80$.

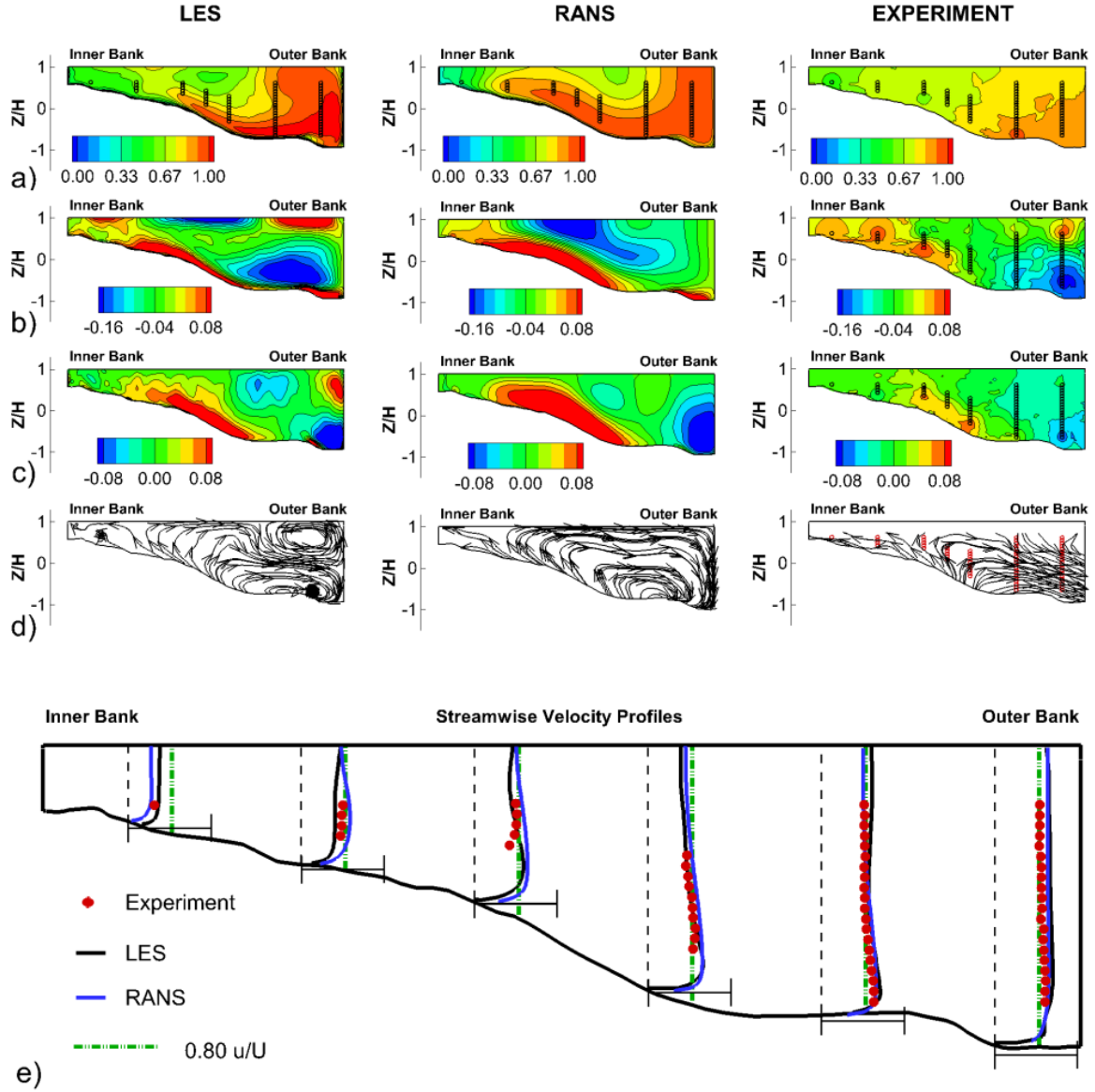


Figure 6.5 Contour plots for section D125 of a) streamwise velocity (u_{ξ}/U), b) cross-stream velocity (u_c/U), c) vertical velocity (u_z/U), and d) 2-D streamlines for (left) LES, (center) RANS, and (right) experiment. Measurement locations are shown by black circles. f) Vertical profiles of streamwise velocity (u_{ξ}/U) values for (red dot) experiment, (black line) LES, and (blue line) RANS. Dashed vertical line shows the location of $u_{\xi}/U=0$, and dashed green vertical line shows $u_{\xi}/U=0.80$.

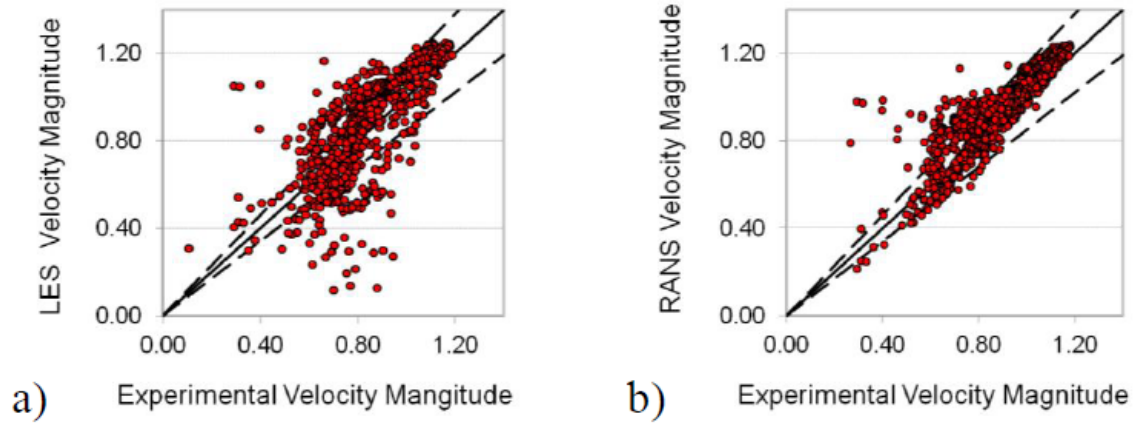


Figure 6.6 Scatter plots for deformed bed cases showing non-dimensional simulated versus experimental velocity magnitudes for a) LES, and b) RANS. The line of equality is shown by a solid line, and the dashed lines represent errors of $\pm 15\%$.

Table 6.2 Statistics for plots shown in Figure 6.6, showing the agreement of the RANS and LES velocity magnitudes against the experimental velocity magnitudes

	r^2_{adj}	ε_a	ε_{rms}	d_{min}	d_{max}	d_{avg}	Percentage (%) $0.5 < d < 2.00$	Percentage (%) $0.75 < d < 1.33$
RANS vs. EXP	0.76	0.081	0.106	0.73	3.36	1.08	99.5	97.1
LES vs EXP	0.52	0.129	0.164	0.14	3.61	1.05	97.3	86.9

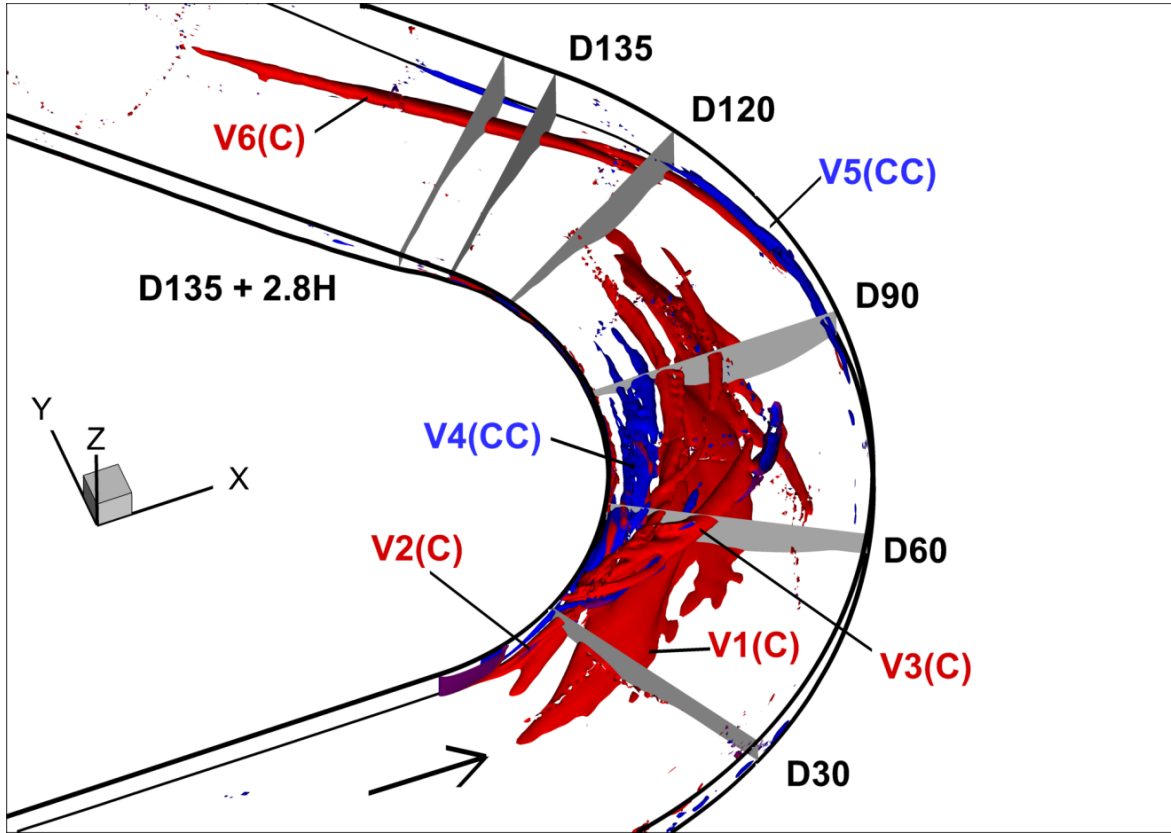


Figure 6.7 3-D visualization of the vortical structure of the mean flow predicted by LES using the Q criterion. C and CC indicate a co-rotating and a counter-rotating vortex, respectively. Positive streamwise vorticity is shown in red, and negative streamwise vorticity is shown in blue.

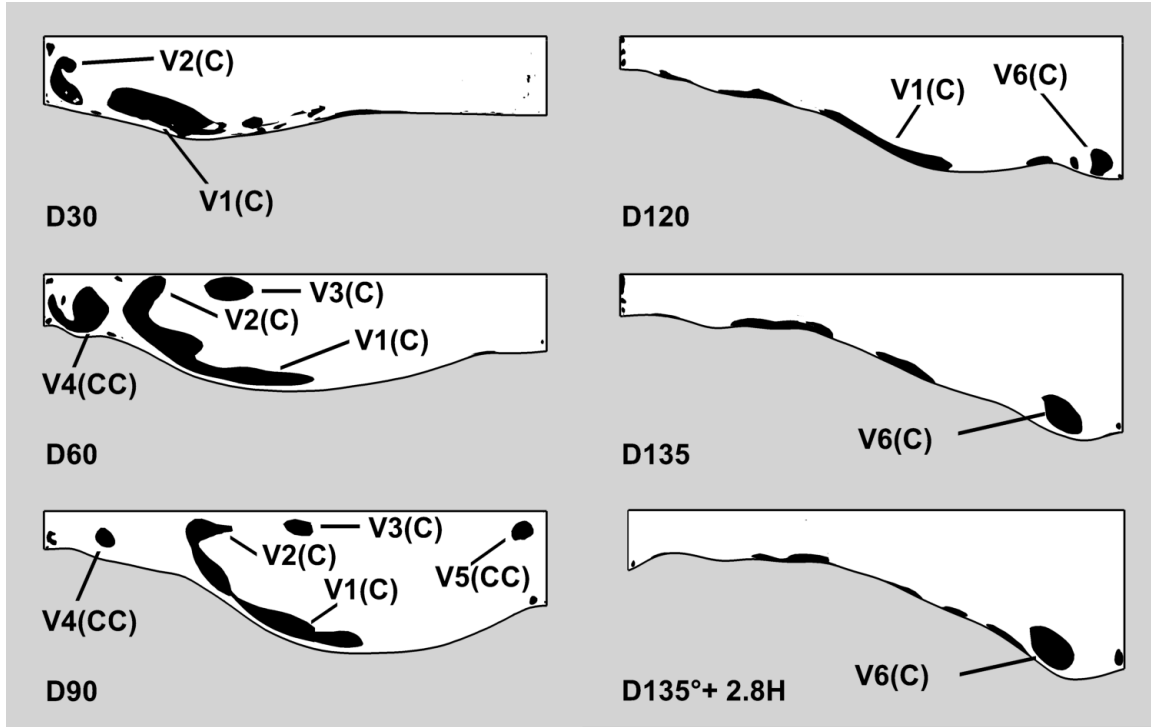


Figure 6.8 Visualization of streamwise oriented vortices (SOVs) in the mean flow in representative cross sections using the Q criterion.

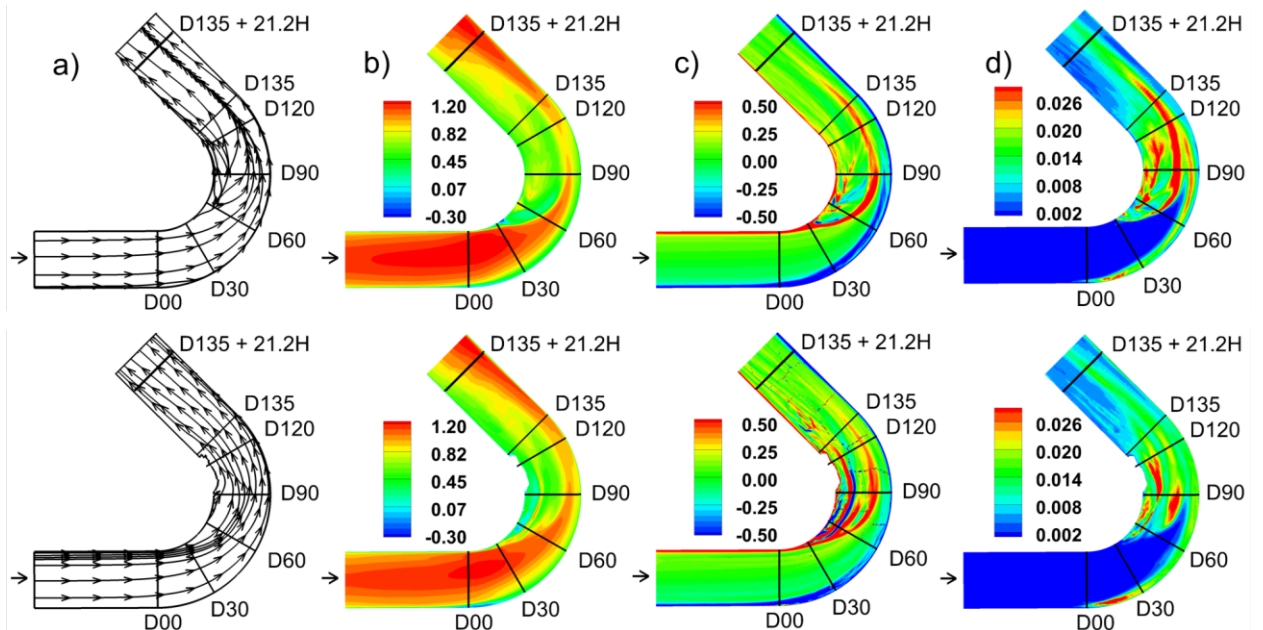


Figure 6.9 Visualization of the mean flow at the free surface (top) and in a horizontal section situated at $z/H=-0.5$ (bottom). a) 2-D streamline patterns; b) streamwise velocity, u_x/U ; c) vertical vorticity, $\omega_z H/U$; d) TKE, k/U^2 .

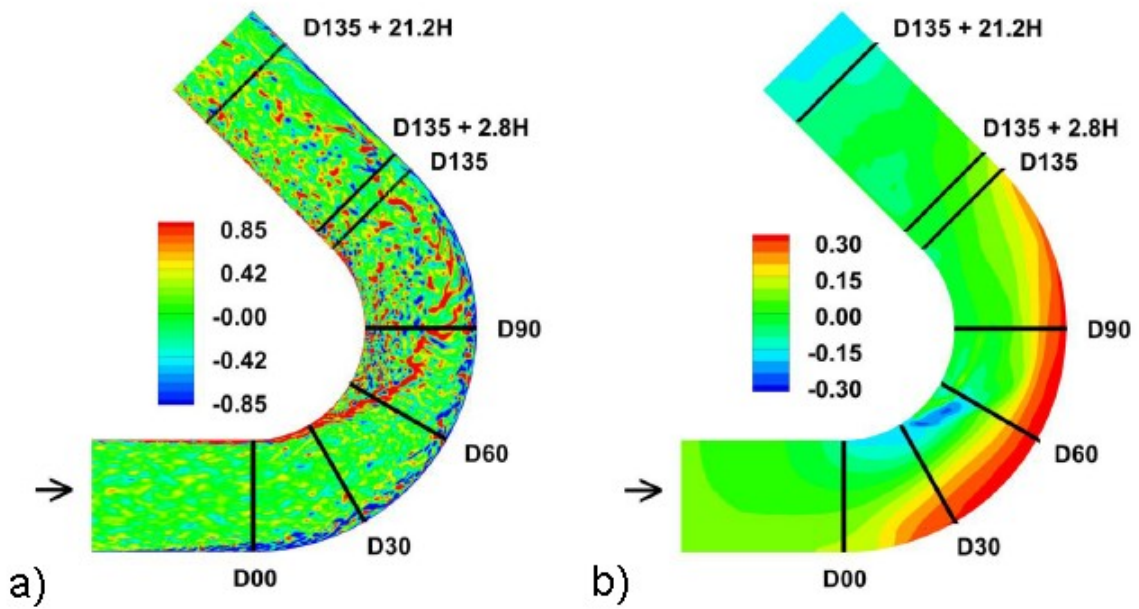


Figure 6.10 Distribution of a) vertical vorticity, $\omega_z H/U$ in the instantaneous flow field and b) mean pressure, $p/\rho U^2$ at the free surface.

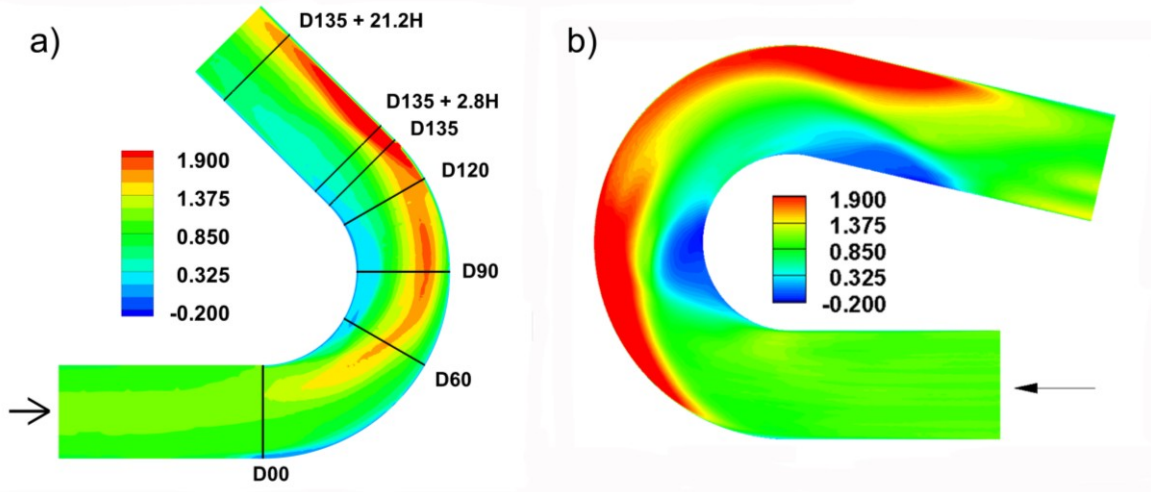


Figure 6.11 Distribution of the normalized streamwise unit discharge q , in the channel for a) the 135° case; b) the 193° case.

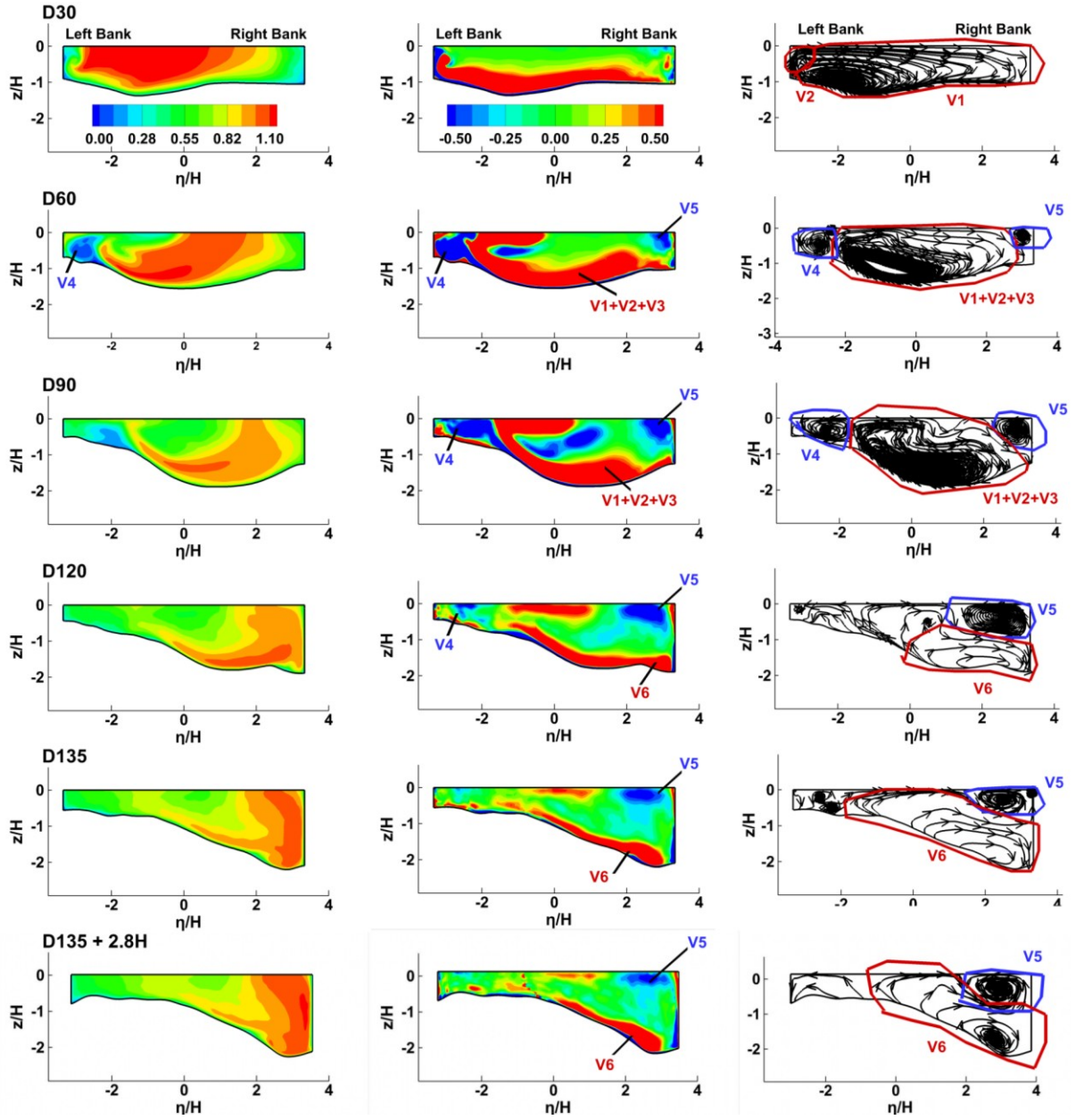


Figure 6.12 Mean flow velocity, u_{ξ}/U (left), streamwise vorticity, $\omega_{\xi}H/U$ (center) and 2-D streamline patterns (right) in representative cross sections.

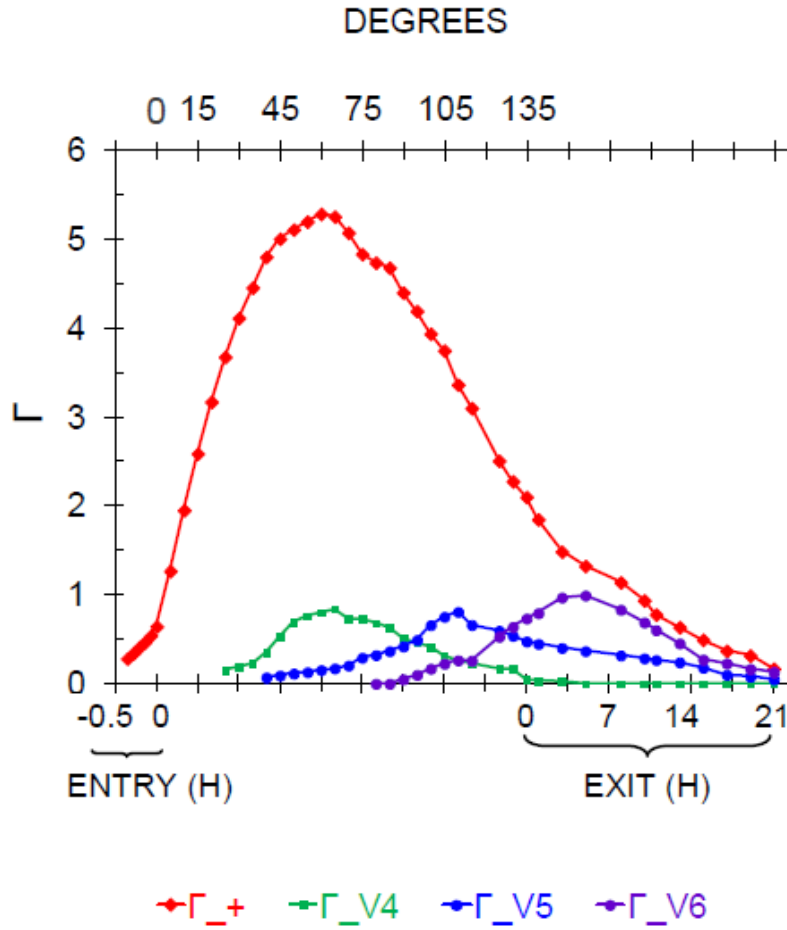


Figure 6.13 Streamwise variation of non-dimensional circulation magnitude, Γ , of the vortical structures associated with the main cell of cross-stream circulation in the 135° bend ($\Gamma_+ = \Gamma_{V1} + \Gamma_{V2} + \Gamma_{V3}$), the main inner bank SOV cell (Γ_{V4}), the (counter-rotating) secondary outer bank cell (Γ_{V5}) and the SOV cell associated with the main cell of cross-stream circulation in the straight outflow reach (Γ_{V6}). The circulation is non-dimensionalized by UH .

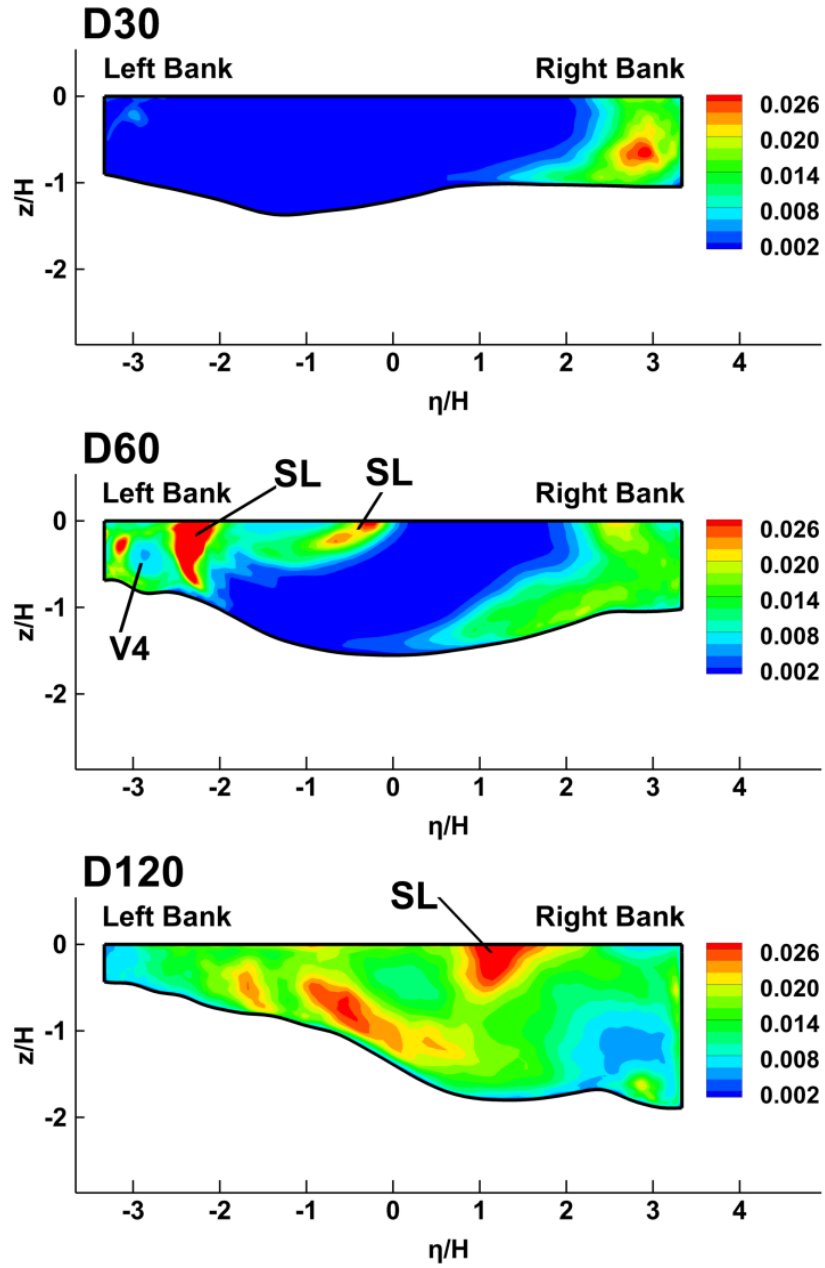


Figure 6.14 Turbulent kinetic energy, $100k/U^2$, in sections D30, D60 and D120 for the 135° bend.

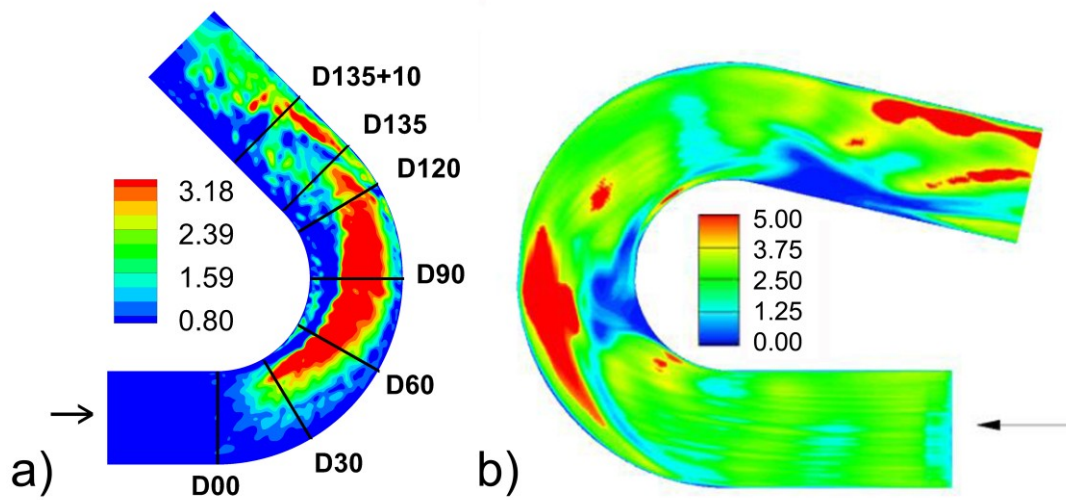


Figure 6.15 Distribution of the non-dimensional shear stress magnitude, τ/τ_0 , at the bed. a) predicted by LES for 135° case; b) predicted by DES for 193° case. Note the different color scales in a) and b). Need to add a) and b) to this diagram.

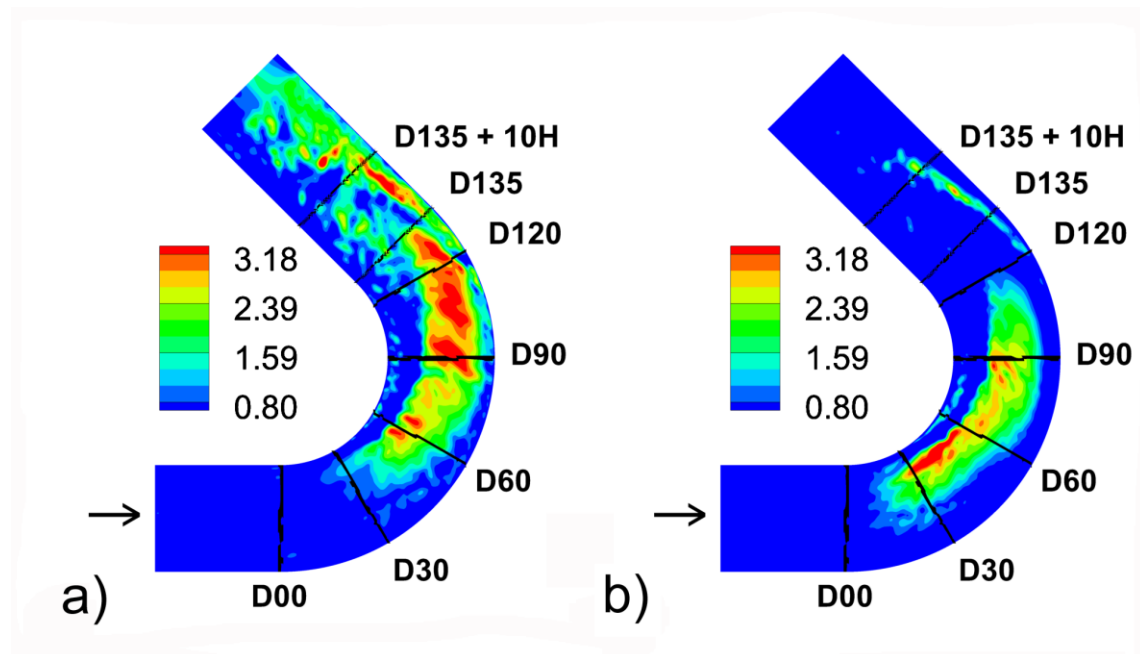


Figure 6.16 LES predictions of the a) streamwise and b) transverse components of the non-dimensional bed shear stress.

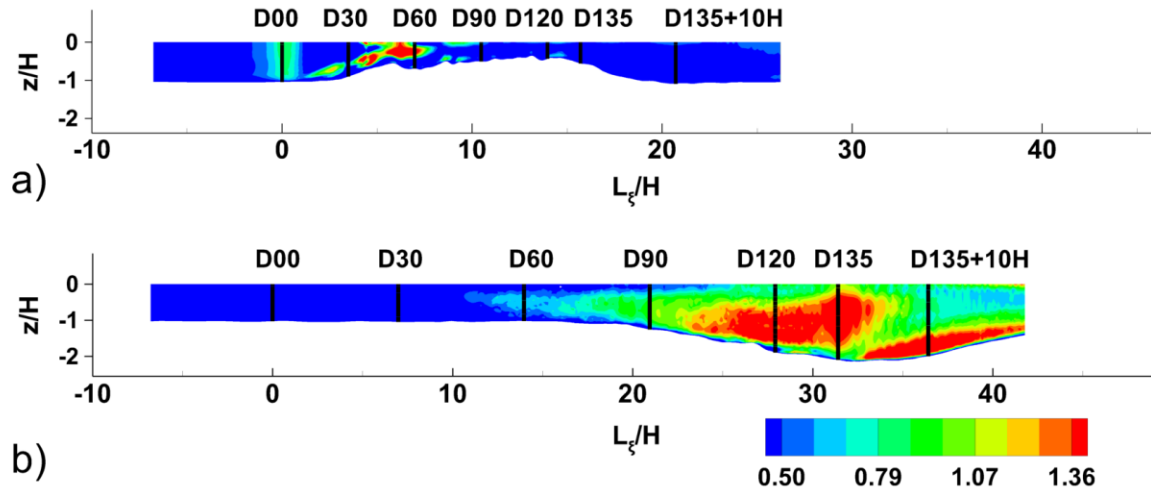


Figure 6.17 Non-dimensional shear stress magnitude, τ/τ_0 , at the channel sidewalls. a) Inner bank and b) outer bank. L_ξ is the streamwise distance measured along the channel sidewall.

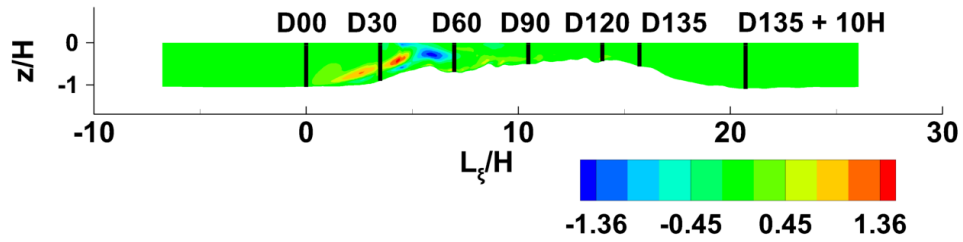


Figure 6.18 LES predictions of the vertical component of the non-dimensional shear stress at the inner bank. L_ξ is the streamwise distance measured along the channel sidewall.

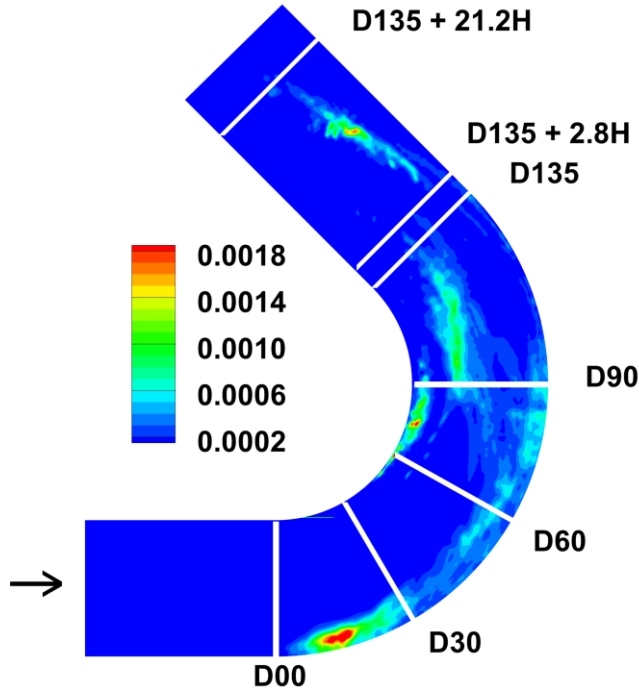


Figure 6.19 Distribution of the mean pressure fluctuations, $\overline{p'^2}/\rho^2 U^4$, at the channel bed predicted by LES for 135° case.

