NUMERICAL INVESTIGATION OF TURBULENT-DRIVEN SECONDARY FLOW

A Thesis in
Civil Engineering

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2016
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Abstract

Secondary flows of second type (also known as turbulent secondary flows) are one of the most important mechanisms responsible for sediment transport processes in fluvial streams. A new two-equation Reynolds-Averaged Navier-Stokes (RANS) based model is investigated in depth in this work, for modelling secondary flows of second type.

This thesis incorporates a new $k - \omega$ model with nonlinear fourth-order closure terms for modelling Reynolds stresses. The model has $k - \omega$ formulation which enables the model to solve for flow equations near the walls without the need for utilizing wall functions. Moreover, $k - \omega$ models are capable of applying roughness on boundaries by imposing rough boundary turbulent attributes through $\omega$ functions. The model was tested in two main categories on five case-studies to observe its ability in simulating turbulent secondary flow in various configurations. The tests carried out case scenarios identical to experimental case studies. First, the model was used in simulating turbulent secondary current in a simple case study conducted inside a rectangular duct with smooth boundaries. The model performed well in this part, when simulated data such as secondary velocity profiles, shear stresses, and secondary current vectors being compared with experimental data.

In the second test, the model was investigated in case scenarios to explore the model’s capacity for carrying out simulation of turbulent secondary currents over rough boundaries. While in case
studies with uniform rough boundaries the model functioned well (velocity profiles, and shear stress distribution, being compared to experimental data), in cases with non-uniform roughness distribution the model needed noticeable tweaking, tuning, and calibration for roughness modelling. However, for validation purposes, the model with calibrated function parameter were tested against other non-uniform distribution case scenarios, in which their results showed excellent agreement with experimental data. The numerical simulations were able to produce secondary velocity profiles very close to experimental studies which are difficult to capture. The proposed roughness height values in roughness modelling function for secondary flows over beds, with nonuniformly distributed roughness, are critically discussed and assessed.

During the tuning of the model, it was detected that the original approach for computing wall shear stresses, using law of the wall, provided dissimilar results compared to results which calculated shear stresses directly from velocity gradients at the wall. This disagreement was investigated in depth, and it was concluded that the calculation of wall shear stress, using law of the wall, was not accurate. Finally, providing accurate result along with computational efficiency (due to RANS-based formulation), and applicability to rough case scenarios, this model is advantageous in investigation of turbulent secondary current.
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The writing of this thesis would not be possible without the guidance, support, encouragement, and assistance of my adviser, Dr. Xiaofeng Liu. Not only he has been a kind adviser for me, he has been a great teacher as well. His expertise and willing attitude helped me also gain a set of computational, vision, and management skills atypical for graduate programs. In addition, I would like to give my deepest gratitude to my committee members Dr. Peggy Johnson and Dr. Alfonso Mejia for their contribution, guidance, and support that have greatly improved the quality of this study.

All my colleagues in the Environmental Fluid Dynamic research group have helped me by providing an inspiring and enjoyable atmosphere. Their comments and questions enhanced the overall quality of my research. This work has improved with the help of Yunxiang Chen, Yuncheng Xu, and Detian Liu.

I thank faculty members and staff of Civil and Environmental Engineering Department who, directly or indirectly, have helped me. I am grateful to Penn State’s Research Computing and CyberInfrastructure for providing the opportunity to use the high performance computers at Penn State.

I am grateful for my friends and family for their support and encouraging me. I am especially indebted to Mohammad Heidarnejad, Peyman Heidary, Atefeh Mohammadpour and my uncle Mehdi Talebpour; without their support, I would have given up long ago. I greatly thank Mohammad Zeini, Soheil Bahrampour, Mahshid Sedghi, Ali Abbaszadeh, Mahdis Aryanpour and Sohrab Rahimi.

Finally, I thank my family. This work was only possible with the endless love, inspiration, support, patience, and encouragement of my wonderful wife, Parichehr, who has been standing beside me throughout my career and writing this thesis. I thank my mom and dad for their unconditional love and support throughout my life. They have always been the greatest mentors of my life who have guided me to be the person I am today. I thank my siblings, Meisam, Milad, and Mina and my sisters-in-law Khatereh and Suran for their kind love.
Dedication

To my parents Mohammad and Mehrangiz
for their endless love and support.
Chapter 1

Introduction

1.1 Problem Statement

The need for appropriate numerical means for studying turbulent secondary flows is indisputable. This phenomena have significant role in fluvial geomorphology. The hydrodynamics of turbulent secondary flow and their interaction with geometry and roughness have been subject of abundant studies in the past (Stoesser et al., 2010). The expense of experimental studies and the limitations and restraints of current measurement tools, made the thorough investigation of such flows difficult. This is specifically more evident, when numerous case studies are needed to obtain insight into interaction of secondary flows with other element (e.g. geometry). Although, experimental studies, over the past decades have provided us with insightful knowledge about secondary flow mechanisms (Nezu, 2005). Developing a numerical framework to study this phenomena is necessary.

Several numerical studies have investigated, modified, and developed Computational Fluid Dynamics
(CFD) models in studying turbulent secondary flows (Ansari et al., 2011; Choi et al., 2007, 2008; Demuren and Rodi, 1984; Naot and Rodi, 1982; Nezu and Azuma, 2004; Stoesser et al., 2010). This paragraph examines present CFD models, considering roughness and geometry effects which require running great deal of case studies. Direct Numerical Simulation (DNS) studies of this phenomena is almost impossible, given the fact that they are computationally expensive, and the current resources would not allow running these simulations. Large Eddy Simulation (LES) of turbulent secondary flows are accurate, and they provide us with perceptive results. Even though considering running numerous case studies, LES studies are not computationally affordable. RANS-based Reynolds Stress Models (RSM) demand lower computational resources and they are much affordable, compared to LES. Yet, they need a lot of tuning which make them problematic. The alternative to all of previous models are RANS two-equation models.

Standard two equation models suffer simulating secondary currents due to their simplified linear modelling of Reynolds stresses (Nezu, 2005). For the aforementioned reasons, the necessity to develop a new numerical framework which is computationally fast, straightforward to implement roughness, and numerically accurate and reliable is obvious.

1.2 Sediment Transport

Sediment transport is one of the most important processes in engineering studies. It has been studied in various scales and diverse fields. From geological and civil engineering studies investigating the transportation of gigantic rocks by glaciers (García, 2008) to built environmental studies exploring the transport of micron size particles in indoor air (Salimifard et al., 2015). It occurs in response to different surface dynamics processes such as glacier movement, forced by gravity on hill slopes,
flows of wind, streams, and oceans. Figure 1.1 and 1.2 illustrate two examples of earth surface changes caused by sediment transport, under different mechanisms. They show Mississippi Delta in Louisiana and Barchan dunes in Peru, respectively. Depending on the mechanism, sediments of various sizes can be moved by these processes. Glaciers can move sediments up to several meters large in diameter, while small-scale streams can only transport sediments as small as sand grains. Scientist have scrutinized these processes in diverse areas such as civil engineering, environmental engineering, earth sciences and oceanography to understand their mechanism and their effects. Having vital impacts on the environment, researchers have studied sediment transport in fluvial geomorphology for decades.

In fluvial rivers and streams, sediment transport has been a research subject for over decades due to its significant influence on the environment. Just to name a few, it is responsible for reservoir sedimentations (Buckley, 2003), changing river paths, providing sediment budget for river deltas, transporting and depositing fine chemical particles and consequently changing ecology balance in environmental habitats. Various mechanisms in fluvial geomorphology are responsible in sediment transport processes. Therefore, understanding these mechanisms plays a crucial role in many engineering practices including river restoration projects, reservoir sediment management, delta management projects, habitat ecological studies and even social and economic studies of cities situated near rivers (MacArthur et al., 2008).

Initiation of motion is the beginning part of sediment transport processes. This is the part in which sediment particles get detached from the bottom or side surfaces. It is important to uncover the physical procedure occur in order for a particle to start its motion. Moreover, the dynamics of the particles at the start point and their potential routes after being dislodged from the ground are vital
for understanding sediment transport dynamics. Depending on the various influential factors such as type of fluid, particle characteristics, and flow field researchers have characterized the initiation of motion. Researchers have correlated initiation of motion for particles at rest in fluids to the shear stress ($\tau_{\text{bed}}$) applied by the fluid on their surface. This shear stress should exceed a critical shear stress ($\tau_c$) for initiation of motion of particles in order for them to be dislodged from the bed and move with the flow (García, 2008).
Depending on the forces exerted by the flow on the suspended particle, the particle size and the flow hydrodynamics, the particle might be deposited after a few number of saltation steps or continue moving along the flow to farther locations (García, 2008). Numerous elements of flow hydrodynamics and bed roughness characterization take part in calculating the critical shear stress and bed shear stress to determine the initiation of motion for particles. This study will look into secondary flows of second type (also called turbulent secondary flow) as one of the flow hydrodynamic mechanisms which has a crucial influence on dislodging particles from the bed and transferring the suspended particles.
1.3 Secondary Flows

1.3.1 Role of secondary flows

Secondary flows have significant impact on fluvial streams including altering their path and changing their boundary configurations Einstein and Li (1958); García (2008); Gessner (1973); Gulliver and Halverson (1987); Nezu (2005); Nezu and Nakagawa (1984); Parker (2008). Given the fact that the mechanism behind the generation and maintenance of turbulent secondary flow is not yet fully understood, this phenomenon in different configurations should be studied in order to obtain better understanding of its generation and maintenance mechanism. The insight into turbulent secondary current mechanism is necessary in many engineering practices projects and scientific
studies including river restoration (Rodríguez and García, 2008), reservoir sediment management, and establishing erosion processes’ criteria and theories.

Secondary flows in fluvial streams have been long recognized as a substantial mechanism for dislodging and picking up sediment particles from erodible boundaries, transferring them in helical routes along streamwise direction and depositing them elsewhere downstream. They have been recognized to alter the path of sediment particle motion and consequently change the river and land surface evolution process. Furthermore, many researchers have discovered noticeable coevolution between sediment transport and secondary flows. This is especially more obvious where erodible boundaries exist (Colombini, 1993; Ikeda, 1981).

1.3.2 Secondary flows of second type

Secondary flows also known as turbulent secondary flows in open channels exist in various forms. They are perpendicular to streamwise direction. In other word, secondary flows are secondary currents (velocity components) in the cross sectional plane at each location. There are two different kinds of secondary flows: the first kind due to curvature in a river bend and the second kind which is believed to be caused by turbulence anisotropy. This study deals with the second kind in straight open channels. For the purpose of simplification, in this study, secondary flow refers to the secondary flow of second type.
1.4 Thesis Aim and Objectives

1.4.1 Motivation of This Thesis

Considering the significant impacts turbulent secondary flow has on fluvial geomorphology, the need for appropriate tools to investigate the mechanisms behind its generation and maintenance is substantial. Researchers have explored these mechanisms throughout the past century, utilizing experimental and numerical methods. Numerical studies are of great importance in shedding light on secondary flow mechanisms and complementing the experimental studies by explaining mechanisms in which experimental apparatuses are restricted and limited. Developing numerical approaches to be capable of carrying out more realistic case scenarios while maintaining and improving the computational efficiencies of the models is necessary.
1.4.2 Scope of This Thesis

This study aims to map the details of secondary flows and their interaction with the boundaries, in straight open channels, in a numerical framework. The purpose is to develop, modify and implement a numerical framework which can simulate secondary currents with high accuracy in a computationally affordable time-line. This numerical framework will be used to accurately study the secondary flows in open channels with different configurations in order to investigate the mechanisms behind the generation and maintenance of secondary flows in straight open channels.

