CHARACTERISTICS OF DENSITY CURRENT DYNAMICS OVER ROUGH CHANNEL BEDS

REZA NASROLLAHPOUR

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

APRIL 2018

This dissertation is dedicated to my beloved parents.

ACKNOWLEDGEMENT

First and foremost, my sincere gratitude goes to my supervisor Dr Mohamad Hidayat Bin Jamal for the guidance, understanding and encouragement throughout these years. I am thankful to him for giving me the opportunity to work under his supervision. I would also like to thank my co-supervisor Dr Zulhilmi Bin Ismail for his help in different aspects of this work.

I am grateful to all the staff at the Laboratory of Hydraulic and Hydrology, Faculty of Civil Engineering for their help during the experimental phase of this work. My special gratitude also goes to Amirul Mustakim Bin Ros, Muhammad Ali Hadi Bin Zakaria and Abdul Qayyum Bin Che Rahim who assisted me in performing the laboratory experiments.

I appreciate the Ministry of Education, Malaysia for the funding the experimentations via the Fundamental Research Grant Scheme (reference number: 4F687). The support of Universiti Teknologi Malaysia through the Research University Grant (reference number: 09H06) is also appreciated.

I thank my friends for their company and my officemates for their comforting words and motivation. Lastly, but by no means least, I take this opportunity to express my sincere gratitude towards my parents. This would have been impossible without their support, care and love.

ABSTRACT

Density currents occur in a variety of natural and man-made scenarios, and this emphasises the importance of studying them. The density-driven currents are the main agent for sediment transportation in many dam reservoirs. In most cases, these currents flow over surfaces which are not smooth; nevertheless, the effect of bottom roughness on the body of these currents has not been fully understood. Hence, this study mainly aims to examine the structure of density currents propagating over rough beds. To achieve this, alterations in the velocity and concentration profiles of the density currents in the presence of different bottom roughness configurations are investigated. The influence of various bottom roughness configurations on entrainment of ambient fluid into these currents is also quantified. Initially, laboratory experiments were carried out with density currents flowing over a smooth surface to analyse the dynamics of the currents with a range of experimental conditions; this provided a baseline for comparison. Then, seven bed roughness configurations (λ/K_r=1, 4, 8, 16, 32, 64 and 128 where λ denotes the downstream spacing between each two subsequent roughness elements and K_r denotes the roughness height) were chosen to encompass both dense and sparse bottom roughness. The rough beds consisted of square cross-section beams which cover the full channel width and are perpendicular to the flow direction in a repeated array. The primary results of this research reveal that the bottom roughness causes deceleration of the currents, reduction of their excess densities and enhancement of water entrainment into them. A critical spacing of the roughness elements (λ/K_r=8) is found for which the currents demonstrate the lowest velocities. For the spacings which are more than the critical value, the controlling influence of the roughness is reduced, and the velocities are increased by expanding the cavities between the elements. The rough bed with λ/K_r=128 roughness has very little influence on the currents and maintained velocities resembling those of the smooth bed. The magnitude of the entrainment rates also varies depending on the roughness configurations with the most substantial entrainment rate occurring for the λ/K_r=8, which is 5.26 times higher than that of the plane surface. Using dimensional analysis, equations are proposed for estimating the mean velocities of the currents and their entrainment rates for various configurations of the bottom roughness. The findings of this research contribute towards a better parameterisation and improved knowledge of density currents flowing over non-plane surfaces. This can lead to a better prediction of the evolution of these currents in many practical cases as well as improved planning and design measures related to the control of such currents.