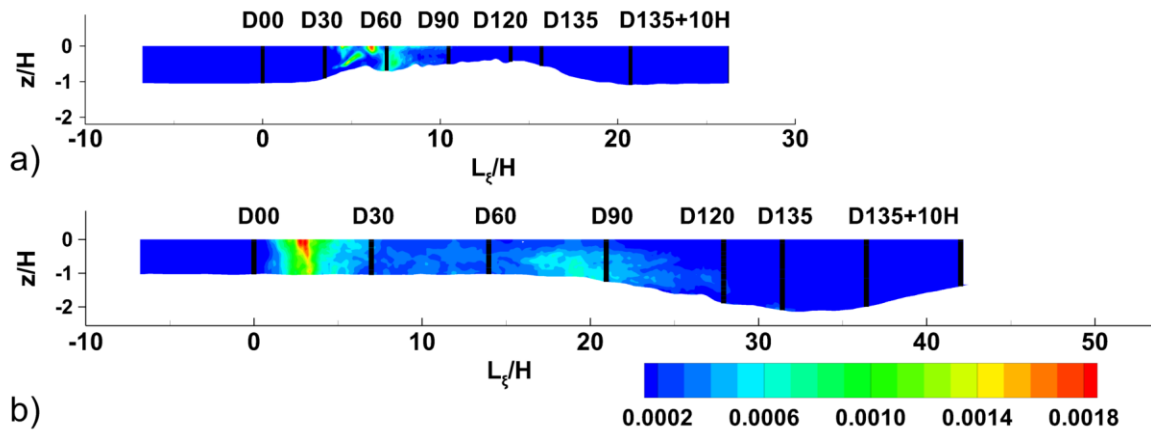


Figure 6.20 LES predictions of the distribution of the mean pressure fluctuations, $\overline{p'^2}/\rho^2 U^4$, at the channel sidewalls: a) inner bank; b) outer bank for the 135° case.

CHAPTER 7: COHERENT STRUCTURES AND SCOUR MECHANISMS AROUND SUBMERGED GROYNES IN A HIGH CURVATURE CHANNEL BEND USING LARGE EDDY SIMULATION: PART I, INITIAL STAGE OF SCOUR

7.1. ABSTRACT

Groynes are a type of flow deflecting structure that are often used to protect against outer bank erosion in river bends. Although they can be very effective under normal flow conditions, their performance is variable, and they often lead to excessive scour in high curvature bends (radius of curvature (R)/channel width (B) ≤ 3). A Large Eddy Simulation (LES) numerical model is employed in this study to investigate the nature of coherent structures and mechanisms leading to scour around a series of submerged groynes in a high curvature ($R/B=1.5$) bend during the initial stages of scour corresponding to a flat sediment bed. Submerged groynes are of interest as they correspond to flood conditions when severe erosion may occur, and which should be regarded when considering groyne design. In this study, the main indicators of scour are predicted high levels of bed friction velocities that exceed Shields critical value and/or high levels of mean pressure fluctuations. The groynes were found to increase both the size and strength of the counter-rotating outer bank cell which is normally present in high curvature bends during initial stages of scour. This outer bank cell was found to keep the core of high streamwise velocity away from the outer bank wall in the region where the groynes were installed. However, downstream of the groyne field, this cell had the potential to endanger outer bank stability by advecting high streamwise velocities very close to the outer wall. Wall friction velocities were also amplified at the outer bank where flow accelerated over the groynes. High levels of mean pressure fluctuations were found along the outer bank wall above the groyne base below a

counter-rotating overtopping vortex that formed as flow exited each embayment, and downstream of the groyne base due to a separation vortex present along each groyne lee-sidewall. Horseshoe necklace vortices (HVs) induced very high levels of bed friction velocities immediately in front of the groyne tips. A very large area of very high mean pressure fluctuations was also present at the bed around the first groyne tip due to the interaction of this groyne with the main channel helical flow.

7.2. INTRODUCTION

In nature, as erosion and deposition processes shape a channel course, there is a tendency for rivers to adopt a meandering form. Channels remain straight when little or no erosion occurs, but will develop some type of meander form when bank erosion occurs (Knighton 1998). For this reason, it is of greater practical interest to study river bends as opposed to straight reaches, as they are more common, and are in greater need of engineering bank stabilization techniques due to the higher levels of scour which they experience. Bank erosion occurs in bends mostly along their outer bank due to the development of secondary cross-stream circulation induced by centrifugal forces. This cross-stream circulation leads to an increase in velocity gradients at both the bed and banks, which in turn increases levels of boundary shear stresses and scour (Kashyap *et al.* 2012). Outer bank erosion and bend migration can be particularly problematic in sharp bends which have a ratio of radius of curvature to bend width ($R/B \leq 3$). From an engineering perspective, it is of interest to control bank erosion as it may cause rivers to impinge upon existing urban developments such as highways and residential lands. It may also lead to the loss of productive and valuable agricultural land, and in areas where soils are unstable, it can cause devastating landslides. River migration poses risks to established bridges, as it can lead to undermining of bridge foundations. This

was demonstrated in the collapse of a bridge on the Hatchie River near Covington, Tennessee in 1989, where bridge undermining due to channel migration led to the death of eight people and the collapse of three roadway spans (Lagasse *et al.* 2004). In recent years, there has been an increased interest in the use of flow deflecting structures such as groynes, which provide a cost effective and environmentally friendly way to deter river bend erosion and migration (Papanicolaou *et al.* 2011; USDA 2007a; USDA 2007b).

Groynes are linear structures, often installed in series at an angle with the river bank line. As mentioned, they are commonly used to deter bank erosion and they may also serve to improve the navigability of a channel by deepening a river close to its centerline. They perform additional functions such as aiding in flood management (Yossef 2005; Hudson *et al.* 2008), and improving aquatic habitats (Kuhnle *et al.* 2002). Many types exist, which have been classified by Przedwojski *et al.* (1995). For example, groynes may be permeable or impermeable, they may be submerged or emergent with respect to normal water levels, and they may be designed to attract or deflect flow. This study examines a particular type of groyne known as a 'stream barb', which points in the upstream direction, and is designed primarily for preventing bank erosion. Stream barbs are constructed of rock, and have a gradually-sloped weir top that is normally partially submerged below the water surface. The findings of this study however, are widely applicable to many types of river groynes used for erosion mitigation, and so the more common term 'groyne' is used in this study to refer to stream barbs. Unlike many conventional stream bank protection measures, groynes are considered to be proactive. Revetment methods such as bed mattresses and riprap work mostly to increase the erosion resistance of banks, but may not prevent the river from re-

establishing its own meander pattern (USDA 1996). Groynes however, disrupt high velocity gradients in the near bank region, and deflect flow and secondary currents away from the river bank, thus moving the channel thalweg closer to the centerline (Matsuura and Townsend 2004).

Studies have shown that determining the optimum configuration for groynes in a channel bend can be difficult. Although several design guidelines exist (Beckstead 1978; USDA 2005), these are based largely on insight gained from field and experimental trials, and from expert opinion. The design of groynes for sharp bends presents an even greater challenge, as performance here is often variable. Flow in sharp bends is more complex than in milder curvature bends, and it shows a nonlinear interaction between the cross-stream circulation and the main channel flow (Blanckaert and de Vriend 2003; Zeng *et al.* 2008). Nevertheless, groynes have been very effective in some situations. A three year assessment of groynes in a sharp bend on the Calapooia River in Oregon, showed groynes to perform very effectively in preventing river bend migration. Prior to the installation of groynes, the river bend was migrating at a rate of 3 m/year (USDA 2007a). On Chalk Creek in Summit County, Utah, groynes effectively prevented bank migration in several reaches. However, on one reach with very high curvature, appreciable scour occurred between the groynes (USDA 2007b). Bendway weirs, which are very similar in structure to groynes, have also shown variable results in sharp bends (Jia *et al.* 2009; WST Inc. 2002). A better understanding of the flow physics, and the mechanisms leading to scour around groynes, may provide greater insight into how to improve the design of groynes and similar structures for sharp channel bends.

Over the years, many studies have investigated flow and scour around groynes in a channel bend. Early experimental/field studies have revealed that factors such as groyne spacing, geometry, and the angle they make with a river bankline, can greatly influence scour distributions (Beckstead 1978; Copeland 1983; Prezedwojski *et al.* 1995). Investigations for sharp bends have shown that scour distributions are highly sensitive to groyne configuration. In particular, Matsuura and Townsend (2004) determined that for submerged groynes, placing one groyne upstream of where scour first impacts the outer bank has a detrimental effect on groyne performance, while placing one additional groyne downstream of the bend decreases outer bank erosion. The USDA (2005) recommends that for sharp bends, groyne spacing should be tighter, and the angle a groyne makes with a river bankline should not exceed 25° . Numerical models have been used to reveal further details of flow around groynes in a sharp bend. The majority of these studies however, have used Reynolds Averaged Navier Stokes (RANS) models (Jia *et al.* 2001; Jia *et al.* 2005; Jia *et al.* 2009; Minor *et al.* 2007a; and Minor *et al.* 2007b). While these studies have uncovered valuable information on details such as secondary circulation patterns, and distributions of parameters such as velocity, vorticity, and bed shear stress, they are unable to capture the details of coherent structures over a wide range of eddy sizes. Submerged groynes are subject to complex 3-D flow patterns, massive separation, and complicated flow structures, and therefore use of an advanced eddy-resolving numerical model such as Large Eddy Simulation (LES) may provide further insight into the nature of flow around them in a sharp bend.

Mechanisms leading to scour around groynes can be complex, and the presence of coherent structures and eddies near boundary surfaces can increase levels of turbulence intensity, which can induce erosion by increasing boundary shear stresses above their mean values. Regions which may be prone to scour due to higher turbulence levels can be identified by high mean pressure fluctuations ($\langle p'^2 \rangle / (\rho^2 U^4)$). The capacity of coherent structures and turbulence to induce erosion in river applications has previously been seen. Constantinescu *et al.* (2011b) demonstrated the important role of coherent structures in erosion of river confluences. Eddy-resolving numerical studies of groynes in a straight channel have been conducted by McCoy (2006), Koken and Constantinescu (2008a), and Koken and Constantinescu (2008b). These studies have shown that in fully turbulent flow, horseshoe vortices form at the bed near the groyne tip which can significantly amplify levels of mean pressure fluctuations and shear stress at the bed beneath them. Also, Weitbrecht *et al.* (2002) and Uijttewaalt *et al.* (2001) have conducted experiments which have shown that complex mixing layers form at the interface between the groyne embayment and the main channel flow in a straight channel due to differences in flow velocities. Highly energetic eddies present within these mixing layers can induce scour at the bed. The case of groynes in a channel bend is more complex due to the interaction of the groynes with the helical flow pattern. Studies have shown that groynes create an additional secondary circulation cell of direction opposite to that of the original helical flow cell which may help protect the outer bank from erosion (Minor *et al.* 2007b; Jia *et al.* 2009). To date however, there are no known studies that have investigated the detailed flow physics around groynes in a channel bend using an eddy-resolving numerical method. Thus, the objective of this study is to use a 3-D LES model to investigate coherent structures and mechanisms leading to scour around

groynes in a high curvature ($R/B=1.5$) channel bend during the initial stages of scour. Submerged groynes are being investigated as they correspond to flood conditions when severe amounts of scour can occur, and therefore should be considered in the design process.

7.3. METHODS

7.3.1. Numerical Solver

The LES solver used in the present work was developed by Mahesh *et al.* (2004). It employs a finite volume method to solve the 3-D spatially filtered Navier Stokes equation given by Equation 7.1 in tensor notation, on a hybrid unstructured grid.

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j}, \frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (7.1)$$

Here the overbar denotes spatial filtering, $\partial \tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j = 2\nu_t \bar{S}_{ij}$ are the subgrid stresses, and ν is the kinematic viscosity, and ν_t is the turbulent eddy viscosity. The LES code is a parallel message passing interface (MPI) solver that uses a collocated finite-volume scheme. In the predictor-corrector formulation the Cartesian velocity components are defined at the center of the cell and the face-normal velocities are treated as independent variables. The fractional step algorithm is second order accurate in both space and time. All the operators in the code, including the convective terms, are discretized using central schemes. The numerical scheme used to solve the Navier-Stokes equations discretely conserves energy. This increases the robustness of the numerical algorithm with the use of numerical dissipation which is essential for accurate LES. Time discretization is achieved using a Crank Nicholson scheme for the convective and viscous operators in the momentum

(predictor step) equations. The system resulting from the implicit time discretization is solved using the successive over-relaxation (SOR) method. The pressure equations are solved using a conjugate gradient method with preconditioning. No wall functions are used, and the governing equations are integrated through the viscous sub-layer. A constant Smagorinski SGS model is used to solve for the subgrid stresses in Equation 7.1 in order to avoid instabilities due to the complex domain geometry and the high Reynolds number involved. Further details on the LES code are given in Appendix A.

7.3.2. Simulation Setup

The numerical domain, flow conditions, and geometry were modeled after a physical groyne experiment conducted at the University of Ottawa in a 135° bend flume. Infact, two experiments with relevance to the current study were conducted, including a flat fixed bed experiment without groynes, and an equilibrium scour experiment with groynes. The two LES cases referred to in this study are one with a flat fixed bed without groynes (FB), and one with a flat fixed bed with groynes (FBG). The bend was a high curvature ($R/B=1.5$) 135° channel with a straight inlet and outlet section. For case FBG, three submerged groynes were placed over the flat fixed bed (Figures 7.1 and 72). The main flow parameters used in the simulations are shown in Table 7.1. The water depth (H) and discharge (Q)= $6.67U/H^2$ were both constant. The bed slope and the water surface slope in the model were both assumed to be zero. The bed slope in the experiment was also zero, and the water surface slope was smaller than the measurement accuracy of the survey instruments. Flow was run such that the bed friction velocity (u^*) in the straight inlet section was below the Shields critical value. The simulation was run non-dimensionally such that the water depth (H) was used as the length scale and the mean inlet flow velocity (U) was used as the velocity scale.

The modelled flume contained a straight inlet section of length $L=14.55H$ and a straight exit section of length $L=11.89H$ (Figure 7.1).

The size, spacing, and location of the groynes were based on previous studies conducted at the University of Ottawa (Matsuura 2004; Minor 2006), and on design guidelines from the USDA (2005). It should be noted that while attempts were made to determine the best configuration for the groynes, the final configuration may not have been optimum for preventing outer bank scour. It was however, adequate to gain an increased knowledge of the coherent structures and mechanisms leading to scour around the groynes. The geometry chosen for the groynes was of a simplified prismatic shape in order to accommodate modeling and meshing requirements for the LES. The top crest of the groyne sloped downwards from the bank at an angle of 6.5° from the horizontal, and the groyne side walls were vertical. The submergence ratio (H/D), where D is the groyne height, ranged from 1.85 at the base of the groyne near the channel outer bank, to 4.29 at the groyne tip. The width ranged from $0.57H$ at the base to $0.33H$ at the tip. The groyne centreline length was $4.00H$, and made an (upstream-side) angle of 25° with the tangent to the outer bank. The first upstream groyne was placed at the point where erosion first impacted the outer wall, as determined from the experimental run. Placements of subsequent downstream groynes were determined using the midpoint spacing method recommended by the USDA (2005) and used by Matsuura (2004). The spacing along the outer bank wall between the groyne centrelines was $4.77H$.

Fully developed mean velocity profiles for the LES inlet were obtained from a preliminary RANS simulation conducted in a straight rectangular channel with the same width (B) and depth (H) as the bend, and the same flow conditions as given in Table 7.1. Zero mean turbulent velocity fluctuations were developed in a separate LES model under the same flow conditions, and were superimposed on the mean velocities obtained from the RANS model to create the final LES fully developed turbulent inlet velocity profiles. All solid boundaries including the fixed bed and the vertical sidewalls were modelled using a ‘non-slip’ boundary condition without wall functions. Wall functions for the LES were not necessary, as the mesh spacing at the solid boundaries was small enough to resolve the viscous sublayer. The LES flow conditions were assumed to be hydraulically smooth, which is considered to be reasonable as the flow conditions in the experiments were also close to being hydraulically smooth. Hydraulically smooth conditions are considered to occur when the height of the effective roughness (k_s) is much less than the viscous sublayer height (García 2008). Therefore, although the LES did not account for k_s at the bed, the effects of roughness on the velocity profiles should have been less than if the flow had been hydraulically rough. The free surface was modeled using a symmetric boundary condition, assuming a rigid lid approximation. This is acceptable (see also discussion in Zeng et al., 2008, van Balen et al., 2010, Constantinescu *et al.*, 2011a) because of the low value (<0.3) of the Froude number (Table 7.1). A convective boundary condition that allows turbulent eddies to exit the computational domain without generating spurious oscillations close to the exit boundary was used at the outlet. The unstructured mesh contained only hexahedral cells and was generated using a paving technique in horizontal planes. It consisted of a total of 6.6 million grid points, including 50 grid points in the vertical direction. The grid cell closest to the bed

and sidewalls usually had a non dimensional size of $(\Delta n/H) \sim 0.0009$, or less than three wall units, which is less than the viscous sublayer height. One wall unit refers to $y^+ = 1 = (\text{Re})(u^*/U)(\Delta n/H) = u^* \Delta n/\nu$. The maximum cell at the surface had $(\Delta n/H) \sim 0.0907$ or about 300 wall units. It should be noted however, that y^+ at the outer bank wall reached up to 20. Friction velocities at the outer bank wall therefore were calculated at $y^+=100$, and multiplied by a factor of 4.2, which was determined to be adequate to give an approximate estimate of friction velocities.

7.3.3. Validation Methods

In order to demonstrate the predictive ability of the LES model, the results for the flat bed case without groynes (FB) are compared to measurements taken from the flat fixed bed flume experiment without groynes, and also to results from a 3-D RANS model, run with a flat fixed bed without groynes. Case FB was chosen for validation since experimental measurements were not available for the flat bed case with groynes (FBG). Validation of case FB will demonstrate the ability of LES to predict flow in a high curvature bend under flat bed conditions, where topographic steering effects are not present. It should be noted that this is the first time that the present LES code has been validated at such a high Reynolds number ($\text{Re}=60\,000$). Experimental validation for the deformed bed case with groynes (DBG) is also provided in Kashyap (2012, Chapter 8).

7.3.3.1. Experimental Methods

The 135° flat bed experiment without groynes was conducted at the University of Ottawa in a flume with a 12.2m straight entrance section, a 3.6m curved section, and a 2.4m straight exit section. The channel side walls were vertical, and $R=1.5\text{m}$, and $B=1\text{m}$. The bed was

fixed using a bed hardening technique described in Kashyap *et al.* (2010) [see Chapter 9], such that it was at a constant elevation throughout the channel. The flow depth (H)=0.15m and discharge (Q)= $6.67U/H^2$ were constant, and the main flow parameters are given in Table 7.1. ADV velocity measurements were taken at the center of six equal 16.67cm intervals across the 1m flume width, and measurements along the vertical were taken at intervals of 1 to 2cm or less. The ADV sampling frequency for all measurements was 200Hz, and measurements were taken for two minutes at each point location. Further details on the experimental methods and flume details can be found in Kashyap (2012, Chapters 5 and 6) and in Post (2007), respectively.

7.3.3.2. RANS Setup

The RANS model used a 3-D steady finite volume method with an RSM turbulence closure. The software of choice was Fluent (Fluent Inc. 2006). The simulation was run in a 135° bend flume with the geometry shown in Figure 7.1, but without groynes. The values of the main flow parameters are given in Table 7.1. Again, the water depth (H)=0.15m, flume width (B)=1m, and flow discharge (Q)= $6.67U/H^2$ were constant. The distributions of velocity and turbulence variables in the inlet section were developed from a preliminary RANS solution of fully-developed turbulent flow in a straight reach with the same width, depth and flow discharge. The bed was flat and fixed, with a constant roughness (k_s) of 0.698mm. The vertical walls and bed were modeled as ‘no-slip’ surfaces with non-equilibrium wall functions at the solid boundaries. The free surface used a rigid-lid approximation with a symmetric boundary condition, and the outlet was set to a free convective outflow. The mesh consisted of hexahedral elements with a total of about 3.4 million hexahedral nodes (37 nodes in the vertical x 160 nodes in the spanwise x 580 nodes in the longitudinal directions).

The mesh spacing at the walls and bed was $y^+ < 8.5$. Further details on the RANS numerical setup can be found in Kashyap (2012, Chapter 5).

7.4. RESULTS AND DISCUSSION

In the following results it should be noted that positive streamwise vorticity refers to flow rotating in the clockwise direction when facing in the downstream direction, and negative streamwise vorticity refers to flow rotating in the counter-clockwise direction.

7.4.1. Validation of the LES Model

Scatter plots showing the agreements between simulated and measured velocity magnitudes for points located between the 0° and 135° sections and their associated statistics are shown in Figure 7.3 and Table 7.2, respectively. It was found that the mean absolute error (ϵ_a) and root mean square error (ϵ_{rms}) were 49% and 34% greater, respectively, for the LES results compared to the RANS results. Nevertheless, errors for both models were considered to be relatively low, with more than 95% of the data falling within the range $0.75 < d < 1.33$, where d is the ratio of simulated to measured velocity magnitude. The small cluster of points in Figures 7.3a and 7.3b where the simulated velocity magnitude has an error greater than 15% (i.e. is above the +15% error line) occurred for points located very close to the bed. Small variations in the elevation of the fixed bed in the experiment resulted in the bed being a fraction of a centimeter ($< 5\text{mm}$) above the zero reference height in some locations. As a result, these measurements were slightly closer to the bed than the corresponding numerical points. This resulted in higher error for this cluster of points, due to the high vertical gradient of streamwise velocity near the bed. For the LES plot in Figure 7.3b, points where the LES underpredicted velocity magnitudes by more than 15% occurred mostly at locations very

close to the inner bank wall. This is likely due to the complex nature of the flow and flow structures present near the inner bank wall, which may lead to greater variations in the levels of velocity.

The contour plots of streamwise velocity (u_z/U), streamwise vorticity ($\omega_z H/U$), and 2-D streamlines help explain differences in the agreement between the simulated and measured results (Figures 7.4 to 7.6). For all sections, the distributions of simulated u_z/U agreed well with the measured ones. In the 45° section (Figure 7.4) high u_z/U are located close to the inner bank wall, which is expected for flow in high curvature bends, and is due to a potential-vortex effect (Blanckaert and de Vriend 2005). In the downstream sections (75° and 120°), the core of high u_z/U gradually moves towards the outer bank wall as the end of the curved reach is approached. The distribution of u_z/U however, is quite skewed across the section width. The greatest differences in u_z/U occur very close to the inner and outer bank walls. These regions are difficult to validate since ADV measurements cannot be taken very close to the flume walls. For the present study, it was found that placing the ADVs closer than 8.3cm to the bank walls lead to excessive measurement noise. For this reason, some of the flow structures predicted by the LES at the inner and outer banks could not be fully validated. In all three sections the 2-D streamline plots showed that the LES predicted a clockwise rotating circulation cell close to the inner bank, and a counter-clockwise cell near the free surface close to the outer bank (Figures 7.4c to 7.6c). These types of flow structures have previously been seen in the numerical and experimental study of van Balen *et al.* (2010), which investigated flow in a high curvature 193° bend during initial stages of scour. The RANS results in the present study (Figures 7.4c to 7.6c) do not clearly predict the inner

bank cell in the 45° and 75° sections, and do not predict the outer bank cell in any of the sections. Although the inner bank and outer bank circulation cells could not be fully resolved in the experiments (Figures 7.4c to 7.6c), the 2-D streamline patterns give strong evidence that such cells were likely present. In summary, it can be said that although the LES results showed slightly greater errors in velocity magnitudes, it seemed to better predict the circulation cells within the flow compared to RANS.

7.4.2. Streamwise Velocity Distribution and Cross-Stream Circulation Strength

The LES results agreed well with previous studies that have investigated flow in sharp bends (Blanckaert 2010; Zeng *et al.* 2008). As mentioned, the LES predicted expected flow patterns characteristic of flow in high curvature bends. For case FB, the depth averaged streamwise velocity plots show that the main core of high u_z/U is located close to the inner bank near the beginning of the curved reach, and then moves towards the outer bank near the end of the curved reach (Figure 7.7a). For case FBG, the groynes do not greatly alter the distribution of depth averaged u_z/U within the bend region, except in the groyne field along the outer bank where depth averaged u_z/U is lower (Figure 7.7b). Although generally the core of high u_z/U also appears to be further from the outer bank over the whole flow depth (as can be seen in the 90° section plots for case FB in Figure 7.7c, and for case FBG in Figure 7.7d), it will be seen later that friction velocities around the groynes on the outer bank wall can be very high. Values of depth averaged u_z/U have increased slightly in the region near the inner bank, likely due to the flow constriction caused by the groynes (Figure 7.7). Values of depth averaged u_z/U are also less in the straight exit reach along the outer bank for case FBG compared to case FB. This is because for case FB the main core of high u_z/U is located closer to the outer bank wall in this region, and is also more evenly distributed over

the entire flow depth compared to case FBG (Figures 7.7e and 7.7f). As will be discussed in greater detail later, a counter-clockwise rotating cell (C1) exists along the outer bank close to the free surface in this region for both cases. The size and strength of this outer bank cell is much greater for case FBG, which makes it more effective in keeping the core of high u_{ζ}/U away from the outer bank near the free surface. This is what causes the region of depth average u_{ζ}/U to be lower in the straight exit reach along the outer bank for case FBG. However, slightly below the free surface the greater strength of the outer bank cell for case FBG causes high u_{ζ}/U to be advected towards the outer bank wall (Figure 7.7f). Infact, the clockwise-rotating cell at the bed near the outer bank wall also helps to advect high streamwise u_{ζ}/U towards the outer wall. As can be seen in Figure 7.8a and 8b, this causes values of friction velocity magnitude (u^*/U) at the outer bank wall in this region to be much greater for case FBG compared to case FB. Therefore, while this outer bank cell can partly protect the outer bank from erosion close to the free surface, it can also precipitate scour by advecting high u_{ζ}/U below it towards the outer bank, if its circulation strength is great enough. This supports the observation of Bathurst et al. (1979) that the advection of high momentum fluid towards the base of the outer bank by the outer bank flow cell can endanger bank stability.

Curvature induced circulation is a characteristic of open channel bend flow, and the mechanisms causing it have been discussed thoroughly by Blanckaert and de Vriend (2004). Cross-stream circulation is important to consider, as it influences the rate at which streamwise velocity is advected towards the outer bank, and may also increase values of cross-stream velocity close to the bed (Zeng *et al.* 2008). The cross-stream circulation can

also advect high u_{ζ}/U close to the bed. For the above reasons cross-stream circulation cells can have important implications on the magnitude of total friction velocity at the boundaries. The distribution of the cross-stream circulation magnitude (Γ) for some of the main circulation cells, as predicted by LES, is shown in Figure 7.9a for cases FB and FBG. Γ is calculated in planes cut perpendicular to the axis of the streamwise oriented vortex (SOV), and is the integral of the streamwise vorticity ($\omega_{\zeta}H/U$) over the cross sectional area of the SOV. Γ_+ is used to represent the strength of the large main channel helical flow cell and is calculated from the sum of Γ for the main clockwise rotating SOVs M1, V1, and V3 shown in Figures 7.9b and 7.9c. For both cases Γ_+ increases rapidly in the upstream half of the bend, and peaks at around 60° for case FB, and around 75° for case FBG (Figure 7.9a). It then decreases more gradually over the remaining length of the bend. The counter-clockwise rotating outer bank cell (C1) can be seen at the outer bank in Figures 7.9b and 7.9c. This type of cell has been previously reported in other bend studies (Zeng *et al.* 2008; van Balen *et al.* 2010). As mentioned, Bathurst *et al.* (1979) have reported that such a cell can endanger bank stability by advecting high momentum fluid towards the base of the outer bank. Other authors have also found that such a cell protects the outer bank from erosion by keeping the core of high u_{ζ}/U away from the outer bank (Blanckaert and Graf 2001). For case FB, C1 starts to form at about 25° and extends far into the straight exit reach. The circulation strength of C1, Γ_{C1} , however is considerably weak compared to the main channel helical flow cell. Nevertheless, it is still found to be able to reduce the gradient of u_{ζ}/U near the outer bank close to the free surface. For case FBG, C1 starts to form around 15° . In this case the groynes increase both the size and strength of C1 downstream of 60° . The groynes are able to increase Γ_{C1} by up to five times, compared to when the groynes are not present. As

noted above, C1 helps keep the core of high u_{ξ}/U away from the outer bank, which results in the lower values of depth averaged u_{ξ}/U found along the outer bank near the groynes for case FBG in Figure 7.7b. This finding is important, as it demonstrates that the groynes help to keep the core of high u_{ξ}/U away from the outer bank in the region where they are installed. One must keep in mind however, that friction velocity magnitudes at the outer bank near the groynes are generally greater for case FBG compared to case FB (Figures 7.8a and 7.8b). The reasons for this will be investigated in greater detail later in this chapter.

7.4.3. Coherent Structures

The main coherent structures found around each groyne, as predicted by LES in the mean flow field for case FBG, are shown in Figure 7.10. In this figure, the flow structures are represented by Q criterion ($Q = -0.5(\delta u_i/\delta x_j)(\delta u_i/\delta x_j)$), which is the second invariant of the velocity gradient tensor (Hunt *et al.* 1988). The main structures include horseshoe necklace vortices (HVs), which are located at the bed near the groyne tip, a separation vortex (SV), which is located on the lee side of the groyne along its length, an overtopping vortex (OTV), found immediately above the groyne along the outer bank wall, and a trailing junction vortex (TJV), located along the outer bank near the bed, immediately downstream of the groyne base. These structures, and their capacity to induce scour, in relation to the plots of boundary friction velocity and mean pressure fluctuations ($\langle p'^2 \rangle / (\rho^2 U^4)$) shown in Figure 7.8, are discussed in the following sections. It should be noted that for the remainder of this chapter the following naming convention will be adopted for the groynes based on their locations (see Figure 7.1): the first upstream groyne is called G1, the second downstream groyne is called G2, and the third downstream groyne is called G3. It should be also noted that in

many of the figures presented, the number shown after each vortex name denotes the groyne number close to the flow structure.

7.4.3.1. Horseshoe Vortices

A HV system is found in front of each groyne tip and consists of a larger primary HV (HVP), and a smaller secondary HV (HVS) (as seen in Figure 7.11 in front of G2 in the instantaneous flow field). These HVs form as the boundary layer of the approaching flow separates due to an adverse pressure gradient near the groyne tips, resulting in the formation of long necklace-like structures that wrap around the front of each groyne. Koken and Constantinescu (2008a) give a more detailed description of the characteristics of these HVs. The locations of the HV systems relative to each groyne can be seen in Figure 7.12 by Q criterion in a horizontal plane cut at $Z/H=+0.05$ above the flat bed surface. Although the coherence of the legs of the HVs is quite low, making them difficult to visualize using Q criterion, it can still be seen that the legs are deflected into the flow at an angle parallel to the flow streamlines, which on the main channel side of the groynes is at an angle of 30° with the groyne centerline. For G2 and G3, the HV legs within the embayments are also deflected at an angle of about 30° from the groyne centerline, causing the HV system to be almost symmetrical about the groyne centerline. For G1 however, the HVP leg within the embayment stays very close to the groyne sidewall. This is because the main channel flow is directly entering this embayment due to the fact that there is no upstream groyne obstructing it. As a result, the flow within the embayment near the bed is directed towards the groyne sidewall, which pushes the HV leg towards the groyne sidewall.

Figure 7.13 shows the structure of each HV system in the mean flow in 2-D vertical planes cutting the centerline of each groyne (the location of the centerline is shown by line *a* in Figure 7.11). These plots show the distributions of turbulent kinetic energy (TKE) (top), total vorticity (middle), and 2-D streamlines (bottom) around the HVs near the tip of each groyne. The characteristics of the HVs will be described by examining the plots for G2 (Figure 7.13b). In this Figure 7.13b, HVP coincides with the large elliptical patch of high TKE (top) and high total vorticity ($\omega H/U$) (middle) located closest to the groyne tip. The elliptical patch of high TKE has three peaks, two located slightly above the bed, and one located very close to the bed. The two peaks above the bed are induced by low-frequency bimodal oscillations of HVP. The patch near the bed is due to the changing direction of the jet-like flow which develops beneath HVP. This change in direction occurs as HVP switches between zero-flow mode (where the core is almost circular and is situated closer to the groyne) and back-flow mode (where the core is more elliptical and is situated further from the groyne face). Devenport and Simpson (1990) and Koken and Constantinescu (2008a, 2008b) provide further details on the characteristics of these two dominant flow modes for horseshoe vortices. The smaller patch of high $\omega H/U$ seen upstream of G2 in Figure 7.13b (middle), is due to HVS. Unlike HVP, HVS does not undergo strong bimodal oscillations, and is not associated with high levels of TKE. The approximate locations of HVP and HVS can be seen in the plots of 2-D streamlines in Figure 7.13b. A quasi-steady separation bubble can also be seen above the groyne tip.

As can be seen in Figure 7.13, important differences exist in the intensities of the HVs in front of each groyne. Levels of TKE and total vorticity within the HV cores progressively

increase for each downstream groyne. These increases are likely caused by increases in the approach velocity in front of each groyne as the core of high u_z/U moves closer to the outer bank as the end of the curved reach is approached. As a result, the downflow velocity magnitude at each downstream groyne tip becomes greater. The increasing strength in HVP for each downstream groyne is also confirmed in the plot of circulation magnitude (Γ) shown in Figure 7.14. In this plot Γ_{HVP} is the out of plane vorticity integrated over the vortex cell area in a plane cut perpendicular to the axis of HVP. There is almost a twofold increase in Γ_{HVP} from G1 to G3. In all cases, Γ_{HVP} peaks along the groyne centerline, and decreases sharply away from the centerline. This decrease is so rapid, that Γ_{HVP} is almost zero at a distance equivalent to one flow depth away from the groyne centerline. The coherence of each HV also increases for each downstream groyne. Infact, HVS cannot even be resolved in front of G1 in the mean flow field (Figure 7.13a). In the instantaneous flow field (not shown), several eddies exist in front of G1 that merge and split, and at times, only one larger eddy is present. For groynes 2 and 3, the presence of HVS in the mean flow is a result of averaging of the smaller eddies in the instantaneous flow. This last observation was also seen by Koken and Constantinescu (2008a) for horseshoe vortices in front of a groyne in a straight channel. For the present study, the most intense bimodal oscillations for the HV occur immediately in front of the groyne tip. Past the corners of the groyne tip, the intensity of the bimodal oscillations is substantially reduced (not shown). Also, as HVP moves into backflow mode, the legs of HVP on the main channel side of the groyne move closer to the groyne sidewall, and eventually break away and dissipate into the flow (not shown). This intermittent shedding of the legs of HVP can cause some local sediment entrainment.

The HVs play an important role in the erosion process during the initial stages of scour. Within the curved section of the channel, the maximum levels of mean bed friction velocity are found immediately upstream of the groyne tips, below the HVs (Figure 7.8c). Here the bed friction velocities are more than twice the maximum levels found in the straight inlet section, and are greater than the Shields critical level for a $d_{50}=0.689\text{mm}$ (Rouse 1939). Bed friction velocity magnitudes also exceed the Shields critical level on the lee-side of the groyne, below the HV legs. However, high bed friction velocities in this area are mostly due to the acceleration of flow around the groynes. It is also useful to investigate the plot of instantaneous bed friction velocity magnitude shown Figure 7.15. While the plot of mean bed friction velocity in Figure 7.8d does not show high levels below the secondary horseshoe vortex, HVS, the instantaneous plot shows levels below HVS exceed Shields critical values for G2 and G3. Therefore the area that may be impacted by scour below the HVs in the instantaneous flow extends further upstream from each groyne compared to in the mean flow.

High $\langle p'^2 \rangle / (\rho^2 U^4)$ are also found in a very small area immediately upstream of the groyne tips below the HVs (Figure 7.8f), which may lead to local sediment entrainment. These pressure fluctuations increase for each downstream groyne. For G1 however, there is also a larger area of high $\langle p'^2 \rangle / (\rho^2 U^4)$ on the lee-side of the groyne which extends across the channel width to the central region of the channel (Figure 7.16a). These fluctuations are not directly related to the HV, but are due to the interaction of the groyne tip with the main channel flow. Figure 7.16a shows several streamwise orientated vortices N1, N2, N3 and N4, which are present in between the large area of high bed $\langle p'^2 \rangle / (\rho^2 U^4)$ and the groyne lee-

sidewall. These vortices are very weak and cannot be resolved by streamlines. It is not entirely clear how these vortices form. Vortices N1 and N2 are at an elevation close to the bed, while vortices N3 and N4 are at an elevation close to the upper surface of the groyne (Figure 7.16b). The angle that these vortices make with the groyne centerline depends on their elevation above the bed. Each one is advected by the local flow and is thus aligned parallel to the horizontal flow streamlines at that particular elevation. The direction of the flow streamlines change in accordance with the direction of the helical flow, and N1 and N2, which are close to the bed, are directed towards the inner bend, and N3 and N4, which are at a higher elevation, are directed almost parallel to the groyne.