1.4.3 Structure of This Thesis

This thesis is divided into seven chapters. The first chapter is a brief introduction to the problem statement, importance of secondary flows, and aim and objectives of this thesis. Providing critical literature review, chapter 2 will focus on the advancements and progresses in the study of turbulent secondary flows. Then, to define the research methodology of this research, chapter 3 outlines the computational details and describes the utilized numerical model. Chapter 4 investigates the performance of the numerical model in simulating turbulent-induced secondary flows in open channels with smooth boundary. In this chapter, the efficiency of the model without consideration of roughness is analyzed. Subsequently, the performance of the model in conjunction with roughness function, in presence of boundaries with uniformly distributed roughness is investigated in chapter 5. Then, chapter 6 examine the combination of the model and roughness function in simulating cellular secondary currents in open channels over beds with alternate rough and smooth boundaries. The modifications required to deploying the function for these configurations is explained. Finally,
chapter 7 provides the concluding remarks of the work presented in this thesis, and recommendations for the future research studies.
Secondary flow in open channels plays an important role in hydrodynamic and sediment transport mechanisms. In the literature, it is stated that Francis (1878) was the first to hypothesize secondary flow for explaining the depression of the point of maximum velocity from the free surface (Gulliver and Halverson, 1987). Nikuradse (1926) examined flow through different non-circular ducts and channels and was the first who could experimentally detect secondary flow cells. Researchers have been investigating secondary flows of both types from different perspectives to explain their generation mechanism, maintenance mechanism, impacts, applications and interaction with other flow hydrodynamics. This chapter will briefly review the research work that have been done on turbulent secondary flow over the past century, in different sections. The first section will briefly recap the research findings and statements on the formation of secondary flow of second type. It will be followed by a concise summary of the research that has been done on the relationship between roughness and shallowness (width-to-depth ratio) of the channel flow with turbulent secondary flow. The final section will look into the progress and advancements of the numerical studies of turbulent
2.1 Origin of secondary flow of second type

The mechanism behind generation and maintenance of secondary current of second type is complex. Nikuradse (1926) was the first to suggest that secondary currents exist in non-circular straight ducts (Moissis, 1957). Prandtl (1927) hypothesized that turbulent fluctuations tangent to the contours of streamwise velocity have higher magnitudes compared to turbulent fluctuations normal to the contours. Based on this theory, Prandtl (1927) derived a postulation that secondary motion moves fluid along corner bisectors toward corners, due to the force generated toward the convex side of the isovels. Prandtl’s speculation was almost the start of the analytical route to analyze this phenomena. Later, Prandtl (1952) developed a theoretical framework to analyze the mechanism of secondary currents in open channels. Prandtl (1952) classified secondary flows in open channel into two categories. The first type is a result of curvature effect and exists in both laminar and turbulent flows. Researchers expressed analytically the mechanism behind generation of this type which is also known as skew-induced streamwise vorticity. The secondary flow of second type, on the other hand is still not fully known and the mechanism behind its generation and maintenance has been a subject of study for decades (Bradshaw, 1987; Einstein and Li, 1958; Gessner, 1973; Gulliver and Halverson, 1987; Ikeda, 1981; Naot and Rodi, 1982; Nezu and Nakagawa, 1984; Perkins, 1970; Prandtl, 1952; Tominaga and Nezu, 1991).

Moissis (1957) examined all types of secondary flows analytically. Assuming Navier-Stocks equations as governing equations, laminar fluid flow, incompressible fluid, and fully developed flow, Moissis analyzed secondary flows in non-circular straight channels. It was shown analytically that secondary
flows of second type do not exist in non-circular straight channels under laminar flow regime. Later, Maslen (1958) and Gessner (1973) provided the same statements, based on their analytical derivations. Although many studies concluded that secondary flows of second type do not exist in laminar flows (Einstein and Li, 1958; Gessner, 1973), Yang et al. (2012) suggest that it does exist in laminar flows, based on theoretical assumptions and derivations.

Einstein and Li (1958) analyzed secondary flow of second type in straight channels, analytically. The derivation of their equation is as follows.

\[
\frac{Du}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \nabla^2 u
\]  
\[
\frac{Dv}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \nabla^2 v
\]  
\[
\frac{Dw}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \nabla^2 w
\]

Here x, y, and z are the Cartesian coordinates, with x denoting the streamwise direction. u, v and w are the velocity components in x, y, and z directions, respectively. p and \( \nu \) are pressure and dynamic viscosity. Then, they introduced vorticity in writing new form of equations.

\[
\xi = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} = w_y - v_z
\]  
\[
\eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} = u_z - w_x
\]  
\[
\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = v_x - u_y
\]
Later, they used Lamb (1932) nomenclature in derivation of this new vorticity based governing equations.

$$\frac{D\xi}{Dt} = \xi u_x + \eta u_y + \zeta u_z + v \nabla^2 \xi \quad (2.3a)$$

$$\frac{D\eta}{Dt} = \xi v_x + \eta v_y + \zeta v_z + v \nabla^2 \eta \quad (2.3b)$$

$$\frac{D\zeta}{Dt} = \xi w_x + \eta w_y + \zeta w_z + v \nabla^2 \zeta \quad (2.3c)$$

with the 'continuity equation' applicable for vorticity as follows:

$$\xi_x + \eta_y + \zeta_z = 0 \quad (2.4)$$

where, $\xi_x$, $\eta_y$, and $\zeta_z$ stand for, vorticity components in x, y, and z coordinates. Correlating turbulent secondary flows to streamwise vorticity ($\xi$), they did further derivations and assumptions, based on which they concluded that turbulent secondary currents are generated from anisotropy of turbulence. In other words, they defined secondary currents as circulation over the cross sectional area perpendicular to streamwise direction and calculated the circulation as integration of $\xi_x$ (vorticity in streamwise direction) over that area. They concluded that $v'^2 - w'^2$ (turbulence anisotropy) term in $\xi_x$ equation is responsible for generation of this circulation. In other words, Einstein and Li (1958) attributed the origin of secondary flows to the gradients of Reynolds normal stresses (term $A_4$ in equation 2.5). Gessner (1973), demonstrated later that this theory is not entirely true.
Gessner (1973) developed a theoretical framework, based on series of experimental measurements, that were performed, in a square duct of airflow. Gessner analyzed energy, vorticity and momentum equations along the corner bisector and the walls. With simplifications throughout the analysis based on the measurements and theoretical assumptions, Gessner examined the previous postulations on mechanism responsible for generation of turbulent secondary current. It was shown that although $v'^2 - w'^2$ are important in maintenance of secondary currents, turbulent shear stresses are the cause of generation of secondary currents (term $A_5$ in equation 2.5). This is in contrast with Einstein and Li (1958) postulation. Gessner also showed that because the postulation did not take into account that streamwise vorticity ($\xi$) is two order of magnitude less than $\eta_y$ and $\zeta_z$, it is not accurate. Later Nezu and Nakagawa (1984) found out that $A_4$ and $A_5$ are both dominant and have opposite signs by measurements. Also, Demuren and Rodi (1984) ascertained the same thing numerically. Based on this, Nezu (2005) stated that, "$A_4$ and $A_5$ generate and suppress secondary currents respectively, with $A_1^*$ being determined by the balance between these two terms."

The generation and maintenance mechanisms of turbulence-driven secondary flows are still being studied (Albayrak and Lemmin, 2011; Anderson et al., 2015; Blanckaert et al., 2010; Rodríguez and García, 2008; Stoesser et al., 2010; Wang and Cheng, 2006; Yang et al., 2012). While it is not fully clear yet, the interaction of wall roughness and shallowness with the generation and maintenance processes of secondary current are evident. The following section will look into research work on these two topics.
2.2 Effect of roughness and shallowness on secondary flows

Ikeda (1981) conducted an experimental study on self-forming open channels with sandy beds. Ikeda was the first to notice that secondary current and sediment transport are coupled with each other in open channels with mobilized sandy bed. Stated in literature, Ikeda (1981) for the first time theorized that in channels with mobilized sandy beds, the formation of cellular secondary flows and longitudinal ridges are coupled (Blanckaert et al., 2010).

Nezu and Nakagawa (1984) measured secondary currents in air ducts with smooth walls using hot wires. Based on results of Naot and Rodi (1982) numerical simulations which included the effect of free-surface, Nezu and Nakagawa (1984) hypothesized that the formation of cellular secondary currents is caused by mutual interaction of secondary currents and sandy bed. In order to investigate this hypothesis, they created a small longitudinal ridge along the duct and measured the secondary currents. They were the first to propose that any disturbance on the bed or nonuniformity of the bed would cause the secondary currents to exist in the middle of the channel; otherwise on a uniformly distributed roughness the secondary flow cells would die out after distance of $2.5 \times h$ ($h=$depth of channel) from the side-walls. In their experiment the longitudinal ridge was fixed, while in Ikeda (1981) experiment the bed was covered with mobilized sand. Based on their experiment, even though there was no transport of sediment, the fixed disturbance on the bed could maintain the secondary flows cells in the middle of channel. It can be concluded that, the maintenance of secondary flow cells in open channels with mobilized bed is due to disturbance elements (longitudinal ridges formed by sediment transport at upflow regions).

Later, Colombini (1993) conducted a linear stability analysis on an infinitely wide channel with
an erodible bed. Colombini utilized a nonlinear turbulence closure scheme by Speziale (1987) to produce turbulence-driven secondary flows. Based on experiments of Nezu and Rodi (1986), Colombini tuned the model to incorporate roughness. Conducting a linear stability analysis of infinitely wide channels with erodible bed, Colombini concluded that: *uniform flow can lose stability to perturbed configurations that are spanwise periodic and still uniform in the longitudinal direction. This instability mechanism can explain the formation of sand ridges when the basic flow does not depend on the lateral coordinate*. This means that there is no need for corner induced secondary flows for formation of longitudinal sand ridges in channels with erodible bed. Considering the interaction of erodible bed and secondary flows, Colombini developed a mathematical model for formation of cellular secondary flows and longitudinal ridges.

The proposed speculation by Nezu and Nakagawa (1984), that on a uniformly distributed roughness the secondary flow cells would die out after distance of $2.5 \times h$ from the side-walls, have been always questionable. Rodríguez and García (2008) designed an experiment to evaluate this hypothesis. They investigated the secondary circulation and flow variability in straight open channel flows with uniformly distributed roughness crushed stones on bed. They illustrated that secondary current in open channels with uniformly distrusted roughness would exist in wide channels with aspect ratios over $b/h > 5$. They tested two channels with aspect ratios of $b/h = 6.3, 8.5$. Albayrak and Lemmin (2011) and Blanckaert et al. (2010) extended these experiments to higher aspect ratios up to $b/h = 12, 20$ which confirmed their findings.

Wang and Cheng (2006) examined six other bed configurations in which they evaluated the cellular secondary currents formation under alternate bed disturbance elements. In two of these case studies they designed the bed with alternate longitudinal rough and smooth strips. In the rest of case
studies they made alternate longitudinal steps or ridges and through in the transverse direction. Although the aspect ratio for the experiments was around $b/h = 8$, they observed very strong cellular secondary current patterns in the middle of the channel. They used two-dimensional Laser Doppler Anemometer and a one-dimensional Ultrasonic Doppler Velocimeter.

Many ambiguities and uncertainties exist in theories behind the mechanism of interaction between roughness and secondary currents. Several studies have recently explored these interactions. However, experimental studies suffer many constraints in accurately measuring and identifying flow hydrodynamic with high resolutions. There have been several studies that employed numerical simulations in studying interaction of secondary flows and roughness (Choi et al., 2007, 2008; Stoesser et al., 2010). Nevertheless, the need for a faster, accurate, and reliable model which could simulate roughness is undeniable.

### 2.3 Role of CFD simulations in studies of turbulent secondary flow

Turbulence-driven secondary flow is crucial in many fluvial processes. It plays an important role in many processes including creation of undulating bed shear stress distribution, detaching sediments from the bed, transferring suspended sediments, changing the bed formation and ice formation. They were discovered almost a century ago and many researchers have recognized them in laboratory or natural channels, however, it has been very hard to measure these velocities for decades (Gessner, 1973; Gulliver and Halverson, 1987). The secondary flows are almost 1-2% of streamwise velocities (Nezu, 2005) which make them difficult to measure. Experimental measurement of these currents was not feasible until 1980s (Gulliver and Halverson, 1987; Nakagawa and Nezu, 1981; Nezu and Nakagawa, 1984; Nezu and Rodi, 1986). Since late 1990s and beginning of 2000 several studies have
utilized apparatuses such as PIV and ADVP to explore this phenomena under more realistic and complicated circumstances in channels, compared to previous studies (Albayrak and Lemmin, 2011; Blanckaert et al., 2010; Rodríguez and García, 2008; Wang and Cheng, 2006).

The difficulty of accurately measuring secondary currents have encouraged researchers to incorporate numerical approach as an alternative to study secondary current of second type. Moreover, many factors including bed roughness alteration, aspect ratio of the channel, and inclination of the banks effect the structure and characteristics of secondary flow in open channel. Investigation of secondary current in experimental setup, under various conditions, is costly and inefficient. Thus there have been numerous studies which have attempted to incorporate numerical methods to study secondary current of second type (Ansari et al., 2011; Choi et al., 2007, 2008; Demuren and Rodi, 1984; Gibson and Rodi, 1989; Kang and Sotiropoulos, 2012; Naot and Rodi, 1982; Stoesser et al., 2015, 2010).

Numerical investigation of secondary currents of second type has been a subject of study for many years. The ambiguity of the mechanism behind its generation and the complexity of its structure entailed extensive research efforts to find suitable numerical methods. The following paragraphs will look into the advances and restrictions of secondary current studies.