ABSTRAK

Arus ketumpatan berlaku dalam pelbagai senario semula jadi dan buatan manusia dan ini menegaskan kepentingan kajian ini dijalankan. Arus didorong ketumpatan adalah agen utama untuk aliran sedimen dalam kebanyakan takungan empangan. Dalam kebanyakan kes, aliran ketumpatan mengalir pada permukaan yang tidak rata; namun begitu, kesan kekasaran dasar pada badan arus ini belum difahami dengan mendalam lagi. Sehubungan itu, tujuan utama kajian ini adalah untuk mengkaji struktur arus ketumpatan yang mengalir pada permukaan dasar yang kasar. Bagi mencapai tujuan ini, perubahan yang berlaku pada halaju dan profil kepekatan arus dengan adanya konfigurasi kekasaran dasar yang berbeza telah disiasat. Pengaruh bentuk kekasaran dasar yang berbeza terhadap kemasukan bendalir ambien ke dalam arus ini juga telah dinilai. Pada mulanya, ujikaji makmal dijalankan dengan arus ketumpatan yang mengalir pada permukaan yang licin untuk menganalisis dinamika arus dengan pelbagai keadaan kajian; ini menjadi asas panduan untuk perbandingan. Seterusnya, tujuh konfigurasi kekasaran dasar (λ/K_r=1, 4, 8, 16, 32, 64 dan 128 di mana λ menunjukan jarak antara setiap dua elemen kekasaran berturutan dan K_r menandakan ketinggian kekasaran) yang dipilih merangkumi kerapatan dan kerenggangan kekasaran dasar. Kekasaran dasar terdiri daripada rasuk segiempat sama yang merentangi kelebaran saluran dan bersudut tepat dengan arah aliran secara berturutan. Hasil utama kajian ini menjelaskan bahawa kekasaran dasar menyebabkan berlakunya nyahpecutan arus, pengurangan ketumpatan berlebihan dan peningkatan kemasukan air ke dalamnya. Jarak kritikal (λ/K_r=8) elemen kekasaran yang diperolehi menunjukkan arus dengan halaju paling rendah. Untuk jarak elemen lebih daripada nilai kritikal, pengaruh kekasaran dasar berkurang dan halaju meningkat dengan pertgmbahan lagi jarak elemen kekasaran tersebut. Kekasaran dasar dengan λ/K_r=128 mempunyai pengaruh yang sangat sedikit pada arus dan hampir menyerupai keadaan arus pada dasar licin. Magnitud kadar kemasukan juga berubah bergantung kepada konfigurasi kekasaran dengan kadar kemasukan yang paling tinggi berlaku pada λ/K_r=8, yang mana 5.26 kali ganda lebih tinggi daripada permukaan licin. Dengan menggunakan analisis dimensi, persamaan telah dicadangkan untuk menganggar halaju purata arus dan kadar kemasukan untuk pelbagai jenis konfigurasi kekasaran dasar. Hasil kajian ini menyumbang kepada parameterisasi yang lebih baik dan meningkatkan pengetahuan berkenaan arus ketumpatan yang mengalir pada permukaan dasar yang tidak licin. Ini membawa kepada ramalan yang lebih baik tentang evolusi arus ini dalam pelbagai kes dan juga memperbaiki perancangan dan reka bentuk yang berkaitan dengan kawalan arus tersebut.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

b	-	Width of the channel
c	-	Concentration at depth z above the bed
$\bar{c}$	-	Depth-averaged concentration of the current
C_D	-	Drag coefficient
C_{in}	-	Initial Concentration of dense fluid
C_m	-	Concentration where maximum velocity occurs
D_b	-	Deposition rate to the bed
E	-	Error
E_b	-	Erosion rate of bed materials
Ed	-	Excess density at distance z above the bed
Ed_{av}	-	Average excess density of the current
E_w	-	Water entrainment rate into the current
Fr_{in}	-	Inlet Froude number
g	-	Gravitational acceleration
g'	-	Reduced gravitational acceleration
$\bar{h}$	-	Depth-averaged height of the current
h_a	-	Height of ambient fluid
h_d	-	Distance above the bed where velocity is zero
h_f	-	Height of the front
h_{in}	-	Inlet gate opening height
h_m	-	Distance above the bed where maximum velocity occurs
K	-	Von Karman constant
k_r	-	Height of roughness elements
OP	-	Outflow pipe