7.4.3.2. Separation Vortices

Flow moving over the groyne from either within the groyne embayment or immediately in front of the groyne tip separates from the downstream edge of each groyne as shown in Figures 7.17a and 7.17b for G1. As a result, a strong counter-clockwise rotating separation vortex (SV) forms on the lee-side of the groyne along its length. The size of the SV is largest for G1 and smallest for G3 (Figures 7.17c, d, and e). The SV is situated just below the upper edge of the groyne, so as it reduces in size from G1 to G3 the core of the vortex becomes elevated higher above the bed. The intensities of the SVs also decrease for each downstream groyne, as shown in the plots of circulation magnitude (Γ_{SV}) in Figure 7.18. Γ_{SV} is equal to the out-of-plane vorticity integrated over the area of the SV in a plane cut perpendicular to the axis of the SV. Γ_{SV} also increases along the length of each groyne, from the groyne tip to its base at the outer bank. The shape of the SV is circular close to the groyne tip, and becomes skewed in the horizontal direction at the groyne base. The results also show that values of u_z/U are very low within the area of the SVs. Thus, as the SVs rotate in the

counter-clockwise direction, they are likely keeping high momentum fluid carrying high u_z/U away from this area. Cross-stream velocities below the SV near G1 are slightly elevated, which leads to a slight increase in cross-stream bed friction velocities (u_c^*/U) below the SV near G1. The SVs however do not cause appreciable amplification of bed friction velocity magnitudes, and only cause values to exceed the Shields critical level in a small region close to mid-length of G1 (Figure 7.8d). For the downstream groynes, G2 and G3, bed friction velocity magnitudes are also elevated on the lee-side of the groynes, but this is not due to the SVs.

The presence of the SVs may also have a beneficial effect, as they help to increase the intensity of the counter-clockwise rotating outer bank cell (C1), which, as discussed above, may protect the outer bank from erosion. At the outer bank, the SV is close to the wall over only a small length immediately downstream of the groyne base before it deflects towards the inner bank (Figure 7.17b). In this area the SV rotates in the counter-clockwise direction, and pushes high momentum fluid away from the outer bank wall, thereby reducing the streamwise component of outer bank friction velocity. The SV is contained within a larger counter-clockwise rotating cell, C1, and therefore does not act by itself in protecting the outer bank wall. As had been seen in Figure 7.9a, C1 maintains a high level of cross-stream circulation throughout the area where the groynes are installed. Overall, the SV contributes about 30% towards the magnitude of Γ_{C1} . In Figure 7.9a, the influence of the SV can also be seen by local peaks in Γ_{C1} that occur just past the end of each groyne. These peaks occur because SV extends past the end of each groyne by about 10° before its circulation becomes low, and hence its circulation is still high as the circulation of the SV for the downstream

groyne increases. The presence of both SVs in this area can be seen in Figures 7.17d and 7.17e.

A comparison of the outer bank wall friction velocity magnitudes for cases FB and FBG is given in Figures 7.8a and 7.8b, respectively. High levels of wall friction velocity magnitude are seen for FBG at mid-depth levels just downstream of the groyne bases. These areas however, do not appear to be caused by the SVs. There is a high gradient of streamwise velocities in this area. It is not fully clear where this high velocity fluid is originating from. As discussed previously, very high friction velocity magnitudes are also present downstream of G3. This is due to the advection of high u_z/U towards the outer bank wall by the counter-rotating cell C1 and the clockwise-rotating cell V4 (Figure 7.7f).

The SVs are also subject to high levels of TKE within their cores, and depending on their proximity to the bed can induce high mean pressure fluctuations at the bed below them. TKE levels are greatest near the groyne tip, and become less towards the groyne base at the outer bank. The SV near G1 amplifies mean pressure fluctuations at the bed between the groyne tip and the mid-length of the groyne. High $\langle p'^2 \rangle / (\rho^2 U^4)$ are also present at the outer bank wall below the SV (dashed circles in Figure 7.19a). The same locations are identified on the plot of streamwise vorticity parallel to the outer bank wall (Figure 7.19b). High $\langle p'^2 \rangle / (\rho^2 U^4)$ occur between the two areas with opposite signs of vorticity which correspond to opposite rotating circulation cells. The circulation cell with negative vorticity is located above the dashed circle and represents the counter-rotating SV. The circulation cell with positive vorticity is located below the dashed circle and represents the trailing junction vortex (TJV),

which forms downstream of the groyne at the junction of the outer bank wall and the bed. In Figure 7.19a it can be seen that mean pressure fluctuations due to the SV are relatively low downstream of G1, but increase for each downstream groyne.

7.4.3.3. Overtopping Vortices

Overtopping vortices (OTV) form as flow escapes from the embayments, and moves over the groyne surface close to the outer bank wall. Most of the fluid within the embayments exits upwards at the boundary between the groyne wall and the outer bank wall, rather than from the central region of the embayment. As discussed previously, flow moving over the groyne wall which is further away from the outer bank forms a separation vortex, SV on the lee-side of the groyne. At the back corner of the embayment part of the flow moves over the groyne and forms a counter-clockwise rotating OTV along the outer bank wall over the groyne surface. The flow which is not able to escape the embayment recirculates in a small volume close to the bed, in front of the corner junction of the groyne wall and the outer bank wall.

The recirculating flow in the area close to the bed may impact scour at the junction of the groyne upstream sidewall with the outer bank wall. A corner recirculation eddy forms here, as flow becomes trapped in front of the corner junction close to the bed (Figure 7.20a). This small eddy has a height of up to 20% of the groyne height at the outer bank, which corresponds to about 10% of the flow depth (Figure 7.20b). There is an almost dead zone present in this region, as the flow velocity is about zero. However, high $\langle p'^2 \rangle / (\rho^2 U^4)$ occur at the outer bank wall within this region, with values at least four times greater than levels on the surrounding wall (Figure 7.20c). An investigation of the instantaneous flow (not shown)

reveals that these fluctuations occur as flow moves against the corner junction, leading to an increase in pressure at the embayment corner. This causes the corner recirculation eddy to compress, and reduce in size. At a certain point, patches of high vorticity fluid are ejected from the recirculation eddy, causing pressure to decrease, and the size of the recirculation eddy to increase. This leads to increased $\langle p'^2 \rangle / (\rho^2 U^4)$ at both the outer bank wall and the bed surface in front of the junction. Bed friction velocity levels within this area, however, are low (Figure 7.8c), because the flow velocity is almost zero. It is interesting to note that although $\langle p'^2 \rangle / (\rho^2 U^4)$ are high along the outer bank wall immediately upstream of the groyne, TKE levels are very low (Figure 7.20d). This suggests that high momentum fluid does not enter the junction zone itself.

Flow exiting the back corner of the embayment forms an OTV over the groyne surface as shown in Figures 7.21a, 7.21b, and 7.21c, for G1, G2, and G3, respectively. This vortex stays very close to the outer bank wall above the groyne surface, but quickly deflects towards the main channel after moving past the groyne. The OTV can only be resolved by Q criterion after it has reached the groyne top surface after exiting the embayment. $\langle p'^2 \rangle / (\rho^2 U^4)$ are about four times greater below the OTV along the outer bank wall than levels on the surrounding wall (Figure 7.19a). The intensities of these fluctuations increase progressively from G1 to G3. Large values of $\langle p'^2 \rangle / (\rho^2 U^4)$ form within the gap between the OTV and the groyne top surface. This gap has a height of about 10% of the flow depth H . The mean pressure fluctuations are most intense at the upstream corner above the groyne base where flow is exiting the embayment. TKE levels associated with the OTVs are also

high, being about one order of magnitude greater than levels in the surrounding flow (Figures 7.21d, 7.21e, and 7.21f).

As the OTV is rotating in the counter-clockwise direction it plays a role in keeping high streamwise velocities away from the outer bank wall. This can be seen in distributions of streamwise velocity in Figures 7.21g, 7.21h, and 7.21i, which show planes cut perpendicular to the axis of the OTVs in locations shown by lines 1 to 3 in Figures 7.21a to 7.21c, respectively. In these plots the OTV can be seen on the right. Another counter-clockwise circulation cell is also present on the left in Figures 7.21h and 7.21i. This is the SV, which has been advected downstream from the upstream groyne. Figures 7.21b and 7.21c show the locations of the SVs relative to the OTVs. The SVs have an almost negligible circulation strength compared to the OTV in these locations. Thus, they do little in preventing high streamwise velocities from reaching the outer bank in this area. Also, although low outer bank wall friction velocities magnitudes coincide with the OTV when it is above the groyne top surface (Figure 7.8b), higher wall friction velocities occur immediately upstream of the top corner of the groynes (Figure 7.8b). These high values appear to be caused as flow accelerates over the upstream top corner of the groyne.

The cross-stream circulation magnitude (Γ_{OTV}) for each OTV along the groyne base is plotted in Figure 7.22. For each OTV there is a smooth decrease in Γ_{OTV} from the upstream groyne sidewall to the downstream groyne sidewall. Also, there is a progressive increase in the levels of Γ_{OTV} for each downstream groyne. This is consistent with the observations that mean pressure fluctuations increase from G1 to G3 on the outer bank wall above the groyne

base, and that Γ_{C1} for the counter-rotating outer bank cell C1 is increasing within the bend until the 135° section.

7.4.3.4. Trailing Junction Vortices

Long narrow streamwise oriented junction vortices (TJV) are present immediately downstream of each groyne base near the bed (Figure 7.23a). They rotate in the clockwise direction and extend from the neighbouring junction vortex forming between the adjacent groyne side wall and the flat bed. They are located very close to the bed (Figure 7.23b), and are small, occupying only up to 15% of the flow depth. It should be noted that the TJV are very weak, and other coherent structures that would normally be seen in Figures 7.23a and 7.23b have been blanked out. Figures 7.23c, 7.23d, and 7.23e, show the size and locations of the TJV by 2-D streamlines and out of plane vorticity for planes cut at lines 1, 2, and 3, respectively, shown in Figure 7.23a.

Although these vortices are small, due to their proximity to the bed, they have some ability to affect distributions of friction velocity. Cross-stream velocities below the TJVs are increased, leading to amplification of cross-stream friction velocities by about three to four times compared to levels in the straight inlet channel. For G1 and G2, total friction velocities below the TJVs are still below the Shields critical level. Downstream of G3 very high bed friction velocity magnitudes are seen along the outer bank wall which are close to the maximum bed friction velocities found within the curved reach of the channel. As this band of high bed friction velocities coincides with the location of the TJV downstream of G3, it is possible that the TJV is helping to advect high u_{τ}/U close to the bed. This however is not

entirely clear, as Figure 7.23h shows that the high u_z/U may also be present in this area due to the flow moving downwards as it reaches the outer bank wall.

7.5. CONCLUSIONS

The design of groynes for river bends has been a challenging task for river engineers, as currently little is known about the details of flow structures present around them, and mechanisms leading to scour. Coherent structures forming around these groynes are unique in that they are influenced by and interact with the distinctive helical secondary flow characteristic of channel bends. Sharp bends have presented the greatest challenges, due to the more complex helical flow which they are subject to. For the first time, this study has employed a 3-D eddy-resolving Large Eddy Simulation (LES) numerical model to investigate the nature of coherent structures around submerged groynes in a sharp channel bend during the initial stages of scour. The groynes in this study were submerged below the water surface, which corresponds to flood conditions when erosion can be more severe, and the three dimensionality of the flow is greatly enhanced.

The investigation confirmed that the groyne field was able to keep the the main core of high streamwise velocity and the primary secondary circulation cell away from the outer bank wall in the region where they were installed by enhancing the size and strength of the counter-clockwise rotating circulation cell along the outer bank. Bed friction velocities within the embayments were mostly reduced, which was also confirmed by the physical experiments that showed an accumulation of sediment within the embayments during the initial stage of scour. There was an increased potential, however, for scour on the vertical

outer bank wall, due to flow structures around the groynes which increased mean pressure fluctuations and wall friction velocities. Outer bank wall friction velocities also increased in areas where flow accelerated around the groynes as it moved up and out of the embayments. The characteristics of the main coherent structures present around the groynes as predicted by LES are summarized below.

1. The horseshoe vortices (HVs) which were located close to the bed around the groyne tips showed the greatest potential to cause scour in a small area immediately upstream of the groyne tips. In these areas bed friction velocities exceeded Shields critical level. Mean pressure fluctuations were also amplified below the HVs very close to the groyne tips. The HV legs were deflected into the flow in the direction of the flow streamlines at the bed. Thus, the characteristics of the HVs were influenced by interaction with the bulk primary and secondary flow field. During the initial stages of scour, the HVs had little impact on outer bank erosion, as the legs within the embayment did not elevate levels above the Shields critical bed friction velocity. However, they did lead to a slight amplification of bed friction velocities on the lee-side of the groyne, although flow acceleration around the groynes had a greater impact on bed friction velocities in this area. The intensities of the HVs increased for each downstream groyne, as did levels of bed friction velocity and mean pressure fluctuations. In order to gain proper insight for their design, it will be important to compare how these intensities change for the case of a deformed bed, when scour is close to equilibrium.

2. A separation vortex (SV) was present along the length of each groyne sidewall facing the main channel. This SV formed because flow moving over the groyne separated from the downstream groyne edge. It rotated in a direction opposite to the main channel helical flow. The implications of the SV on bed friction velocity at the bed depended on its proximity to the bed. When it was close to the bed it increased the radial component of bed friction velocity. Within the SVs however, the component of streamwise velocity was low, and therefore they had little impact on the streamwise component of bed friction velocity. Mean pressure fluctuation appeared high below the SV near the first upstream groyne, and decreased for each downstream groyne. The SVs also appeared to increase mean pressure fluctuations immediately downstream of the groyne base along the outer wall.
3. A counter-clockwise rotating overtopping vortex (OTV) formed over the top of the groyne surface, close to the outer bank wall, as flow exited the embayment at the junction of the groyne sidewall and the outer bank wall. Levels of wall friction velocity were elevated at the upstream top corner of the groyne base due to flow acceleration around the groynes. High levels of mean pressure fluctuations occurred just below the OTV above the groyne surface along the outer bank wall.
4. Clockwise-rotating junction vortices (TJV) were present close to the bed immediately downstream of each groyne base. The intensities of these vortices increased for each downstream groyne. Although these vortices were small and weak, they had the potential to slightly amplify bed friction velocities due to their proximity to the bed.

In summary, this study suggests that during the initial stage of scour, the HVs had a strong impact on bed scour, but had little impact on outer bank wall scour. The LES results revealed that the circulation strength for each HV increased for each downstream groyne because the main core of high streamwise velocity moved progressively closer to each downstream groyne. This demonstrates the importance of understanding the effect of flume geometry on the position of the main core of streamwise velocity within the flume, as it can directly impact the intensity of the HVs, which in turn can affect their ability to induce scour. At the outer bank wall the main mechanisms leading to scour were flow accelerating up and out of the embayments, flow being trapped at the downstream end of the embayments, and vortical structures such as the OTV and SV which increased mean pressure fluctuations in some areas.

7.6. NOTATION

B = channel width (m)

d = discrepancy ratio = ratio of simulated to measured velocity magnitude

d_{avg} = minimum discrepancy ratio

d_{50} = median sediment size (mm)

D = groyne height (m)

Fr = non-dimensional Froude number = $U/(gH)^{1/2}$

g = acceleration due to gravity (m/s^2)

H = water depth (m)

k = kinetic energy (m^2/s^2) = $0.5(\langle(u_1')^2\rangle + \langle(u_2')^2\rangle + \langle(u_3')^2\rangle)$

k_s = roughness value (mm)

L = length (m)
 p = pressure (N/m²)
 p' = pressure fluctuation (N/m²)
 Q = discharge (m³/s)
 r^2_{adj} = adjusted coefficient of determination
 R = radius of curvature at channel centerline (m)
 Re = non-dimensional main channel Reynolds number = UH/ν
 Re^* = non-dimensional particle Reynolds number = $u^* d_{50}/\nu$
 t = time (s)
 u = velocity magnitude (m/s)
 u^* = bed friction velocity magnitude (m/s)
 u_C = cross-stream velocity (m/s)
 u^*_C = cross-stream bed friction velocity magnitude (m/s)
 u^*_{cr} = Shields critical friction velocity (m/s)
 $\dot{u}_i$ = fluctuating component of velocity (m/s)
 u^*_{0} = bed friction velocity magnitude at the inlet section (m/s)
 u_ξ = streamwise velocity relative to the channel centerline (m/s)
 U = mean velocity in the inlet section (m/s)
 w = vertical velocity (m/s)
 y^+ = non-dimensional mesh spacing = $(\text{Re})(u^*/U)(\Delta n/H)$
 Z = vertical length dimension (m)

 Γ = non-dimensional cross-stream circulation

Γ_+ = total positive non-dimensional cross-stream circulation

Δn = dimensional grid size (m)

ε_a = non-dimensional mean absolute velocity error

ε_{rms} = non-dimensional root mean square velocity error

ρ = water density (kg/m³)

τ_{ij} = non-dimensional subgrid scale stresses

ν = kinematic fluid viscosity (m²/s)

ω = total vorticity magnitude (1/s)

ω_ξ = streamwise vorticity = (dw/dy)-(du/dz) (1/s)

7.7. REFERENCES

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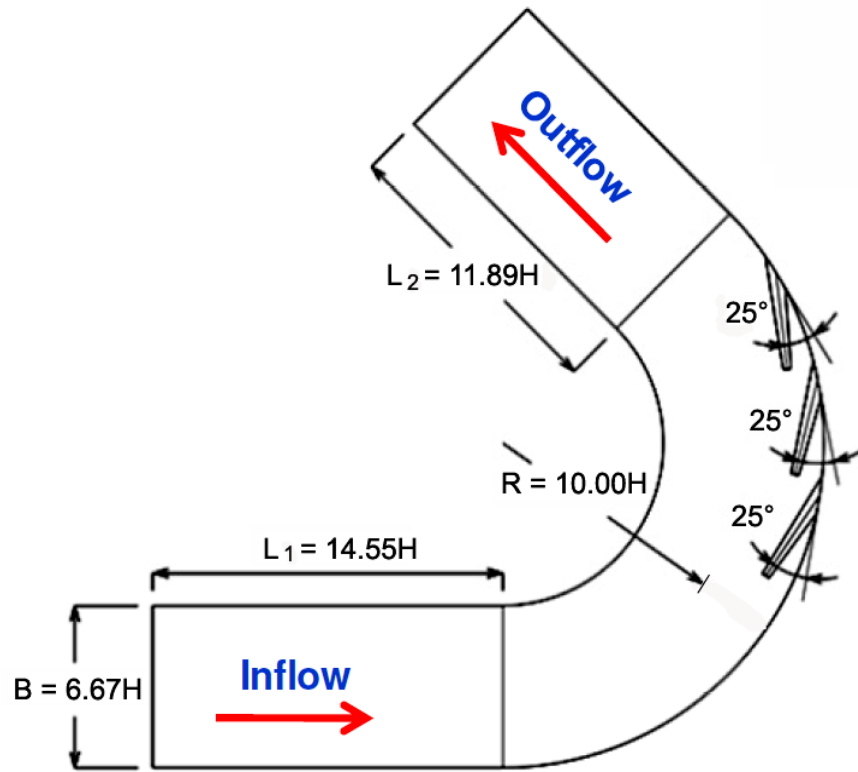


Figure 7.1 Plan view of the computational domain showing the groyne positions for case FBG.

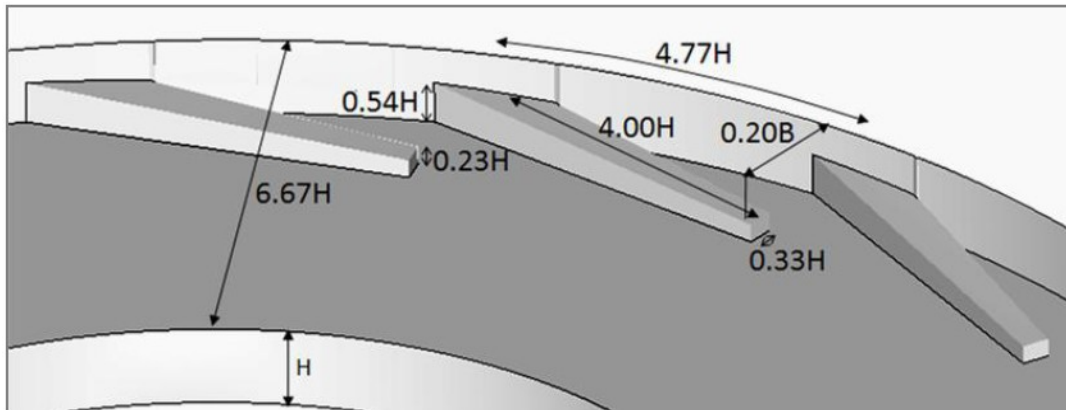


Figure 7.2 Perspective view of groyne dimensions and configuration within the bend for case FBG. Dimensions are in terms of the initial water depth, $H=0.15\text{m}$, and channel width, $B=1\text{m}$.

Table 7.1 Flow parameters in the straight approach channel for the experiments and LES simulations

U (m/s)	H (m)	u_0^* (m/s)	u_{cr}^* (m/s)	d_{50} (mm)	Re^* (u^*d_{50}/ν)	Re (UH/ν)	Fr (Ug/H) ^{1/2}
0.310	0.150	0.0152	0.0197	0.689	13.8	60 000	0.255

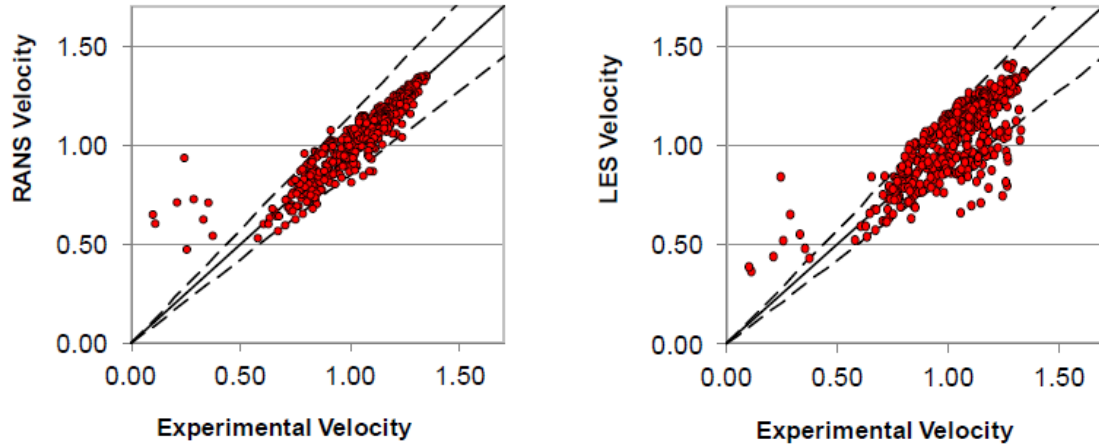


Figure 7.3 Scatter plots for case FB showing simulated versus experimental velocity magnitudes (u/U) within the curved reach for (left) RANS and (right) LES. The line of equality is shown by a solid line, and the dashed lines represent errors of $\pm 15\%$.

Table 7.2 Statistics for plots shown in Figure 7.3 showing the agreement of the RANS and LES velocity magnitudes (u/U) with the experimental velocity magnitudes (u/U) for case FB

	r^2_{adj}	ϵ_a	ϵ_{rms}	d_{avg}	Percentage (%) 0.5< d <2.00	Percentage (%) 0.75< d <1.33
RANS vs. EXP	0.81	0.049	0.081	1.04	98.9	98.4
LES vs. EXP	0.64	0.096	0.122	1.04	98.9	96.5

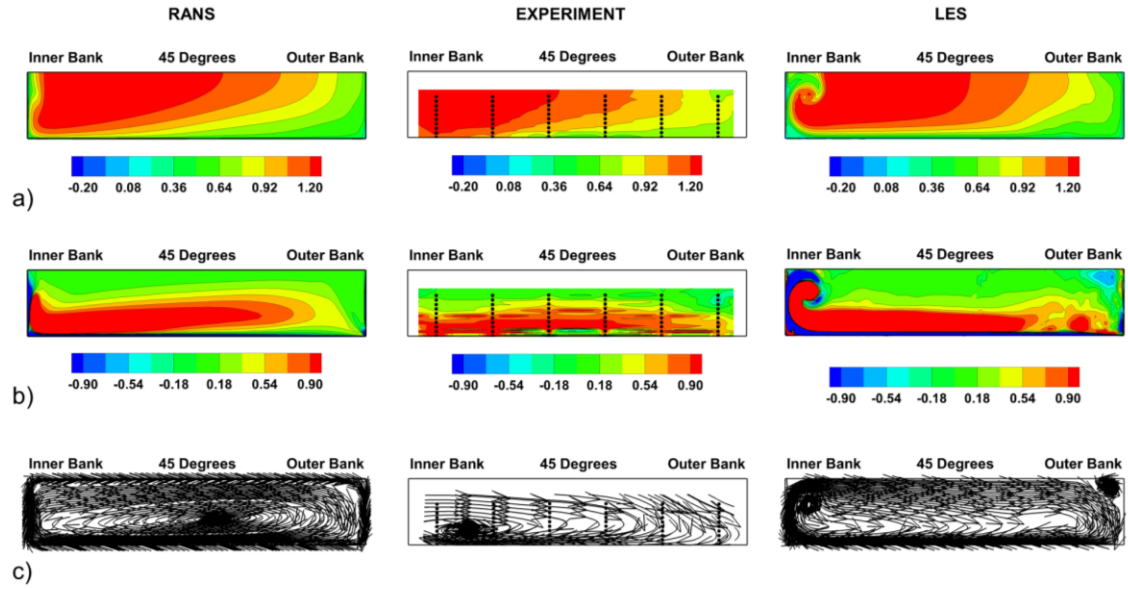


Figure 7.4 Contour plots for the 45° section for case FB showing a) streamwise velocity (u_z/U), b) streamwise vorticity ($\omega_z H/U$) and c) 2-D streamlines for (left) RANS, (center) Experiment, and (right) LES. Measurement locations for the experiment are shown by black circles.

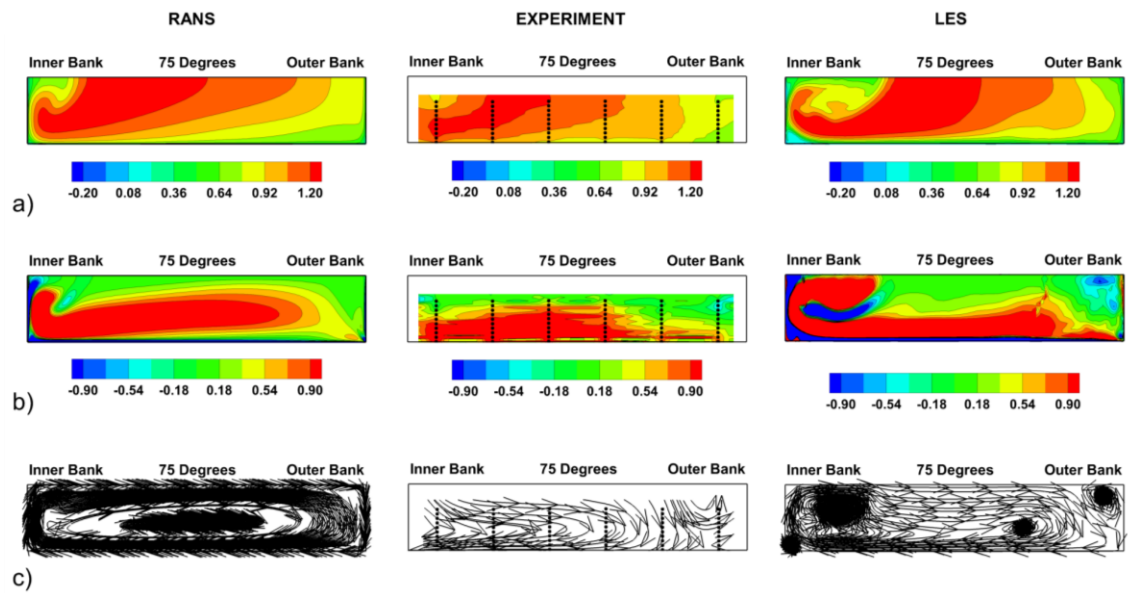


Figure 7.5 Contour plots for the 75° section for case FB showing a) streamwise velocity (u_z/U), b) streamwise vorticity ($\omega_z H/U$) and c) 2-D streamlines for (left) RANS, (center) Experiment, and (right) LES. Measurement locations for the experiment are shown by black circles.

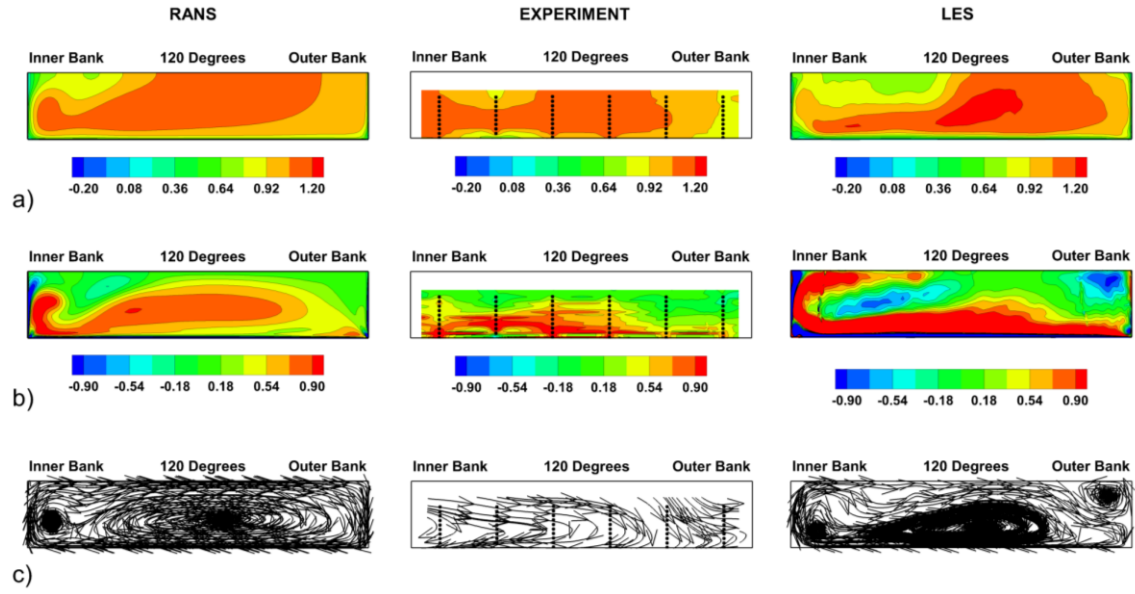


Figure 7.6 Contour plots for the 120° section for case FB showing a) streamwise velocity (u_{ξ}/U), b) streamwise vorticity ($\omega_{\xi}H/U$) and c) 2-D streamlines for (left) RANS, (center) Experiment, and (right) LES. Measurement locations for the experiment are shown by black circles.

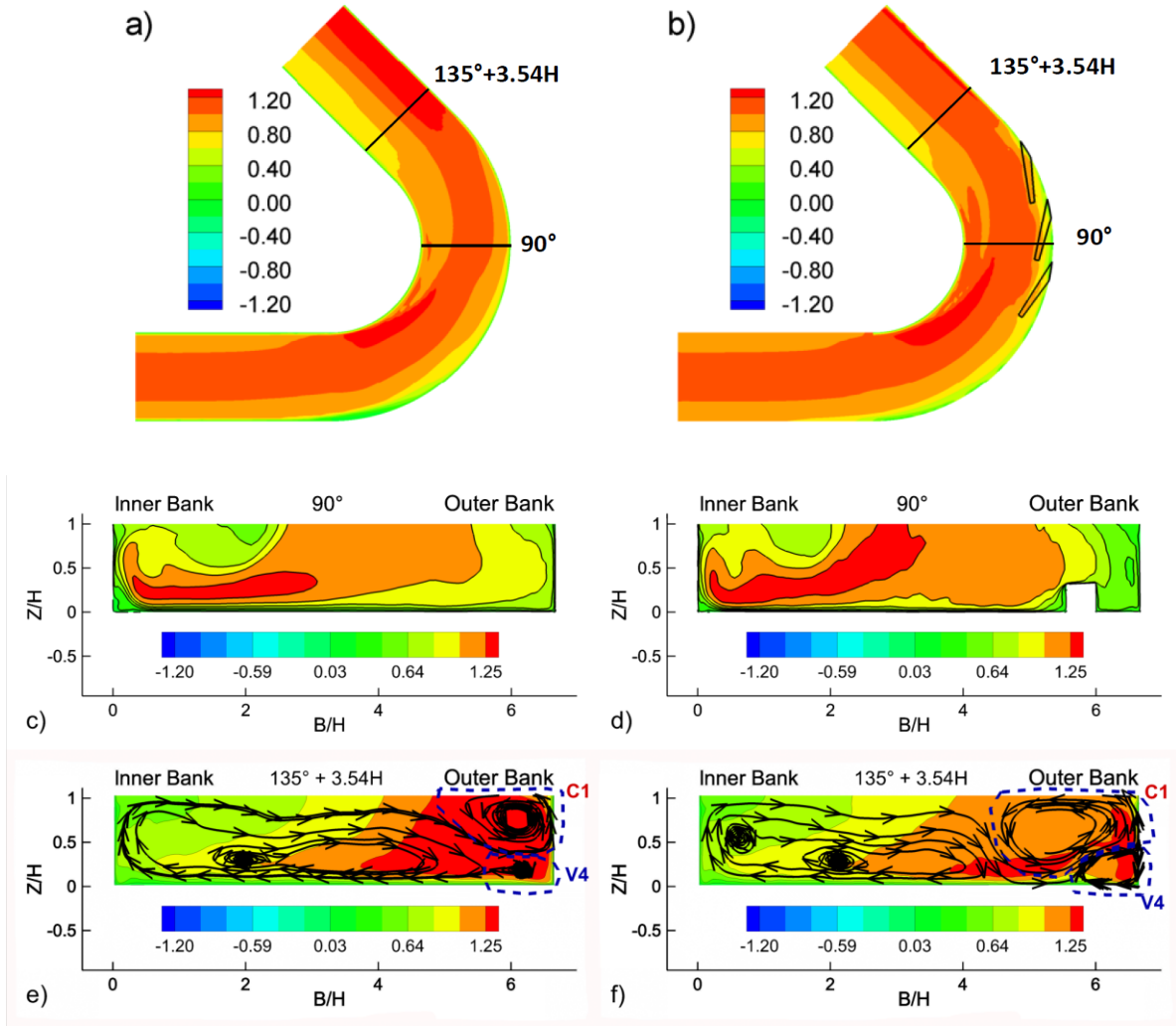


Figure 7.7 Distribution of mean streamwise velocity, (u_z/U) (a) averaged over the depth for case FB, b) averaged over the depth for case FBG, c) in the 90° section for case FB, d) in the 90° section for case FBG, e) in the $135^\circ + 3.54H$ section for case FB and f) in the $135^\circ + 3.54H$ section for case FBG. C1 is the counter-rotating outer bank cell, and V4 is a clockwise-rotating cell.

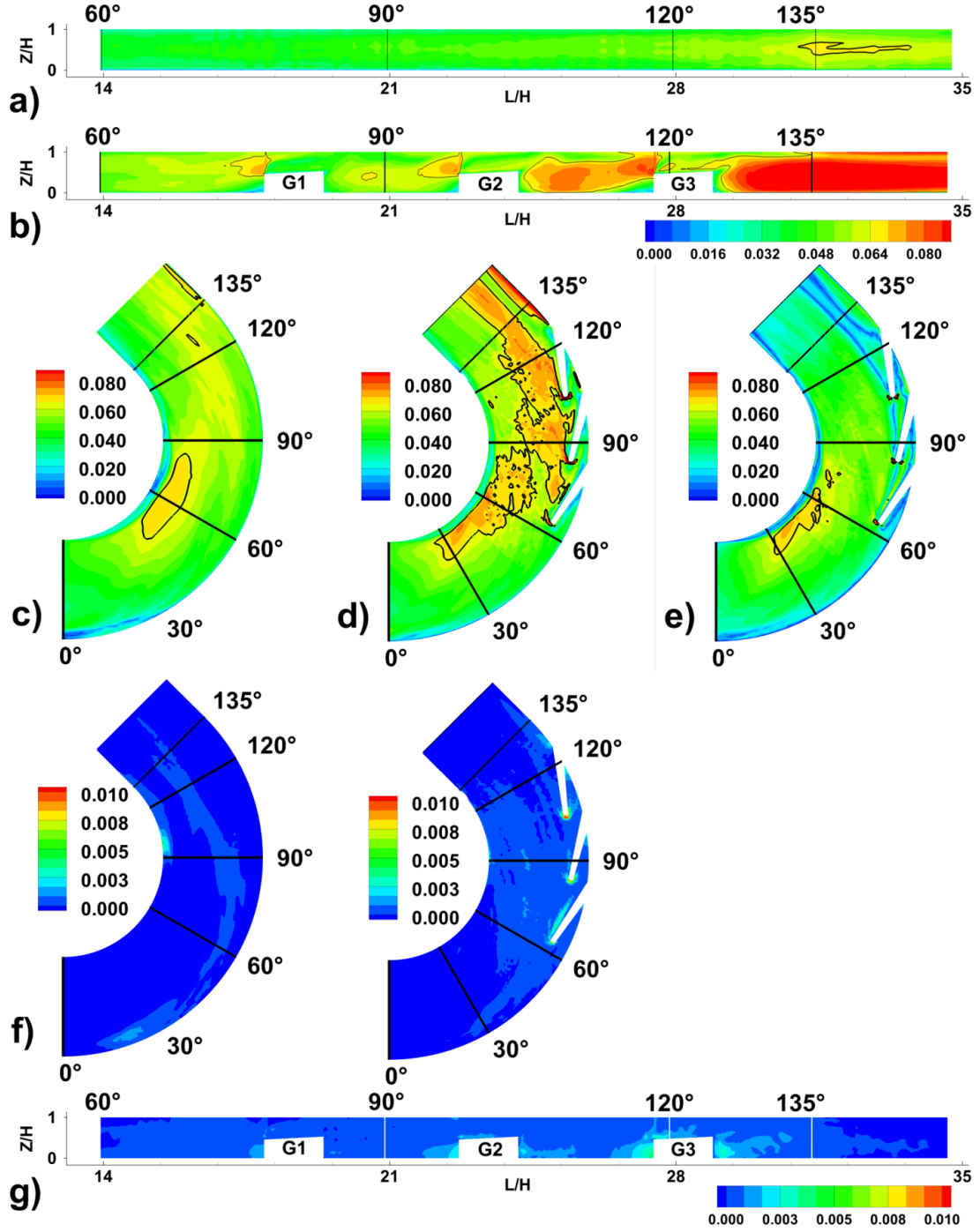


Figure 7.8 Mean friction velocity magnitude (u^*/U) predicted by LES a) at the outer bank wall for case FB, b) at outer bank wall for case FBG, c) at the bed for case FB, and d) at the bed for case FBG. e) Cross-stream mean friction velocity magnitude (u_c^*/U) at the bed for case FBG. The black lines correspond to the Shields critical friction velocity ($u^*/U=0.064$). Mean pressure fluctuations $\langle p'^2 \rangle / (\rho^2 U^4)$ f) at the bed for (left) cases FB and (right) FBG, and g) at the outer bank wall for case FBG.