According to Naot and Rodi (1982), Launder and Ying (1973) was the first to numerically simulate secondary flows with a turbulence model. They used an algebraic stress model to represent the Reynolds stresses. Several studies followed their work including Naot and Rodi (1982), who demonstrated a new model in which they incorporated a new algebraic stress modelling method without the need to model a full stress-equation model. They introduced a simpler algebraic model capable of simulating the main characteristics of open channel flow. Also, their model was able to incorporate wall and free surface effects quite easily. Considering the fact that standard
linear $k - l$ and $k - \varepsilon$ were incapable of accurately predicting secondary flows, Speziale (1987) presented a new nonlinear $k - l$ and $k - \varepsilon$ model. The model performed quite better performance, compared to the standard models in simulating turbulent flow structures including secondary flow structures. Speziale’s nonlinear modelling of Reynolds stresses have been widely used since, due to their accuracy and their computationally affordability, compared to other methods. Gibson and Rodi (1989) utilized a Reynolds Stress Model (RSM) to simulate 2-D Open channel flows. They showed that anisotropy of turbulence induced by free surface can be adequately modelled with RSM simulations.

Being coupled with turbulent characteristic, such as anisotropy of turbulence, have made accurate modelling of turbulence characteristics and specially Reynolds stresses inevitable. Running DNS models with high Re numbers and complexity in bed configurations is impossible with existing computational power. LES models are also computationally expensive considering running numerous case studies of various configurations in research practices. Besides, LES models are far beyond engineering practices needs. More importantly, roughness directly effects these flow structures. There are small number of studies able to implement roughness in LES simulations. One reason might be the computational costs of LES simulations for tuning and validation of models for roughness implementation. Kang and Sotiropoulos (2012) used very fine mesh to capture every roughness elements on their bed in their simulation. In their case, the roughness element, however, were big and almost uniform size. Recently, Stoesser et al. (2015) incorporated a new model to implement roughness in LES simulation. The urge to find an alternative fast and reliable method capable of incorporating roughness should be addressed.

RANS simulations are computationally affordable. Although the role of non-linearity of turbulence
in secondary current simulations seem to be crucial, many studies have reported the standard two-
equation RANS models to be incapable of simulating secondary current of second type (Choi et al.,
2007; Kang and Sotiropoulos, 2012; Sotiropoulos and Ventikos, 1998). These models are based on the
assumption of isotropic Reynolds stresses. For many engineering practices where only overall average
flow field measurements are needed, these models carry out decent simulations. However, when
it comes to simulating many flow features, including secondary currents and recirculation regions
these models are incapable. Another well-known RANS-based model is Reynolds stress equation
model (RSM), which computes all the Reynolds stresses terms individually. RSM models are not
practical, because of the tremendous effort needed for calibration and tuning of the parameters for
each simulation. An alternative to all the preceding models are nonlinear eddy viscosity models.

Nonlinear eddy viscosity models are RANS-based models. In these models, the mean turbulence
fields are associated with mean velocity field via nonlinear constitutive relationship. Sotiropoulos
and Ventikos (1998) studied performance of nonlinear two-equation models. The performance of two
nonlinear models and two standard models with experimental measurements, in predicting various
flow field parameters, were compared. Sotiropoulos and Ventikos (1998) showed that nonlinear
models involving nonisotropic constitutive relationship of cubic order and higher orders for Reynolds
stresses, have decent performances in simulations of three-dimensional flows.

Choi et al. (2007) and Choi et al. (2008) evaluated the performance of RSM and nonlinear $k - \varepsilon$
models in simulating secondary currents with non-uniform roughness. It was reported that the
RSM model has done an excellent job in simulating these flows although the RSM models demand
extensive tuning time of the parameters. Consequently, considering RSM tuning time, compared
to RSM the $k - \varepsilon$ is more time affordable. However, they reported that the performance of $k - \varepsilon$
was quite poorer compared to LES and RSM simulations in predicting Reynolds stresses and other turbulent flow characteristics.
Chapter 3

Computational Details and Numerical Models

This chapter briefly describes the computational and numerical methods employed in this study. The first section is devoted to the governing equations. That is followed by the description of new fourth-order nonlinear $k - \omega$ model in section 2. Roughness implementation is presented in section 3. Finally, OpenFOAM® CFD package, pre-processing, and post-processing tools and techniques are presented in the last section.

3.1 Governing Equations

Fluid of various kinds exist in different flow conditions. From viscous blood flowing in small veins to massive cyclones in forms of spiraling winds, are represented by governing equations. Elaborating their physics, mechanics, dynamics, these governing equations, in most cases, illustrate fluid flows
in mathematical form. Researchers apply the governing equations to analyze and describe the fluid flows. Depending on the scope of analysis and studies, open channel flows can be represented by different forms of governing equations. In this section, the Navier-stokes equations and continuity are first explained as the most general form of open channel flow governing equation. Subsequently, the Reynolds Averaged Navier-stokes (RANS) equations which are the averaged forms of Navier-stokes equations over time are represented.

3.1.1 The Navier-stokes and The Continuity Equations

Claude-Louis Navier the French engineer (1785-1836) and George Gabriel Stokes (1819-1903), applied Newton’s second law to viscous fluids, to describe their motions. Employing appropriate physical and mathematical laws and valid assumptions, they derived a new form of Newton’s second law which is simply a declaration of the momentum balance. The Navier-Stokes (N-S) equations can be written in different forms, provided what type of fluid flow it represents. For an incompressible flow of a Newtonian fluid, the momentum equation can be written as

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) - \mu \nabla^2 \mathbf{u} = -\nabla p + \rho \mathbf{g}$$

(3.1)

where $\rho$, $\mathbf{u}$, $\mu$, $p$, and $\mathbf{g}$ are density, fluid velocity vector field, dynamic viscosity of the fluid, pressure field, and the gravitational acceleration vector, respectively.

Even though the momentum equations represents the motion of fluid, more information is needed to describe the fluid flow. The continuity equation represents the conversation o mass as follows
\[ (\partial \rho/\partial t) + \nabla \cdot (\rho \mathbf{u}) = 0 \]  \hspace{1cm} (3.2)

### 3.1.2 The Reynolds-Averaged Navier-stokes (RANS) Equations

Equation 3.1 and 3.2 describe the fluid flows precisely. However, solving these equations for high Reynolds number flows and in this case open channel flows is difficult. Reynolds-averaged Navier-stokes (RANS), which is the time-averaged form of N-S equations, are the alternate simpler version of Navier-stokes equations. Averaged over time, RANS equations represent fluid flows in a rigorous manner. The RANS form for continuity and momentum equations are shown by

\[ \frac{\partial \overline{u_i}}{\partial x_i} = 0 \]  \hspace{1cm} (3.3)

\[ \frac{\partial \overline{u_i}}{\partial t} + \overline{u_j} \frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \overline{u_i}}{\partial x_j} \right) - \frac{\partial \overline{u_i' u_j'}}{\partial x_j'} + g_i \]  \hspace{1cm} (3.4)

where \( \overline{u_i' u_j'} \) is the Reynolds stresses.

### 3.1.3 Turbulence Modelling for RANS Equations

As shown Reynolds stresses are obtained in RANS equations, as a consequence of averaging Navier-stokes. These additional terms which are new unknowns, account for turbulent fluctuations. With respect to the fluid flow RANS equations represent, importance of the subject, and how detailed the flow characteristics are needed to be, the Reynolds stresses are modelled. Numerous turbulence
models are designed to compute the Reynolds stresses. RANS-based turbulence models are in three
general forms: Linear eddy viscosity models, nonlinear eddy viscosity models, and Reynolds stress
model (RSM). This study take advantage of a new fourth-order nonlinear $k - \omega$ model for simulating
secondary current of second type.

3.1.3.1 Reynolds stress closure modelling

As shown Reynolds stress are obtained in RANS equations, as a consequence of averaging Navier-
stokes. These additional terms which are new unknowns, account for turbulent fluctuations. With
respect to the fluid flow RANS equations represent, importance of the subject, and how detailed
the flow characteristics are needed to be, the Reynolds stresses are modelled. Numerous turbulence
models are designed to compute the Reynolds stresses. RANS-based turbulence models are in three
general forms: Linear eddy viscosity models, nonlinear eddy viscosity models, and Reynolds stress
model (RSM). This study take advantage of a new fourth-order nonlinear $k - \omega$ model for simulating
secondary current of second type.

As stated in literature, linear eddy viscosity models are incapable of accurately simulating turbulent
secondary flows (Speziale, 1987), Colombini (1993), Sotiropoulos and Ventikos (1998)). The reason
lies within the facts that linear eddy viscosity models, using Boussinesq hypothesis, model the
Reynolds stresses in a linear constitutive correlation with the mean flow straining field, as:

\[-\rho \langle u'_i u'_j \rangle = 2 \mu_t S_{ij} - \frac{2}{3} \rho k \delta_{ij}\]

where $\mu_t$ is the turbulent viscosity or eddy viscosity; $k = (\langle u_1 u_1 \rangle + \langle u_2 u_2 \rangle + \langle u_3 u_3 \rangle)$ is the mean
turbulent kinetic energy; and \( S_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{1}{3} \frac{\partial U_k}{\partial x_k} \delta_{ij} \) is the mean strain rate tensor. With Boussinesq hypothesis:

\[
\bar{u}_i' u'_j = \nu_t \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \tag{3.5}
\]

The linear viscosity models, also have three major subcategories: Algebraic models (zero-equation), one equation models, and two equation models. They are basically named after the number of extra equations they introduce to calculate the Reynolds stresses. For example two equation models, such as \( k - \omega \) and \( k - \varepsilon \) require to solve two more equations for \( k, \omega, \) and \( \varepsilon \). As mentioned above, owing to the fact that all these models apply a linear relationship to model the Reynolds stresses, they are impotent where anisotropy of turbulence matters.

Anisotropy of turbulence, generally is the term used when two of normal Reynolds stresses \( (u'^2, v'^2, w'^2) \) have significant difference in magnitude. Such scenarios occurs in many of recirculating flows and regions. Because of this, secondary flows as an example of flows with high degree of anisotropy of turbulence, cannot be modelled with standard linear eddy viscosity models.

In contrast to linear eddy viscosity models, nonlinear eddy viscosity models, represent the Reynolds stresses in a nonlinear relationship with mean velocity field. Their constitutive correlation is

\[
-\rho \langle u'_i u'_j \rangle = 2 \mu_t F_{nl}(S_{ij}, \Omega_{ij}, ...)
\]

where \( \Omega_{ij} \) is the mean vorticity. The purpose of such relationship is to introduce an approach in modelling Reynolds stresses in a more accurate method. More information on this constitutive
relationship will be provided in the next section. Finally, as discussed earlier in section 2.3, RSM models solve for all the Reynolds stresses. However, their tuning process is time-consuming. In this study, a new two-equation \((k-\omega)\) model was chosen, with a fourth-order nonlinear relationship, correlating turbulence velocities to mean velocity field.

### 3.1.3.2 two-equation modelling

In order to account for history effects of the flow, caused by turbulence, two-equation models use two extra transport equations. These two extra equations along with continuity and momentum equations are solved to compute flow properties. The two extra transport equations, depending on type of applications, representing a combinations of \(k\) (turbulent kinetic energy), \(\varepsilon\) (turbulent dissipation), or \(\omega = \frac{\varepsilon}{k}\). \(k-\omega\) and \(k-\varepsilon\), as two equation models, are two of the most prominent turbulence models.