Q_{in}	-	Inflow discharge
q_{in}	-	Inflow discharge per unit width
R^2	-	Coefficient of determination
Re_{in}	-	Inlet Reynolds number
Ri	-	Richardson number
S	-	Bed slope
S_1	-	Data collection station 1
S_2	-	Data collection station 2
S_3	-	Data collection station 3
u	-	Velocity at depth z above the bed
$\bar{u}$	-	Depth-averaged velocity of the current
u*	-	Shear velocity
u_a	-	Velocity of ambient fluid
u_f	-	Velocity of front
u_{in}	-	Velocity of the current at inlet
u_m	-	Maximum velocity of the current
u_O	-	Velocities yielded from the observed data at the experiments
u_P	-	Velocities predicted by the proposed relationships
W_e	-	Entrainment velocity
X	-	Distance from the inlet gate
z	-	Distance above the bed
z_0	-	Zero velocity roughness height
ρ_a	-	Density of ambient fluid
ρ_d	-	Density at depth z above the bed
$\overline{\rho_d}$	-	Average density of the current
ρ_{in}	-	Initial density of the current
Θ	-	Bed slope angel
Π	-	Dimensionless number
τ	-	Bottom shear stress
μ_d	-	dynamics viscosity of the dense fluid at the inlet

ν_{in}	-	Kinematic viscosity of dense fluid at inlet
ν	-	Kinematic viscosity of water
λ	-	Streamwise spacing between roughness elements
λ/K_r	-	Roughness parameter

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Problem

Density currents are generated when the fluid of one density is released into another fluid with a different density. These currents can be created even by a small density difference of only a few percents. The density difference can result from temperature gradients, dissolved contents, suspended particles or a combination of them. These currents are known as turbidity currents in the case where the main driving mechanism is obtained from suspended sediments.

Density currents occur in many natural and man-made environments. These currents can form in different ways depending on the density of the current and that of the ambient fluid. The most usual type of these currents is an underflow produced when a flow is introduced into an ambient fluid of a lower density. An overflow can be generated if the flow is lighter than the ambient fluid. An interflow can be created between two density-stratified fluids if the current's density is of an intermediate value. The following examples of density currents can make the relevance of this study clear.

In the atmosphere, density currents usually develop in the form of large-scale atmospheric movements (Figure 1.1) and thunderstorm outflows. Sea breeze fronts are another type of atmospheric density currents driven by differences in temperature between two air masses. In this case, a density current formed by cooler sea air passes into air heated by land, which is typically associated with the presence of suspended dust and insects (Neufeld, 2002). Avalanches are a devastating form of density current affecting mountainous areas, resulting from suspension of ice, snow, rock or soil suspension in water (mudflows). Volcanic activities can also create atmospheric density currents in the form of volcanic ash flows and pyroclastic density currents (Capra et al., 2016; Johnson et al., 2015).

Figure 1.1 A huge cold, dusty air mass (Karamzadeh, 2004)

Density currents are also found in a variety of industrial environments. For example, accidental release of dense gases which are heavier than air. In case of the leakage, the gases can travel quickly in the form of density currents through mine shafts, which might be poisonous, suffocating or explosive (Peters, 1999). Knowing dynamics of these currents is vital for proper ventilation and safety purposes. Oil slicks are another form of industrial density current, which might result in severe and wide-spread environmental impacts. Regulating the transport and cleaning up of these dangerous materials requires studying of density currents. Other examples include propagation of smoke or heat in buildings and discharge of sewage or power plant cooling water from an outlet pipe into the rivers and sea.

In oceanic and river systems, such currents occur because some of the water in an estuary, ocean or lake is colder, saltier or contains more suspended sediment and hence is denser than the surrounding water (Nogueira et al., 2014). The turbid water from the incoming rivers can make turbidity currents at the mouth of estuaries, as seen in Figure 1.2. The density difference between saline oceanic water and fresh river water can create salt wedges (Ismail et al., 2016) and river plumes (Stashchuk and Hutter, 2003). Also, earthquakes can trigger massive suspensions of organic material and sediments leading to underwater turbidity currents. The creation of many deep valleys has been attributed to these currents (Li et al., 2012). These flows are the primary sediment transport mechanism in deep submarine canyons (Lai et al., 2016), travelling long distances and transforming the topography of ocean floor (Stagnaro and Pittaluga, 2014).