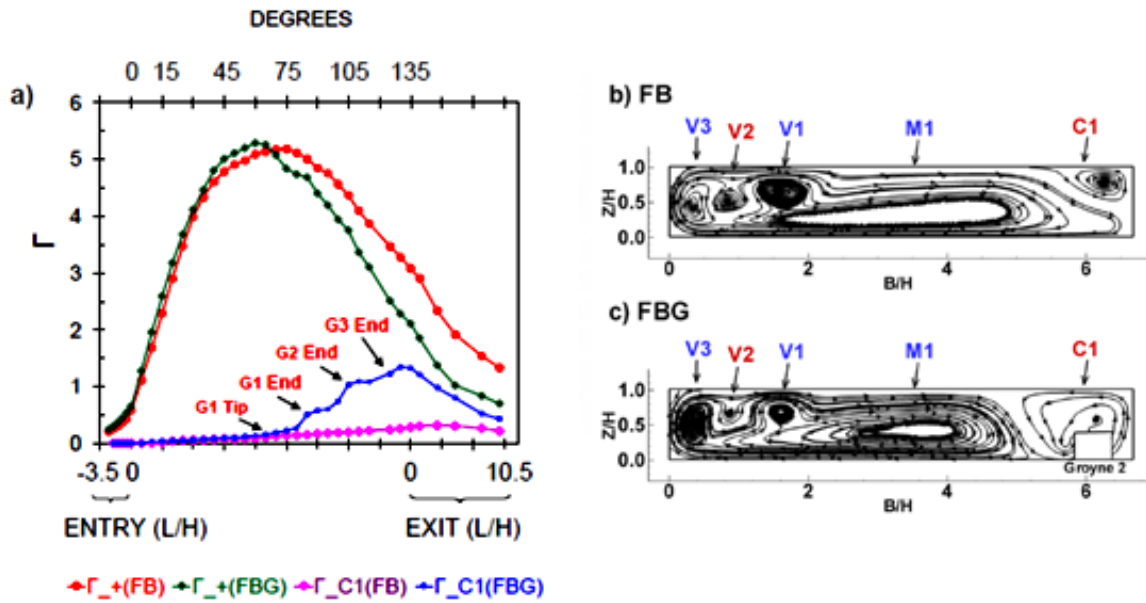


Figure 7.9 a) Streamwise variation of non-dimensional cross-stream circulation (Γ) in the channel mean flow predicted by LES for cases FB and FBG: (Γ_{+}) accounts for contributions from clockwise rotating vortices M1, V1 and V3, and ($\Gamma_{-}C1$) accounts for the outer bank counter-clockwise rotating cell C1. b) and c) show 2-D streamline patterns visualizing secondary circulation cells present in the mean flow in the 95° cross section for cases FB and FBG, respectively.

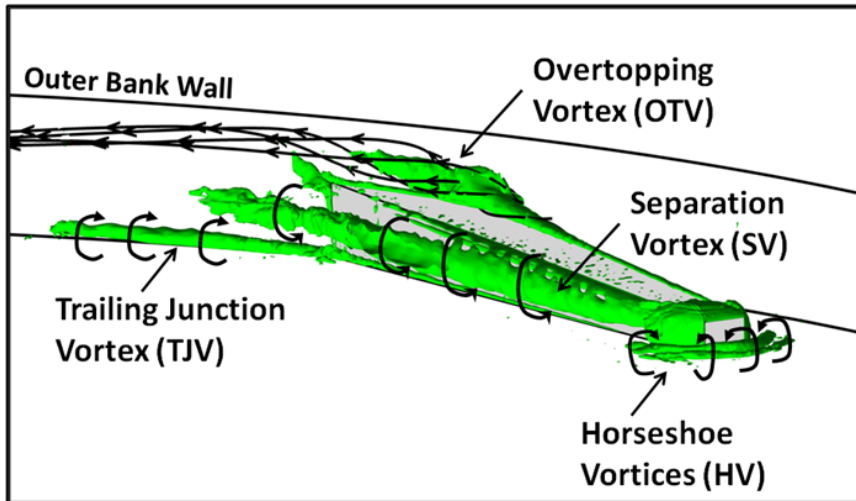


Figure 7.10 Main coherent structures found in the mean flow field around each groyne for case FBG, as visualized by Q criterion.

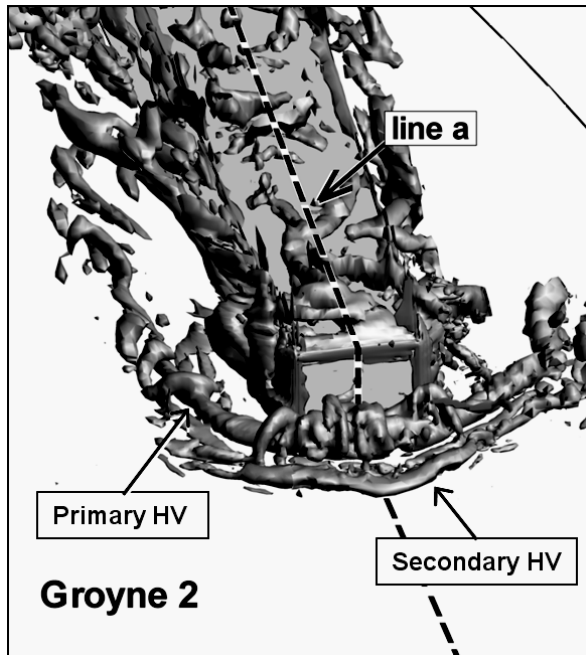


Figure 7.11 Visualization of the horseshoe vortex system around G2 in the instantaneous flow by Q criterion. Line a shows the location of the centerline of G2.

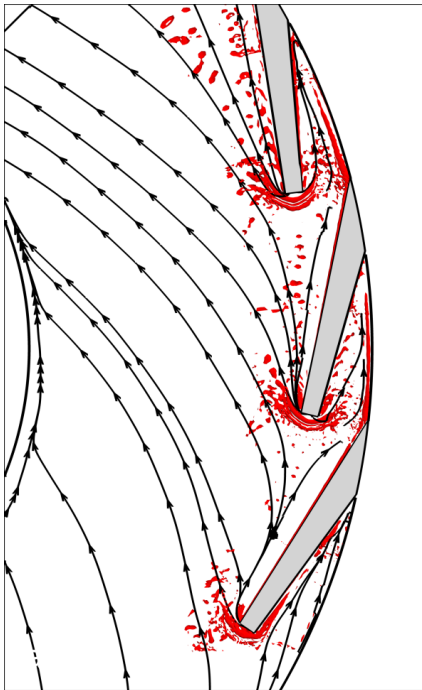


Figure 7.12 2-D horizontal plane at $Z/H=0.05$ showing 2-D streamlines and a constant value of Q criterion (in red) in the mean flow.

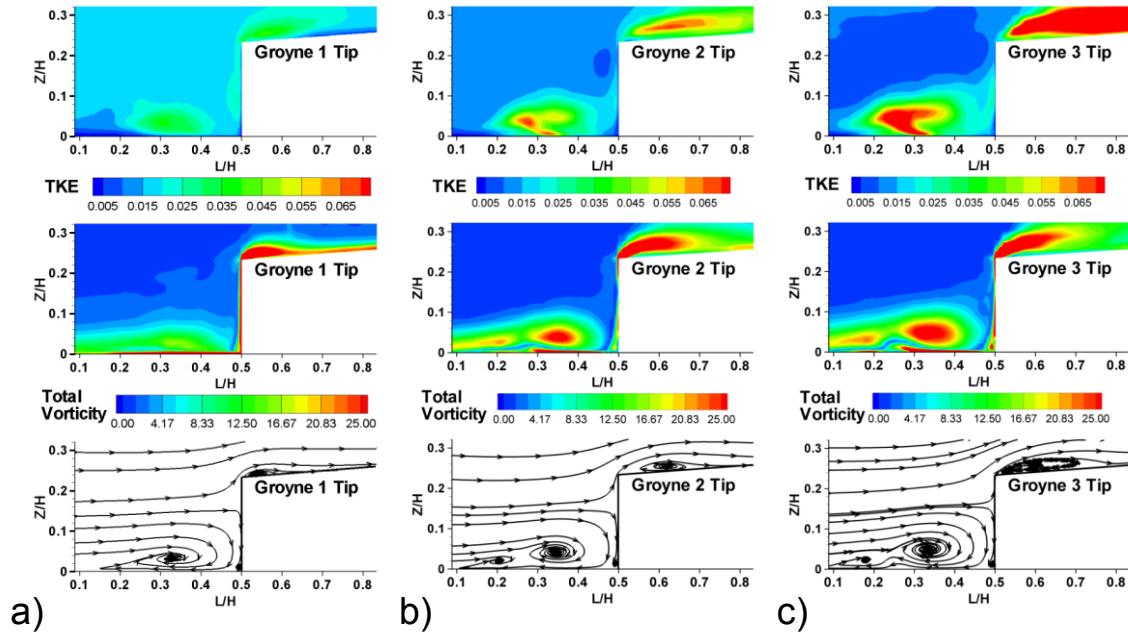


Figure 7.13 Horseshoe vortex system structure in the mean flow in a vertical plane cut along the groyne centerline (line *a* in Figure 7.11), for a) G1, b) G2, and c) G3. Top plots show TKE (k/U^2), middle plots show total vorticity ($\omega H/U$), and bottom plots show 2-D streamlines.

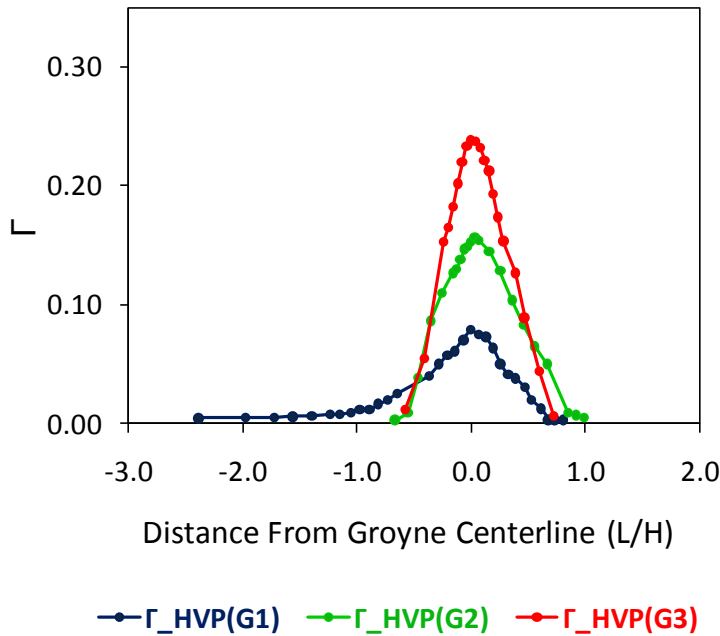


Figure 7.14 Non-dimensional circulation magnitude (Γ) of main horseshoe vortices (HVPs) in the mean flow for G1, G2, and G3 for case FBG. $+L/H$ is towards the main channel side, and $-L/H$ is towards outer flume wall.

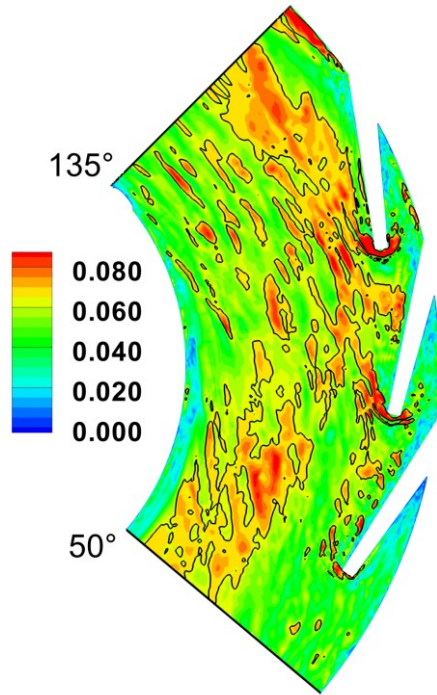


Figure 7.15 Bed friction velocity magnitude (u^*/U) in the instantaneous flow field for case FBG. The black lines correspond to the Shields critical friction velocity ($u^*/U=0.064$).

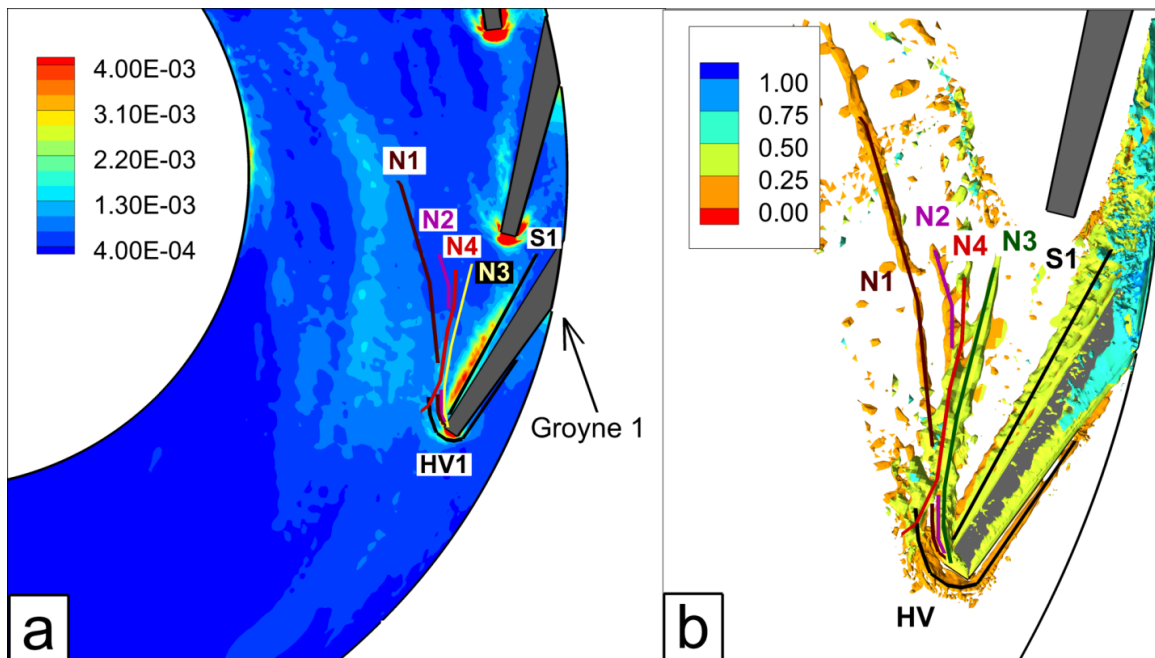


Figure 7.16 a) Plan view of locations of weak streamwise oriented vortices N1, N2, N3 and N4 found near the tip of G1 in the mean flow. Contours show mean pressure fluctuations $\langle p'^2 \rangle / (\rho^2 U^4)$ at the bed. b) Streamwise vortices N1, N2, N3 and N4 as visualized by Q criterion. Contours show the elevation (Z/H) above the bed. S1 is the separation vortex along the length of G1, and HVP is the primary horseshoe vortex in front of G1.

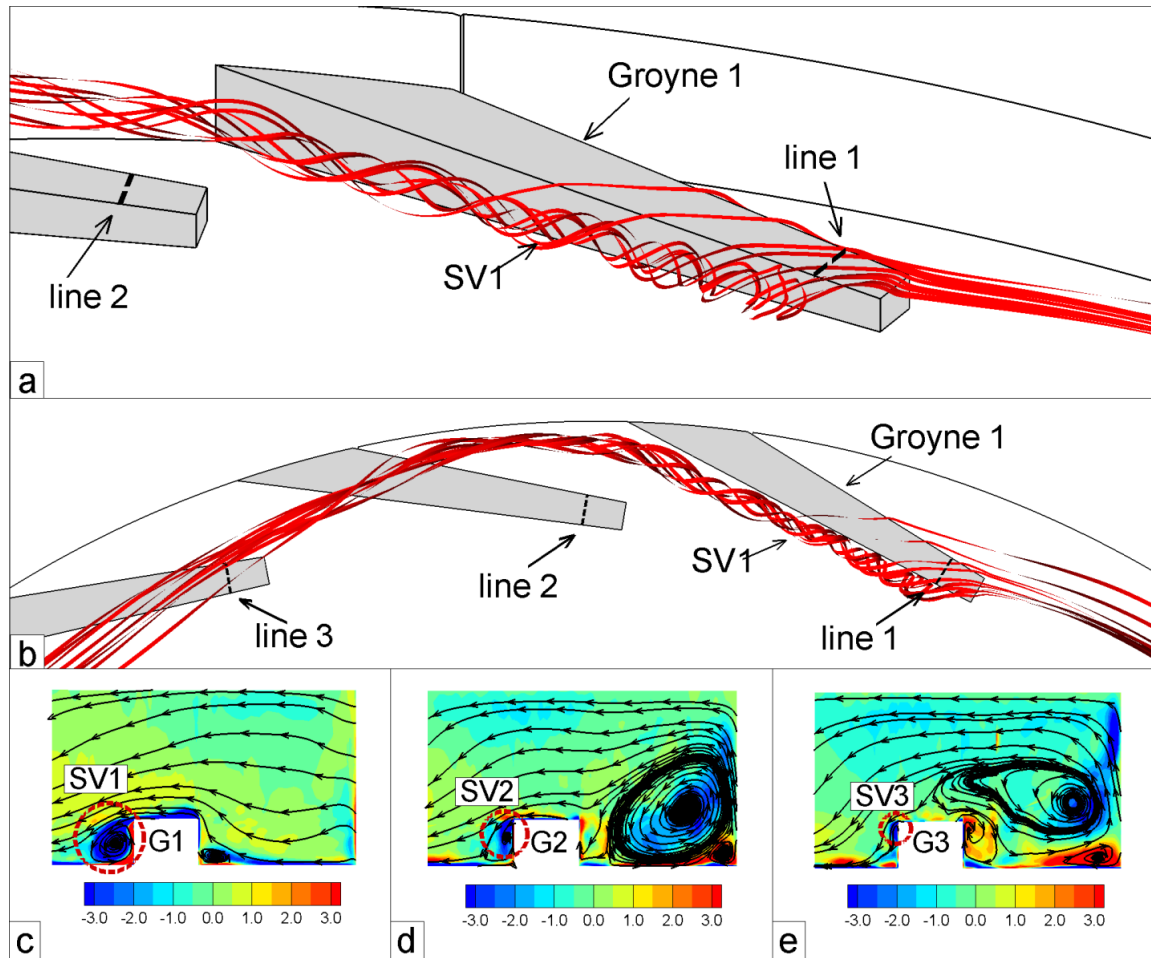


Figure 7.17 a) Perspective view of separation vortex (SV1) along the length of G1 shown by 3-D streamlines. b) Plan view of SV1 close to G1 shown by streamlines. (bottom) Planes perpendicular to the groyne length showing 2-D streamlines and non-dimensional out of plane vorticity for c) G1, d) G2, and e) G3. The plane locations for a), b) and c) are shown by lines 1, 2 and 3, respectively. All diagrams are for the mean flow field.

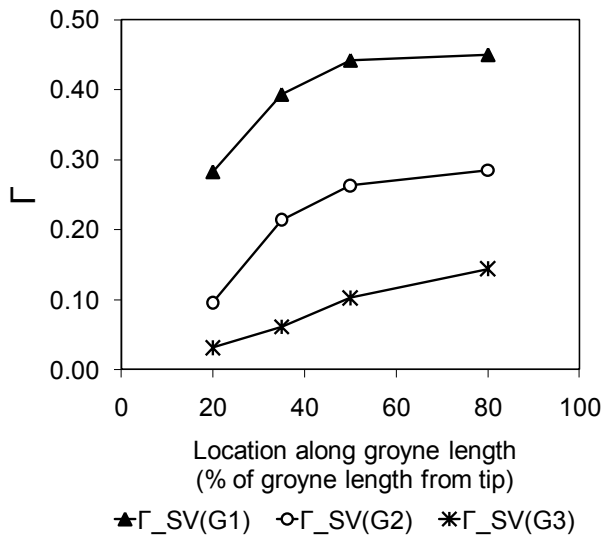


Figure 7.18 Non-dimensional circulation magnitude (Γ_{SV}) in the mean flow for counter-clockwise rotating separation vortex S1 in a plane cut perpendicular to the groyne length. Plots show Γ_{SV} for S1 along the lengths of G1, G2, and G3.

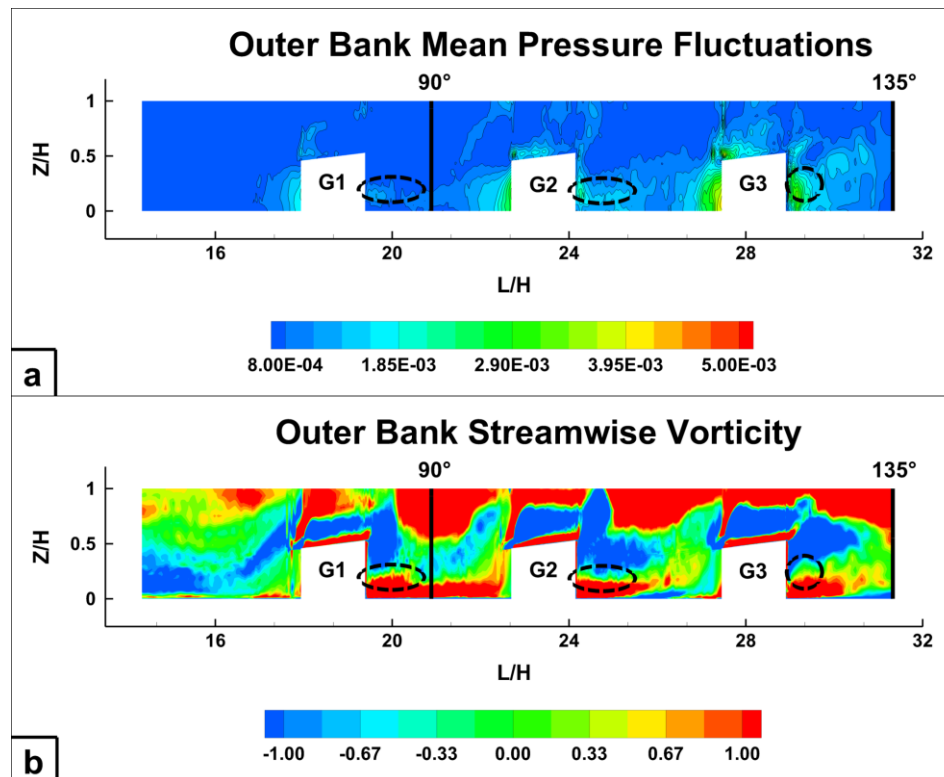


Figure 7.19 a) Mean pressure fluctuations $\langle p'^2 \rangle / (\rho^2 U^4)$ and the outer bank wall and b) streamwise vorticity ($\omega_{\xi} H / U$) in a plane cut very close to the outer bank wall in the mean flow for case FBG.

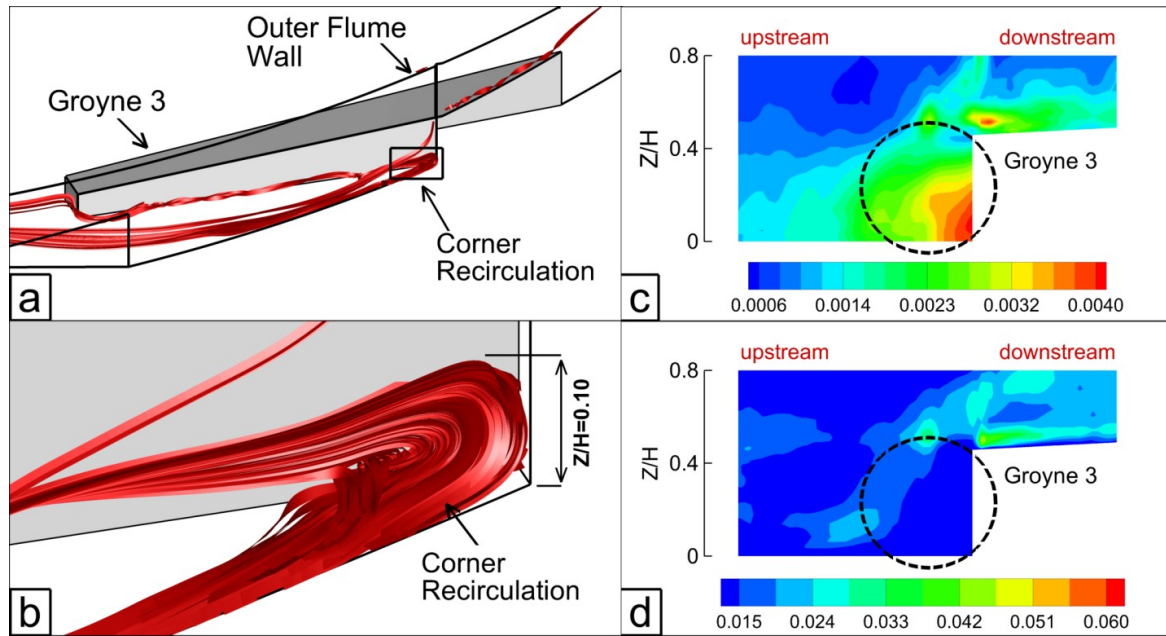


Figure 7.20 a) 3-D view of corner recirculation in the mean flow shown by streamlines at the junction of G3 inner sidewall and the outer flume wall. b) Enlarged view of corner recirculation in the mean flow within the boxed area shown in a). c) Mean pressure fluctuations $\langle p'^2 \rangle / (\rho^2 U^4)$ and d) TKE (k/U^2) on the outer flume wall around G3. Area within dashed circle is immediately upstream of G3.

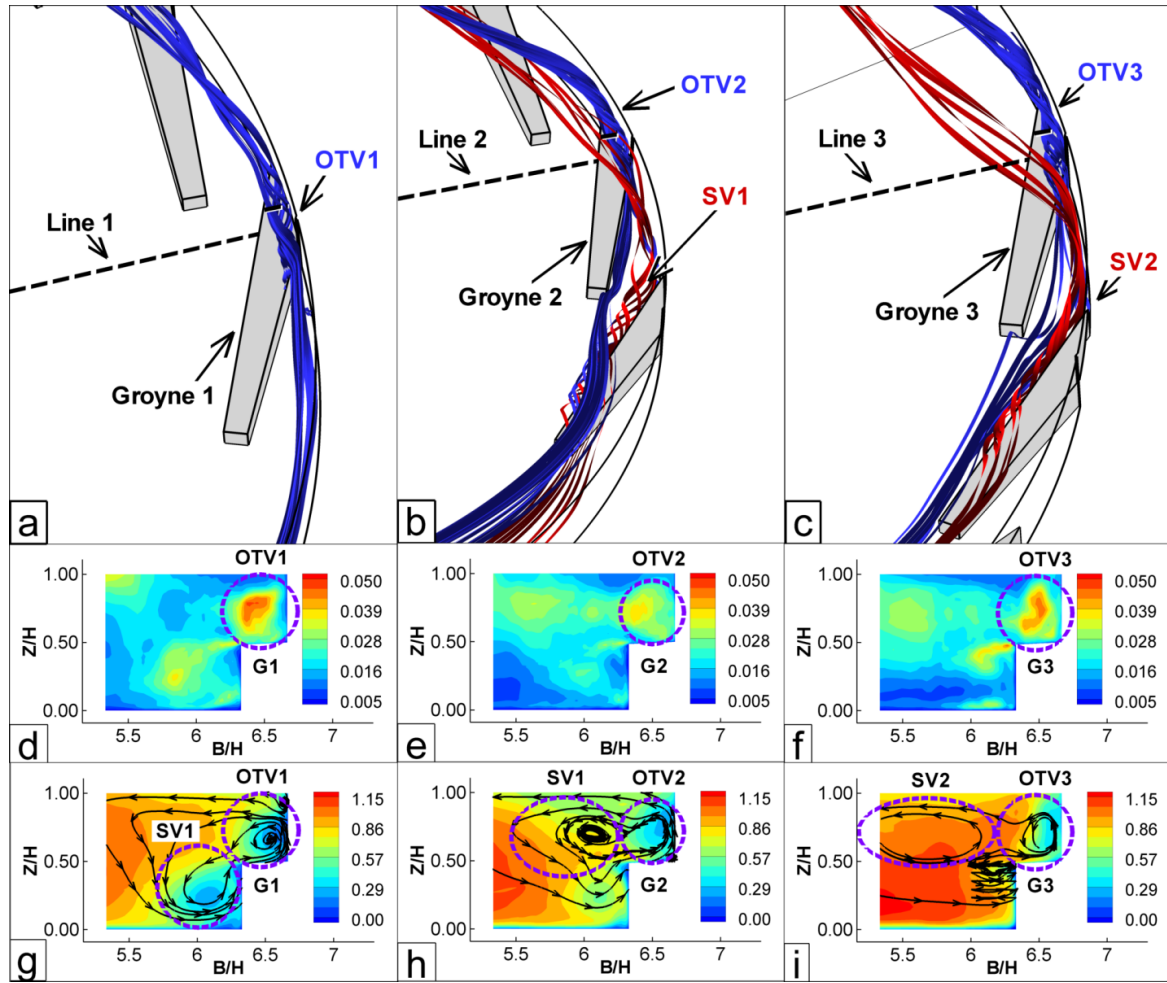


Figure 7.21 (Top) 3-D views of overtopping vortices OTV1, OTV2, and OTV3 (in blue) above a) G1, b) G2, and c) G3, respectively. (Middle) Distribution of TKE (k/U^2) in planes cut perpendicular to the axis of d) OTV1, e) OTV2, and f) OTV3. The OTV is within the purple dashed circle. (Bottom) Distributions of streamwise velocity (u_z/U) and 2-D streamlines in same the planes as the middle plots for g) G1, h) G2, and i) G3. Locations of SV and OTV are within purple dashed lines. The locations of the planes are shown in the top frames by line 1, line 2, and line 3, for G1, G2, and G3, respectively. All diagrams are for the mean flow field.

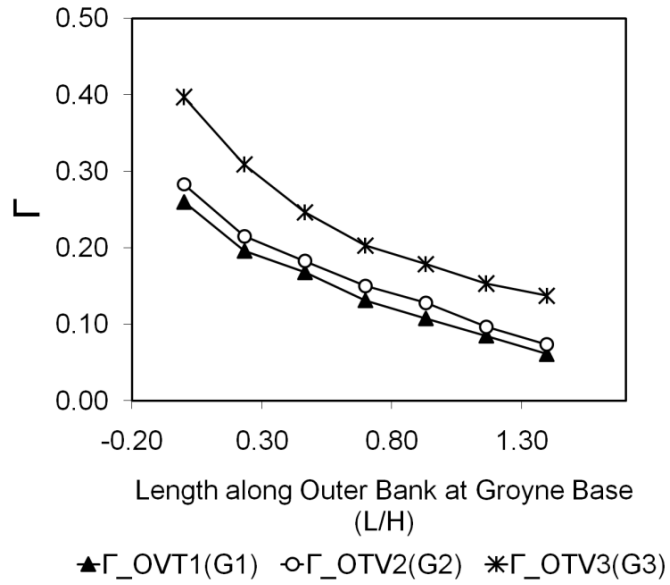
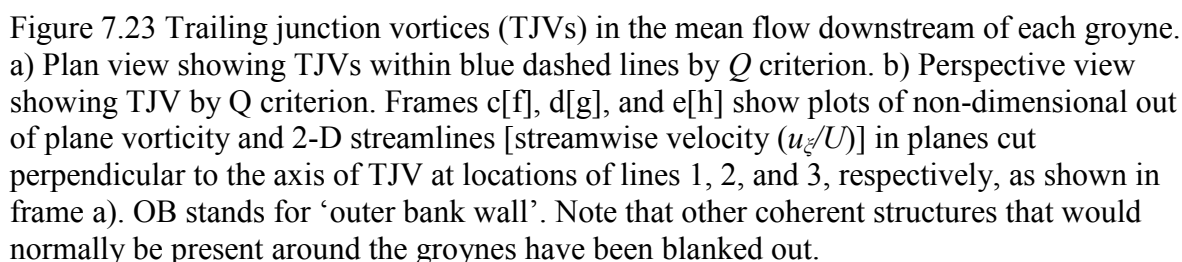


Figure 7.22 Non-dimensional cross-stream circulation (Γ) magnitude for counter-clockwise rotating overtopping vortex OTV in the mean flow in a plane cut perpendicular to the axis of OTV along the top of the groyne base. $L/H=0$ is the upstream face of the groyne.



CHAPTER 8: COHERENT STRUCTURES AND SCOUR MECHANISMS AROUND SUBMERGED GROYNES IN A HIGH CURVATURE CHANNEL BEND USING LARGE EDDY SIMULATION: PART II, A LATER STAGE OF SCOUR

8.1. ABSTRACT

River groynes are flow deflecting structures which present a viable solution for preventing erosion at the outer banks of rivers bends. In high curvature bends (radius of curvature (R)/channel width (B) ≤ 3.0) however, their performance can be variable, and they are sometimes subject to high levels of local erosion. Little is understood about the flow around groynes in a channel bend and the mechanisms leading to erosion around them. Therefore, in this study a highly resolved Large Eddy Simulation model is employed to gain insight into the characteristics of coherent structures and mechanisms leading to scour around a series of submerged groynes (initial water depth (H)/groyne height (D) ≥ 1.8) in a high curvature ($R/B=1.5$) channel bend (at a channel Reynolds number (Re) of 60,000). The channel is a 135° bend with vertical sidewalls, and the groynes are located over a fixed deformed sediment bed corresponding to the later stages of scour. The results show that although the channel thalweg and main channel core of high streamwise velocity have moved very close to the groynes, due to the effects of topographic steering, the groynes still appear effective in keeping the high streamwise velocity core away from the outer bank wall in the region where they are installed. However, as indicated by amplified boundary friction velocities and mean pressure fluctuations, high levels of erosion can still occur around the groynes at both the bed and outer bank wall. A complex system of vortices present near the first upstream groyne (G1) interacts with the main channel flow to induce severe levels of mean bed pressure fluctuation (~ 7 times greater than levels in the straight approach reach), near G1.

Also, flow accelerating out of the embayments amplifies wall friction velocities at the outer bank wall. Downstream of the groynes a counter-rotating outer bank cell advects fluid containing high streamwise velocities towards the outer bank wall at mid-depth levels which can substantially endanger the stability of the outer bank wall.

8.2. INTRODUCTION

The protection of rivers against bank erosion and channel migration is considered to be a challenging yet often necessary task in order to protect existing infrastructure and prevent the loss of valuable land. The migration patterns of rivers are often difficult to predict, and erosion can pose a risk to established infrastructures such as bridges and roads years after they have been constructed (Lagasse *et al.* 2004). The majority of rivers in nature tend to be curved, and erosion is normally greatest along their outer bank. Groynes are a special type of hydraulic structure used in rivers to deter outer bank erosion, and control river meander migration. Compared to commonly used revetment methods such as bed mattresses, stakes, and riprap (USDA 1996), groynes are considered to be proactive in that they deflect high velocity currents away from river banks, thereby reducing the propensity for outer bank erosion. Groynes also provide additional benefits such as improving channel navigability by deepening the river along the channel thalweg (Brügelmann and Bollweg 2004), aiding in flood management (Yossef 2005; Hudson *et al.* 2008), and improving aquatic habitats (Kuhnle *et al.* 2002).

The use of groynes dates back to at least the early 1700s (Wijbenga *et al.* 1994), when groynes were used in the Netherlands by private land owners to protect their land against floods and increase sedimentation. Initially, their construction was unregulated, and they

were commonly placed irregularly along a river, leading to flow constriction and frequent ice jams in the winter (Wijbenga *et al.* 1994; Nienhuis 2008). Although committees were subsequently formed to regulate their construction, considerable public controversy has existed over their installation and impact. Today about 500 groynes exist along the River Waal in the Netherlands (Wijbenga *et al.* 1994), and about 3000 exist along the River Elbe (Wirtz 2004). In recent years, the use of groynes has been increasing in North America, particularly along the Mississippi River (Hudson *et al.* 2008). Their performance however, has been variable and they can be subject to high levels of local scour in high curvature channel bends (USDA 2007).

Although considerable research has been conducted over the years to try and gain a better understanding of the nature of flow around groynes, there is still much knowledge needed about the fine details of the flow around groynes in a channel bend, and the mechanisms leading to scour. Experimental and field studies have mostly focussed on determining the optimum configuration and geometry for groynes by examining scour and velocity distribution patterns (Copeland 1983; Beckstead 1978; Prezedwojski *et al.* 1995b). Prezedwojski (1995a) found that scour depth near a groyne is related to its location along a channel bend. His field studies revealed that scour tends to be greatest for groynes installed downstream of the bend apex. He derived an equation to predict the maximum scour depth near a groyne as a function of flow depth, flow velocity, spacing between the groynes, their orientation relative to the flow, and their location within the bend. Matsuura and Townsend (2004) conducted extensive laboratory studies on optimizing the geometry, spacing, and location of submerged groynes for high curvature bends. Their study determined that the

optimum angle for installing submerged groynes in a bend relative to the upstream outer bank to be 30° for a 135° bend. They also found that placing one groyne upstream of where scour first impacts the outer bank had a detrimental effect on groyne performance, while placing one additional groyne downstream in the straight exit channel helped to decrease outer bank erosion. While such experimental and field studies are very useful for understanding how to improve the performance of groynes, they do not sufficiently resolve the flow field, which makes it difficult for them to capture fine details of the coherent structures that can influence scour.