### 3.2 New Two-Equations \(k-\omega\) Turbulence Closure Model by Hellsten (2004)

This study take advantage of a new fourth-order nonlinear \(k-\omega\) model for simulating secondary current of second type. Sotiropoulos and Ventikos (1998) demonstrated that nonlinear models involving nonlinear constitutive relationship of cubic order and higher orders for Reynolds stresses, have decent performances in simulating three-dimensional flows. Compared to standard two-equation models, in this nonlinear two equation model, the eddy viscosity coefficient has nonlinear relationship with mean flow variables. These constitutive models are called Explicit algebraic Reynolds stress
models (EARSM).

\[
\frac{\partial \pi_i}{\partial t} + \sum_j \frac{\partial \pi_i}{\partial x_j} = \frac{\partial}{\partial x_j} [ (-\bar{p} \delta_{ij} + \nu (\frac{\partial \pi_i}{\partial x_j} + \frac{\partial \pi_j}{\partial x_i}) - u'_i u'_j] \tag{3.6}
\]

This halts the trace of Reynolds stress tensor:

\[
k = \frac{1}{2} \overline{u'_i u'_j} \tag{3.7}
\]

Let Reynolds stress \( \overline{u'_i u'_j} \) be equal to isotropic stress + deviatropic stress :

\[
\overline{u'_i u'_j} = \frac{2}{3} k \delta_{ij} + [\overline{u'_i u'_j} - \frac{2}{3} k \delta_{ij}]
\]

Then the RANS equation becomes:

\[
\frac{\partial \pi_i}{\partial t} + \sum_j \frac{\partial \pi_i}{\partial x_j} - \frac{\partial}{\partial x_j} [ \nu_{eff} (\frac{\partial \pi_i}{\partial x_j} + \frac{\partial \pi_j}{\partial x_i})] - \frac{\partial}{\partial x_i} (\bar{p} + \frac{2}{3} k) \tag{3.8}
\]

The pressure term on the last term on the RHS of equation 3.8 is modified pressure.

\[
\nu_{eff} = \nu + \nu_t
\]
3.3 Roughness Implementation

The $k - \omega$ formulation of the model, allows constructing functions for implementation of rough boundaries. With regards to the boundary roughness the viscous sub-layer for rough boundary, either does not exist or it is very thin compared to smooth boundary. As a result, right above the boundary, the turbulent flow characteristics can be identified. In the vicinity of rough boundaries the turbulent kinetic energy is considerable. It is in contrast with smooth boundaries which have zero turbulent kinetic energy (TKE) in the vicinity of the walls. Wilcox (1994) introduced a function, through which TKE can be increased. The function employs this method to manipulate the TKE near rough boundaries, in order to explicitly resemble rough boundaries. This is done by assigning low $\omega$ values near these boundaries which lead to increase of TKE. As explained earlier (section 3.1.3.2), specific dissipation ($\omega$) corresponds to TKE as

$$\omega = \frac{\varepsilon}{k}$$

Hence, assigning low $\omega$ values to boundaries, deliberately leads to $\varepsilon$ decrease and $k$ production. To establish a function which replicate rough boundaries correctly, Wilcox (1994) proposed a $\omega$ boundary correlation as

$$\omega_w = \frac{u'^2}{v} S_R$$

to implement roughness through $S_R$ a function was introduced. The following is the modified version
of that function by Hellsten (2004) as,

\[
S_R = \begin{cases} 
[50/\max(k_s^+; k_{smin}^+)]^2 & \text{for } k_s^+ > 25 \\
100/k_s^+ & \text{for } k_s^+ \leq 25 
\end{cases} 
\]  

(3.9)

where \( k_s^+ = k_s u_r / \nu \) is the scaled sand roughness. The roughness then can be produced with respect to the equivalent sand roughness. Also, \( k_{smin}^+ \) plays an important role here for smooth walls. In this situation if the roughness element is very small and an adequate choice \( k_{smin}^+ \) will eliminate the grid sensitivity of the function (Hellsten, 2004). The \( k_{smin}^+ \) proposed by Hellsten (2004) is,

\[
k_{smin}^+ = \min[2.4(y_1^+)^{0.85}; 8]
\]

### 3.4 Computational Resources

In this section, the pre-processing, solving, and post-processing techniques and utilities are briefly described.

#### 3.4.1 OpenFOAM® CFD Package

All of the simulations and CFD studies in this study were executed in OpenFOAM® platform. OpenFOAM® is an open source CFD package under Gnu General Public License by the company OpenCFD Ltd (Tabor et al., 2011). Throughout the years OpenFOAM® has gained a vast user base over the world. The open source aspect of the package, as in other open source software packages, allow many contributors around the world to modify and add the source code. This
feature, along with other advantageous characteristics made OpenFOAM® a powerful, resourceful and well-established CFD software. Some of these advantageous characteristics of OpenFOAM® are:

- Fine handling of semi-auto parallelization of the simulations
- Providing powerful tools for pre-processing and post-processing processes
- Facilitating collaboration with other third party CFD software packages and pre-processing and post-processing utilities

OpenFOAM® consists of plentiful C++ libraries, written in a truly complex object oriented structure. This is highly regarded as a serious disadvantage of OpenFOAM®, specifically for beginners who want to utilize the software. Moreover, the open source basis of the code comes at the price of lack of any customer service support. Complexity of the code, the lack of any customer service plus other preliminary required computational knowledge to use the software, have prevented many industrial firms and individuals from utilizing OpenFOAM®.

In this study, the new fourth order nonlinear $k - \omega$ model by (Hellsten, 2004) and the rough-wall boundary function, is implemented into OpenFOAM® platform. The tuning, validation and verification of $k - \omega$ model and the wall-function with respect to the experimental data were done smoothly in OpenFOAM® platform.

### 3.4.2 Pre-processing Techniques and Utilities

Every steps of the preparation and development of the numerical case studies up to the point where the simulation starts to run (the equations start to be solved) are pre-processing steps. From
defining the geometry and creating the mesh to setting up the numerical schemes and assigning boundary conditions, all belong to pre-processing procedures. The most general pre-processing procedures are explained concisely in the following paragraphs.

### 3.4.2.1 meshing process

In essence, mesh generating is the first step of computational procedures toward a CFD case study. In other words, after every preliminary research about the parameters and conditions of the case study (e.g. type of fluid, type of flow, numerical schemes, and boundary conditions) the first step to execute the CFD study plan is to generate the mesh. This study employed OpenFOAM® software package, which is explained in detail in the next section, as the CFD package. OpenFOAM® is a Finite Volume Method based code. So, the meshes needed to be suitable for final volume method.

All the studies are based on channel flows or duct flows of rectangular cross section. To generate the mesh, m4 script (a general-purpose macro processor included in all UNIX-like operating systems) was used to create blockMeshDict dictionary files. blockMeshDict is the basic mesh generator dictionary in OpenFOAM®. Since the geometries were simple, blockMeshDict was the mesh generator tool. Also, m4 provide a convenient platform for quickly creating, modifying and reproducing multiple blockMeshDict dictionaries. A sample of m4 script and blockMeshDict used in one of the numerical case studies is provided in appendix B. The mesh specifications are explained for each case study in the following chapters.
3.4.2.2 boundary and initial conditions

The boundary conditions are assigned at each boundaries (i.e. smooth wall) representing either the field variables’ (i.e. velocity) fixed value or gradient value, at that boundary. Imposed on the boundaries, the boundary conditions dictate the solution to take that value along that boundary for that variable. There are two types of boundary conditions: (1) Dirichlet boundary condition and (2) Neumann boundary condition. For example, the boundary condition for velocity at smooth wall is a Dirichlet boundary condition fixed as zero due to no slip condition at the walls. Boundary conditions are described for each case separately.

Each case study was run on a coarse mesh with simpler $k-\omega$ turbulence model for several thousand time steps (50000 in most of the cases), depending on the mesh size and complexity of the flow. These initial simulations help the solution march faster compared to the more complex turbulence models on finer meshes. Then, the solution for the variables from the last time step are mapped to new cases, with fine mesh and the designated turbulence model, as the initial condition for the case.

The boundary and initial conditions are normally put in folder named "0", in separate dictionary files for each variable. For instance, a dictionary file named k, contains all the boundary and initial conditions for turbulent kinetic energy. Samples of velocity ($U$), pressure $p$, and $\omega$ (omega) dictionary files are provided in appendix A.

3.4.2.3 system directory

Without exception, all the cases in OpenFOAM® contain a folder names system. In this folder, a dictionary named controlDict consist of all the essential parameters for navigating the simulation
and the output data creation. controlDict provides the switches to choose the N-S solver algorithm (e.g. PISO), selecting time steps, and simulation times when the output data needed to be written. Depending on the type of turbulence model and simulation, additional features are given to set the simulation to automatically choose times steps in manner which satisfies the CFL number criteria. A sample of controlDict dictionary containing the most general switches used in this study is provided in appendix A.

The system directory encompasses other dictionaries, provided what type of simulation and settings are desired. fvOptions, fvScheme, and fvSolution are the most useful dictionaries after controlDict. fvOptions has the ability to set a physical source or constraint on the governing equation, e.g. porous media and body forces. Utilized in all the case studies of this studies, fvOptions dictated the solution to use $\overline{U}$ (averaged streamwise velocity) as an explicit source for pressure gradient source. This was set through pressureGradientExplicitSource class. This explicit pressure gradient source was used to drive the flow in our simulations. $\overline{U}$ were obtained from the reported cross sectional average streamwise velocities in each case study. In other words, fvOptions used the $\overline{U}$ to compute the pressure gradient. Then, it employs the pressure gradient to solve for other variables, depending on the solver chosen in the study.

fvScheme is the dictionary in which the numerical schemes i.e. interpolation schemes are set. Since the schemes are different case by case, a sample is explained for each cases in their designated chapter. fvSolution assists imposing convergence criteria for the simulation by setting the desired final residuals for each variable. Relaxation factors can also be set in fvSolution.

Other practical dictionary in system folder is decomposeMeshDict through which, the parallelization scheme and number of cores are configured. At this point, the case is almost ready to be run.
3.4.3 Post-processing Techniques and Utilities

Post-processing include all the steps and procedures taken after the simulation is converged, for visualization and analysis purposes. OpenFOAM® facilitated the post-processing of the data, intelligently. Not only OpenFOAM® has provided the clients with profound tools and utilities installed and easily accessible for post-processing the data, but also made it quite straightforward to output and extract the data for other third-party utilization. Here, a few number of the most useful tools and techniques adopted in this study, are explained in a nutshell.

3.4.3.1 Paraview

According to their website description “ParaView is an open-source, multi-platform data analysis and visualization application”. ParaView provides insightful views of the flow field structures along with plentiful tools and techniques to measure, calculate, plot and extract the data. Every versions of OpenFOAM® come with the latest version of ParaView, at the time of OpenFOAM® release, ready to be installed as a third-party software. OpenFOAM® made all the required setups in bash environment which make the communications of the two software quite smooth. This cooperation assist the real time monitoring and analysis of the simulations and accelerate the visualization processes.

A few number of the most useful applications of ParaView in this study can be categorized as

- Assisted with visualization of the generated mesh domain, schematic view of the cell growth, overall quality of the mesh including aspect ratios. It also helps with locating visible errors in mesh generating process, i.e. wrongful aspect ratios or cell sizes.
• Visualized initial and boundary conditions in colourful views. This would help a lot if some values are not assigned in a righteous way or if the direction of a gradient or variable is not right.

• Visualized contour plots and distribution of field data including velocity components, pressure gradients, shear stresses, and TKE on any plane or along any line of choice.

• Displayed perceptive images of the secondary current velocity vectors with tools to manipulate the their outlook to gain knowledge about their mechanism. Plotting secondary current velocity vectors on top of contour plot of pressure gradients was particularly insightful.

The velocity vtk surface data required for plotting secondary current velocities and velocity contour plots are extracted in ParaView.

3.4.3.2 sample

In addition to ParaView, OpenFOAM® has number of other post-processing tools. sample utility is a smart and robust tool for extracting data from the simulation. sample utility uses a sample dictionary, located in system directory, to sample data along any line or on any plane and output the data to various widespread format. Defining lines and surfaces, specifying number of sampling points, and choosing variables and parameters to be extracted are done in an effortless procedure in sample dictionary. After configuring the sample dictionary, the data get extracted with a single line of command to a folder named postprocessing. Almost all of the graphs and plots, except secondary current vectors and velocity contour plots, are generated using the data extracted with sample utility.
3.4.3.3 Python

Finally, all the plots and graphs are generated utilizing *Python* scripts. Providing open source, robust, and intelligent libraries to compute, plot and visualize the data, *Python* facilitated generating magnificent plots.
Chapter 4

Simulation of Turbulent Secondary Flows Over Bed with Uniformly Distributed Roughness

4.1 Introduction

As pointed out in chapter 2, boundary roughness effect the formation and configuration of turbulent secondary flows. The need for a suitable CFD model, able to accurately model secondary flows over rough boundaries is obvious. This chapter investigates the performance of the proposed wall function for roughness implementation (eq. 3.9). Particularly, the ability of this function in conjunction with the new $k - \omega$ model, for simulating turbulent secondary flows, is evaluated. The detailed description of the function was described in previous chapter (3.3).
4.2 Rodríguez and García (2008) Uniform Rough Bed with Smooth Walls (Case FB1)

Rodríguez and García (2008) proved that cellular secondary flows exist in the middle of channels with aspect ratios higher than five \((b/h > 5)\), with uniformly distributed immobilized bed roughness. It was proposed by Nezu and Nakagawa (1984) that on a uniformly distributed roughness the secondary flow cells would die out after distance of \(2.5 \times h\) from the side-walls. Rodríguez and García (2008) showed for the first time that this hypothesis does not hold. This study incorporate this case study to examine the ability of the \(k - \omega\) model and the roughness function in simulating cellular secondary flows over rough boundaries.