Figure 1.2 Turbid inflows from a river plunging under seawater in an estuary (Ghomeshi, 2012)

Reservoir sedimentation is a worldwide issue hindering the sustainable use of reservoirs and the sediment balance of impacted rivers (Chamoun et al., 2017). In dam reservoirs, turbidity currents are believed to be responsible for sediment transport and subsequently effecting the dam’s operation (Asghari Pari et al., 2016; Cesare et al., 2001).

Many countries are stricken by several major flood events during intense rainfall season. In Malaysia, during the monsoon season, large parts of the country experience intense rainfalls causing prolonged flooding. Sediment discharge of rivers flowing into dam reservoirs is typically very high during flood events (Diman and Tahir, 2012). This can induce turbidity currents in the reservoirs which are a major mechanism for sediment transport.

When the turbid flood flows to freshwater of the reservoir, the turbid inflow displaces the ambient water until it reaches a balance of forces plunging under the water surface, as shown in Figure 1.3. This region is named plunge point and is typically located downstream area of delta deposition in reservoirs (Lai et al., 2015). The plunging flow causes a weak counter current making the clear water move toward it (Schleiss et al., 2016). After that, a turbidity current is formed advancing over the reservoir bed through its leading edge known as the head that is deeper than the following flow. The shallower source layer forms the body of these currents. The surface water is muddy up to the plunge area and clear after that.

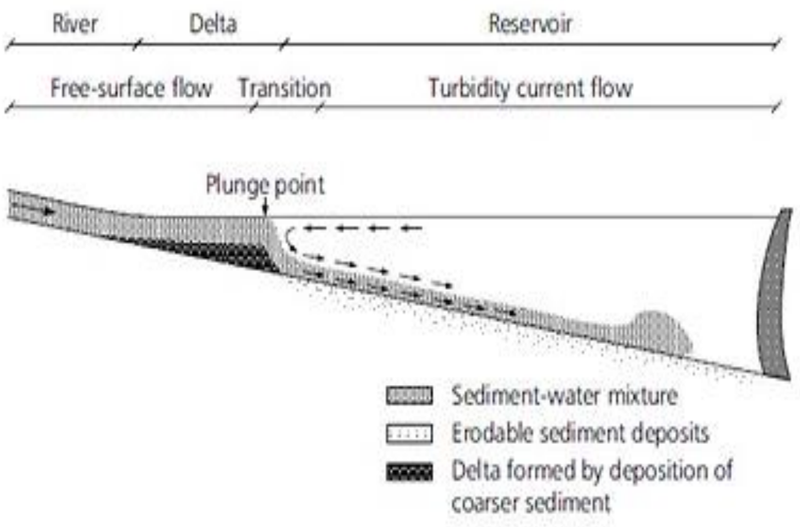

Figure 1.3 Turbid inflow entering a reservoir, plunging and creating a turbidity current which transports the incoming suspended sediments and erodible sediments to the area near the dam (Oehy, 2003)

The general approach for density current studies have been simplifying the situation by regarding the bed as smooth. However, the sea floor and avalanche path are not smooth. A cold front can occur over a variety of terrains. In case of heavier than air gas release, the density current interacts with the environment where the surface might not be smooth. Turbidity currents travelling over reservoir beds interact with a variety of topographic features. Besides, to control turbidity currents in reservoirs, it is vital to understand the impact of barriers to stop, divert or dilute these currents. This work intends to extend previous studies by considering the effect of bottom roughness on these currents.

1.2 Statement of the Problem

Density currents occur commonly in numerous natural and man-made scenarios. These currents have been actively studied to improve understanding of their processes and dynamics. Most of the works regard the case of density currents flowing over smooth beds, for example, Altinakar et al. (1996), Firoozabadi et al. (2009), Hosseini et al. (2006), Islam and Imran (2010), Khavasi et al. (2012), Kneller et al. (1999), Nourmohammadi et al. (2011), Cossu and Wells (2012) and Cortés et al. (2014).