In recent years, numerical models have helped to reveal more details of the flow around groynes. The majority of these studies however, have involved groynes in a straight channel (Jia and Wang 2000; Bhuiyan *et al.* 2004; McCoy 2006; Koken and Constantinescu 2008a; Koken and Constantinescu 2008b; Zhang *et al.* 2009). Studies involving groynes in bends are limited, and have commonly used Reynolds Averaged Navier Stokes (RANS) models. While these models are useful in understanding mean flow patterns, they cannot capture coherent structures over a wide range of eddy scales. Submerged groynes are subject to complex 3-D flow patterns involving massive flow separation, high velocity gradients, and dynamic coherent structures. In addition, many existing studies do not specifically involve groynes, but similar structures such as bendway weirs (the studies of Jia *et al.* 2001, Jia *et al.* 2005, Huang and Ng 2007, Abad *et al.* 2008, Jia *et al.* 2009 all involve bendway weirs). The studies of Minor *et al.* (2007a and 2007b) investigated flow and scour around a type of submerged groyne known as a ‘stream barb’ (see below) in a high curvature laboratory channel using a 3-D RANS model. These two studies showed that stream barbs create a

counter-rotating circulation cell (opposite to the direction of the main channel helical flow cell) that seems to help protect against outer bank erosion. The study of Minor *et al.* (2007b) found that vorticity magnitudes around a groyne field in a 90° bend during the final stages of scour were greatest at the tip of the first upstream groyne. Abad *et al.* (2008) investigated flow around submerged bendway weirs using a 3-D RANS model at various flow rates corresponding to low, medium and high submergence levels. They showed that as submergence levels increased, the magnitudes of shear stress around the weirs also increased at both the bed, and outer bank wall above the groyne. Also, an increase in submergence caused recirculation within the groyne embayments to become weaker, and streamlines within the embayment to become aligned almost parallel to the main channel flow. To date there have been no known studies that have investigated the flow and coherent structures around submerged groynes in a channel bend using an eddy-resolving numerical model such as Large Eddy Simulation (LES).

This study employs LES to model flow around a series of submerged groynes in a high curvature (radius of curvature (R)/channel width (B) ≤ 3) bend with a fixed deformed bed, corresponding to the later stages of scour. This simulation is modeled after a physical groyne experiment conducted at the University of Ottawa. The bathymetry used to create the fixed bed for the simulation was obtained from the experiment once it was completed. This study focusses on a particular type of groyne known as a ‘stream barb’ (USDA 2005), which is a linear type structure, normally constructed of rock, and designed primarily for preventing bank erosion. Stream barbs are typically installed in series and have a gradually-sloped top weir that is partially submerged below the water surface under normal flow conditions. The

findings of this study however, are widely applicable to many types of river groynes used for erosion mitigation, and so the more common term ‘groyne’ is used in this study to refer to stream barbs. The main objective of this study is to use a 3-D LES model to understand better the nature of coherent structures and mechanisms leading to scour around groynes in a high curvature ($R/B=1.5$) channel bend during the later stages of scour. Submerged groynes (initial channel depth (H)/groyne height (D) ≈ 1.8) are investigated as this operating arrangement corresponds to flood conditions, when scour is expected to be greatest. Kashyap (2012, Chapter 7) reported the findings from a corresponding LES study which also investigated the same bend case with groynes, but under conditions corresponding to initial stages of scour. It is expected that the characteristics of the coherent structures and their capacity to induce erosion may be substantially different during the later stages of scour. Koken and Constantinescu (2008b) have shown that for groynes in a straight channel, the presence of a scour hole can cause horseshoe vortices to stabilize during the final stages of scour. The physical experiments for this present study revealed that the scour distribution pattern around the groynes changed considerably as erosion progressed. At the beginning of the experiment the maximum scour depth occurred at the tip of the most downstream groyne. However, during the later stages of scour, erosion was greatest at the first upstream groyne. Also, scour at the first upstream groyne did not appear to reach a state of equilibrium, whereas scour at the most downstream groyne did. It is expected that the results from this study may also help to gain insight into the nature of flow around other types of similar structures in channel bends such as bendway weirs and rock vanes.

8.3. METHODOLOGY

It should be noted that for both the experimental and LES cases the following nomenclature has been adopted throughout this chapter: FB refers to a ‘flat bed without groynes’, FBG refers to a ‘flat bed with groynes’, DB refers to a ‘deformed bed without groynes’, and DBG refers to a ‘deformed bed with groynes’. In all cases ‘flat bed’ refers to the initial flat sediment bed which would be present before scour starts, and ‘deformed bed’ refers to the bed condition obtained near the later stages of scour, which for these cases was obtained at the end of each experiment. Also the nomenclature adopted for the groynes is as follows: the first upstream groyne is called G1, the second downstream groyne is called G2, and the third downstream groyne is called G3.

8.3.1. Experimental Methods

All of the physical experiments were conducted in the University of Ottawa 135° bend flume with the same straight approach section flow conditions as given in Table 8.1. The flume had a 12.2m straight approach section, a 3.6m curved (bend) reach, and a 2.4m straight exit reach. The curved reach had a constant curvature ratio, $R/B=1.5$. The flume had vertical sidewalls and a constant width, $B=1\text{m}$ (see Post, 2007 for further flume details). For cases DB and DBG, flow was run over an initial flat sediment bed ($d_{50}=0.689\text{mm}$) with a zero bed slope, under clear water scour conditions, until the bed reached close to the final stages of scour. It should be noted that cases DB and DBG were run for a total of 167 and 267 hours, respectively. Case DBG was run for a longer period of time as scour levels around G1 were high. The approach flow was considered to be steady and close to uniform, with a constant discharge, $Q=0.0464\text{m}^3/\text{s}$, and a constant initial water depth, $H=0.15\text{m}$.

For case DBG, three submerged groynes were installed in the bend region with the dimensions and layout shown in Figures 8.1 and 8.2 (note that in Figure 8.2 the groynes are shown with the final scoured bed). The groyne design and configuration were based on USDA recommendations (USDA 2005), and previous studies conducted at the University of Ottawa (Matsuura 2004; Minor *et al.* 2007a). They were designed to have a simple prismatic shape in order to accommodate meshing requirements for the LES. The groyne sidewalls were vertical, and the top crest sloped downwards from the bank, making an angle of 6.5° with the horizontal. The initial (flat bed) submergence ratio (H/D) ranged from 1.85 at the (bank-wise) base to 4.29 at the (stream-wise) toe. The groyne width ranged from $0.57H$ at the base to $0.33H$ at the toe. The groyne centerline made an (upstream-side) angle of 25° with the outer bank tangent (Figure 8.1). The base of the first upstream groyne was placed at the location where erosion first impacted the outer wall, as determined from the DB experiment. The placement of subsequent downstream groynes relied on the midpoint spacing method (USDA 2005), which resulted in a spacing along the outer bank wall between the groyne centerlines of $4.77H$.

Velocity measurements were taken using three Nortek[®] Acoustic Doppler velocimeters (ADV) for up to 48 hours before the end of the experiment. The ADVs had a measurement accuracy of $\pm 0.5\%$ of the measured velocity $\pm 1\text{mm/s}$ (Nortek 2011). Each ADV measured four velocity components, streamwise, cross-stream, vertical, and a second vertical velocity measurement to compute error. Velocities were measured relative to the flume walls at a sampling frequency of 200Hz for a period of two minutes. Post processing code was used to remove mean velocities with low correlations ($<70\%$), and low signal to noise ratios (<10).

Apparent outliers in single ping velocities, with values which exceeded four standard deviations from the mean, had errors in vertical velocities greater than 0.1m/s, or had accelerations $>1.5 \times (\text{gravitational acceleration})$ were corrected by using a value interpolated between the previous and subsequent instantaneous velocity values. The velocity profiles were measured at the center of six equal 16.67cm intervals across the 1m flume width. The ADV transducers were submerged at least 5mm below the water surface, and the sample volume was 4.5 to 5.5cm below the transducer. Therefore, the first sample volume was located 5 to 6cm below the water surface. Measurements were taken at 1cm intervals starting near the bed, and increasing to a maximum of 2cm as the water surface was approached. It should be noted that for cases DB and DBG, measurements were sometimes located further from the bed than desired, due to difficulties in estimating the distance of the ADV to the sediment bed. Water discharge (Q) was measured using a V-notch weir installed at the flume exit tank, and validated by calculating Q from ADV measurements in the straight inlet section. Bathymetry measurements were taken with a Leica DistoTM pro4a laser altimeter which had an accuracy of $\pm 0.0015\text{m}$. Bathymetry measurements were taken in sections which were situated across the flume width, and at 1cm intervals along each section. The sections were spaced at 5° intervals along the bend length. Additional measurements were also taken in the straight entry and exit reaches. These bathymetry measurements were used to create the fixed deformed bed surfaces used in the LES simulations.

8.3.2. Numerical Solver

The LES solver used in the present work was developed by Mahesh *et al.* (2004). It employs a finite volume method to solve the 3-D spatially filtered Navier Stokes equation given by Equation 8.1 in tensor notation, on a hybrid unstructured grid.

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j}, \frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (8.1)$$

Here the overbar denotes spatial filtering, $\partial \tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j = 2\nu_t \bar{S}_{ij}$ are the subgrid stresses, and ν is the kinematic viscosity, and ν_t is the turbulent eddy viscosity. The LES code is a parallel message passing interface (MPI) solver that uses a collocated finite-volume scheme. In the predictor-corrector formulation the Cartesian velocity components are defined at the center of the cell and the face-normal velocities are treated as independent variables. The fractional step algorithm is second order accurate in both space and time. All the operators in the code, including the convective terms, are discretized using central schemes. The numerical scheme used to solve the Navier-Stokes equations discretely conserves energy. This increases the robustness of the numerical algorithm with the use of numerical dissipation which is essential for accurate LES. Time discretization is achieved using a Crank Nicholson scheme for the convective and viscous operators in the momentum (predictor step) equations. The system resulting due to the implicit time discretization is solved using the successive over-relaxation (SOR) method. The pressure equations are solved using a conjugate gradient method with preconditioning. No wall functions are used, and the governing equations are integrated through the viscous sub-layer. A constant Smagorinski SGS model is used to solve for the subgrid stresses in Equation 8.1 in order to avoid instabilities due to the complex domain geometry and high Reynolds number involved. Further details on the LES code are given in Appendix A.

8.3.3. Simulation Setup

As mentioned, the LES simulations were modeled after the physical experiments. The flume geometry and the set up of the groynes were identical to the experiment, except that the straight 12.2m approach section from the experiment was shortened to 2.2m (or $14.55H$) for the simulations, as shown in Figure 8.1. The deformed bed face was created by interpolating bathymetry points obtained from the experiment using a Spline technique in Ansys® Gambit™ software. The numerical meshes were unstructured and contained only hexahedral elements. The meshes for cases DBG and FBG contained approximately 6.6 million nodes, while for cases DB and FB they contained approximately 3.4 million nodes. An example of the mesh for case DBG is given in Figure 8.3. The non-dimensional mesh spacing at the boundaries is defined as $y^+ = (\text{Re})(u^*/U)(\Delta n/H) = \Delta n(u^*/\nu)$ where Δn is the dimensional grid spacing, H is the initial approach section water depth, ν is the kinematic viscosity, U is the main channel mean velocity, and u^* is the entry channel friction velocity. For cases FB, and DB, $y^+ < 6$ at all solid boundaries, which was less than the viscous sublayer height. This was also true for case FBG, however y^+ at the outerbank wall sometimes reached 20. For case DBG, $y^+ < 6$ at most solid boundaries, except at the bed near the tip of G1, where it was increased to 10, and at the bed in the straight exit section where it approached 88 in some local areas. The mesh spacing was increased in these areas in order to help convergence of the code. The value of y^+ within the groyne embayments at the outer bank wall also approached 20 in some areas.

The flow parameters for all simulations were the same as the experiments and are given in Table 8.1. The initial water depth, $H=0.15\text{m}$, and the mean inlet approach velocity, $U=0.3095\text{m/s}$, were used as the length and velocity scales, respectively, for non-

dimensionalizing the flow and geometric variables. Fully developed mean velocity profiles for the LES inlet were obtained from a preliminary RANS simulation conducted in a straight rectangular channel with the same width (B) and depth (H) as the bend and the same flow conditions as given in Table 8.1. Zero mean turbulent velocity fluctuations were developed in a separate LES model under the same flow conditions, and were superimposed on the mean velocities obtained from the RANS model to create the final LES fully developed turbulent inlet velocity profiles. For the bend simulations, the free surface was modelled using a symmetric boundary condition, assuming a rigid lid approximation. This is considered acceptable due to the low Froude number ($Fr=0.255$) involved in the simulation. Generally for $Fr<0.5$, approximations associated with a rigid lid assumption are considered to be acceptable (Rodi 1997; Zeng *et al.* 2006). Furthermore, water surface deflections in the DBG experiment were less than 6mm, which was less than 5% of the flow depth, and thus the rigid lid assumption was applicable for this case. All solid boundaries including the fixed bed, vertical flume sidewalls, and groyne surfaces were modelled using ‘non-slip’ boundary conditions without wall functions. A convective boundary condition that allows turbulent eddies to exit the computational domain without generating spurious oscillations close to the exit boundary was used at the outlet.

All cases were run with a non-dimensional time step of $L/U=0.01$, except for case DGB which was run at $L/U=0.005$. Here L is the length, and U is the main channel mean velocity. The instantaneous solution was considered to be converged when the pressure residuals reached 1×10^{-8} , and the momentum residuals reached 1×10^{-6} . Once the instantaneous solution reached a statistically steady state, the statistics (mean solutions) were calculated

from a series of 100 instantaneous solutions spaced at a non-dimensional time interval of $L/U=0.5$. The simulations were run in parallel on a multiple processor computer system at the University of Iowa.

8.3.4. Analytical Methods

For all cases, bed and wall friction velocities were calculated within the viscous sublayer ($y^+ < 8$) using the formula $u^* = (\nu dV/dy)^{1/2}$, where ν is the kinematic viscosity of water, and dV/dy is the velocity gradient. It should be noted however that for case DBG, due to local areas at the bed and outer bank where the grid sizes were larger (up to $y^+=88$), friction velocities were calculated at $y^+=100$ at the bed and outer bank wall in order to make sure that the contour plot had continuous lines. These friction velocities were found to be less than values which were calculated within the viscous sublayer where $y^+ < 6$. Therefore friction velocities at $y^+=100$ were multiplied by a factor of 4.2, which was determined to be adequate to give an approximate estimate of friction velocities calculated within the viscous sublayer. It should be noted therefore, that magnitudes and distributions of friction velocities for case DBG at the outer bank and bottom bed have been calculated from this adjusted value at $y^+=100$, and therefore may not be exact but should give an approximate idea of the general distribution.

The magnitude of the cross-stream circulation magnitude (Γ) associated with a certain cell was calculated in cross sections perpendicular to the axis of the vortex/circulation cell. Values of Γ were calculated by integrating the out-of-plane vorticity in these cross sections over the area of the vortex/circulation cell. The total positive cross-stream circulation (Γ_+)

was calculated as the sum of Γ for all circulation cells with positive vorticity (i.e. rotating in the same direction as the main channel helical flow cell, which is clockwise).

8.4. RESULTS AND DISCUSSION

The general characteristics of the flow patterns and coherent structures around the groynes are presented in this section. Validation of the LES model for case DBG is also presented, which will compare the measured versus the LES predicted velocity magnitudes, and will also consider distributions of streamwise velocity and vorticity at individual sections. It should also be noted that in these results, positive streamwise vorticity refers to flow rotating in the clockwise direction when facing in the downstream direction, and negative streamwise vorticity refers to flow rotating in the counter-clockwise direction.

8.4.1. Bathymetry and Streamwise Velocity Distributions

Contour plots showing the bathymetry obtained from the experiments during the later stages of scour for both cases DB and DBG, are shown in Figure 8.4. For case DB the channel thalweg is located close to the inner bank at the entrance to the curved reach, and gradually moves towards the outer bank as the end of the curved reach is approached. A point bar is present starting at around section D30 and remains attached to the inner bank until the end of the curved reach. The maximum scour is $Z/H=-1.3$, and occurs along the outer bank, just downstream of the 135° section. For case DBG (Figure 8.4b), the deepest areas of scour occur near the groyne tips, the maximum scour occurs near G1, where it is $Z/H=-1.8$. Some deposition occurs along the inner bank, although this deposition is less compared to case DB. The mechanisms leading to this distribution of scour will be discussed in greater detail later.

A plan-view plot of the depth averaged streamwise velocity for case DB is shown in Figure 8.5a. It shows a distribution that is characteristic of sharp bend flow (Zeng *et al.* 2008; Kashyap *et al.* 2012) where the core of high streamwise velocity is close to the inner bank near the beginning of the curved reach, and reaches the outer bank near the end of the curved reach. The mechanisms leading to this redistribution of streamwise velocity within a sharp channel bend have previously been discussed by Zeng *et al.* (2008), Constantinescu *et al.* (2011), and Kashyap (2012, Chapter 5). In general, for case DB, the core of high streamwise velocity coincides with the location of the channel thalweg. However, when interpreting the depth averaged plots care must be taken, as the core of high streamwise velocity is not uniform over the flow depth, and is skewed across the channel width. This can be seen in the 90° section plot of streamwise velocity shown in Figure 8.6a. The depth averaged plot (Figure 8.5a) does not fully capture the nonuniformity in the distribution of the core of high streamwise velocity.

The depth averaged streamwise velocity plot for case DBG is shown in Figure 8.5b and reveals that the groynes disrupt the core of high streamwise velocity. The plots suggest that the groynes are able to lower the streamwise velocities along the outer bank wall where they are located. A comparison of the streamwise velocity in the 90° sections in Figures 8.6a and 8.6b (for cases DB and DBG, respectively), also suggests that the groynes are able to reduce streamwise velocity along the outer bank over the channel depth. As will be seen later however, there are local areas along the outer bank where the groynes cause an increase in the gradient of streamwise velocity. The depth averaged plot of Figure 8.5b for case DBG

also shows that high streamwise velocities are also concentrated in the areas around the groynes. This is partly due to the larger flow depths around the groynes, due to the greater levels of scour around them, which cause flow and high streamwise velocities to be topographically steered towards the groynes (see Zeng *et al.* 2008 for a description of topographic steering). However, as will be discussed later, the cross-stream circulation cells and coherent structures also play an important role in redistributing streamwise velocities around the groynes.

8.4.2. Coherent Structures

Figure 8.7 shows the main coherent structures present around each groyne in the mean flow as predicted by the Q criterion ($Q = -0.5(\delta u_i / \delta x_j)(\delta u_i / \delta x_j)$), which is the second invariant of the velocity gradient tensor (Hunt *et al.* 1988). These include the primary horseshoe necklace vortices (HVPs), the separation vortices (SVs) found along the length of each groyne, the overtopping vortices (OTVs), located above the groyne surface, and the trailing junction vortices (TJVs), found downstream of each groyne base. Note that a number shown after each vortex name denotes the groyne number close to the flow structure. The characteristics of these vortices and their implications on sediment erosion, in relation to the plots of boundary friction velocity and mean pressure fluctuations (Figures 8.8 and 8.9, respectively), will be discussed in the following sections.

8.4.2.2. Horseshoe Vortices

The primary horseshoe necklace vortices (HVPs) present around each groyne tip can be seen in Figure 8.7. The secondary horseshoe vortices that were seen around the groynes in case FBG (Kashyap 2012, Chapter 7), are not resolved by Q criterion for case DBG. As can be

seen in Figure 8.7, several additional vortices are also present around G1, which are not present around the downstream groynes (G2 and G3). We refer to these as a ‘complex vortex system’ which will be discussed later. As was found for case FBG, the legs of the horseshoe vortices (HVs) deflect into the flow in the direction of the velocity streamlines close to the bed (Figure 8.10), which on the main channel side of the groyne is about 30° from the groyne centerline. For G1, HVP1 reaches the outer flume wall before entering the groyne embayment, and for G2 and G3, HVP is obstructed by the upstream groyne before it transports flow into the groyne embayment. The high levels of scour that are present near the outer bank wall, near the tip of G1 may be due to the contact that HVP1 makes with the outer bank wall. For G2 and G3, the HVPs also likely contribute to scour at the base of the upstream groyne near the outer bank wall due to an increase in mean pressure fluctuations (Figure 8.9b).

Figures 8.7a and 8.7b show that the coherence of the HVs is greatest in front of G1, and decreases for each downstream groyne. Infact, HVP in front of G3 is almost indiscernible by Q criterion, even though total vorticity and streamlines plots (not shown) still show it to be present up to a distance of $1.3 L/H$ from the groyne centerline, on the main channel side of the groyne. This is opposite to what was observed for the case FBG (Kashyap 2012, Chapter 7), where the coherence of the HVP increased for each downstream groyne. Figure 8.11, shows that TKE and total vorticity levels are amplified within the core of HVP. As was found for case FBG (Kashyap 2012, Chapter 7), high levels of TKE within the core are due to low-frequency bimodal oscillations. For case DBG however, the characteristic ‘C’ shape of the TKE distribution (see Koken, 2008, for a description of the ‘C’ shape distribution of

TKE) in front of G1 is not as clear as it was for case FBG. Moreover, for G2 and G3, this ‘C’ shape does not appear to be present. The instantaneous flow (not shown) however, still shows bimodal oscillations to be present for HVP in front of all groynes. Figure 8.11 also shows that TKE and total vorticity levels decrease from G1 to G3. This is opposite to what was seen for case FBG where levels increased from G1 to G3. These differences are likely related to differences in the distribution of streamwise velocity for case FBG compared to case DBG which can be seen in the plane $Z/H=0.05$ in Figures 8.12a (case FBG) and 12b (case DBG). This shows that for case FBG, streamwise velocities are greater near the groynes situated downstream of the bend apex for. For case DBG, the core of high streamwise velocity has moved closer to the upstream groyne, leading to an increase in streamwise velocities around the upstream groyne, and a decrease in streamwise velocities around the downstream groynes. Also, the downflow intensity (magnitude of vertical velocity directed towards the bed) at G1 is 1.3 and 8.4 times greater than G2 and G3, respectively.

Differences in the intensity of HVP can be seen through plots of cross-stream circulation magnitude (Γ) for each HVP (Figure 8.13). Recall that Γ is the integral of the out-of-plane vorticity (in a plane cut perpendicular to the axis of HVP) over the cell area of HVP. Figure 8.13 shows that $\Gamma_{\text{HVP}(G1)}$ is about 8 times greater than $\Gamma_{\text{HVP}(G3)}$. This is opposite to what was seen for case FBG, where Γ_{HVP} increased for each downstream groyne. Also, for case DBG, $\Gamma_{\text{HVP}(G1)}$ is less symmetrically distributed around the groyne centerline.

Each HVP induces high friction velocities at the bed around the groyne tips (Figure 8.8d). Peak bed friction velocity magnitudes due to the HVPs are 1.8 and 3.5 times greater around G1 compared to G2 and G3, respectively. Also, the peak magnitude near G1 occurs towards the main channel. High levels of bed friction velocity in front of the groynes are caused mostly by the component of velocity perpendicular to the axis of the HVPs. For G1, HVP also induces high levels of mean pressure fluctuations on the outer bank wall (Figure 8.9b) which can induce high levels of scour. The strength of HVP at each groyne decreases in the legs away from the groyne tip, and the legs of the HVPs do not appear to greatly increase bed friction velocities on the main channel side of each groyne. For G2 and G3, HVP is weak, (Figure 8.13) and therefore does not induce high levels of bed friction velocity magnitude. Rather, high levels of bed friction velocity on the main channel side of each groyne are mainly due to the main channel circulation cell (N4), which has moved very close to the groynes (see Figures 8.8d and 8.14). The main circulation cell induces both high cross-stream bed friction velocities and also advects high momentum fluid containing high streamwise velocities close to the bed (Figure 8.15a).

8.4.2.3. Complex Vortex System at Groyne 1

As mentioned, for case DBG a unique set of coherent structures exists around G1, which are not present around the downstream groynes (Figure 8.14). The main primary horseshoe vortex, HVP1 was discussed in detail previously. X1 is a necklace vortex, oriented almost parallel to HVP1 on the main channel side of G1. It has the same rotational direction as HVP1, as can be seen in the 70° section showing streamwise vorticity predicted by the LES in Figure 8.15a. The presence of X1 can also be seen in the plane cutting the centerline of G1 in Figure 8.11, in the plots of out-of-plane vorticity and 2-D streamlines. It is possible that

X1 originally formed as a secondary horseshoe vortex, upstream of HVP1, and that its legs were deflected into the flow in the direction of the velocity streamlines. In Figure 8.14, a vortex X2 is situated between X1 and HPV1, which has an opposite rotational sense compared to X1 and HPV1 (see the 70° degree section cut of the LES streamwise vorticity in Figure 8.15a). Similar to X1, the coherence of X2 is greatest along the side of G1, rather than in front of it. Initially one may think that X2 results from the jet flow caused by the strong downflow in front of G1. However, an investigation of the instantaneous flow does not clearly indicate this. It is more likely that X2 forms because it is situated between two clockwise rotating vortices, X1 and HPV1. Also, since it is on the lee side of the ridge forming at the top of the primary scour hole, it may have formed due to flow separating as it moved over this ridge (see Figure 8.15a, 70° section).

Figures 8.14a and 8.14b show that a large streamwise orientated vortex, N4 is present close to the lee-sidewall of G1. N4 extends from the outer bank wall, immediately upstream of the large scour hole found in front of G1, deflects into the streamwise direction, and then crosses above X1, X2, and HPV1. As can be seen in Figure 8.15a, N4 has the same rotational sense as HPV1 and X1. Also, streamlines and vorticity levels show that N4 extends along the side of G2 and G3, and eventually reaches the straight exit section (see Figure 8.15b and 15c, showing the 90° and 110° sections, respectively). Figure 8.15 shows that N4 is the largest streamwise orientated circulation cell within all the sections shown, and for this reason can be considered to be the main channel helical flow cell. This conclusion has important implications for the distribution of high streamwise velocity within the bend, as it causes the core of high streamwise velocity to move closer to the groynes, and further induce scour near

the groyne tips. Close to G1, N4 and HVP1 are located so close together that they may be considered to work together in increasing cross-stream circulation within the scour hole near G1.

Figure 8.15 also shows the distributions of streamwise vorticity and streamwise velocity determined from interpolation of the measured data (second row of each frame). The distributions of measured streamwise velocities show similar trends to those predicted by the LES. For example, in the 70° section, the 2-D streamlines for the experimental plots also suggest the presence of cell N4. For both plots, high streamwise velocities are found around the boundary of N4, while lower velocities are located within the core center. Although the agreement between the LES and experimental plots in Figure 8.15 is not perfect, correspondence is reasonable considering the highly dynamic nature of the flow, and helps to increase confidence in the results obtained from the LES model. Comparisons of experimental and LES velocity profiles are also shown in the third row of Figure 8.15 for each frame. Discrepancies appear to be present when the locations of patches of high velocity fluid do not coincide exactly between the measured and LES data. Plots of measured streamwise vorticities in Figure 8.15 show higher levels in the area of the large circulation cell N4. However, due to the sparseness of the measurement data, smaller circulation cells such as X1 and HVP are not resolved by the measured data.

The distribution of cross-stream circulation (Γ) for HVP+N4 for case DBG along the flume length is shown in Figure 8.16a. $\Gamma_{\text{HVP+N4(DBG)}}$ peaks at about 60° which is very close to the tip of G1, and then rapidly decreases. It can also be seen that HVP+N4 makes up the

majority of the total positive cross-stream circulation (Γ_{+DBG}) downstream of 60°. Levels of Γ_{HVP+N4} near G1 are two to three times greater compared to those at G2 and G3 (Figure 8.16a). An observation of the section cuts in Figure 8.15 shows that these higher levels are due mainly to higher levels of vorticity rather than differences in the cell sizes. The average out-of-plane vorticity for HVP+N4 is about two to three times greater in the 70° section compared to in the 90° and 110° sections. These levels have important implications on cross-stream friction velocities due to the proximity of HVP+N4 to the bed. It is clear in Figure 8.8e that cross-stream friction velocity levels due to N4 are substantially greater near G1 compared to G2 and G3. One factor that may contribute to this is that for case DBG, high streamwise velocities have increased in front of G1 compared to case FBG, while they have decreased for the downstream groynes. As noted previously, this leads to an increase in downflow intensity at G1 which is 1.3 to 8.4 times greater compared to G2 and G3, respectively. As a result, we would expect the intensity of HVP1 at G1 should also be greater compared to the downstream groynes.

As can be seen in Figure 8.9d, very severe mean pressure fluctuations (~7 times greater than levels in the straight approach reach) are also present near G1. These high mean pressure fluctuations near G1 are due to the interaction of G1 with the highly complex flow field in this area. As can be seen in Figure 8.12b, two bands of high streamwise velocity exist upstream of G1. The first is located closer to the inner bank between the bend entrance and the tip of G1, and is commonly found in this area in high curvature bends due to the potential vortex effect. The second band is found immediately upstream of G1, and is closer to the outer bank. High flow velocities in this area are likely due to the effect of topographic

steering, since the highest flow depths are found near G1. These two bands of high streamwise velocities are close to merging immediately upstream of G1. The complexity of the flow in this area can be better understood by examining the plots of pressure and streamwise velocities in both the mean and instantaneous flow in Figure 8.17. The mean pressure and velocity distributions in Figures 8.17a and 8.17e, respectively, show that as the band of high streamwise velocity from the inner bank reaches vortex N4, a region of high pressure develops adjacent to N4, on the side of N4 facing the inner bank. Within the core of N4 however, pressure is negative, and streamwise velocity is low. It should be emphasized, as was seen in Figure 8.15a, that although N4 is associated with high levels of vorticity, the streamwise velocity within the core may be low. N4 appears to advect high streamwise velocity towards G1, and towards the bed. The instantaneous flow field diagrams (Figures 8.17b to 8.17d for pressure, and 8.17f to 8.17h for streamwise velocity) reveal that the two bands of high streamwise velocity periodically merge and diverge. As they merge, the area of negative pressure dissipates, and flow moves towards G1. As they diverge, the area of negative pressure reappears, and a region of negative streamwise velocity forms between the two bands of high streamwise velocity (Figures 8.17f and 8.17g). It is likely that high mean pressure fluctuations within the complex vortex system are also partly responsible for the high levels of turbulence within HVP1, which are imparting high mean pressure fluctuations on the outer bank wall.

8.4.2.5. Overtopping Vortices

The OTVs are located close to the outer bank wall above the top surface of each groyne. For each groyne they form within the embayment from flow which has primarily entered the front of the embayment near the groyne tip, rather than from flow entering from above the

embayment (see Figure 8.18 for OTV1, and Figure 8.19 for the OTVs near each groyne). As the flow moves towards the end of the embayment it converges, and the majority of it overtops the groyne near the outer bank wall, while the remaining portion recirculates near the bed in the area near the corner junction of the groyne sidewall and the outer flume wall (Figure 8.18). 3-D streamlines in Figure 8.18a show that OTV1 is fed from both the main channel flow and from fluid transported into the embayment from HVP1. For G2 and G3 the HVP contributes much less to the formation of the OTV, as HVP is much weaker for these groynes, and does not directly enter the embayment since it is obstructed by the upstream groyne.

The portion of fluid which recirculates in the scour hole at the junction of the outer bank wall and the groyne sidewall near the bed (Figure 8.18a) has velocities which are about 80% lower than those of the flow moving above it. It was seen for case FBG (Kashyap 2012, Chapter 7) that this recirculation eddy induces high mean pressure fluctuations at both the outer bank wall, and the bed, and could cause sediment erosion in these areas. In this study, for case DBG, mean pressure fluctuations associated with the recirculation eddy have decreased slightly for G2 and G3, compared to case FBG, although they are still relatively high near G1 (Figures 8.9b and 8.9d). Also the height of the recirculation eddy near G1 is about eight times greater for case DBG compared to that for case FBG (Kashyap 2012, Chapter 7), and a larger volume of fluid is trapped within the scour hole for case DBG. It is likely that the scour hole at the embayment junction for G2 and G3 is closer to equilibrium compared to the one at G1, as boundary friction velocities are also very low in these regions for all three groynes (Figures 8.8b and 8.8d).

For the portion of flow exiting through the top of the embayment, maximum velocities near the groyne surface occur slightly upstream of the junction of the groyne sidewall with the outer bank wall, and are about 30% lower compared to velocities at this junction near the groyne surface. The bulk of the flow starts to exit the top of the embayment slightly further upstream compared to what was seen for case FBG (Kashyap 2012, Chapter 7). The accelerating flow leaving the embayment leads to increases in levels of friction velocity magnitudes at the bed within the first half of the embayment by about 40% compared to levels on the surrounding bed (Figure 8.8d), and also at the outer bank wall (Figure 8.8b). It should be noted that friction velocities at the outer bank wall adjacent to the recirculation area near the bed at the groyne junction remain low. The effect of flow moving out of the embayment on mean pressure fluctuations is greatest for G1, and decreases for each downstream groyne (Figure 8.9b).

The OTV rotates in the counter-clockwise direction (the opposite direction of the main channel helical flow) over the base of the groyne near the outer flume wall. The strength of the OTV has been quantified along the groyne base in Figure 8.20 by cross-stream circulation magnitude (Γ) which is the integral of out-of-plane vorticity over the cell area in a plane cut perpendicular to the axis of OTV. For all groynes, the trend of Γ_{OTV} is the same. It decreases from the upstream edge of the groyne base to its downstream edge. $\Gamma_{OTV(G1)}$ is about 20 to 35% greater than $\Gamma_{OTV(G2)}$ and $\Gamma_{OTV(G3)}$ along the groyne base. This is opposite to what was seen for case FBG (Kashyap 2012, Chapter 7) where $\Gamma_{OTV(G3)}$ was greater than $\Gamma_{OTV(G1)}$ and $\Gamma_{OTV(G2)}$. The reason for this is not entirely clear but may be related to the fact that

streamwise velocities have increased in front of G1, and decreased in front of G3, for case DBG.

The position of the OTV near each groyne, relative to the counter-clockwise rotating separation vortex (SV) forming along the length of the upstream groyne is shown in Figures 8.19a to 8.19c. It can be seen in these figures that flow from the upstream SV moves above the downstream groyne top surface close to the OTV. While one may expect that the SV contributes to the circulation strength of OTV, the strength of SV is almost negligible when it reaches the downstream groyne. The position of OTV in Figure 8.19 in a plane cut perpendicular to the axis of OTV, depicted by Lines 1, 2, and 3, in frames a, b, and c, respectively, are shown in frames d, e, and f, by out of plane vorticity, and in frames g, h, and i, by 2-D streamlines over a contour of streamwise velocity (velocity parallel to the bend walls). In frames g, h, and i, low values of streamwise velocity are associated with the location of OTV. It appears that above the groyne base OTV is having a protective effect on the outer bank walls by reducing the gradient of high streamwise velocities close to the outer bank wall. Care must be taken however in analyzing the total friction velocity magnitudes in this area, since if the cross-stream circulation magnitude of OTV (Γ_{OTV}) is sufficiently high, the total friction velocity magnitude can also be high due to the vertical component of velocity. This can be seen above the base of G1 in Figure 8.8b.

8.4.2.5. Separation Vortices

As seen in Figures 8.19b and 8.19c, for G2 and G3, a separation vortex (SV) forms along the length of the lee-sidewall of each groyne as flow separates at the downstream edge of the groyne. This vortex extends the entire length of the groyne and rotates in the counter-

clockwise direction (i.e. opposite to that of the main channel helical flow). The size and position of the SV near each groyne can be seen in Figures 8.19g,h, and i, which show 2-D streamlines and out-of-plane velocity in a plane cut perpendicular to the groyne center line.

The size and position of the SVs can also be seen by 2-D streamlines overlain on a plot of out-of-plane vorticity for a plane cut perpendicular to the axis of SV near mid-length of each groyne in Figure 8.21. This figure shows that the SV extends from the groyne surface, to almost one-half the groyne height at any given location. For case DBG, the SVs have little effect on bed friction velocities and bed mean pressure fluctuations, as they are located quite far from the bed. They also have little effect on outer bank friction velocity magnitudes and mean pressure fluctuations. They do, however, contribute to the strength (~5 to 40%) of the counter-rotating circulation cell created by the groyne field which appears to help to keep high streamwise velocities away from the outer bank wall in the area near the groynes. The cross-stream circulation magnitude (Γ) for the SV in a plane cut perpendicular to the axis of SV is shown in Figure 8.22. Γ_{SV} increases from the groyne tip to the base and $\Gamma_{SV(G2)}$ is greater than $\Gamma_{SV(G1)}$ and $\Gamma_{SV(G3)}$.

8.4.2.6. Trailing Junction Vortices

Junction vortices are present along the length of each groyne at the junction of the groyne lee-sidewall, and the fixed bed. These vortices are aligned parallel to the groyne length, and rotate in a direction similar to the main channel helical flow, which is towards the outer bank near the top of the vortex, and towards the inner bank near the bottom of the vortex. They are small however, and have a diameter that is almost negligible compared to the water flow depth. As they extend beyond the groyne base, they run parallel to the outer flume wall. In

this study, the portion of this vortex that is located downstream of the groyne base is called a trailing junction vortex (TJV) (Figures 8.23a and 8.23b show these vortices using Q criterion). The TJVs downstream of G1 and G2 (TJV1 and TJV2, respectively) are very small in diameter, and do not have a noticeable impact on streamwise friction velocities or mean pressure fluctuations at the bed. They do lead to a small elevation in cross-stream friction velocity at the bed, although as it is small, it should not impact scour within the embayments. However, the TJV downstream of G3, TJV3, substantially impacts bed friction velocities. TJV3 is relatively large, as can be seen in Figures 8.23c to 8.23e, and has a diameter of about 50% of the initial flow depth H . An investigation of the instantaneous flow reveals that TJV3 advects high streamwise velocities from the surrounding flow towards the bed. Figure 8.23d shows the mean streamwise velocity in the 135° section, and it can be seen that TJV3 increases the streamwise velocity gradient close to the bed below the portion of the cell close to the outer bank wall. This is reflected in the increase in bed friction velocity magnitude which can be seen in Figure 8.23a below TJV3, and which extends to the outer bank wall. In fact, friction velocity magnitudes in this area are comparable to the maximum bed friction velocity magnitudes found within the bend, which occur close to the tip of G1. Figure 8.23a also shows an area of lower friction velocity magnitudes at the bed on the side of TJV3 facing the inner bank wall. Figure 8.23d shows that a low gradient of streamwise velocities is found close to the bed on this side of TJV3, likely because in this area TJV3 is pushing fluid upwards away from the bed, whereas on the side close to the outer bank wall, fluid is being pushed towards the bed. Increases in cross-stream bed friction velocities are also seen below TJV3 in Figure 8.23b. While these increases are relatively high their values are much lower than the streamwise component. It is also interesting to note that the effect of

the counter-rotating outer bank cell, C1, on outer wall friction velocities can be seen in Figure 8.23d. While C1 is keeping high streamwise velocities away from the outer bank wall near the free surface, at mid-depth levels it is advecting high streamwise velocities towards the outer bank wall. Infact, both TJV3 and C1 are acting together to advect high streamwise velocities towards the outer bank wall. This can be confirmed by examining the plot of outer bank friction velocity in Figure 8.8b. Downstream of the groynes C1 and TJV3 have caused wall friction velocity magnitudes to be very high, and infact in this region, they are greater for case DBG than for case DB. A similar situation was found downstream of the groynes for case FBG compared to case FB (see Kashyap, 2012, Chapter 7).