4.2.1 Description of Geometry

The channel is straight with width and depth of 0.91 and 0.6, respectively. The aspect ratio of the case is \(b/h = 8.5\). This aspect ratio lies within a range which is neither assumed as wide \((b/h \geq 10)\) nor narrow \((b/h \leq 5)\). The water depth for the FB1 case was 0.11\(m\). They used commercial 3/8” crushed stones \((D_{90} = 100mm\) and \(D_{50} = 57mm\)) to prepare a uniformly distributed fixed roughness on the bed.
4.2.2 CFD Case Setup

4.2.2.1 mesh generation

The mesh for this case consists of 1,000,000 cells. The \( y^+ \) value is almost 1 for the first cells on the walls. A growth rate of 1.003 for the cells outward from the side walls was used, resulting in cells width in the center 20 times bigger than the cells widths on the side walls; And growth rate of 1.011 was used from the bottom to the top. The top cells had heights 25 times of the cells height on the bottom. This mesh configuration would create cell aspect ratios around 20.

4.2.2.2 initial and boundary conditions

As explained in the Chapter 3 an initial case, with a coarse mesh, was run to help increasing the convergence rate. The initial case was run for almost 20000 time steps, with simple boundary conditions and \( k-\omega \) SST solver. Then the final time step solution was mapped to a new case as initial condition.

Table 4.1 illustrates the boundary conditions, used in this case study. As shown in the table, the roughness height value, chosen for the rough bottom, was \( k_N = D_{90} = 1 \text{cm} \). For the smooth boundaries of side walls, the suggested roughness height value in the literature is 0.0000015. This value produce \( \omega \) values in the order of \( 10^9 \). These \( \omega \) values implicitly eliminates turbulent kinetic energy which enables development of viscous sub-layers on the smooth surfaces.
Table 4.1: Boundary conditions for Rodríguez and García (2008) FB1 case.

<table>
<thead>
<tr>
<th>Boundaries</th>
<th>$U$</th>
<th>$P$</th>
<th>$k$</th>
<th>$\omega$</th>
<th>$\nu_t^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>inlet</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
</tr>
<tr>
<td>outlet</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
</tr>
<tr>
<td>top</td>
<td>slip</td>
<td>zero-gradient</td>
<td>zero-gradient</td>
<td>(Free Surface)$^*$</td>
<td>calculated</td>
</tr>
<tr>
<td>bottom</td>
<td>no-slip</td>
<td>zero-gradient</td>
<td>fixed value (0)</td>
<td>$k_s = D_{90} = 0.01m^\dagger$</td>
<td>fixed value (0)</td>
</tr>
<tr>
<td>side walls</td>
<td>no-slip</td>
<td>zero-gradient</td>
<td>fixed value (0)</td>
<td>$k_s = 1e^{-6} m^\ddagger$</td>
<td>fixed value (0)</td>
</tr>
</tbody>
</table>

$^*$ Turbulent viscosity or eddy viscosity.

$^1$ A function developed by Gibson and Rodi (1989) to account for free surface effects.

$^\dagger$ $k_s = D_{90} = 0.01m$ is the size reported by Rodríguez and García (2008) as roughness height. This study used this value for the rough boundary in Hellsten (2004) rough boundary function.

$^\ddagger$ for smooth boundary, $k_s = 1e^{-6} m$ was used in Hellsten (2004) rough boundary function. This is the roughness height value reported in literature for smooth boundaries.

4.2.3 Results and Discussions

Figure 4.1 shows the secondary current pattern for the FB1 case. The number of the patterns of cellular secondary current patterns matches the patterns of the experimental data.

![Secondary flow patterns](image)

Figure 4.1: Secondary flow patterns for Rodríguez and García (2008) FB1 case.

Figure 4.2a and 4.2b demonstrate comparisons between the dimensionless mean streamwise velocities profiles of the experiment data and the present study. The profiles are along vertical lines at different transverse normalized distance ($z/b$) from the wall. In both figures, the profiles of present study
have excellent agreement with the experimental profiles.

In figure 4.2a, the profiles follow the line plotted by equation 4.1, which represents law of the wall in hydraulically rough conditions. Also, the outer scaled profiles in figure 4.2b, follow the line generated by equation 4.2. As reported by Rodríguez and García (2008), the data are collapsed with the scaling variables $U_*$ (local value) and $k_s$ in equation 4.1. They have used law of the wall to compute the shear velocities locally at each of the transverse locations along the bed. The present study used $U_*$ values for scaling, close to the average values reported by Rodríguez and García (2008). Table 4.2 shows the values of the present study and the average value used in Rodríguez and García (2008) for both figures. The roughness height value ($k_s$) was fixed for all of the plots equal to the value reported by the experiment and also the same as the value used in the $\omega$ wall function in simulations. The average value of shear velocity at the bed reported by Rodríguez and García (2008), calculated by log law is $4.5\,(cm/s)$. The average value in the present study computed from outer scaling and inner scaling are $4.02$ and $4.16$, respectively.

In both figures, it can be seen that the profiles at $y/b = 0.08$ and $y/b = 0.12$ are bent with distance from the bottom. The curve is more obvious at $y/b = 0.08$. This is due to the fact that near the walls the streamwise velocity profiles do not follow law of the wall all the way to the top. However, this curve is not noticeable in Rodríguez and García (2008) data.

\[
\frac{U}{U_*} = \frac{1}{\kappa} \ln\left(\frac{z}{k_s}\right) + 8.5 \quad (4.1)
\]

\[
\frac{U_{max} - U}{U_*} = -\frac{1}{\kappa} \ln\left(\frac{z}{h}\right) + \frac{2\Pi}{\kappa}\cos^2\left(\frac{\pi z}{2h}\right) \quad (4.2)
\]
Table 4.2: Local $U_*$ values used for scaling the data

<table>
<thead>
<tr>
<th>$y/b$</th>
<th>$U_{*1}$ a (cm/s)</th>
<th>$U_{*2}$ b (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>0.12</td>
<td>4.15</td>
<td>4.15</td>
</tr>
<tr>
<td>0.17</td>
<td>4.25</td>
<td>3.9</td>
</tr>
<tr>
<td>0.23</td>
<td>4.15</td>
<td>4.15</td>
</tr>
<tr>
<td>0.34</td>
<td>4.25</td>
<td>3.9</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>4.16</strong></td>
<td><strong>4.02</strong></td>
</tr>
</tbody>
</table>

a The $U_{*1}$ are calculated from Fig.4.2a
b The $U_{*1}$ are calculated from Fig.4.2b

Figure 4.3 shows the normalized transverse distribution of bed shear stress. Rodríguez and García (2008) calculated the bed shear stress using shear velocity values which they obtained from law of the wall. They used the cross sectional average shear stress $\langle U_* \rangle = (\langle \tau \rangle / \rho)^{0.5}$ to normalize the bed shear stress values at different locations. As it can be seen the data from present study have a very good agreement and has the same pattern. Although the data oscillates around the average cross sectional shear stress value, there are some differences in the values of bed shear stresses. In other words, although the values from this study also oscillates around the average cross-sectional value (this is more obvious in figure 4.3), considerable difference between shear stress values from the experiment can be noticed.

This study incorporated a tool in OpenFOAM® which calculates shear velocity and shear stress values directly using the following equations,
(a) inner scaling (eq. 4.1)  

\[ U^* = \sqrt{\nu \frac{\partial u_x}{\partial y}} \]  

(4.3)

(b) outer scaling (eq. 4.2)  

\[ \tau = \nu \rho \frac{\partial u_x}{\partial y} \]  

(4.4)

where \( u_x \) is the local value of the streamwise velocity value at the first cell on the wall. \( \nu \) is the kinematic viscosity and \( \frac{\partial u_x}{\partial y} \) is the local gradient of streamwise velocity at the wall. It was found that the values for local \( \tau \), calculated in this way are significantly differ from the values computed from law of the wall. Table 4.3 shows the values of local bed shear stress (\( \tau \)) computed from these two methods at five different locations along the bed. These transverse locations are the ones from the experiment at which the authors validated the velocity profile and law of the wall for them (4.2a). From the values shown in table 4.3, it is obvious that the shear stress values calculated from log-law are almost twice the values calculated from equation 4.4. Moreover, as it is shown in figure
Table 4.3: Local values of $U_*$ and $\tau$ at five different transverse locations along the bed.

<table>
<thead>
<tr>
<th>$y/b$</th>
<th>$U_{*1} \text{a} (m/s)$</th>
<th>$\tau_1 (N/m^3)$</th>
<th>$U_{*2} \text{b} (m/s)$</th>
<th>$\tau_2 (N/m^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>0.040</td>
<td>1.6</td>
<td>0.0295</td>
<td>0.87</td>
</tr>
<tr>
<td>0.12</td>
<td>0.0415</td>
<td>1.72</td>
<td>0.0305</td>
<td>0.92</td>
</tr>
<tr>
<td>0.17</td>
<td>0.0425</td>
<td>1.81</td>
<td>0.0311</td>
<td>0.96</td>
</tr>
<tr>
<td>0.23</td>
<td>0.0415</td>
<td>1.72</td>
<td>0.0305</td>
<td>0.92</td>
</tr>
<tr>
<td>0.34</td>
<td>0.0425</td>
<td>1.81</td>
<td>0.0314</td>
<td>0.98</td>
</tr>
</tbody>
</table>

\text{a} The values are calculated using law of the wall from velocity profile. Index 1 stands for law of the wall method of calculation.

\text{b} The values are calculated using equations 4.4 and 4.3. Index 2 stands for values calculated by the tool using aforementioned equations.

4.2a and 4.2b, the streamwise velocity profiles from the simulation have excellent agreement with the experimental data and equation 4.1 and 4.2. And the average shear velocity values calculated from these profiles which have used to normalize them are very close to the average value from the experiment.

\[
\frac{\text{Shear velocity calculated from log-law in this study}}{\text{Shear velocity calculated from log-law in Rodríguez and García (2008) experiment}} = \frac{0.0425}{0.0450} = 0.94% 
\]

Based on the previous discussions it was concluded that calculating shear stress from shear velocities obtained from log-law is not accurate.
4.3 Summary

The performance of the Hellsten (2004) $k - \omega$ model in conjunction with a roughness wall function, in simulating turbulent secondary flows over bed with uniformly distributed roughness was tested. This chapter used case $FB1$ from Rodríguez and García (2008) for validation of the model. The result show excellent agreement in most of the comparisons.

The ability of the model in calculation of secondary flows of second type is beneficial for accurate calculation of important parameters including bed shear stress distribution, shear velocities, and velocity distribution. These parameters are vital in many engineering practices. For instance to evaluate sediment transport processes in an stream, accurate computation of bed shear stress distribution is needed.

The number of cellular secondary patterns match the reported number in Rodríguez and García
(2008) (figure 4.1). The two corner bottom vortices which could not be seen in Rodríguez and García (2008) due to limitations in measurement are clearly seen by the simulation. As reported by Rodríguez and García (2008) the corner surface vortices are stronger and bigger than corner bottom vortices.

As shown in figures 4.2 and 4.1, the vertical streamwise velocity profiles follow the law of the wall similar to Rodríguez and García (2008) data. A small curve can be seen at the higher heights of the profiles for $y/b = 0.08$ and $0.12$ which is completely expected near the walls. As the vertical profiles of streamwise velocity get closer to the wall, they do not follow the law of the wall, owing to the side wall effect. However this was not seen in Rodríguez and García (2008) profiles.

The bed shear stress distribution of the simulation follows the same trend as Rodríguez and García (2008) data. This study incorporated a tool to compute wall shear stresses, using equations 4.3 and 4.4. The reported $U_*$ from this tool was totally different from the average $U_*$ reported by Rodríguez and García (2008). Although as shown in table 4.2, the computed $U_*$ values from law of the wall are close to ones reported by Rodríguez and García (2008). This study conclude that computing average cross sectional $U_*$ and $\tau_{bed}$ is not an accurate method. Table 4.3 show the computed $U_*$ values computed by the two methods from the simulation.
Chapter 5  

Simulation of Turbulent Secondary Flows Over Bed with Alternate Rough and Smooth Strips

5.1 Introduction

This chapter examines the capability of the new $k - \omega$ model and the roughness function by Hellsten (2004) in performing simulations of turbulent secondary flows over bed with nonuniform roughness distribution. The previous chapter illustrated that the model and the roughness function perform well in simulating turbulent secondary flows in open channels over beds with uniformly distributed roughness. To investigate open channels with nonuniformly distributed roughness on bed, this study selected two very well established experimental case studies, named S75 and S50,
by Wang and Cheng (2006). This chapter presents the simulations of these two case studies and investigates the model and the wall function performance.


Wang and Cheng (2006) studied the cellular secondary flows induced by longitudinal bed forms. Case S75 and Case S50 were the case studies which had alternate longitudinal rough and smooth strips sit side by side on the bed. Figures 5.1 and 5.2 show the schematic view of the case geometries and the secondary flow circulations.

5.2.1 Description of Case S75 Setup

![Figure 5.1: Schematic view of Wang and Cheng (2006) case S75 experiment.](image)

Wang and Cheng (2006) investigated the effect of bed roughness configuration on generation and maintenance of secondary currents in open channels. They prepared the rough strips with fine gravels packed densely, which were fixed in place during the experiment. The sizes were almost uniform with $D_{50} = 2.5mm$. The smooth strips were made with PVC plates. Figure 5.1 shows bed roughness configurations for case S75.
The flume has 0.6m width and 0.6m depth. The mean water depth for S75 case was 75mm. The smooth strips have 75mm width. The first and last rough strips are 37.5mm and the three middle rough strips are 75mm.

This study incorporates S75 case study to investigate the wall function performance. The purpose is to tune and modify the model for running simulations of cellular secondary flows over alternate rough and smooth strips.

5.2.2 Description of Case S50 Setup

Figure 5.2: Schematic view of Wang and Cheng (2006) case S50 experiment.

Figure 5.2 shows bed roughness configurations for case S50. The flume has the same width and depth as case S75. The mean water depth for S50 case was 75mm. For case S50 the smooth strips have 50mm width. The first and last rough strips are 50mm and the three middle rough strips are 100mm.

This study incorporates S50 case study to validate the modifications and tuning processes that were done in S75 case study. The purpose is to check if the tuned parameters would result in accurate prediction of secondary flows in case S50. If the tuned parameter perform well in this case, the tuned parameters are validated.
Table 5.1: Boundary conditions for Wang and Cheng (2006) S75 and S50 cases.

<table>
<thead>
<tr>
<th>Boundaries</th>
<th>U</th>
<th>P</th>
<th>k</th>
<th>ω</th>
<th>νt</th>
</tr>
</thead>
<tbody>
<tr>
<td>inlet</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
</tr>
<tr>
<td>outlet</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
<td>cyclic</td>
</tr>
<tr>
<td>top</td>
<td>slip</td>
<td>zero-gradient</td>
<td>zero-gradient</td>
<td>(Free Surface)(^*)</td>
<td>calculated</td>
</tr>
<tr>
<td>rough strips</td>
<td>no-slip</td>
<td>zero-gradient</td>
<td>fixed value (0)</td>
<td>(k_s = 2 \times D_{50} = 0.005m)^*</td>
<td>fixed value (0)</td>
</tr>
<tr>
<td>smooth strips</td>
<td>no-slip</td>
<td>zero-gradient</td>
<td>fixed value (0)</td>
<td>(k_s = 1e^{-6}m, 0.0075m)^*</td>
<td>fixed value (0)</td>
</tr>
<tr>
<td>side walls</td>
<td>no-slip</td>
<td>zero-gradient</td>
<td>fixed value (0)</td>
<td>(k_s = 1e^{-6}m^a)</td>
<td>fixed value (0)</td>
</tr>
</tbody>
</table>

\(^*\) \(k_s = 2 \times D_{50} = 0.005m\) is the size reported by Wang and Cheng (2006) as roughness height. This study used this value for the rough boundary in Hellsten (2004) rough boundary function.

\(^\ast\) The smooth strips roughness height values are the tuning parameters. More explanation is provided in this section.

5.2.3 Initial and Boundary Conditions

Like FB1 case in Chapter 4, an initial case, with a coarse mesh, was run to help increasing the convergence rate. The initial case was run for both cases for almost 50000 time steps, with simple boundary conditions and \(k - \omega\) SST solver. The final time step solutions were mapped to new cases in each study (S75 and S50) as initial condition.

Table 5.1 illustrates the boundary conditions, used in S75 and S50 case studies. As shown in the table, the roughness height value, chosen for the rough bottom, was \(k_N = 2 \times D_{50} = 0.005m\). For the smooth boundaries of side walls and smooth strips, the suggested roughness height value in the literature is 0.0000015. This value produce \(\omega\) values in the order of \(10^9\). These \(\omega\) values implicitly eliminates turbulent kinetic energy which enables development of viscous sub-layers on the smooth
surfaces. However, this study found out that the combination of these rough and smooth values will generate very high $\omega$ gradient and the border of strips. This will lead to generation of high pressure gradients and higher secondary current velocities near the bod at the edge of the strips. This study discovered that if the smooth strip roughness height value changes from 0.0000015 to 0.00075, this high gradient of omega and the discrepancies of the data will be damped. More information on this tuning process will be provided in the next section.

5.3 Results and Discussions

5.3.1 mesh independence study

Figure 5.3: Grid independence study of the numerical solution for case S75. This figure shows comparisons of transverse and vertical velocity profiles, for case S75, along vertical lines parallel to the channel sides, for the three meshes.

For the purpose of verification of the numerical model, a grid independence study was carried out. Case S75 in the Wang and Cheng (2005) experiments was used for this purpose which had the
most complicated configurations and computational setups between the case studies. The coarse mesh utilized for the case consists of almost 32,000 cells. The medium sized mesh was generated by doubling the grids in y and z direction resulting total number of 126,900 cells. The number of grid points in vertical and transverse direction were doubled again in the fine mesh with 507,600 cells. Figure 5.3 compares the transverse and vertical velocity profiles for the three mesh with experimental data. As it can be seen the medium and fine mesh show identical profiles which means that the solution is independent of the grid size for these two mesh configurations.

5.3.2 Wang and Cheng (2006) S75 case

In these study, case s75 was used to tune the roughness height parameter in the wall function. It is shown that the traditional value \((k_N = 0.0000015)\) for smooth walls would generate excessive pressure gradients at the edge of the strips. These excessive pressure gradients would cause extra transverse velocities \((W)\) at the edge of the strips. This study found out increasing the roughness height value (decreasing the \(\omega\) gradient) would diminish this effect.

Figure 5.4 and 5.4 are the vertical and transverse velocity patterns. These two figures compare the data from four most important test studies, in which the study tested different combinations in introducing roughness in the wall function, to address this issue. The experimental data are also plotted in these figures for comparison. The following sections describe each of these case studies.

5.3.2.1 traditional rough and smooth values

The suggested value for roughness parameter \((k)\) in literature, for the smooth surfaces, is \(k_{\text{smooth}} = 0.0000015m\). This parameter is proportional to the roughness height. Also, for the rough surfaces the
Figure 5.4: Comparisons of vertical velocity (V) profiles along vertical lines across the section. The results are from five different roughness configurations in the simulations.

Figure 5.5: Comparisons of transverse velocity (W) profiles along vertical lines across the section. The results are from five different roughness configurations in the simulations.

The suggested value is in range of 0.5-6 $D_{50}$. In this study, $k = \{0.5, 1, 2, 4, 6\} \times D_{50}$ were tested. But for the sake of space only results of $k_{\text{rough}} = 2 \times D_{50} = 0.005m$ are shown. In this case, $k_{\text{rough}} = 0.005m$ which is twice $D_{50}$ reported by Wang and Cheng (2006). The smooth strip roughness height is $k_{\text{smooth}} = 0.0000015m$. This combination as mentioned above generate high pressure gradient at the boundary of strips and leads to extra transverse velocity values near to the bed (figures 5.5 and 5.4).

5.3.2.2 transitional roughness values

In order to address the high pressure gradient caused by $\omega$ values, a hyperbolic function was utilized to smooth the roughness height value in the vicinity of the strips border. There were two cases
with different hyperbolic factor values in these studies. Figure 5.5 and 5.4 illustrate the velocity profiles for these two cases. As it can be seen the two cases, have velocity profiles very similar to the velocity profile in the previous cases. It should be mentioned that although the roughness height values for smooth and rough strips are changing gradually in transverse direction, they reach to the same values for smooth and rough strips as in the traditional case. However, as shown in figures 5.5 and 5.4, the transitional roughness height values did not effect the velocity profiles except a very small changes which is negligible.

5.3.2.3 \( \kappa_{smooth} = 0.00075m \) and \( \kappa_{rough} = 0.005m \)

Testing several combinations of the roughness values for smooth and rough strips in the wall function, this study found a appropriate combination. The roughness height value of \( \kappa_{smooth} = 0.00075m \) which is two orders of magnitude higher than what is suggested in the literature and \( \kappa_{rough} = 0.005m \) have resulted in legitimate secondary current values. As it can be seen in figures 5.5 and 5.4, the secondary current profiles in this case have very good agreement with experimental data. However there is a slight difference in the values in figure 5.5. Figure 5.6 shows the transverse distribution of transverse velocity (W) along four different lines parallel to bed at different heights. The profiles here also have good agreement with the experimental profile.

As reported in previous studies (Choi et al., 2008; Yang et al., 2012), Wang and Cheng (2006) measured only streamwise (U) and vertical (V) velocities and then calculated the transverse velocity (W) from continuity equation. So this study suspected that these discrepancies in transverse velocity profiles in figures 5.5 and 5.6 for this case might be due to the way the experimental data have been calculated here.
The roughness height value of \( k_{\text{smooth}} = 0.00075 \text{m} \) needs further investigation. The resulting value for \( \omega \) is around 3500 which is very low, compared to \( 10^9 \) order values, for smooth boundaries. Such \( \omega \) values belong to turbulent flow regimes. This is in contrast with the physical reality. One explanation is that the combination of rough and smooth strips on the bed affect the turbulence structure near the smooth bed. So it is possible that the viscous layer near smooth bed is perturbed by the adjacent rough strips. So, the traditional \( \omega \) values for smooth boundaries might not be suitable for this situation. Because the pressure gradient, near the bed, is absolutely different in this situation compared to only rough or only smooth bed cases. Moreover, the wall-function was originally designed for a 2-D case. Hence, the pressure gradient cased by the \( \omega \) combinations in transverse direction might have some effects on the performance of the wall function.

Figure 5.6: Comparisons of transverse velocity (W) profiles along horizontal lines, parallel to bed, across the section for S75 case. The lines are at four different levels: 1, 20, 40, 70 mm. The solid lines are model predictions and the dots are from Wang and Cheng (2006) S75 case experiment.
Figure 5.7 shows the distribution of streamwise velocities along vertical profiles at five different transverse locations along the bed. As it can be seen, the experimental data from the experiment and the numerical results from this study have very similar profiles.

Figure 5.7: Dimensionless streamwise mean velocity distribution along vertical lines at different transverse locations.

Figure 5.8 illustrates transverse bed shear stresses. The pattern of bed shear stress is very close to the pattern of experimental data. Moreover the pattern is almost the same as the pattern of bed shear stress distribution by Choi et al. (2007), except in the middle of the smooth strips. In the center of the smooth strips, a small shift can be seen in the shear stress distribution. This change can not be seen in the data by Choi et al. (2007). The sudden drop at the center of second smooth strip from left (x = 3 in figure 5.8) is due to the upwelling effect which can be seen in figure 5.11. Although the rise in the first smooth strip (at x = 1) can be due to similar effect but down-welling, it is not obvious since it has the opposite direction to the experimental data of Wang and Cheng (2005). It is suspected that the complexity of the flow at that location might cause such difference.
The pattern of secondary currents are more complex and strong near the walls.

Figure 5.8: Comparisons of transverse bed shear distribution between this study, Choi et al. (2007) numerical study and Wang and Cheng (2005)

5.3.3 Wang and Cheng (2006) S50 case

In order to validate the introduced combination for roughness values for smooth and rough strips, this study incorporated S50 case to be tested. S50 is also an experimental case study in Wang and Cheng (2006) with different configurations for the strips 5.2. Figures 5.12 and 5.13 show the comparisons of the results of present study simulations with experimental data. The comparisons
between these profiles also demonstrate good agreement with experimental velocity profiles.

5.4 Summary

The proposed value for the roughness parameter in smooth boundaries for smooth and rough strips produced excellent results for the S75 case. Nevertheless, the proposed value’s performance and its applicability should be tested and validated in other similar cases. Wang and Cheng (2006) S50 case is the benchmark in this study.