Although the TJVs helped to elevate mean pressure fluctuations at the outer bank wall for case FBG (Kashyap 2012, Chapter 7), their effect for case DBG is relatively mild, particularly for G2 and G3. Substantial mean pressure fluctuations however, still occur downstream of G1 as can be seen in Figure 8.9b. Examination of the flow field however, shows that these high pressure fluctuations are not directly caused by the TJV, but appear to be caused by high vorticity (counter-clockwise rotating) fluid present near the bed downstream of G1. Figure 8.24 shows that immediately upstream of the junction of the groyne base and outer bank wall, several counter-clockwise rotating vortices are present, which may impact mean pressure fluctuations at the wall. A counter-clockwise vortex, BV1, forming near the junction of the groyne sidewall and the fixed bed (Figure 8.24) merges with the primary horseshoe vortex, HVP2 (present at the downstream end of G1), before it reaches the outer bank wall. For G2 and G3, the mean pressure fluctuations downstream of

the groyne base are less, as a counter-clockwise rotating vortex does not appear near the bed for these groynes. Also, the primary horseshoe vortex for G3 is very weak.

8.5. CONCLUSIONS

This study uses Large Eddy Simulation (LES) to gain insight into the flow and main coherent structures present around a series of three submerged groynes in a high curvature channel bend during the later stages of scour. This study is the second part of two stage study, in which the first part investigated coherent structures around the same series of groynes during the initial stages of scour, corresponding to a flat sediment bed (Kashyap 2012, Chapter 7). These studies aim to gain a better understanding of mechanisms leading to scour around groynes in a sharp bend, in order to improve recommendations and guidelines for their design.

The present study reveals that many similar flow structures are present around groynes during the later stages of scour (case DBG), as during the initial stages of scour (case FBG which is described in Kashyap, 2012, Chapter 7). The characteristics of many of these flow structures and their impacts on erosion however, are considerably different during the later stages of scour. This is partly due to the difference in the distribution of streamwise velocity due to the presence of an equilibrium scoured bathymetry and the effects of topographic steering. The deformed bed also affects the size and shape of the vortices, and the interactions that occur between the vortices and the groyne structures. The following points attempt to summarize the characteristics of the flow field and coherent structures around the groynes during the later stages of scour based the predictions of an LES model.

1. The groynes appear to be effective in keeping the main channel core of high streamwise velocity away from the outer bank wall in the region where they are installed. However, due to the presence of coherent structures and flow moving around the groynes, friction velocities on the outer bank wall around the groynes are very high. Also, due to local scour present around the groynes and the effects of topographic steering, the channel thalweg has also moved very close to the groynes. As a result, streamwise velocities near G1 have increased considerably for case DBG compared to case FBG.
2. A very complex system of vortices is present around G1 that is not present around the downstream groynes, G2 and G3. This complex vortex system causes very severe levels of mean pressure fluctuations to occur at the bed near G1. These pressure fluctuations occur as the main core of high streamwise velocity, originating from the inner bend, moves close to the tip of G1. The complex vortex system partially obstructs the high velocity core from reaching the deep scour region near G1, causing pressure to periodically increase and decrease as the core of high streamwise velocity moves past this vortex system. The severe mean pressure fluctuations lead to high levels of scour around G1, which may prevent erosion in this area from reaching equilibrium.
3. Mean pressure fluctuations along the outer bank wall decrease from G1 to G3 for case DBG. This is opposite to the trend that was seen for case FBG where there was an increase from G1 to G3. Close to G1, the horseshoe vortex system appears to be the main factor leading to an increase in mean pressure fluctuations along the outer bank wall upstream of G1. This is partly because the horseshoe vortex (HV) is now making direct

contact with the outer bank wall. For case FBG the HVs dissipated before reaching the outer bank wall. Also, for both cases friction velocities on the outer bank wall are amplified just upstream of each groyne in the region where flow accelerates just before it moves out of the embayments.

4. For case DBG, a very sharp increase in total positive cross-stream circulation magnitude (Γ_+) was predicted by LES near the tip of G1. This sharp increase was not predicted for case FBG, and is partly due to an increase in the intensity of streamwise vorticity near G1, and to a lesser extent, by an increase in size of the main channel helical flow cell. Further investigation would be needed to determine reasons for the increase in vorticity in this area. The high levels of Γ_+ near G1 are important as they substantially increase levels of cross-stream friction velocities at the bed around G1.
5. The counter-rotating outer bank cell present around the groynes appears to be mostly beneficial in the region where the groynes are installed by keeping the core of high streamwise velocity away from the outer bank wall. Downstream of where the groynes are installed however, this counter-rotating cell advects high streamwise velocity towards the outer bank wall at mid-depth levels which substantially increases friction velocities on the outer bank wall, which can endanger its stability.

This study suggests that during the later stages of scour, the main mechanisms leading to high levels of erosion around the groynes are the very severe mean pressure fluctuations occurring around G1 due to the interaction of the complex vortex system with the main

channel flow. These high pressure fluctuations are likely preventing the scour around G1 from reaching equilibrium. Generally, during the later stages of scour, erosion is of a much greater concern around G1 compared to the downstream groynes and it is possible that removing G1 could prove to be beneficial.

8.6. NOTATION

B = channel width (m)

D = groyne height (m)

d_{50} = median sediment size (mm)

Fr = non-dimensional Froude number = $U/(gH)^{1/2}$

g = acceleration due to gravity (m/s^2)

H = initial water depth in the straight inlet section (m)

k = kinetic energy (m^2/s^2) = $0.5(\langle (u_1')^2 \rangle + \langle (u_2')^2 \rangle + \langle (u_3')^2 \rangle)$

L = length (m)

p = pressure (N/m^2)

p' = pressure fluctuation (N/m^2)

Q = discharge (m^3/s)

R = radius of curvature at the channel centerline (m)

Re = non-dimensional main channel Reynolds number = UH/ν

t = non-dimensional time

T = temperature ($^{\circ}C$)

TKE = non-dimensional turbulent kinetic energy = k/U^2

u^* = bed friction velocity magnitude (m/s)

u_C = cross-stream velocity (m/s)

u_{cr}^* = Shields critical friction velocity (m/s)

u_C^* = cross-stream bed friction velocity (m/s)

u_i' = fluctuating component of velocity (m/s)

u_ξ = streamwise velocity relative to the channel centerline (m/s)

U = mean velocity in the straight inlet section (m/s)

w = vertical velocity (m/s)

$y^+ = (\text{Re})(u^*/U)(\Delta n/H) = \Delta n(u^*/\nu)$ = non-dimensional mesh spacing

Z = vertical distance from initial bed level (m)

Γ = non-dimensional cross-stream circulation magnitude

Γ_+ = total positive non-dimensional cross-stream circulation

Δn = dimensional mesh spacing (m)

ρ = water density (kg/m³)

τ_{ij} = non-dimensional subgrid scale stresses

ν = kinematic fluid viscosity (m²/s)

ω = total vorticity magnitude (1/s)

ω_ξ = streamwise vorticity = (dw/dy)-(du_c/dz) (1/s)

8.7. REFERENCES

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Table 8.1 Parameters in the straight approach channel for the experiments and LES simulations

	Re	Q	U	u^*	u^*_{cr}	B	H	R/B	Fr	d_{50}	Max T
		[m ³ /s]	[m/s]	[m/s]	[m/s]	[m]	[m]			[mm]	[°C]
DBG	60 000	0.0464	0.3095	0.0152	0.0195	1	0.15	1.5	0.255	0.698	33

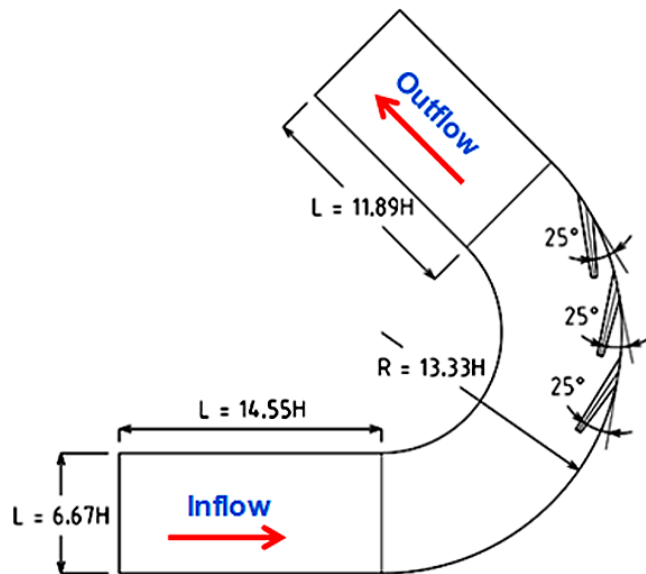


Figure 8.1 Plan view of the computational domain showing the groyne positions for case DBG. Dimensions are in terms of initial water depth $H=0.15\text{m}$.

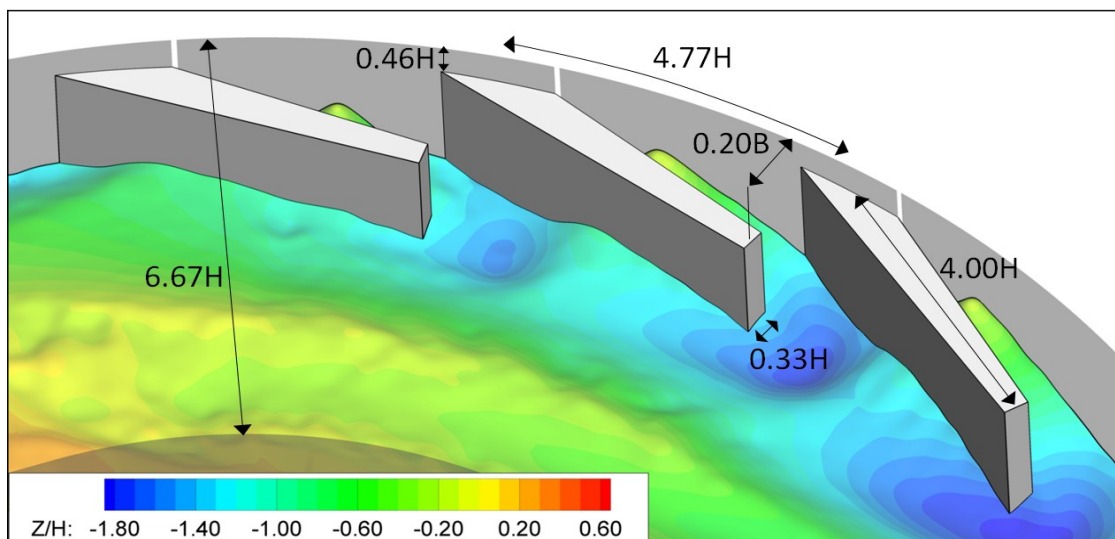


Figure 8.2 3-D view showing groyne locations and dimensions within the bend, and bed contour levels (Z/H) for case DBG. Dimensions are in terms of the initial water depth $H=0.15\text{m}$, and channel width, $B=1\text{m}$.

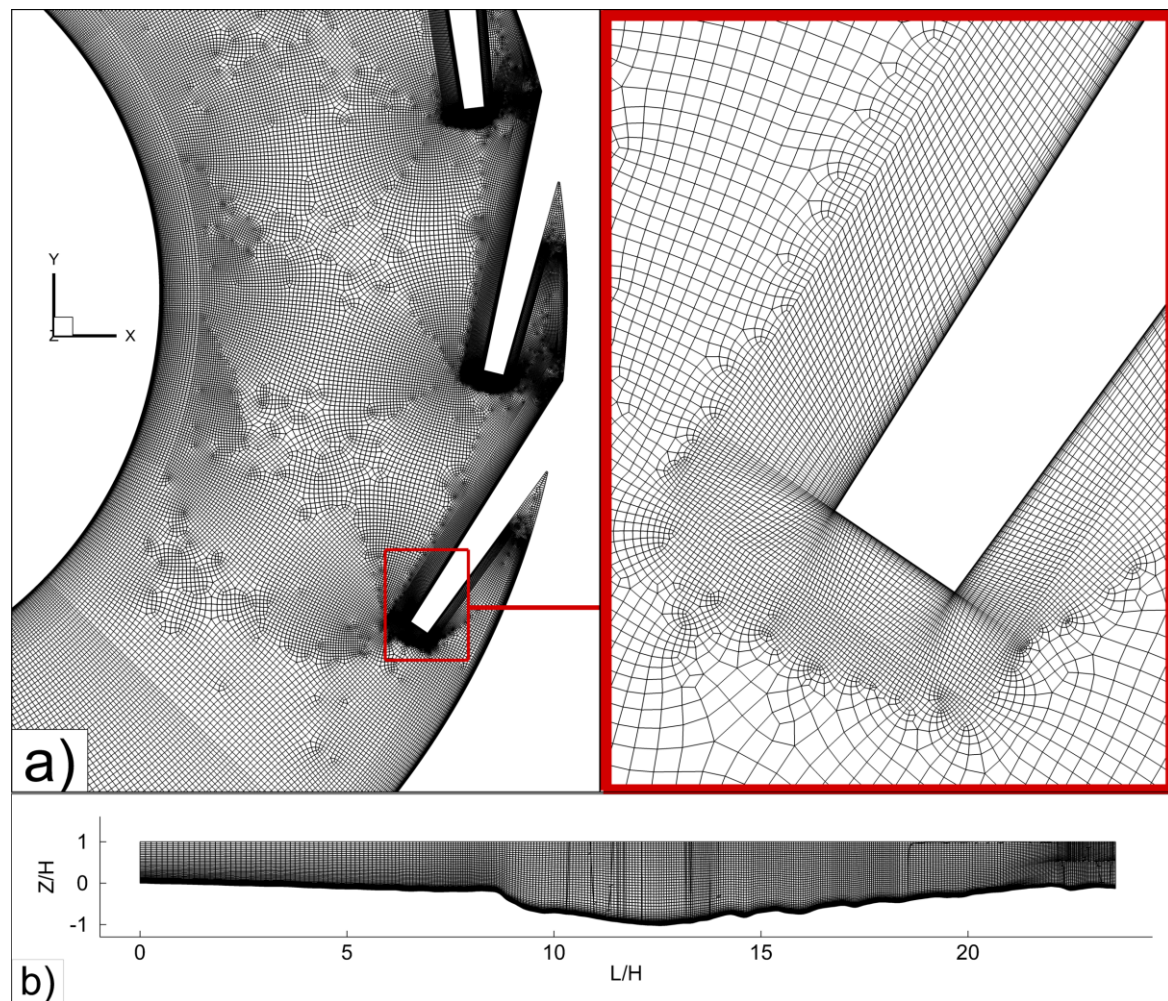


Figure 8.3 Mesh for case DBG a) in the horizontal plane $Z/H=0$ (left), with a close-up of the first groyne tip (right), and b) in a vertical plane along the channel centerline between 0° and 135° .

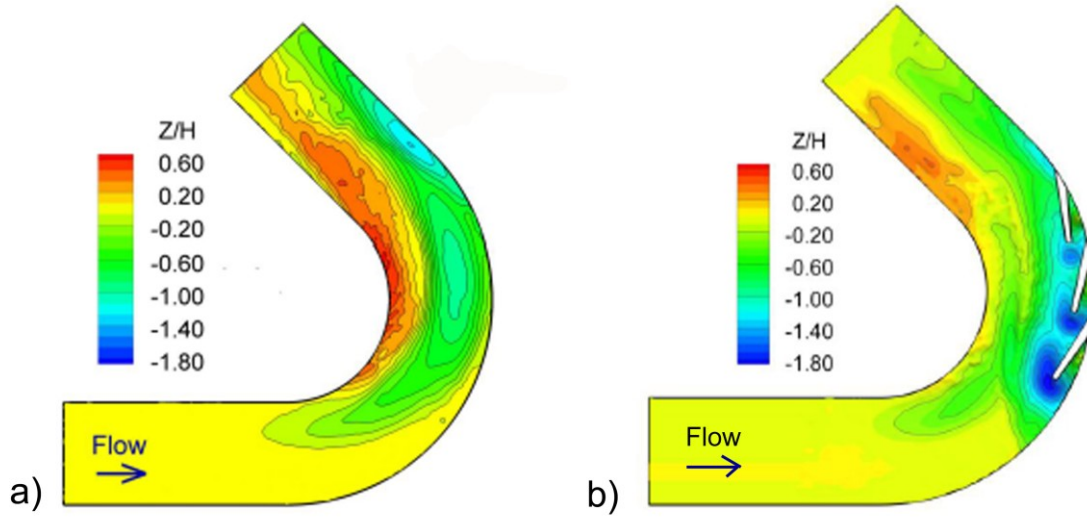


Figure 8.4 Contour plots showing the final bed elevations (Z/H) used in the LES simulations for a) case DB and b) case DBG. Elevations are measured from the initial sand level of $Z/H=0$, with deposition being (+) and erosion being (-).

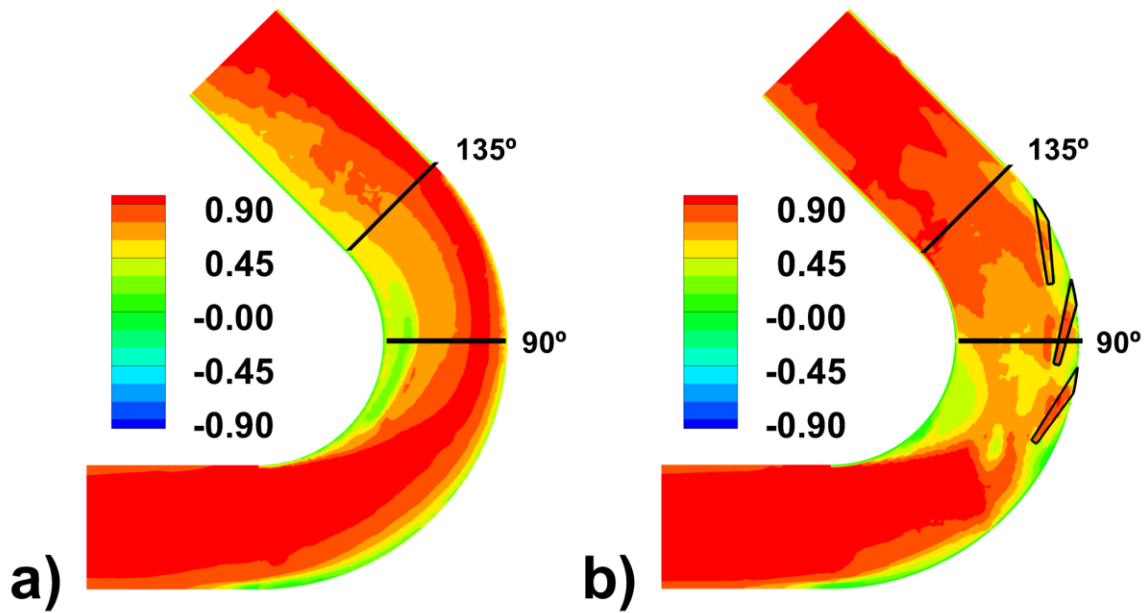


Figure 8.5 Contour plots showing depth averaged streamwise velocity (u_x/U) in the mean flow as predicted by LES for a) case DB and b) case DBG.

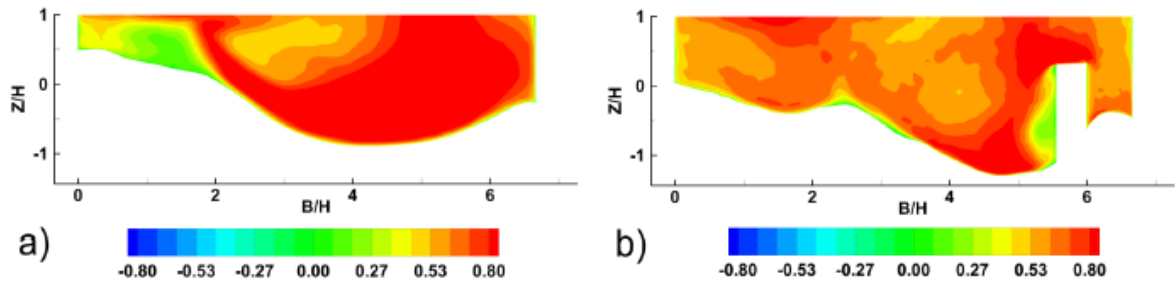


Figure 8.6 Contour plots of the 90° section showing streamwise velocity (u_z/U) in the mean flow predicted by LES in for a) case DB and b) case DBG.

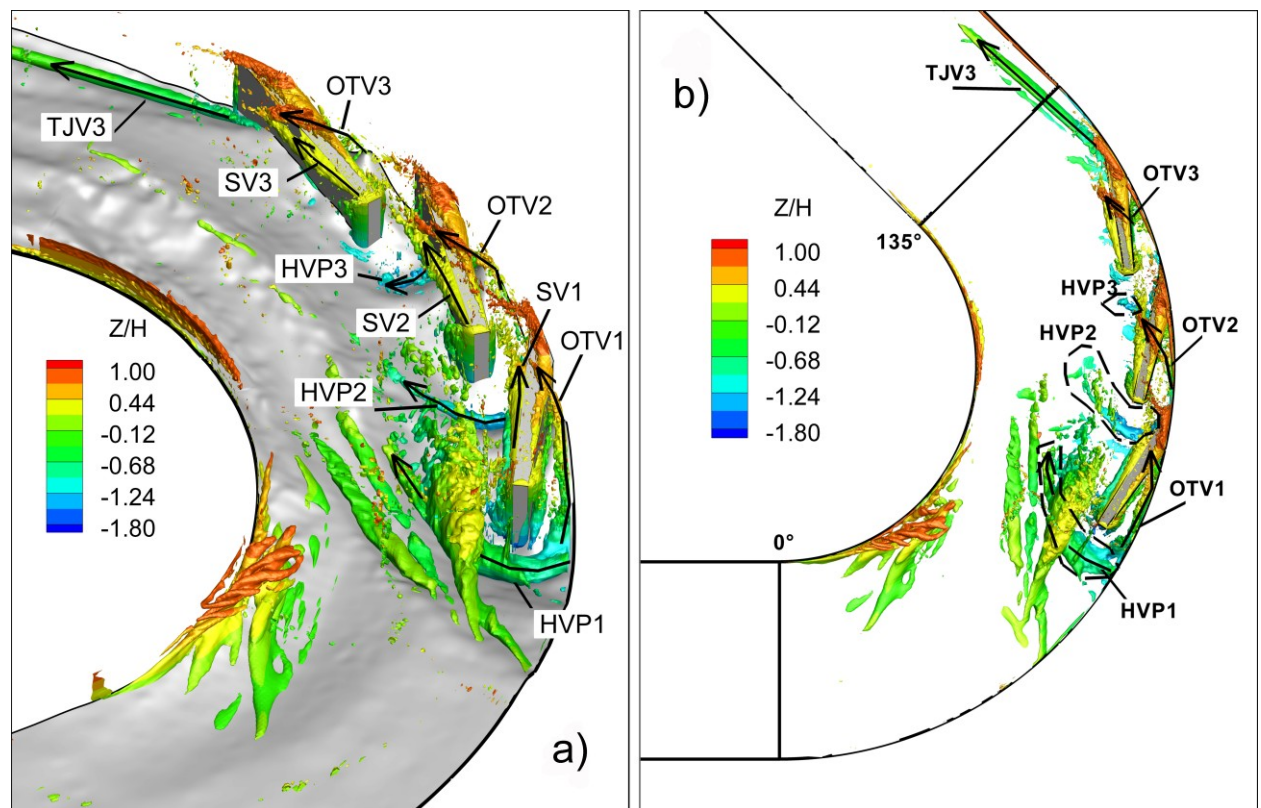


Figure 8.7 Vortical structures present in the LES mean flow for case DBG, as visualized by Q criterion in a) perspective and b) plan views. Contour levels for the vortices show elevation (Z/H) relative to the initial sand surface at $Z/H=0$.

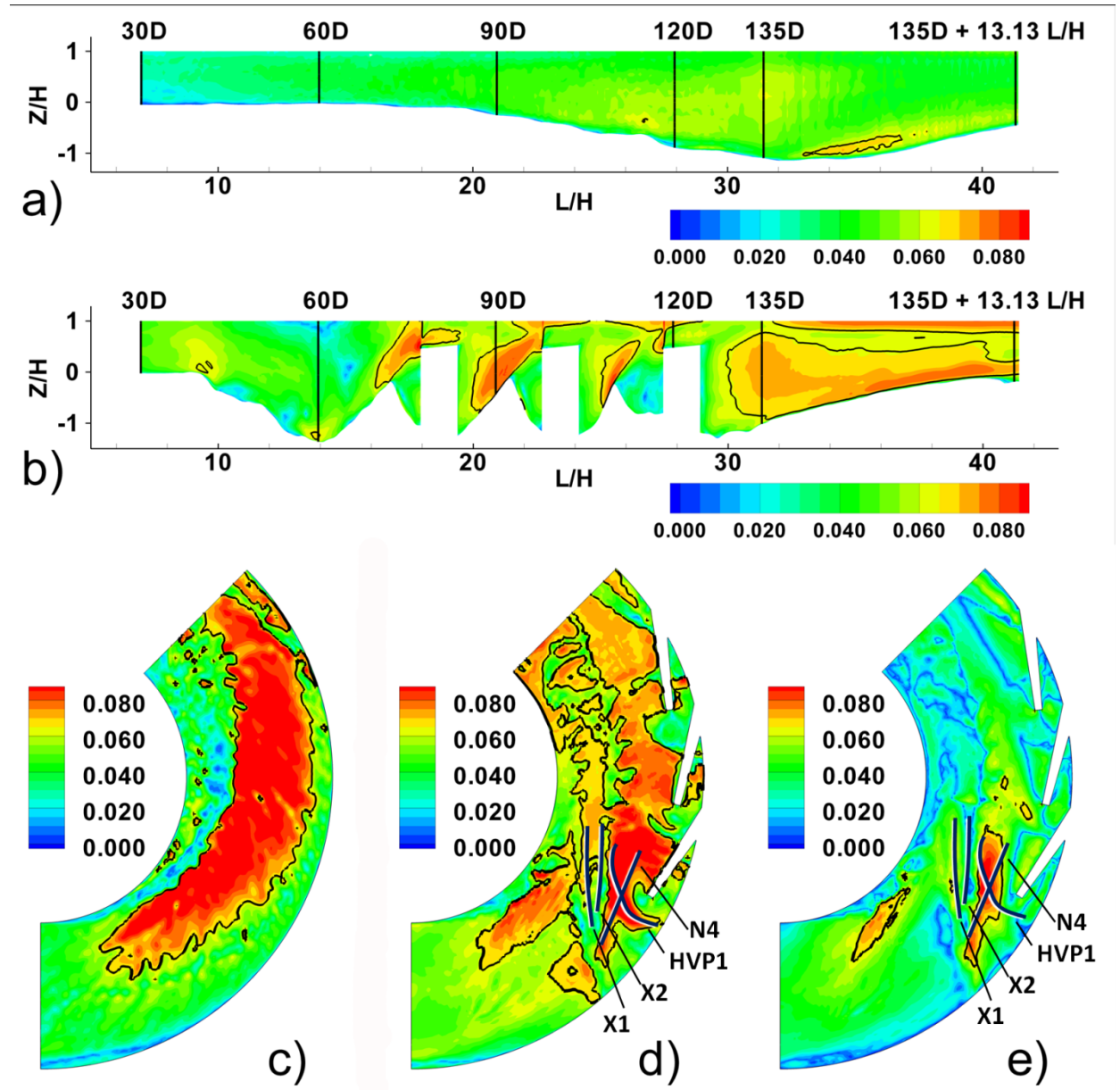


Figure 8.8 Friction velocity magnitudes (u^*/U) in the mean statistics at the outer bank wall for a) case DB, and b) case DBG, and at the bed for c) case DB, and d) case DBG. d) Cross-stream friction velocity magnitudes (u_c^*/U) for case DBG. Locations of vortices X1, X2, HVP1, and N4 are shown in d) and e) by blue lines.

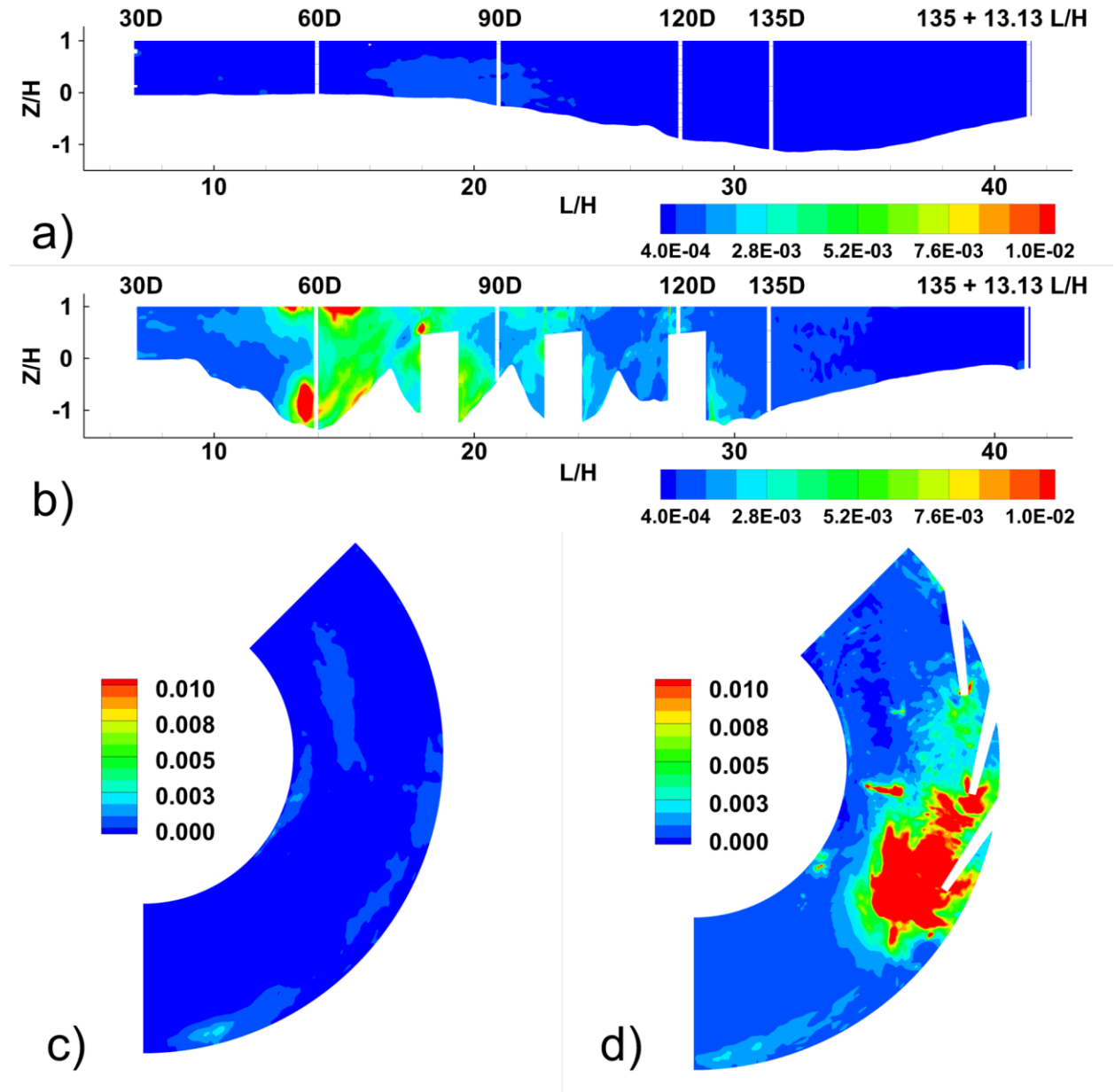


Figure 8.9 Mean pressure fluctuations, $\langle p'^2 \rangle / (\rho^2 U^4)$, at the outer bank wall for a) case DB and b) case DBG, and at the bed for c) case DB, and d) case DBG.

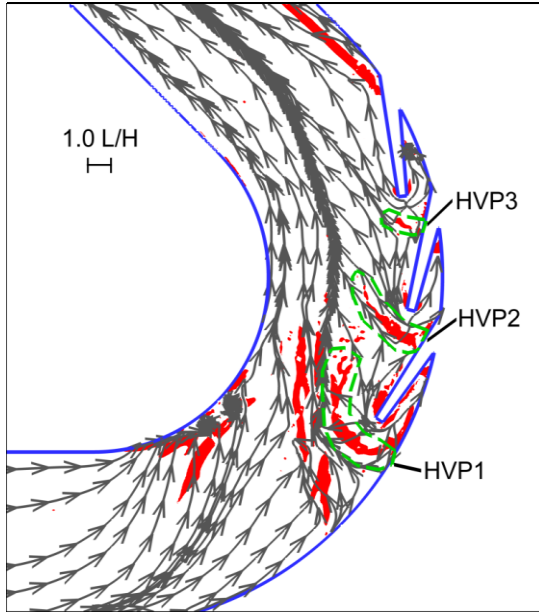


Figure 8.10 2-D Velocity streamlines for case DBG in the mean flow on a surface parallel to the bed at $Z/H=0.05$ above the fixed bed surface. Vortices visualized by Q criterion on a surface at $Z/H=0.20$ above the fixed bed are shown in red.

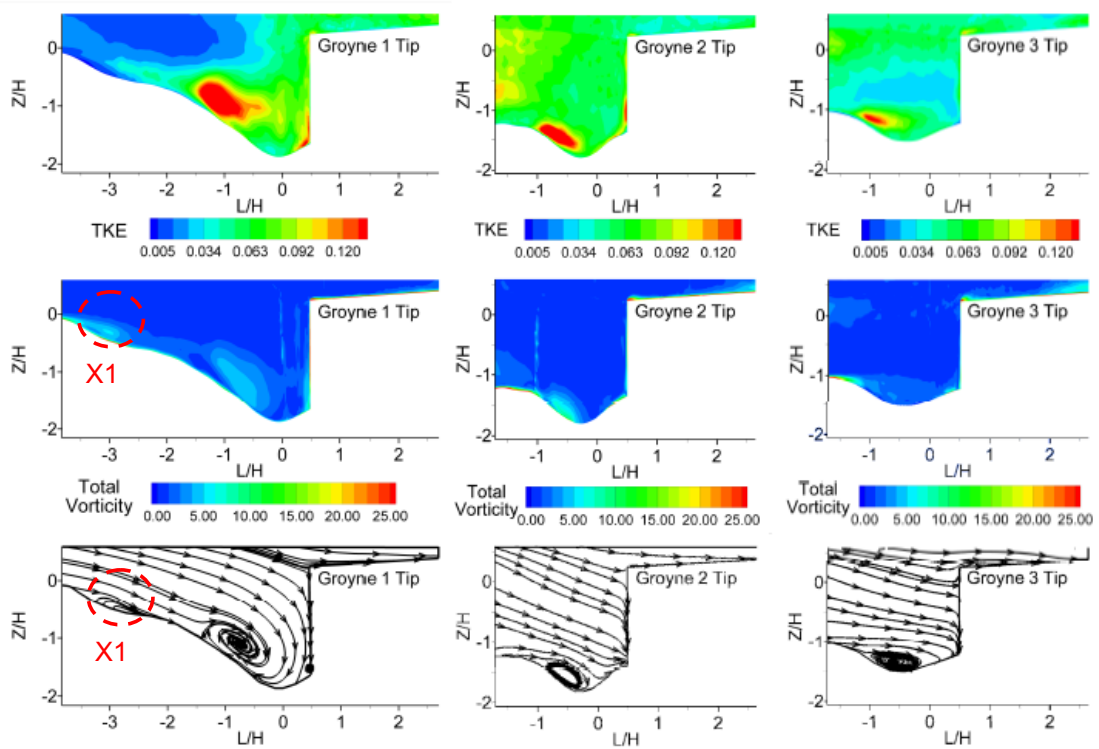


Figure 8.11 Horseshoe vortex system structure in the mean flow in a vertical plane cut along the groyne centerline for (left) G1, (center) G2, and (right) G3. Top plots show TKE (k/U^2),

middle plots show total vorticity ($\omega H/U$), and bottom plots show 2-D streamlines. X1 is a necklace vortex which is part of the complex vortex system shown in Figure 8.14.

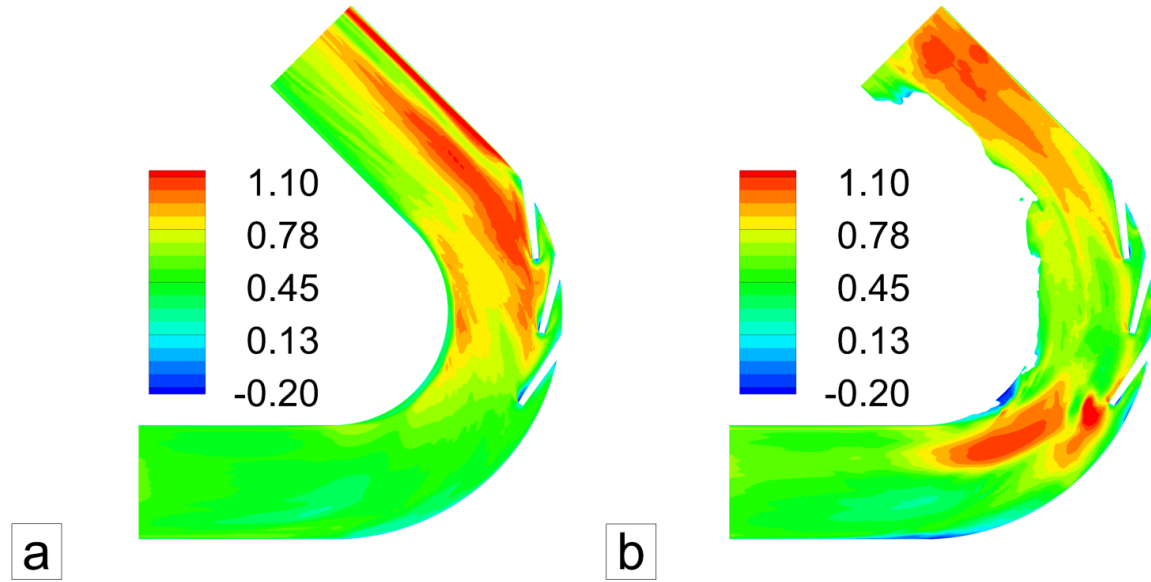


Figure 8.12 Contour plots showing streamwise velocity (u_z/U) as predicted by LES in the mean statistics in the horizontal plane $Z/H = 0.05$ for a) case FBG and b) case DBG.