The width of the strips are different from S75 case. The purpose was to check if the results of the S50 simulation matches the experimental data. Figures 5.12 and 5.13 show the comparisons of the
Figure 5.10: Contour plots of vertical velocity; a) URANS simulation in this study; b) Wang and Cheng (2005) experimental data

results for S50 simulation case with experimental data. The results showed very good agreement between experimental and simulated data. The new combination of roughness parameter for rough and smooth strips have performed well. However, future work is needed to find more accurate relationship between configurations of the strips and patches with $\omega$ values in three dimensional flows.
Figure 5.11: Secondary current vector plot; a) URANS simulation in this study; b) Wang and Cheng (2005) experimental data
Figure 5.12: Comparisons of transverse and vertical velocity ($W$ and $V$) profiles along vertical lines across the section for the S50 case in Wang and Cheng (2006) paper. The solid lines are model predictions and the dots are from Wang and Cheng (2006) experiment. The top figure shows the result for vertical velocity profiles and the bottom figure shows the transverse velocity profiles. The solid lines are the simulated data and the dots are from Wang and Cheng (2006) S50 case experiment.
Figure 5.13: Comparisons of transverse velocity (W) profiles along horizontal lines, parallel to bed, across the section for S50 case. The lines are at four different levels: 1, 20, 40, 70 mm. The solid lines are model predictions and the dots are from Wang and Cheng (2006) S50 case experiment.
Chapter 6

Summary and Conclusion

6.1 Highlights

Accurate computation of secondary flows of second type is important in fluvial geomorphology. It affects the boundary shear distribution, flow hydrodynamics and even configuration of the boundary in erodible streams. It is also very important in calculation of sediment transport parameters such as bed shear stress, shear velocity and therefore stress balance. A new nonlinear fourth-order $k - \omega$ model is implemented in OpenFOAM® in order to simulate secondary current of second kind in open channels.

The RANS-based structure of the model make the simulations of secondary current computationally efficient. The fourth order nonlinearity of the model leads to highly accurate modelling of the Reynolds stresses terms. The model has the ability to model secondary current of second type in open channel with decent accuracy.
The $k - \omega$ formulation give the ability to implement roughness through $\omega$ boundary conditions. Wilcox (1994) introduced a wall function through which, one can correlate roughness height to $\omega$. Hellsten (2004) modified this wall function. This study implements this wall function in OpenFOAM\textsuperscript{®}. The $k - \omega$ model and the wall function were initially designed and tuned for a two-dimensional case. The correlation of roughness height to $\omega$ was under the assumption of a uniformly rough boundary with a single value of roughness height for the boundary. Under this assumption, the wall function correlates the roughness heights to expected $\omega$ values which are measured in experiments. The performance of the $k - \omega$ model and the wall function in uniformly distributed rough bed case study of Rodríguez and García (2008) was tested. The results show that the model is very capable in simulating open channel flows with rough bed and smooth walls. The number of cellular secondary currents were the same as cellular secondary currents in Rodríguez and García (2008).

In their experimental study, due to the constraint of measurements near the walls, Rodríguez and García (2008) were not able to see the bottom vortices. However, as it can be seen in figure 4.1, the numerical model could identify these vortices. Although, as expected they have very small structure compared to the corner vortex.

The streamwise velocity profiles has excellent resemblance to experimental profiles. Also, it was detected that the average shear velocity values for these profiles is 94% of the value reported in the experiment. Despite these similarities, this study observed a great difference, when comparing the shear velocity values estimated from law of the wall and the values computed directly by equation 4.3. It was concluded that the shear velocity calculated by log-law is not accurate.

In many real-world scenarios, the bed roughness is non-uniform. Most of the time this roughness is distributed in different rough or smooth patch or strips. This roughness distribution and the
secondary current of second type coexist in rivers. This study tuned the wall function for three
The proposed value for smooth boundaries roughness parameter \( k_S \), is far from what it was proposed
in the literature. This roughness height value produces quite lower values of \( \omega \), almost in the order of
\( 10^5 \). This \( \omega \) value is four order of magnitude less than what was proposed for smooth boundaries in
the literature. However, the results show to have better agreement with the experiments. This study
validated the proposed tuned value with another case (S50) of Wang and Cheng (2006) experiments.
The results of S50 case is in very good agreement with the experiment. So, it can be concluded
that although the proposed value generates \( \omega \) values four orders of magnitude less than what is
expected in the literature, in conditions with alternate rough and smooth strips, these roughness
height values generate more accurate results compared to the traditional values.

This study explains the inconsistency of the \( k_S \) value for smooth boundary from two aspects. First,
the wall functions originally proposed by Wilcox (1994) and modified by Hellsten (2004), are tested
and validated for 1-D flows. However, in the three-dimensional flow situation the proposed values
might be different as the flow is more complex in these situation.

Second, the proposed values for rough and smooth \( k_S \) were tested for situations in which only the
rough or smooth boundary existed at any time. However in rough and smooth strip cases which
they sits side by side, these values might not be appropriate. The reason is that the implementation
of these values would produce an unrealistic extra pressure gradient at the strips’ edges in the
transverse direction. This leads to higher secondary currents in the vicinity of the bed, at the edge
of adjacent strips.

The new model is capable of producing profiles of secondary velocities (V and W) in S50 and S75
cases of Wang and Cheng (2006). This is the first time a numerical model is capable of generating such profiles comparable to the experimental results. With this accuracy, one would be able to measure many turbulence structures and analyze the mechanisms behind secondary current of second type. Since the model is computationally very fast and efficient, it can be used to simulate numerous case studies with various bed configurations. This is helpful in recognizing the patterns and mechanisms in secondary currents.

### 6.2 Recommendations for Future Studies

This model should be used in studies of numerous case studies of secondary currents in open channel flows. The model should be tuned for cases with various configuration of bed roughness distributions in order to find patterns and more detailed information on the mechanism behind generation and continuation of secondary flows in open channels channel. It is recommended to investigate the effect of roughness changes, shallowness, width to depth ratio and inclination of the banks on the secondary current formations inside open channels.

Further investigation is needed for implementation of the roughness function in more realistic case studies. The function should be modified in a way to have more flexibility in deploying in more drastic changes in roughness on the bed. Also, for cases with roughness patches there might be a good contribution to adjust the model to be able to get roughness configurations in three directions.
Appendix A
OpenFOAM® Case Setup Files

A.1 Overview

This appendix provides a few number of important case setup files for the case studies in this thesis.

A.2 Boundary and Initial Condition Setup

This section demonstrate some of the boundary and initial setup method in OpenFOAM®. Due to length of dictionaries and similarity of them only a few samples of dictionaries are presented. The libraries are from (Wang and Cheng, 2006) S75 case study.

A.2.1 $U$, velocity dictionary

dimensions [0 1 -1 0 0 0 0];

internalField nonuniform List<vector>

507600

(0.0005164 -1.57494e-05 -1.50883e-05)
(0.00188583 -3.17315e-05 -7.40208e-05)
(0.00326727 -2.17473e-05 -0.000147584)
(0.0858535 6.00729e-06 6.77571e-05)
(0.0524518 3.64564e-06 -1.20506e-05)
(0.0320772 2.18708e-06 -6.20289e-05)
)
A.2.2 \( p \), pressure dictionary

dimensions \[ [0 \ 2 \ -2 \ 0 \ 0 \ 0 \ 0] \];
internalField  nonuniform List<scalar>
507600
(
0.000250559
0.000250343
0.000249237
.
.
-5.25497e-06
-4.53525e-05
-6.30699e-05
);
;
boundaryField
{
  cyc_Inlet
  {
    type cyclic;
  }
  cyc_Outlet
  {
    type cyclic;
  }
  top
  {
    type zeroGradient;
  }
  bottom-smooth
  {
    type zeroGradient;
  }
  bottom-rough
  {
    type zeroGradient;
  }
  left-wall
  {
    type zeroGradient;
  }
  right-wall
  {
    type zeroGradient;
  }
}
A.2.3  \textit{omega, \omega} dictionary

dimensions  \[0 0 -1 0 0 0 0]\;

internalField  \text{nonuniform List<scalar>}
507600
(25248.5
8584.2
2487.87
.
.
.
4580.68
16028
26370.5
)
;

boundaryField
{

cyc_Inlet
{
  type cyclic;
}
cyc_Outlet
{
  type cyclic;
}
top
{
  type omegaFreeSurface;
  value uniform 3.56433;
  H 0.02;
}
bottom-smooth
{
  type omegaRoughWallHellsten2004;
  kN 0.00075;
  value nonuniform List<scalar>
600

72
(343962
 335593
332947
.
 332919
335566
343935
)
;
  }
  bottom-rough
  {
    type omegaRoughWallHellsten2004;
    kN 0.005;
    value nonuniform List<scalar>
  810
  (80
125.186
163.756
  .
  163.714
125.155
80
)
;
  }
  left-wall
  {
    type omegaRoughWallHellsten2004;
    kN 0.00075;
    value nonuniform List<scalar>
  360
  (190668
224031
240898
  .
  .
  .
  .)
right-wall
{
    type omegaRoughWallHellsten2004;
    kN 0.00075;
    value nonuniform List<scalar>

A.3 Libraries from system Directory

A.3.1 controlDict

The controlDict dictionary provides tools to control and monitor the simulation including selecting the numerical algorithm to solve Navier-Stokes equations, selecting how simulation march in time, and setting up the output data settings.

application simpleFoam;
startFrom latestTime;
startTime 0;
stopAt endTime;
A.3.2 \textit{fvOption}

The \textit{fvOption} dictionary provides options to set physics that can be represented as sources or constraints on the governing equations. Here a sample used in this study with \texttt{pressureGradientExplicitSource} is presented.

\begin{verbatim}
momentumSource
{
    type pressureGradientExplicitSource;
    active on;  //on/off switch
    selectionMode all;  //cellSet // points //cellZone

    pressureGradientExplicitSourceCoeffs
    {

    }
}
\end{verbatim}
A.3.3 fvScheme

The fvScheme dictionary sets the numerical schemes for each term of the governing equations. Interpolation schemes are configured here. The most general fvScheme in this study is

```plaintext
fieldNames (U);
Ubar ( 0.4691 0 0 );
}
}

ddtSchemes
{
    default steadyState;
}

gradSchemes
{
    default Gauss linear;
    grad(p) Gauss linear;
    grad(U) Gauss linear;
}

divSchemes
{
    default Gauss linear;
    div(phi,U) bounded Gauss linear;
    div(phi,k) bounded Gauss limitedLinear 0.5;
    div(phi,epsilon) bounded Gauss limitedLinear 0.5;
    div(phi,omega) bounded Gauss limitedLinear 0.5;
    div(phi,R) bounded Gauss limitedLinear 1;
    div(R) Gauss linear;
    div(phi,nuTilda) bounded Gauss limitedLinear 1;
    div((nuEff*dev(T(grad(U))))) Gauss linear;
    div(nonlinearStress) Gauss linear;
}

laplacianSchemes
{
    default Gauss linear corrected;
}

interpolationSchemes
{

default    linear;
interpolate(U) linear;
}

snGradSchemes
{
    default corrected;
}

fluxRequired
{
    default no;
    p
    
}

A.3.4  fvSolution

The *fvSolution* dictionary controls the equation solvers, tolerances and algorithms.

solvers
{
    p
    {
        solver       GAMG;
tolerance    1e-08;
relTol       0.001;
smoother     GaussSeidel;
nPreSweeps   0;
nPostSweeps  2;
cacheAgglomeration true;
nCellsInCoarsestLevel 10;
agglomerator faceAreaPair;
mergeLevels  1;
    }
    pFinal
    {
        solver       GAMG;
tolerance    1e-08;
relTol       0.001;
smoother     GaussSeidel;
cacheAgglomeration true;
nCellsInCoarsestLevel 10;
    }
}
agglomerator  faceAreaPair;
mergeLevels  1;

"(U|k|omega|epsilon)"
{
solver PBiCG;
preconditioner DILU;
tolerance  1e-08;
relTol  0.001;
}

SIMPLE
{
  nNonOrthogonalCorrectors  0;
pRefCell  0;
pRefValue  0;

  residualControl
  {
    p  1e-8;
    U  1e-8;
    k  1e-8;
    omega  1e-6;
    nuTilda  1e-6;
  }

  relaxationFactors
  {
    fields
    {
      p  0.3;
    }
    equations
    {
      U  0.7;
      k  0.7;
      epsilon  0.7;
      omega  0.7;
      nuTilda  0.7;
    }
  }
}
Appendix B
Mesh Generation Scripts

This appendix presents the mesh generation utilities used in this study.

B.1  m4 script