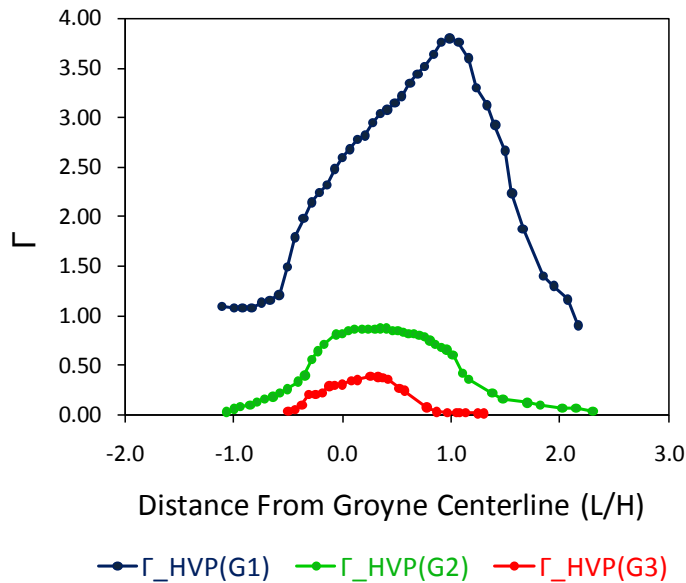


Figure 8.13 Non-dimensional circulation magnitude (Γ) of main horseshoe vortices (HVPs) in the mean flow for G1, G2, and G3 for case DBG. $+L/H$ is towards the main channel side, and $-L/H$ is towards outer flume wall.

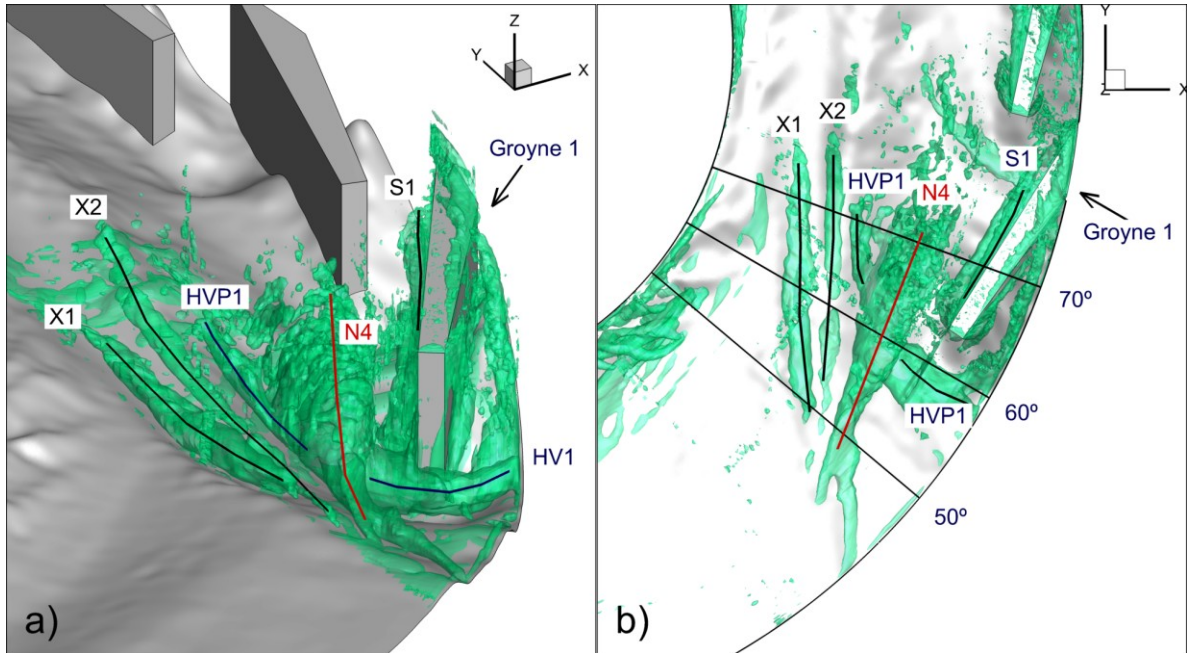


Figure 8.14 a) Perspective and b) plan view of vortices present around G1 in the LES mean flow as visualized by Q criterion.

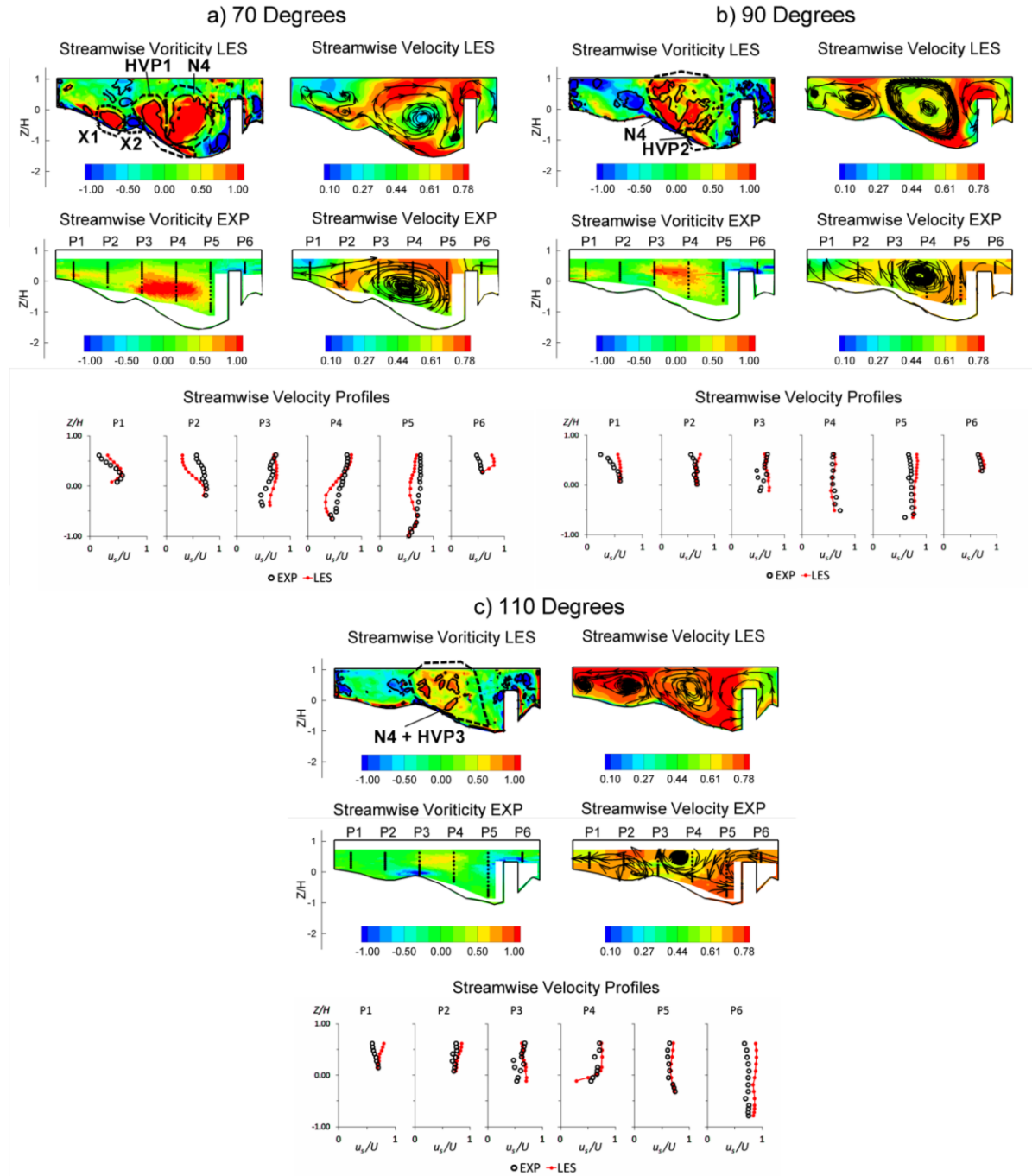


Figure 8.15 Mean plots of the a) 70°, b) 90°, and c) 110° sections for case DBG. In each set the first two rows show the streamwise vorticity ($\omega_x H/U$) (left) and streamwise velocity (u_x/U) (right) predicted by LES (top row) and by interpolation of experimental data (second row). Measurement points are shown by black dots, and 2-D streamlines are shown over velocity contours. Locations of vortices N4, X1, X2, and HPV are shown within the dashed lines. The bottom row shows streamwise velocity profiles at the given sections.

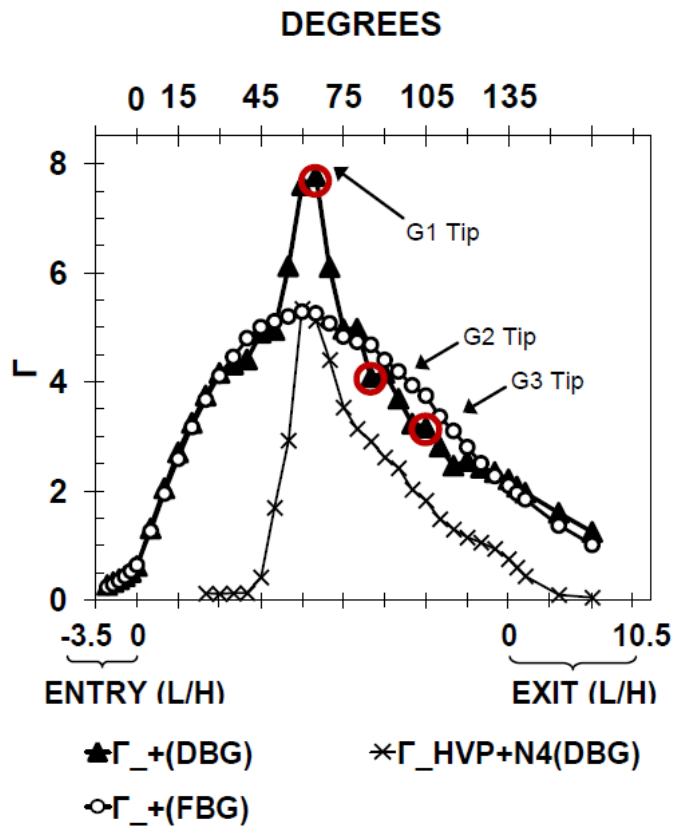


Figure 8.16 Total cross-stream circulation magnitude (Γ) predicted by LES along the flume length for case DBG and FBG, and for cells HVP+N4 for case DBG. The location of each groyne tip is shown by a red circle. Γ_+ denotes total positive cross-stream circulation.

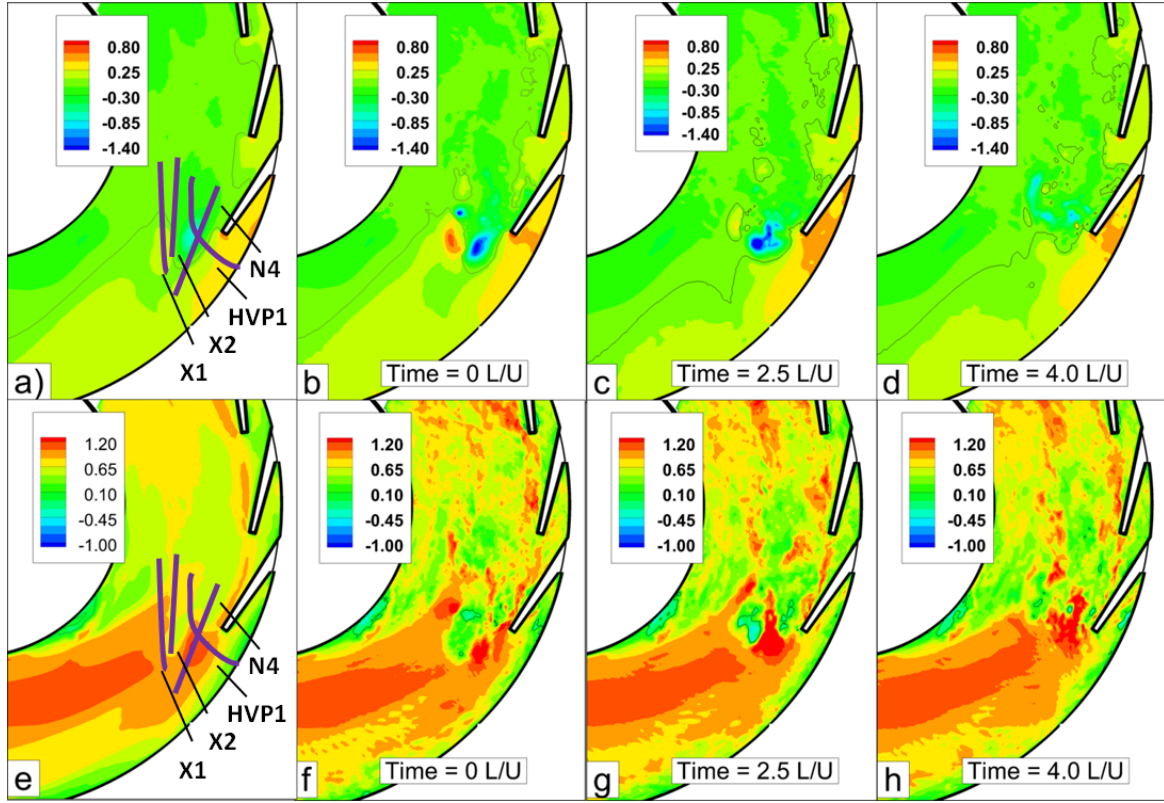


Figure 8.17 Plan view of mean pressure ($p/\rho U^2$) [streamwise velocity (u_z/U)] in a) [e] the mean flow statistics, and the instantaneous flow field after statistically steady flow has been reached at b) [f] $t=0 L/U$, c) [g] $t=2.5 L/U$, and d) [h] $t=4.0 L/U$ at the horizontal plane $Z/H=0.20$. Black contour lines represent a value of zero for the given parameter. Locations of vortices in the complex vortex system around G1 are shown in a) and e).

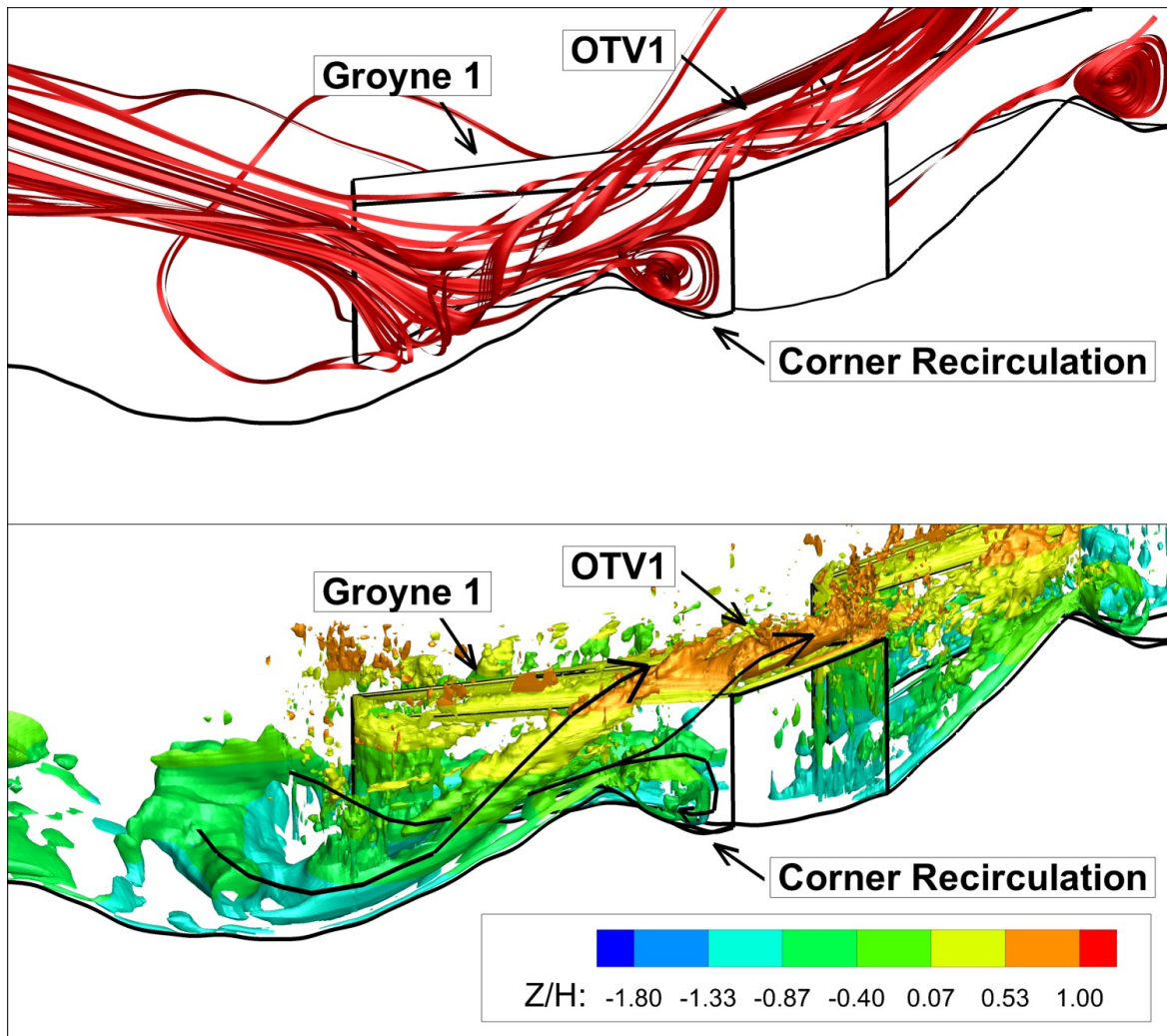


Figure 8.18 a) 3-D view of overtopping vortex (OTV) and corner recirculation in the mean flow at the junction of the inner sidewall of G1 and the outer flume wall as visualized by a) 3-D streamlines, and b) Q criterion. Contour levels for the vortices show elevation (Z/H) relative to the initial sand surface $Z/H=0$.

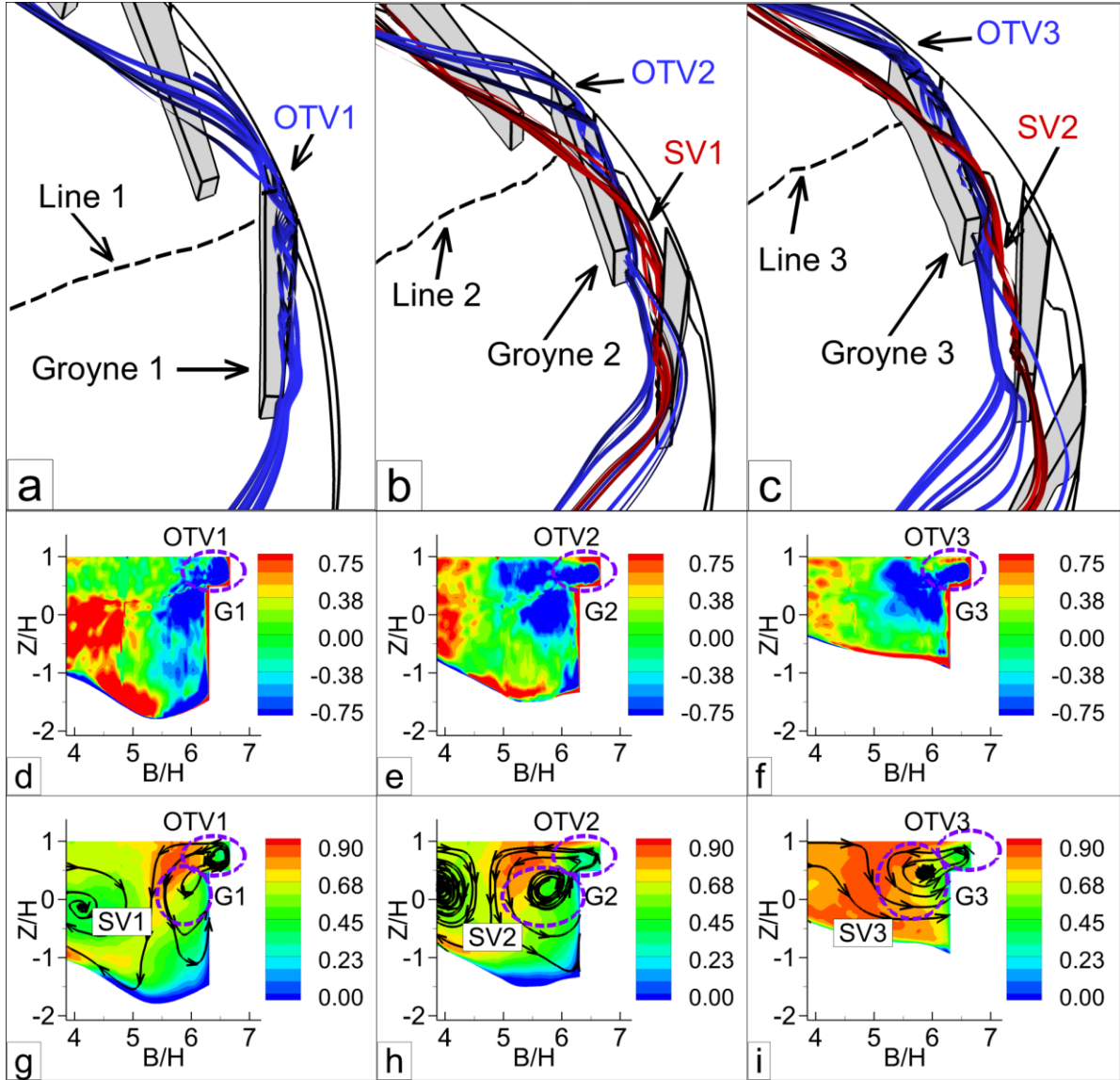


Figure 8.19 (Top) 3-D views of overtopping vortices OTV1, OTV2, and OTV3 (in blue) above a) G1, b) G2, and c) G3, respectively in the LES mean flow. (Middle) Non-dimensional out-of-plane vorticity in planes cut perpendicular to the axis of d) OTV1, e) OTV2, and f) OTV3. The locations of the planes are given by line 1 (G1), line 2 (G2), and line 3 (G3) in frames a), b) and c), respectively. (Bottom) Non-dimensional streamwise velocities and 2-D streamlines for g) G1, h) G2, and i) G3.

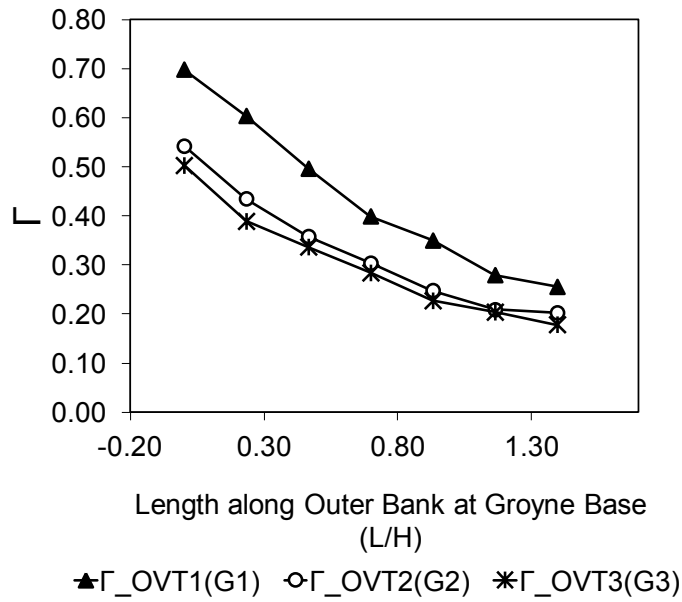


Figure 8.20 Non-dimensional cross-stream circulation (Γ) magnitude for the OTVs in the LES mean flow. $L/H=0$ is the upstream edge of the groyne surface.

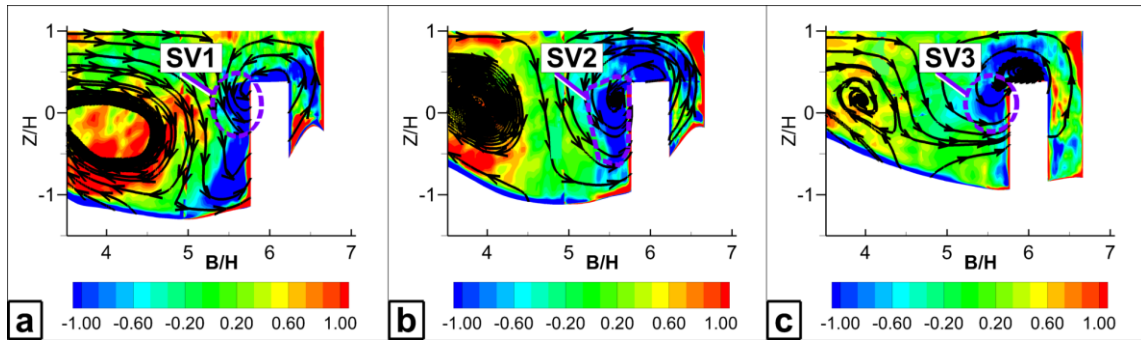


Figure 8.21 Separation vortices (SVs) shown by 2-D streamlines, and non-dimensional out-of-plane vorticity in a plane cut perpendicular to a) G1, b) G2, and c) G3 near mid-groyne-length.

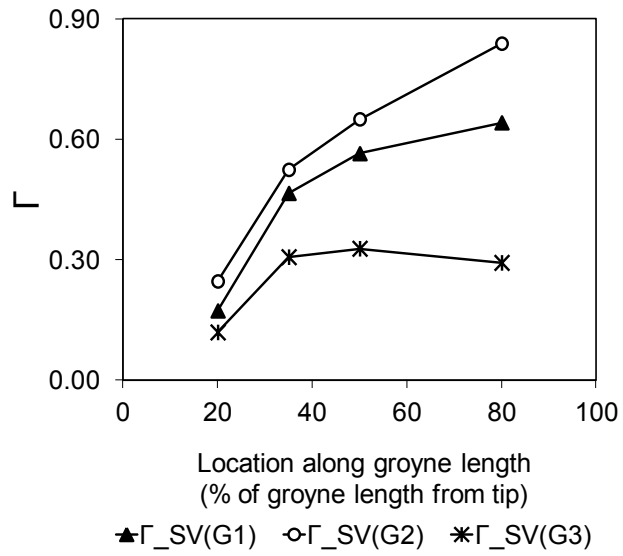


Figure 8.22 Non-dimensional circulation magnitude (Γ) in the LES statistics for the counter-clockwise rotating separation vortex (SV) for G1, G2, and G3.

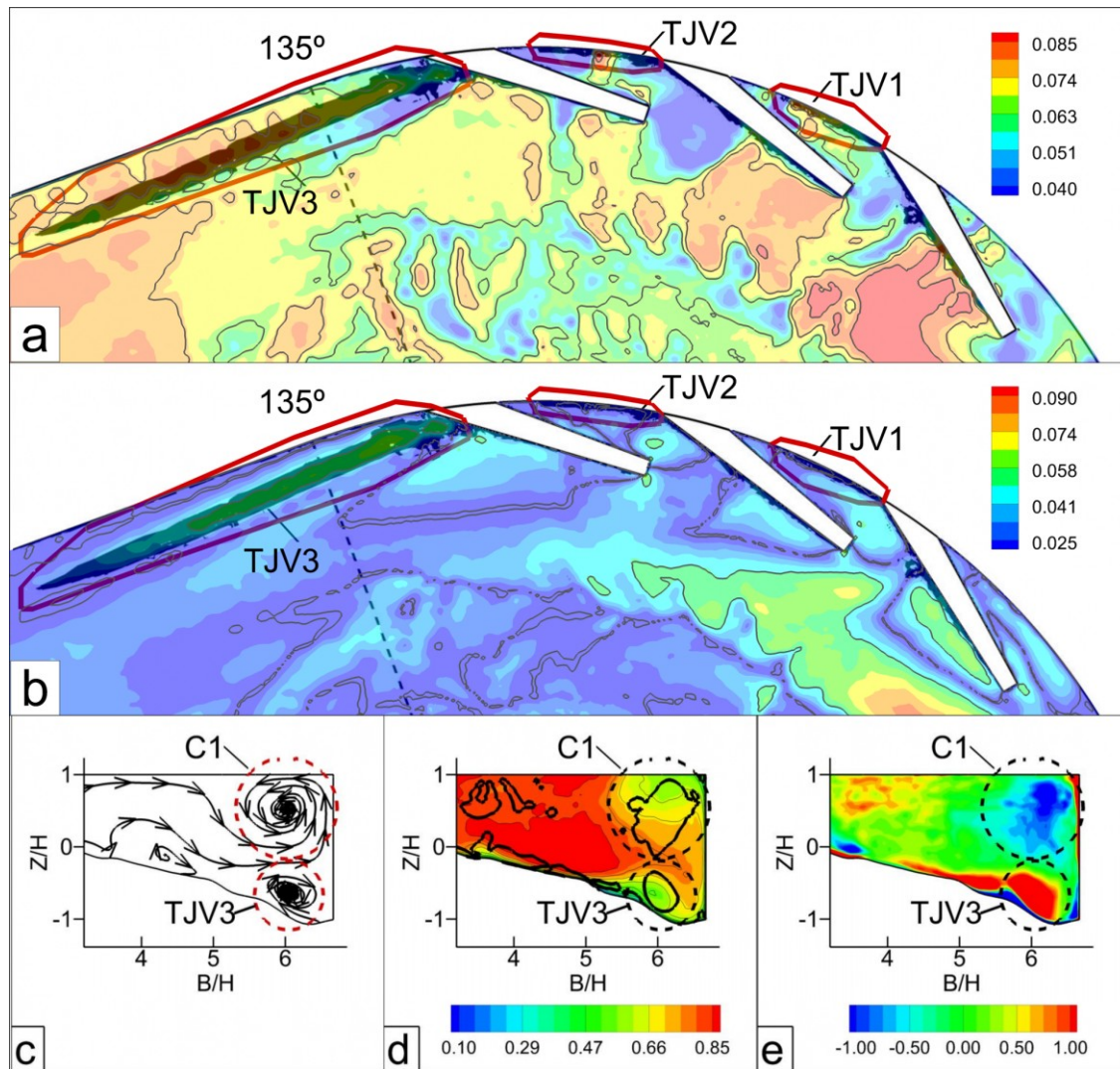


Figure 8.23 Trailing junction vortices (TJVs) in the mean flow shown by Q criterion over contours of a) bed friction velocity magnitude (u^*/U), and b) cross-stream bed friction velocity magnitude (u_c^*/U). TJV are shown in a semi-opaque shade. A vertical section cut at 135° is shown depicting c) 2-D streamlines, d) streamwise velocity (u_x^*/U) (with black lines of constant Q criterion), and e) non-dimensional out-of plane vorticity. TJV3 is the clockwise-rotating TJV downstream of G1. C1 is the counter-rotating outer bank cell near the free surface.

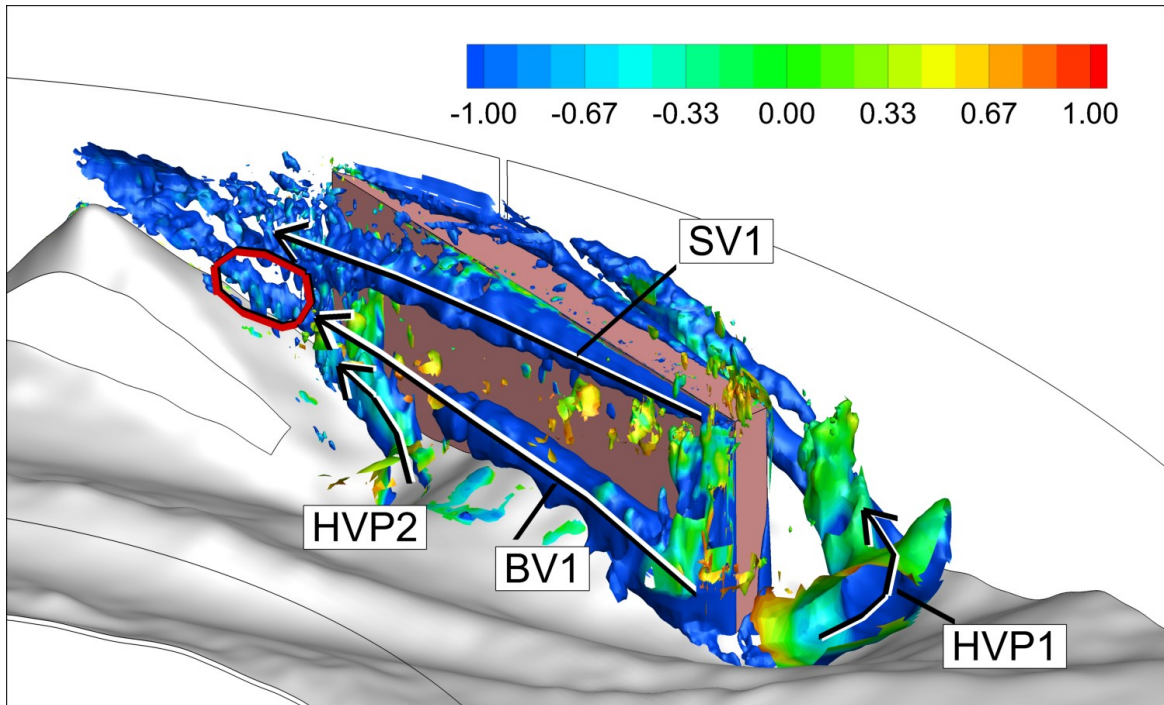


Figure 8.24 Counter-clockwise rotating vortices present around G1. Contour shows streamwise vorticity ($\omega_z H/U$), with (+) being clockwise, and (-) being counter-clockwise. Area of high mean pressure fluctuations at the outer bank wall is shown within the red circle. SV1 is the separation vortex, HVP1 is the primary horseshoe vortex in front of G1, BV1 is the bottom vortex, and HVP1 is the primary horseshoe vortex for G2. Note: clockwise rotating vortices, and vortices in the surrounding flow away from the groyne have been removed from this picture.

CHAPTER 9: A SEMI-PERMANENT METHOD FOR FIXING SAND BEDS IN LABORATORY FLUMES

9.1. ABSTRACT

A new flume bed-sediment hardening method employing a surficial layer of plaster of Paris coated by spar urethane, has been developed and tested for sand beds placed in laboratory flumes. Unlike existing bed-hardening techniques, this method is gentle enough to be used in and subsequently removed from a laboratory flume made of Plexiglas, yet is durable enough to last several days under flowing water. Tests showed that artificially fixed beds using this new technique withstand an estimated bed shear stress of up to 0.251 N/m^2 for 52 hours. The effects of the hardening technique on bed roughness were evaluated. A mean absolute difference in the bed roughness estimate between fixed and loose beds of 0.166 mm was found when tested on a sand bed. Although roughness estimates seemed reasonable, standard deviations were high. Further testing under a wider range of flow conditions and sediment sizes is required to assess the effect of the hardening technique on roughness.

9.1. INTRODUCTION

Flow phenomena in alluvial channels are often studied using physical models. Analyzing time-dependent flow and scour patterns can be challenging, so many studies focus on the equilibrium scour stage. This complicates the study of the temporal development of scour patterns. A method to fix bed morphology at intermediate development stages would help to understand and better relate flow conditions at different times. Currently there are few methods available for hardening sand beds in laboratory flumes made of Plexiglas, which are durable enough to last for long periods underwater.

Bagnold (1936) was likely the first to utilize a technique to harden sediment beds to study the dynamics of desert sands. He used a dilute sodium solution to preserve sand ripples formed in a wind tunnel. Vanoni and Nomicos (1959) developed a more durable semi-permanent technique that could be used underwater for perhaps one day, using sodium aluminate, sodium silicate, and calcium chloride, followed by a coat of varnish. Khalil (1972) developed a permanent technique using a mixture of urea formaldehyde with formic acid, and demonstrated that the method did not noticeably impact bed roughness. However, formic acid would likely damage Plexiglas. Permanently-molded concrete beds have been used by Hooke (1974) and Yen (1970). Best (1988) semi-permanently fixed a bed using urethane varnish followed by acetone diluted epoxy resin spray. Spray application of varnish may increase the risk of damage to a Plexiglas flume. A non-permanent method by Benson *et al.* (2001) employed sodium silicate solution followed by application of a sodium bicarbonate solution. Finally, Blanckaert (2002) semi-permanently sprayed paint on the surface. Of the semi-permanent methods previously described, there appears to be a need for a more durable semi-permanent method which is gentle enough to be used in a Plexiglas flume yet durable enough to withstand continuous use for periods longer than 24 hours. The purpose of this study is to introduce such a method for sand beds by employing both plaster and urethane, and to assess how it may alter the effective bed roughness value.

9.2. METHODS

9.2.1. Bed Hardening Tests

The experiments described below were performed at the Hydraulics Laboratory, University of Ottawa. A preliminary experiment with 2 bedforms present over half the flume length was

performed to test the durability of the hardening method in a small 2 m long $\times$ 0.61 m wide straight flume. A steady discharge close to uniform flow was run in the main channel with a flow depth of 2.7 cm and a mean velocity of 0.39 m/s, measured using a Pitot tube.

A second experiment was performed in a 1.0 m wide $\times$ 20.0 m long Plexiglas bend flume, under flat bed conditions with no bedforms present. Two tests T1 and T2 were completed under loose bed conditions and one Fixed Bed (FB) test was made for the identical condition. The hardening technique was applied to a sand sediment bed of median grain size $d_{50} = 0.689$ mm (Figure 9.1), using the same sediment as for the loose bed runs. All tests T1, T2 and FB were conducted under a steady almost uniform flow, with a zero bed slope, and a constant flow depth of 0.15 m. Water surface slopes were smaller than the measurement accuracy of the survey instruments. Parameters for T1, T2 and FB are listed in Table 9.1. All tests were conducted slightly below the critical Shields shear velocity for the sediment of 0.020 m/s, such that there was no sediment movement in the straight entrance channel. Differences in kinematic viscosities substantially impacted Reynolds numbers. Discharges were measured with a V-notch weir, and were also calculated from six Nortek[®] Vectrino Acoustic Doppler Velocimeter (ADV) profiles equally spaced across the 10 m section. Although attempts were made to maintain a constant discharge for all tests, the maximum difference between the measured weir discharges was $\pm 2\%$, and between the calculated ADV discharges was $\pm 9.5\%$.