```plaintext
dnl> <STANDARD DEFINITIONS>
dnl>
changepath(changequote([,]) dnl>
define(calc, [esyscmd perl -e 'print ($1)']) dnl>
define(VCOUNT, 0) dnl>
define(vlabel, [[// ]pt VCOUNT ($1) define($1, VCOUNT)define([VCOUNT], incr(VCOUNT))]) dnl>
define(hex2D, hex ($1i $2i $3i $4i $1o $2o $3o $4o)) dnl>
define(quad2D, ($2i $1i $1o $2o)) dnl>
define(quad2Db, ($1i $2i $2o $1o)) dnl>
define(inletQuad, ($2i $1i $4i $3i)) dnl>
define(outletQuad, ($1o $2o $3o $4o)) dnl>
dnl>
dnl> </STANDARD DEFINITIONS>
dnl>
//refine times
define(refine, 1)

define(n1, 1) dnl>
define(n2, calc(refine*45)) dnl> Number of grid points
define(n3, calc(refine*90)) dnl> Number of grid points
```
define(n4, calc(refine*38)) dnl> Number of grid points

//Defining the lengths
define(L1,0.01) dnl> //domain length in x direction dnl>
define(L2,0.3) dnl> //domain depth of the channel and width of the steps dnl>
define(L3,0.075) dnl> //domain height of the steps dnl>

//Defining the distances in each direction
define(z0,0) dnl>
define(z1,calc(L1)) dnl>
define(y0,0) dnl>
define(y1,calc(L3)) dnl>

define(x0,calc(-L2)) dnl>
define(x1,calc(-L2+(L3/2))) dnl>
define(x2,calc(-L2+(3*(L3/2)))) dnl>
define(x3,calc(-L2+(5*(L3/2)))) dnl>
define(x4,calc(-L2+(7*(L3/2)))) dnl>
define(x5,calc(L2-(7*(L3/2)))) dnl>
define(x6,calc(L2-(5*(L3/2)))) dnl>
define(x7,calc(L2-(3*(L3/2)))) dnl>
define(x8,calc(L2-(L3/2))) dnl>
define(x9,calc(L2)) dnl>

//Defining the Grading levels
define(gradingp1,10) dnl>
define(gradingp2,20) dnl>
define(gradingp3,1) dnl>

//Defining the Vertices
convertToMeters 1;
vertices

( //vertex on the inlet
  (x0 y0 z0) vlabel(a0i)
  (x1 y0 z0) vlabel(a1i)
  (x2 y0 z0) vlabel(a2i)
  (x3 y0 z0) vlabel(a3i)
  (x4 y0 z0) vlabel(a4i)
  (x5 y0 z0) vlabel(a5i)
  (x6 y0 z0) vlabel(a6i)
  (x7 y0 z0) vlabel(a7i)
)
(x8  y0  z0) vlabel(a8i)
(x9  y0  z0) vlabel(a9i)

(x0  y1  z0) vlabel(a10i)
(x1  y1  z0) vlabel(a11i)
(x2  y1  z0) vlabel(a12i)
(x3  y1  z0) vlabel(a13i)
(x4  y1  z0) vlabel(a14i)
(x5  y1  z0) vlabel(a15i)
(x6  y1  z0) vlabel(a16i)
(x7  y1  z0) vlabel(a17i)
(x8  y1  z0) vlabel(a18i)
(x9  y1  z0) vlabel(a19i)

// vertex on the outlet
(x0  y0  z1) vlabel(a0o)
(x1  y0  z1) vlabel(a1o)
(x2  y0  z1) vlabel(a2o)
(x3  y0  z1) vlabel(a3o)
(x4  y0  z1) vlabel(a4o)
(x5  y0  z1) vlabel(a5o)
(x6  y0  z1) vlabel(a6o)
(x7  y0  z1) vlabel(a7o)
(x8  y0  z1) vlabel(a8o)
(x9  y0  z1) vlabel(a9o)

(x0  y1  z1) vlabel(a10o)
(x1  y1  z1) vlabel(a11o)
(x2  y1  z1) vlabel(a12o)
(x3  y1  z1) vlabel(a13o)
(x4  y1  z1) vlabel(a14o)
(x5  y1  z1) vlabel(a15o)
(x6  y1  z1) vlabel(a16o)
(x7  y1  z1) vlabel(a17o)
(x8  y1  z1) vlabel(a18o)
(x9  y1  z1) vlabel(a19o)

);

blocks
(
    // block 0

Blocks
hex2D(a0, a1, a11, a10)
block0 ( n2 n3 n1 ) simpleGrading (gradingp1 gradingp2 gradingp3)

// block 1
hex2D(a1, a2, a12, a11)
block1 ( n4 n3 n1 ) simpleGrading (1 gradingp2 gradingp3)

// block 2
hex2D(a2, a3, a13, a12)
block2 ( n4 n3 n1 ) simpleGrading (1 gradingp2 gradingp3)

// block 3
hex2D(a3, a4, a14, a13)
block3 ( n4 n3 n1 ) simpleGrading (1 gradingp2 gradingp3)

// block 4
hex2D(a4, a5, a15, a14)
block4 ( n4 n3 n1 ) simpleGrading (1 gradingp2 gradingp3)

// block 5
hex2D(a5, a6, a16, a15)
block5 ( n4 n3 n1 ) simpleGrading (1 gradingp2 gradingp3)

// block 6
hex2D(a6, a7, a17, a16)
block6 ( n4 n3 n1 ) simpleGrading (1 gradingp2 gradingp3)

// block 7
hex2D(a7, a8, a18, a17)
block7 ( n4 n3 n1 ) simpleGrading (1 gradingp2 gradingp3)

// block 8
hex2D(a8, a9, a19, a18)
block8 ( n2 n3 n1 ) simpleGrading (calc(1.0/gradingp1) gradingp2 gradingp3)

);

edges
(
);

boundary
(

cyc_Inlet
{ 
  type cyclic;
  neighbourPatch cyc_Outlet;
  faces
    ( 
      inletQuad(a1, a0, a10, a11)
      inletQuad(a2, a1, a11, a12)
      inletQuad(a3, a2, a12, a13)
      inletQuad(a4, a3, a13, a14)
      inletQuad(a5, a4, a14, a15)
      inletQuad(a6, a5, a15, a16)
      inletQuad(a7, a6, a16, a17)
      inletQuad(a8, a7, a17, a18)
      inletQuad(a9, a8, a18, a19)
    );
}

cyc_Outlet
{
  type cyclic;
  neighbourPatch cyc_Inlet;
  faces
    ( 
      outletQuad(a1, a0, a10, a11)
      outletQuad(a2, a1, a11, a12)
      outletQuad(a3, a2, a12, a13)
      outletQuad(a4, a3, a13, a14)
      outletQuad(a5, a4, a14, a15)
      outletQuad(a6, a5, a15, a16)
      outletQuad(a7, a6, a16, a17)
      outletQuad(a8, a7, a17, a18)
      outletQuad(a9, a8, a18, a19)
    );
}

top
{
  type patch;
  faces
    ( 
      quad2D(a11, a10)
      quad2D(a12, a11)
      quad2D(a13, a12)
      quad2D(a14, a13)
      quad2D(a15, a14)
      quad2D(a16, a15)
    )
}
quad2D(a17, a16)
quad2D(a18, a17)
quad2D(a19, a18)
);
}

bottom-smooth
{
  type wall;
  faces (
    quad2D(b(a2, a1)
    quad2D(b(a4, a3)
    quad2D(b(a6, a5)
    quad2D(b(a8, a7)
  );
}

bottom-rough
{
  type wall;
  faces (
    quad2D(b(a1, a0)
    quad2D(b(a3, a2)
    quad2D(b(a5, a4)
    quad2D(b(a7, a6)
    quad2D(b(a9, a8)
  );
}

left-wall
{
  type wall;
  faces (    quad2D(a9, a19)
  );
}

right-wall
{
  type wall;
  faces (    quad2D(a10, a0)
  );
}
mergePatchPairs
(
);

B.2 The blockMesh Dictionary

The resulted OpenFOAM® dictionary from the m4 script is

//Defining the Vertices
cvtColorToMeters 1;

vertices
(
    //vertex on the inlet
    (-0.3  0  0) // pt 0 (a0i)
    (-0.2625 0  0) // pt 1 (a1i)
    (-0.1875 0  0) // pt 2 (a2i)
    (-0.1125 0  0) // pt 3 (a3i)
    (-0.0375 0  0) // pt 4 (a4i)
    (0.0375 0  0) // pt 5 (a5i)
    (0.1125 0  0) // pt 6 (a6i)
    (0.1875 0  0) // pt 7 (a7i)
    (0.2625 0  0) // pt 8 (a8i)
    (0.3  0  0) // pt 9 (a9i)

    (-0.3  0.075 0) // pt 10 (a10i)
    (-0.2625 0.075 0) // pt 11 (a11i)
    (-0.1875 0.075 0) // pt 12 (a12i)
    (-0.1125 0.075 0) // pt 13 (a13i)
    (-0.0375 0.075 0) // pt 14 (a14i)
    (0.0375 0.075 0) // pt 15 (a15i)
    (0.1125 0.075 0) // pt 16 (a16i)
    (0.1875 0.075 0) // pt 17 (a17i)
    (0.2625 0.075 0) // pt 18 (a18i)
    (0.3  0.075 0) // pt 19 (a19i)

    //vertex on the outlet
    (-0.3  0  0.01) // pt 20 (a0o)
((-0.2625  0  0.01) // pt 21 (a1o)
(-0.1875  0  0.01) // pt 22 (a2o)
(-0.1125  0  0.01) // pt 23 (a3o)
(-0.0375  0  0.01) // pt 24 (a4o)
( 0.0375  0  0.01) // pt 25 (a5o)
( 0.1125  0  0.01) // pt 26 (a6o)
( 0.1875  0  0.01) // pt 27 (a7o)
( 0.2625  0  0.01) // pt 28 (a8o)
( 0.3   0  0.01) // pt 29 (a9o)

((-0.3  0.075  0.01) // pt 30 (a10o)
(-0.2625  0.075  0.01) // pt 31 (a11o)
(-0.1875  0.075  0.01) // pt 32 (a12o)
(-0.1125  0.075  0.01) // pt 33 (a13o)
(-0.0375  0.075  0.01) // pt 34 (a14o)
( 0.0375  0.075  0.01) // pt 35 (a15o)
( 0.1125  0.075  0.01) // pt 36 (a16o)
( 0.1875  0.075  0.01) // pt 37 (a17o)
( 0.2625  0.075  0.01) // pt 38 (a18o)
( 0.3  0.075  0.01) // pt 39 (a19o)
);

blocks
{
   // block 0
   hex (0 1 11 10 20 21 31 30)
   block0 ( 45 90 1 ) simpleGrading (10 20 1)

   // block 1
   hex (1 2 12 11 21 22 32 31)
   block1 ( 38 90 1 ) simpleGrading (1 20 1)

   // block 2
   hex (2 3 13 12 22 23 33 32)
   block2 ( 38 90 1 ) simpleGrading (1 20 1)

   // block 3
   hex (3 4 14 13 23 24 34 33)
   block3 ( 38 90 1 ) simpleGrading (1 20 1)

   // block 4
   hex (4 5 15 14 24 25 35 34)
   block4 ( 38 90 1 ) simpleGrading (1 20 1)

   86
// block 5
hex (5 6 16 15 25 26 36 35)
block5 ( 38 90 1 ) simpleGrading (1 20 1)

// block 6
hex (6 7 17 16 26 27 37 36)
block6 ( 38 90 1 ) simpleGrading (1 20 1)

// block 7
hex (7 8 18 17 27 28 38 37)
block7 ( 38 90 1 ) simpleGrading (1 20 1)

// block 8
hex (8 9 19 18 28 29 39 38)
block8 ( 45 90 1 ) simpleGrading (0.1 20 1)

);

boundary
{

cyc_Inlet
{

type cyclic;
neighbourPatch cyc_Outlet;
faces
(0 1 11 10)
(1 2 12 11)
(2 3 13 12)
(3 4 14 13)
(4 5 15 14)
(5 6 16 15)
(6 7 17 16)
(7 8 18 17)
(8 9 19 18)
);
}

cyc_Outlet
{

type cyclic;
neighbourPatch cyc_Inlet;
faces

(21 20 30 31)
(22 21 31 32)
(23 22 32 33)
(24 23 33 34)
(25 24 34 35)
(26 25 35 36)
(27 26 36 37)
(28 27 37 38)
(29 28 38 39)
);

top
{
  type patch;
  faces
  (
    (10 11 31 30)
    (11 12 32 31)
    (12 13 33 32)
    (13 14 34 33)
    (14 15 35 34)
    (15 16 36 35)
    (16 17 37 36)
    (17 18 38 37)
  )
bottom-smooth
{
  type wall;
  faces ( 
    (2 1 21 22)
    (4 3 23 24)
    (6 5 25 26)
    (8 7 27 28)
  );
}

bottom-rough
{
  type wall;
  faces ( 
    (1 0 20 21)
    (3 2 22 23)
    (5 4 24 25)
    (7 6 26 27)
left-wall
{
  type wall;
  faces ( (19 9 29 39) );
}

right-wall
{
  type wall;
  faces ( (0 10 30 20) );
}

mergePatchPairs
(
);

B.3 Mesh View From Paraview
Figure B.1: View of generated mesh for S75 case study in *paraview.*


Francis, J. B. (1878). On the cause of the maximum velocity of water flowing in open channels being below the surface. *Trans. ASCE*.