Velocity measurements were taken using ADVs in the 12.2 m long straight entrance section at a distance of 10 m from the entrance (2.2 m upstream of the bend section). This location

gave a maximum length to achieve fully-developed flow, while avoiding secondary circulation effects caused by the downstream bend. A sampling frequency of 200 Hz for 2 minutes was used, and velocities were prefiltered to remove obvious errors. Two profiles were measured for each run, at 0.417 m (denoted P1) and 0.583 m (denoted P2) from the outer flume wall. These ADVs had an accuracy of $\pm 0.5\%$ of the measured value ± 1 mm/s (Nortek 2009). Measurements started along each vertical profile at least 1 cm above the bed, at intervals of 1 cm, to a maximum of 10 cm. Small variations (< 5 mm) in the locations were due to variations in the sample volume location below each transducer, which were specific for each ADV probe.

9.2.2. New bed hardening method

The new bed hardening method employs plaster of Paris coated by urethane. These steps were applied:

- 1) Run experiment to the desired bed configuration. When draining the flume leave ~ 1 or 2 cm standing water on the surface to prevent the plaster from clumping on the surface.
- 2) Use dry plaster of Paris mix with a fairly short setting time. An initial test should be done to compare strengths of different plaster brands. Plaster has advantages over other materials, such as cement products, in that it is water soluble, and can thus be cleaned easily from flume walls. A 10 kg bag covers approximately 2.0 m^2 . A double sieve with a 1.0 mm mesh opening was used to dust the dry plaster onto the water/sand surface.
- 3) If standing water is present, apply half of the powder in the first coat, and then slowly drain the water, such that the dissolved plaster settles on the sand surface. A second dusting of plaster should be applied on top of the first using ~ 2 mm. Be sure that the

sand is completely covered with plaster. A fine mist spray bottle should be used to saturate the dry plaster. After spraying, allow ample time for the plaster to set.

- 4) If no standing water is present, apply one coat of dry plaster (2-3 mm thick) evenly across the section ensuring that no sand can be seen underneath. Spray water with a fine mist spray bottle directed parallel to the surface to prevent water drops from changing the surface roughness. The plaster should be fully saturated. It should also be noted that once the dry plaster is fully saturated the thickness of the layer should be less than 1mm, and some of this wet plaster will percolate through the sand to a depth no greater than 1 cm.
- 5) After the plaster is set, spar urethane (preferably without a gloss finish) should be applied with a brush, covering all crevices. The urethane coat allows a fixed bed to perform for a longer period underwater. Urethane can not be physically or chemically removed from Plexiglas without damaging it; thus, leave a margin of 1 to 2 cm from the wall where no urethane is applied, also leaving an area for water to drain. If the discharge is expected to be larger than required for particle entrainment, this margin should be minimized to avoid sediment entrainment/deposition if the unprotected plaster dissolves. Masking tape along the walls may be used for added protection. A 1 liter bottle of spar urethane covers 3 m². Use the urethane within 1 day, as it will thicken after exposure to air.
- 6) Once dry, start the flow by first saturating the sand, and then slowly letting the water rise above the bed to prevent cracking. Initially, air may become trapped beneath the plaster bed, but a slow saturation of the sand bed allows this air to escape.

- 7) Allow the water level in the flume to rise to the desired depth and then set the desired discharge. This hardened bed should last for two to three days underwater.
- 8) When finished, drain the water from the flume. Remove the plaster with a shovel. About 1 cm of sand depth will be lost.

9.3. RESULTS

9.3.1. Durability of hardened bed

The first experiment in the small flume lasted for 18 hours under a discharge of $0.006 \text{ m}^3/\text{s}$. The bed remained intact throughout the run, although the spar urethane coating started to erode along the side walls, and at some arbitrary locations (Figure 9.2), which may have been prevented by applying a second coat of spar urethane.

The second experiment (in the bend flume) was run with a discharge of $0.051 \text{ m}^3/\text{s}$, and an estimated bed shear stress of 0.251 N/m^2 for 52 hours. Except for some erosion near the side walls, the hardened bed remained intact even in the bend section with higher bed shear. Figure 9.3 shows the straight entry section once the experiment was finished. Areas of darkness in Figure 9.3 may be due to small local sediment deposits and/or discoloration of the bed. This sediment is a combination of residuals from the reservoir water and the test sand which may have eroded beneath the false bed at the entrance, or along the margin near the flume wall where no spar urethane was applied.

9.3.2. Effect of bed hardening on roughness

The velocity log law as defined by Yalin (García 2008) may be used to describe the velocity profile in the log layer for hydraulically smooth, transitional, and hydraulically rough flows as

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{k_s}\right) + B_s \quad (1)$$

where u = mean velocity measured at elevation z above bed, and B_s = function of Reynolds roughness $R_* = k_s u_* / \nu$. Hydraulically smooth flow occurs if $R_* < 5$, transitional flow if $5 \leq R_* < 70$, and fully rough flow if $R_* \geq 70$. Parameter B_s can be defined by the empirical fit given by Yalin (García 2008)

$$B_s = 8.5 + [2.5 \ln(R_*) - 3] e^{-0.12 [\ln(R_*)]^2} \quad (2)$$

A plot of Eq. (2) for the different flow ranges is given by García (2008). A profile of u versus $\ln(z)$ may be used to solve for u_* and subsequently for k_s using Eqs. (1) and (2). Values of k_s may be solved for flows with $R_* \geq 1$. For $R_* < 1$, B_s cannot be computed. Also, for flows in the hydraulically smooth range, the computed value of k_s decreases considerably as u_* slightly decreases causing $R_* < 1$, and thus making Eq. (1) unsolvable. Accurate estimates of u_* are thus important in the hydraulically smooth regime. This sensitivity became an important issue herein because $R_* < 20$, given that the shear velocity was just below the critical Shields shear velocity of 0.020 m/s. This categorizes the flow as likely transitional, but close to being hydraulically smooth. Initial attempts to solve Eq. (1) using the velocity profile data resulted in $R_* < 1$ and hence Eq. (1) being unsolvable. However, the velocity profiles provided poor estimates of u_* , likely because only 3 or 4 measurements were available in the valid log-law region of 20% of the flow depth near the bed. Although the

flow was considered close to fully developed, it is possible that it was not, because the Reynolds stress profiles did not extrapolate to zero at the free surface (Figure 9.4), and the maximum profile velocity was located 50% below the free surface. Nevertheless, these profiles suggest that all test flows were at the same flow development stage.

As an alternative approach, the Reynolds stress profile was used to estimate the bed shear stress τ_{bed} (Kim *et al.* 2000, Rodríguez and García 2008). Reynolds stress is equal to $-\rho\langle u'w' \rangle$, where ρ = water density, u' and w' = fluctuating components of streamwise and vertical velocities, respectively, and $\langle \rangle$ denotes time-average. The Reynolds stress should increase linearly from zero at the water surface to a maximum close to the bed, and then decrease within the viscous sublayer to zero at $z=0$. The bed shear stress τ_{bed} is then determined by extrapolating the best fit line in the linear portion of z versus $-\rho\langle u'w' \rangle$ to $z=0$ (Figure 9.4). The value of $-\rho\langle u'w' \rangle$ on this line at $z=0$ is equal to τ_{bed} (Nikora and Goring 2000). The bed shear velocity u_* can then be calculated using the relation $u_*^2 = \tau_{\text{bed}}/\rho$. This method gave a more reasonable estimate of u_* as compared to the velocity profile, and was closer to the critical Shields value of 0.020 m/s (Table 9.2). This estimate of u_* was then used to determine the slope of a best fit line for u versus $\ln(z)$, and the y -intercept value was determined by minimizing the residuals (Figure 9.5). This y -intercept was then used to solve for k_s using Eqs. (1) and (2) (Table 9.2). To compare, Eq. (1) was also solved using a constant value of $B_s = 9.25$ which is suitable for $3.4 < R_* < 20$ (García 2008). For $R_* < 3.4$ with $B_s = 9.25$, results were noted to be invalid.

From the estimates given in Table 9.2, it was difficult to state that the hardening method did not alter roughness. Although k_s for test FB was within the standard deviations of the mean k_s values for tests T1 and T2, standard deviations ranged from 63 to 78% of the mean values. However, estimated k_s values seemed reasonable for flow being close to hydraulically smooth, as they were lower on average than the d_{50} size of 0.689 mm. Further testing would be required under fully-rough turbulent flow conditions and a variety of sand sizes to assess the effect of the hardening method on k_s . However, it is expected that for sand beds with $d_{50} < 1.5$ mm, under clear water scour conditions, it is common to have flow in the transitional range. To maintain the original sand roughness, sand may also be sprinkled on the polyurethane before it dries. This should adhere to the surface for about three days under similar flow conditions.

9.4. CONCLUSIONS

This study introduces a new method for fixing sand beds in laboratory flumes by employing both plaster and urethane. The effect of the hardening technique on bed roughness was evaluated. The following results were obtained:

1. The tests performed indicate that the artificially fixed sand bed is able to withstand an appreciable bed shear stress under continuous underwater testing for at least 2 days, which is currently not possible with previously reported non-permanent and semi-permanent techniques
2. This new technique has the advantage of being semi-permanent, and thus the hardened surficial layer can be easily removed. Compared to many existing permanent hardening methods, the new technique is also less likely to damage Plexiglas flumes.

3. It was difficult to assess the effects of the hardening technique on the bed roughness, due to difficulties in estimating the shear velocity. Although roughness estimates seemed reasonable, standard deviations were high. Further testing is needed under fully-rough turbulent flow conditions to assess the effect of the hardening technique on roughness.

9.5. NOTATION

B_s	function of R^*
D	flow depth (m)
d	sediment size (mm)
d_{50}	median sediment size (mm)
k_s	effective roughness height (mm)
R^*	Reynolds roughness = $k_s u_* / \nu$
T	water temperature (°C)
u	streamwise mean velocity (m/s)
u'	fluctuating streamwise velocity (m/s)
u_*	streamwise shear velocity (m/s)
w'	fluctuating vertical velocity (m/s)
z	elevation above bed (m)
κ	von Karman constant = 0.41
ρ	water density (kg/m ³)
τ_{bed}	bed shear stress (N/m ²)
ν	kinematic viscosity (m ² /s)
Φ	percent passing through sieve

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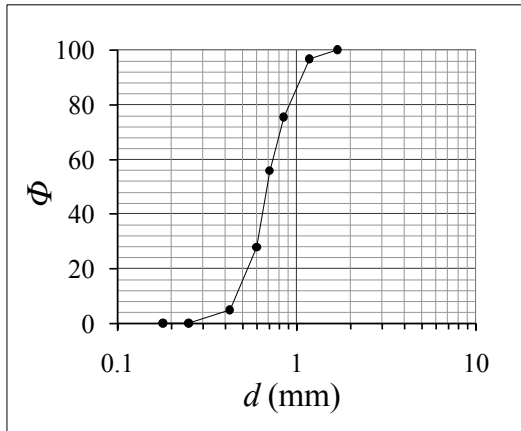


Figure 9.1 Sediment distribution with percent passing Φ vs. sediment size d for tests FB, T1 and T2

Table 9.1 Summary of flow parameters

Test	Weir discharge [m ³ /s]	ADV discharge [m ³ /s]	T [°C]	Water density [kg/m ³]	Kinematic viscosity [m ² /s]	Mean velocity (from ADV) [m/s]	Mean Velocity (from Weir) [m/s]	R, from ADV Velocity [-]
FB	0.049	0.0514	29	996	8.226E-07	0.342	0.329	62,400
T1	0.050	0.0471	26	997	8.813E-07	0.314	0.332	53,400
T2	0.049	0.0465	29	996	8.226E-07	0.310	0.329	56,500

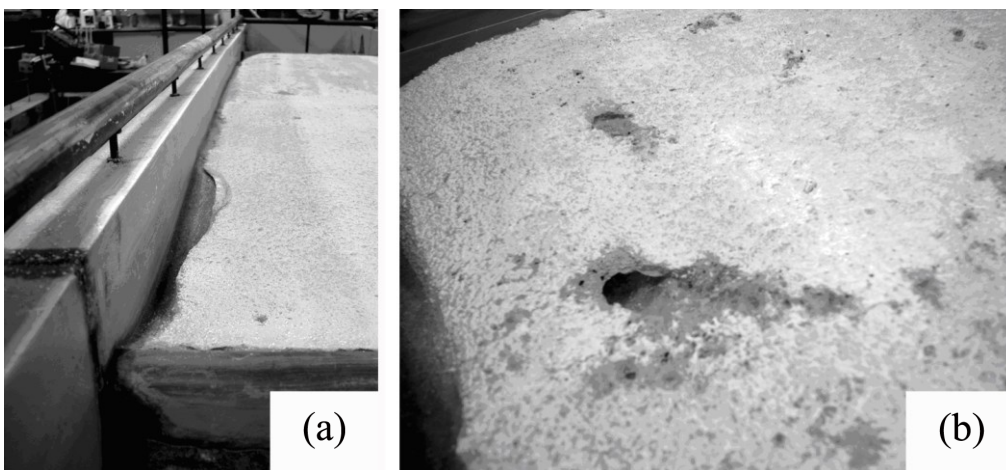


Figure 9.2 Erosion of spar urethane at end of first experiment (a) along sidewall and (b) at arbitrary point locations



Figure 9.3 Condition of bed after fixed bed (FB) test run in large flume

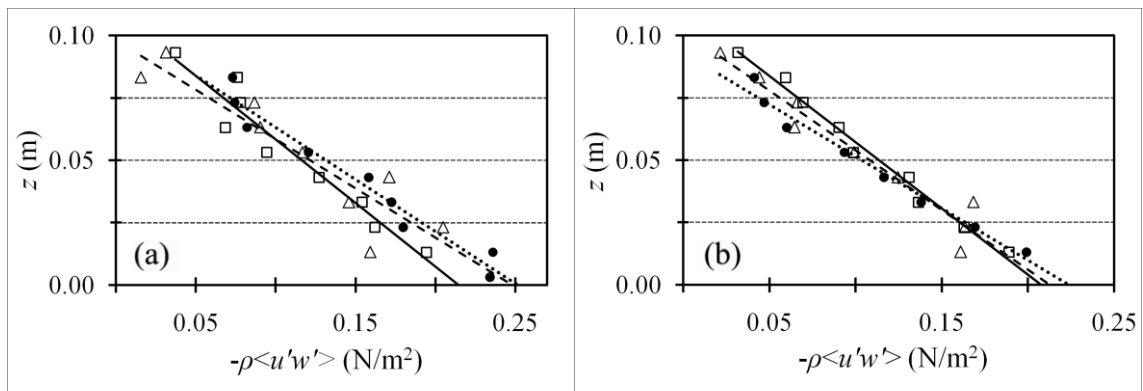


Figure 9.4 Distance from bed z versus Reynolds stress $(-\rho\langle u'w' \rangle)$ for (a) Profile 1 and (b) Profile 2 for (●) FB, (□) T1 and (△) T2 using the best fit lines (LT) to data for FB (dotted), T1 (solid) and T2 (dashed)

Table 9.2 Calculations for cases T1, T2 and FB, with profiles P1 and P2

Test (Profile)	u^* From velocity profile (m/s)	u^* From Reynolds stress profile (m/s)	τ_{bed} From Reynolds stress profile (N/m ²)	k_s Eq. (1) (mm)	R^* Eq. (1)	k_s Eq. (1), $B_s=9.25$ (mm)	R^* Eq. (1), $B_s=9.25$
T1 (P1)	0.0117	0.0147	0.215	0.258	4.29	0.289	4.81
T1 (P2)	0.0129	0.0144	0.208	unsolvable	n/a	0.209	3.42
T2 (P1)	0.0124	0.0158	0.248	0.779	15.0	0.710	13.6
T2 (P2)	0.0127	0.0146	0.213	0.195	3.47	0.256	4.54
mean (T1,T2)	0.0124	0.0149	0.221	0.411	7.6	0.366	6.6
standard deviation (T1,T2)	0.0005	0.0006	0.019	0.321	6.4	0.232	4.7
FB (P1)	0.0105	0.0159	0.251	0.245	4.74	0.258	4.99
FB (P2)	0.0117	0.0150	0.224	unsolvable	n/a	not valid	not valid
mean (FB)	0.0111	0.0154	0.238	0.245	4.74	0.258	4.99
mean (FB) – mean (T1,T2)	-0.0013	0.0005	0.017	-0.166	-2.8	-0.108	-1.6

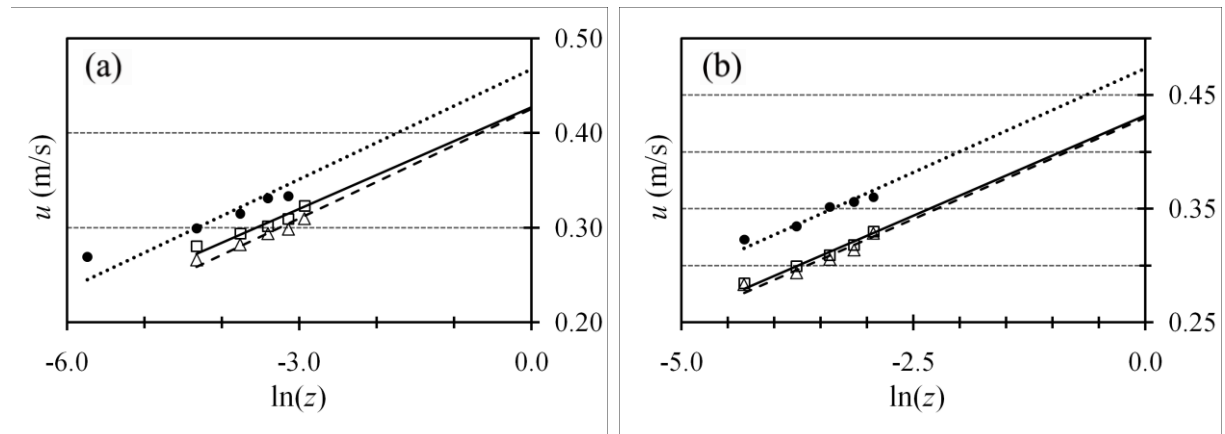


Figure 9.5 Plots of mean velocity u versus $\ln(z)$ for (a) Profile 1 and (b) Profile 2 for (●) FB, (□) T1 and (△) T2. Constant slope lines (RF) for FB (dotted), T1 (solid) and T2 (dashed) calculated using u^* from Reynolds stress profile fitted to data for each run by minimizing residuals

10. CONCLUSIONS

The erosion and migration of river bends can be challenging to understand, but often needs to be considered in civil engineering projects dealing with the construction and maintenance of infrastructure such as roads and bridges. This thesis conducts an in-depth analysis of flow, turbulence, and mechanisms leading to scour in a high curvature 135° channel bend both with, and without a series of submerged groynes. Flow is considered during the initial and final/late stages of scour using a validated highly resolved Large Eddy Simulation (LES) numerical model. Selected analysis is also completed using a Reynolds Averaged Navier Stokes (RANS) model. Finally, the last chapter of this thesis presents a new bed hardening technique for fixing sand beds that was developed at the University of Ottawa. The main findings from this thesis are given below.

It should be noted that for the LES cases, FB refers to a ‘flat bed without groynes’, FBG refers to a ‘flat bed with groynes’, DB refers to a ‘deformed bed without groynes’, and DBG refers to a ‘deformed bed case with groynes’.

1. For the 135° bend studies without groynes, the LES and RANS results suggest that in addition to the large main channel secondary circulation cell, smaller streamwise orientated vortices (SOVs) can also affect the local distributions of velocity within a channel bend. These SOVs can advect streamwise velocities both laterally and vertically, and can increase the gradients of cross-stream and vertical velocities near the channel boundaries due to their cross-stream circulation. In turn, this can affect levels of friction velocities (shear stresses) at the banks and bed, depending on circulation intensity of the

SOVs, their propensity to advect fluid momentum, and their proximity to the channel boundary.

2. The RANS study in Chapter 5 revealed that for the range of geometry considered, and for conditions corresponding to the initial stages of scour, a decrease in channel curvature ratio (R/B) is associated with an increase in cross-stream circulation strength. Moreover, a decrease in R/B from 8 to 1.5 leads to an increase in peak bed shear stress within the channel by about 70%. Also, a change in aspect ratio (B/H), at a constant flume width (B), substantially affects cross-stream circulation strength. An important finding is that for the high curvature bend case ($R/B=1.5$), a decrease in H from 20cm to 8cm causes the location of maximum bed shear stress to move from the outer bank downstream of 135° , to the inner bank closer to the beginning of the curved reach.
3. For the groyne studies, the LES predicted that both during the initial (case FBG), and later stages of scour (case DBG), the groynes were effective in keeping the main channel core of high streamwise velocity away from the outer bank wall in the region where they were installed. However, for both cases, the potential for scour along the outer bank wall was greater compared to when groynes were not present, mainly due to the interaction of the groynes with the bend flow.
4. For the flat bed groyne case (case FBG), the LES predicted that the main mechanisms leading to scour around the groynes at the outer bank wall were: 1) flow accelerating up and out of the embayments before moving over the groynes; 2) high mean pressure

fluctuations induced from flow being trapped near the bed at the downstream end of the embayments; and 3) coherent structures causing slight amplification of mean pressure fluctuations just above the groyne top surface, and immediately downstream of the groyne base.

5. For the deformed bed groyne case (case FBG), the LES predicted that the main mechanisms leading to scour around the groynes at the outer bank wall were: 1) the horseshoe vortices, which induced high mean pressure fluctuations, particularly upstream of the first groyne; 2) flow accelerating up and out of the embayments; and 3) flow moving over the base of the first upstream groyne near the outer bank wall. The potential for scour appeared much greater around the first upstream groyne compared to the downstream groynes. Also, the LES predicted very severe mean pressure fluctuations at the bed on the lee-side of the first upstream groyne due to the combined effects of interactions between a complex vortex system around the first groyne and the main channel flow, and flow redirection due to topographic steering.
6. For cases FB, DB, FBG, and DBG, the LES predicted a counter-rotating outer bank cell which appeared to keep high streamwise velocities away from the outer bank wall close to the free surface throughout most of the bend. However for cases DB, FBG, and DBG, this cell appeared to endanger the stability of the outer bank wall close to the end of the curved reach. This is because for these cases, it appeared to advect high streamwise velocities towards the outer bank wall at its bottom boundary. This resulted in outer bank wall friction velocities (shear stresses) being strongly amplified at mid-depth levels near

the end of the curved reach. Its effectiveness in advecting high streamwise velocities towards the outer bank wall depended on its circulation strength, its proximity to high streamwise velocities, and also on the presence and strength of a clockwise-wise rotating cell located beneath it near the bed, which also helped to advect high streamwise velocities towards the outer bank wall.

7. Finally, a bed hardening technique was developed to fix sand beds in laboratory flumes using a combination of Plaster of Paris, and urethane. The hardened bed was found to withstand an estimated bed shear stress of up to 0.251 N/m^2 for 52 hours under flowing water. Its impact on bed roughness however, was difficult to estimate, and further testing would be needed under fully-rough turbulent flow conditions to fully assess such effects.

11. RECOMMENDATIONS

The following recommendations are made based on the findings from this thesis.

1. While eddy-resolving numerical techniques are likely the most accurate methods to identify mechanisms leading to erosion in field sites, they may not be practical/possible to apply in such applications due to the high channel Reynolds numbers ($>100,000$) that natural rivers are subject to, the detailed bathymetry measurements required, and the long time required to run such models (on the order of weeks or even months). Therefore, results from the current study may be of practical use in calibrating existing analytical models, or 2-D depth averaged numerical models which are still a popular tool used to understand river erosion.
2. The RANS parameter study in Chapter 5 revealed that in a high curvature bend, outer bank bed shear stress may be reduced by lowering the water depth. It is possible such information could be practically used in field applications, and would provide a non-invasive method for controlling river erosion. However, further physical and/or numerical modeling would be required to determine the ranges of B , H , R , and/or their combinations, for which such a method could be applied.
3. For the groyne studies, it is expected that removing the first upstream groyne for the present configuration may be beneficial in reducing scour. Currently, the effects of topographic steering near the first groyne contribute to severe mean pressure fluctuations around this groyne. It is expected that if the first groyne were located further downstream, the transition from the naturally occurring channel thalweg, to the one located very close to the groynes would not induce such severe mean pressure

fluctuations, as the naturally occurring thalweg would be located closer to the groynes. Again, this hypothesis would need to be tested through a physical model before being implemented in the field, or recommended as a guideline.

4. For the groyne studies, it is also expected that installing an additional groyne downstream of the third groyne, in the straight exit section, may be beneficial in reducing bed friction velocities at both the outer bank wall and the channel bed near the end of the curved reach. This may prevent high streamwise velocities from being advected towards the outer bank wall by both the counter-rotating outer bank cell near the free surface, and the clock-wise rotating outer bank cell near the bed in this region. It is expected that past the end of the curved reach, the strength of this outer bank cell will continue to decrease even if an additional groyne is present. It is recommended however, that this hypothesis be tested through a physical model before being implemented in the field.
5. It is possible that groyne performance could also be improved by placing rip rap in the far corner of the groyne embayment, such that flow could easily move out of the embayments, without becoming trapped near the bed where high mean pressure fluctuations can develop and lead to scour.

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APPENDIX A – LES METHOD

A.1. LES SOLVER

The LES solver used in the present work was developed by Mahesh *et al.* (2004). It has been proven to be robust in complex geometries with unstructured grids at high Reynolds numbers (Mahesh *et al.* 2004; McCoy *et al.* 2007). It is solved on an unstaggered grid with Cartesian velocities (u_i) and pressure (p), both located at the cell centroid (Figure A.1). In addition, face normal velocities (v_n) are located at the centroids of each face and are treated as independent variables. The algorithm below is quoted directly from Mahesh *et al.* (2004). It is capable of being applied on a complex 3-D unstructured grid composed of tetrahedral, hexahedra, wedges or prisms, which may be highly skewed.

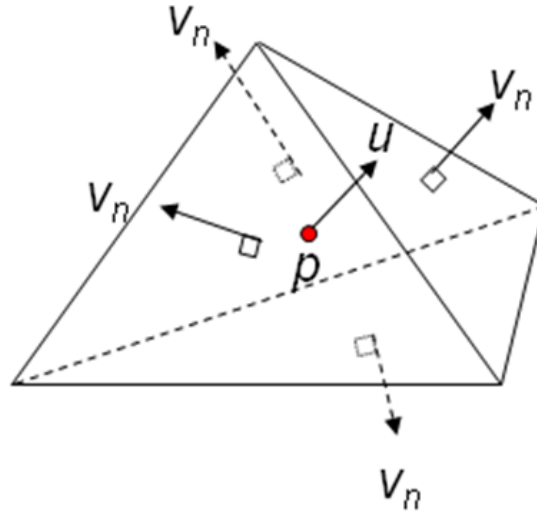


Figure A.1. Unstaggered grid element showing resultant

Cartesian velocity (u), face normal velocities (v_n) and pressure (p)

It is based on a predictor-corrector method. A Crank-Nicolson implicit fractional step method is used to advance the solution in time. The Crank-Nicolson scheme, although more

complicated than the explicit or fully-implicit scheme, is more accurate at small time steps (Patankar 1980) which will be used in the LES. This method is considered second-order accurate in space and time. Central schemes are used to discretize the remaining terms in the Navier Stokes equations.

The first step of the method is applied to the discretized form of Equation (A.4), neglecting the pressure term (Equation A.1). It involves predicting an intermediate velocity $\hat{u}_i$ between the current time step (k) and the next time step ($k+1$). NL and VISC denote the nonlinear and viscous terms, respectively.

$$\frac{\hat{u}_i - u_i^k}{\Delta t} = \frac{1}{2} [0.5(\text{NL} + \text{VISC})^k + (\text{NL} + \text{VISC})^{k+1}] \quad (\text{A.1})$$

This predicted value of $\hat{u}_i$ is then used to determine a predicted value ($\hat{v}$) for the face normal velocities.

$$\hat{v} = \left(\frac{\hat{u}_i^{\text{icv1}} - \hat{u}_i^{\text{icv2}}}{2} \right) n_i \quad (\text{A.6})$$

Here n_i denotes the face normal and icv1 refers to the current element, while icv2 refers to the neighbour element which shares a common face. $\hat{v}_i$ is then projected to the actual face normal velocity (v_n) using

$$\left(\frac{v_n + \hat{v}}{\Delta t} \right) = - \frac{\delta p}{\delta n} \quad (\text{A.7})$$

where δn refers to the distance between the central centroids of the two cells.

The divergence-free constraint requires that

$$\sum_{faces\ of\ cv} v_N A_f = 0 \rightarrow \Delta t \sum_{faces\ of\ cv} \frac{\delta p}{\delta N} A_f = \sum_{faces\ of\ cv} \hat{v} A_f \quad (A.8)$$

where “ N ” denotes the direction along the face-normal in the outward direction, and A_f is the face area. This equation is solved iteratively for p . The updated value of the Cartesian velocity u_i^{k+1} is obtained using

$$\left(\frac{u_i^{k+1} - \hat{u}_i}{\Delta t} \right) = - \frac{\delta p}{\delta x_i} \quad (A.9)$$

The gradient theorem is used to compute $\frac{\delta p}{\delta x_i}$ at the cell center.

$$\frac{\delta p}{\delta x_i} = \frac{1}{V_{cv}} \sum_{faces} p_{face} A_f N_i \quad (A.10)$$

where V_{cv} is the volume of the cell. For a fully-staggered grid the pressure gradient is discretely energy conserving, although this is not normally true for a non-staggered grid. The reasons for this will be explained in the following lines. u_i is computed as

$$\frac{u_i - \hat{u}_i}{\Delta t} = - \frac{1}{V_{cv}} \sum_{faces\ of\ cv} \frac{(p_{icv} + p_{nbr})}{2} N_i A_f \quad (A.11)$$

The above equation implies that the pressure gradient contributes to the energy equation as

$$\sum_{volumes} u_i \frac{\delta p}{\delta x_i} V_{cv} = \sum_{volumes} \sum_{faces\ of\ cv} \frac{(p_{icv} + p_{nbr})}{2} u_i N_i A_f \quad (A.12)$$

which is equal to

$$\sum_{volumes} \sum_{faces\ of\ cv} (p_{icv} + p_{nbr}) v_{Ni} A_f \quad (A.13)$$

which may be expressed as

$$\sum_{\text{volumes}} p_{\text{icv}} \sum_{\text{faces of cv}} v_N A_f + \sum_{\text{volumes}} \sum_{\text{faces of cv}} p_{\text{nbr}} v_N A_f \quad (\text{A.14})$$

This is not expressible solely in terms of contributions from the boundary faces. The pressure-gradient term is therefore not conservative, in terms of its contribution to the kinetic energy. The main reason for this is that the projected face-normal velocities

$$v_n \neq \left(\frac{\hat{u}_i^{\text{icv}1} - \hat{u}_i^{\text{icv}2}}{2} \right) n_i \quad (\text{A.15})$$

The following procedure was derived for the pressure-gradient to advance the Cartesian velocities at the centers of the volumes. Equation A.11 implies that

$$(u_i^{\text{icv}1} - u_i^{\text{nbr}}) n_i - (\hat{u}_i^{\text{icv}1} - \hat{u}_i^{\text{icv}2}) = -\Delta t \left(\frac{\delta p^{\text{icv}}}{\delta x_i} + \frac{\delta p^{\text{nbr}}}{\delta x_i} \right) n_i \quad (\text{A.16})$$

Summing over the faces of each control volume and invoking the projection step (Equation A.4) yields

$$\sum_{\text{faces of cv}} N_i \left(\frac{u_i^{\text{icv}1} - u_i^{\text{nbr}}}{2} \right) A_f - \Delta t \sum_{\text{faces of cv}} \frac{\delta p}{\delta N} A_f = -\frac{\Delta t}{2} \sum_{\text{faces of cv}} \left(\frac{\delta p^{\text{icv}}}{\delta x_i} + \frac{\delta p^{\text{nbr}}}{\delta x_i} \right) N_i A_f \quad (\text{A.17})$$

We would like

$$\sum_{\text{faces of cv}} N_i \left(\frac{u_i^{\text{icv}1} - u_i^{\text{nbr}}}{2} \right) A_f \quad (\text{A.18})$$

to be as small as possible. This is possible if $\frac{1}{2} \left(\frac{\delta p^{\text{icv}}}{\delta x_i} + \frac{\delta p^{\text{nbr}}}{\delta x_i} \right) N_i$ across each face is as

close to $\frac{\delta p}{\delta N}$ as possible. Since $\frac{\delta p}{\delta x_i}$ is located at the volumes, while $\frac{\delta p}{\delta n}$ is located at the

faces, this relation cannot be imposed exactly. Our approach to make the pressure-gradient

term be as energy-conserving as possible is to satisfy the relation in a least-squares sense; i.e., by minimizing

$$\sum_{\text{faces of } cv} \left(\left. \frac{\delta p}{\delta x_i} \right|_{\text{ivc}} n_i^{\text{face}} - \left. \frac{\delta p}{\delta n} \right|_{\text{face}} \right) A_f \quad (\text{A.19})$$

This minimization allows $\frac{\delta p}{\delta x_i}$ to be computed in terms of the nearest neighbours.

A.2. SUBGRID MODEL

The subgrid stresses (τ_{ij}) from Equation A.4 are not resolved in LES, and must be modeled with a subgrid scale (SGS) model. In this study either the constant or dynamic SGS model was used. For the flat bed and bathymetry groyne runs, a constant Smagorinski SGS model (Constantinescu, 2010) was used in order to avoid instabilities, due to the complex geometry and high Reynolds number involved. Details on the dynamic Smagorinsky model are given in Mahesh *et al.* (2004).

For the Constant SGS model the SGS stress is given by:

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i} \overline{u_j} = 2\nu_t \overline{S_{ij}} \quad (\text{A.20})$$

where ν_t is the turbulent eddy viscosity, and $\overline{S_{ij}}$ is the deformation tensor. The turbulent eddy viscosity (ν_t) is given by:

$$\nu_t = C_s \Delta^2 |\overline{S}| \quad (\text{A.21})$$

where C_s is the Smagorinsky constant, Δ is the characteristic subgrid-scale length (filter width), and

$$|\bar{S}| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}} \quad (\text{A.22})$$

where the deformation tensor is

$$\bar{S}_{ij} = \frac{1}{2} \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) \quad (\text{A.23})$$

The Smagorinsky constant (C_s) usually takes values between 0.18 and 0.23.

APPENDIX A NOTATION

A_f	= face area
C_s	= Smagorinsky constant
icv1	= current cell volume
icv2	= neighbour cell volume which shares a common face with icv1
k	= current time step
$k+1$	= time step after k
n_i	= face normal direction vector
nbr	= neighbour control volume
δn	= distance between centroids of two cell volumes
N	= direction along face normal n_i in the outward direction
NL	= nonlinear terms
p	= pressure at centroid of the cell volume
p_{face}	= pressure at the face
δp	= difference in the pressure
$\bar{S}_{ij}$	= deformation tensor
t	= time

- u_i = Cartesian velocity at centroid of the cell volume
 $\hat{u}_i$ = intermediate velocity at cell centroid between the first time step (k) and the next time step ($k+1$).
 $\hat{v}$ = predicted value for face normal velocity v_n
 v_n = face normal velocities at the center of the face
 ν_t = turbulent eddy viscosity
 V_{cv} = volume of the cell
VISC = viscous terms
 x_i = Cartesian direction

 Δ = characteristic subgrid-scale length (in this study the filter width)
 τ_{ij} = subgrid scale stress

APPENDIX B – FLUENT SIMULATION INPUTS

Below are the options selected for the Fluent simulations. The simulations used a Reynolds Averaged Navier Stokes Equation Model with a Reynolds Stress turbulence closure.

In the ‘Viscous Model’ panel

Under ‘Model’

→ choose ‘Reynolds Stress [7 eqn]’

Under ‘Reynolds-Stress Model’

→ choose ‘Linear Pressure-Strain’

Under ‘Near-Wall Treatment’

→ choose ‘Non-Equilibrium Wall Functions’

Under ‘Enhanced Wall Treatment Options’

→ do not select any

Under ‘Options’

→ do not select any

Under ‘Model Constants’

→ $C_{\mu} = 0.09$

→ $C_1\text{-Epsilon} = 1.44$

→ $C_2\text{-Epsilon} = 1.92$

→ $C_1\text{-PS} = 1.8$

In the ‘Materials’ panel

Click the ‘Fluent Database..’ button

Under ‘User-Defined Fluid Materials’

choose ‘water-liquid [h₂o<l>]’

This should be the Material used in all the panels

In the 'Operating Conditions' panel

'Operating Pressure (pascal)' = 101325

'Reference Pressure Location', $x=0$, $y=0$, $z=0$

'Gravity' → check

'Gravitational Acceleration'

$X = 0$

$Y = 0$

$Z = -9.81 \text{ m/s}^2$

In the 'Boundary Conditions' panel

→ For the 'Inlet' zone choose 'Velocity Inlet'

→ Under 'Momentum' tab choose:

Velocity Specification Method: 'Magnitude and Direction'

Reference Frame: Absolute

Coordinate System: Cartesian

X-Velocity: velocity-profile, choose 'x-velocity' from the user defined profile created from the separate Fluent simulation in a straight channel with a periodic boundary condition.

The Y and Z components are set to 0 m/s.

The Turbulent Kinetic Energy and Turbulent Dissipation rate were also input from the user defined profile.

→ For the 'Outlet' zone choose 'Outflow'

→ For the 'Sidewalls' choose

Under the 'Momentum' tab → Wall Motion 'Stationary Wall'

Shear Condition ‘ No Slip’

Wall Roughness: Roughness Height: 0

For all other tabs, leave the default values, as these do not apply

→ For the ‘Bed’ choose

Under ‘Momentum’ tab → Wall Motion ‘Stationary Wall’

Shear Condition ‘ No Slip’

Wall Roughness: Roughness Height: 0.689 mm

For all other tabs, leave the default values, as these do not apply

→ For the ‘Free Surface’ choose ‘Symmetric Boundary Condition’

→ For the ‘Interior Mesh’ choose ‘interior’

In the ‘Solutions Controls’ panel

→ For the Pressure-Velocity coupling algorithm choose the ‘Simple Algorithm’

→ For the discretization use the first order upwind scheme for all of the parameters.

General Comments:

- The solution should be run under ‘steady-state’ conditions to a minimum pressure and momentum residual of 1×10^{-15} .
- The solution should be checked periodically in tecplot to see whether there are any changes in the flow patterns. It was found that the presence of the counter-clockwise rotating outer bank cell only appeared after the solution was run for several days after the pressure and momentum residuals had reached 1×10^{-15} . Therefore, very small changes

in the solution, which did not seem to affect the residuals, still had substantial impacts on the flow structures.

- The solution was initialized using the mean inlet x-velocity for each specific run.