In practical cases, these currents usually flow over the beds which are not smooth. This involves mobile beds, obstacles, grain roughness (e.g. sand or gravel) and form roughness (e.g. ripples or dunes). The behaviour of density currents flowing over non-plane beds is complex and not yet fully understood.

In nature, density currents usually travel over loose beds that are not plane. Bedforms can be found in the river beds and seafloors as ripples, dunes or anti-dunes. The bed forms provide additional energy dissipation mechanism largely affecting water entrainment and sediment transport capacity of these currents compared to the case of the plane surface (Tokyay, 2010). However, not much is known about the interaction of density currents with the bed over which they travel, in particular regarding the body of these currents.

There have been limited investigations in respect with the effect of form roughness on density currents, including Negretti et al. (2008), Peters (1999), Tanino et al. (2005), Tokyay (2010), Chowdhury (2013) and Bhaganagar (2014). However, these works have been focused on the frontal region of the currents, and understanding of bottom roughness impacts on the body of these currents is still lacking.

There is still a gap in knowledge on the interaction between arrays of roughness elements and density currents. This type of roughness can be a representative of various natural scenarios where density currents flow over non-plane beds. Therefore, there is a need to investigate adjustments in the structure of these currents encountering roughness arrays. This can contribute toward explaining the evolution of these currents over rough beds, which is of significant concern in many engineering areas due to its impact on the environment.

Turbidity currents carry the incoming suspended sediments and existing sediment deposits over the reservoir bed to the area near the dam. The turbidity currents decelerate as approaching the dam and thus the sedimentation occurs. The loss of storage capacity in dam reservoirs due to sedimentation caused by turbidity currents has been an issue of great concern and a topic of research (Fan and Morris, 1992a; Guo et al., 2011; Kostic and Parker, 2003; Xiao et al., 2015). Different measures have been studied for controlling sedimentation in reservoirs by Fan and Morris (1992b). Several mitigation measures have been investigated such as placement of obstacle (Asghari Pari et al., 2016; Oehy and Schleiss, 2007; Oshaghi et al., 2013; Yaghoubi et al., 2017) and jets (Bühler et al., 2012; Oehy et al., 2010). However, most of the literature concerns the case of density currents encountering an isolated (single) roughness element or obstacle.

The impact of bottom roughness on the reservoir sedimentation due to density currents is an important research area. Employing roughness arrays can have many engineering applications regarding control of density currents. In dam reservoirs, turbidity currents are often responsible transport mechanism for suspended sediments (Cao et al., 2015). They mainly cause redistribution of the sediments within reservoirs through entraining sediment particles and carrying them to the deepest area of the reservoirs. This study can also contribute to planning and design measures related to the reservoir sedimentation management.

1.3 Objectives of the Study

The main aim of this research is to provide a better understanding of the structure of density currents propagating over different rough beds. This study is carried out to achieve the following objectives:

i. To examine the influence of different experimental conditions on the dynamics of density currents flowing over a smooth surface.

ii. To acquire the vertical structure of streamwise velocities within the body of density currents, and to investigate alterations in the velocity profiles of the currents in the presence of various bed roughness configurations

iii. To obtain the vertical structure of concentration within the body of density currents, and to analyse adjustments in the concentration profiles of the currents flowing over different bottom roughness configurations.

iv. To quantify the effect of different configurations of bottom roughness on entrainment of ambient fluid into the density currents.

1.4 Scope of the Study

Different types of density currents occur in natural and industrial environments, which have been studied by scientists of various disciplines. The scope of the present study is summarised herein.

This laboratory study uses experiments to investigate two-dimensional density currents. The essential features of density currents can be well described through a two-dimensional approach. This research focuses on saline density currents in which dissolved salt is used to create dense fluids. Dye is added to the dense fluids for visibility purposes.

A lock-exchange configuration is employed herein, in which there is a gate separating two fluids with different densities. Initially, the denser lock fluid occupies the volume between the rear wall and the lock gate. The sudden removal of the vertical lock gate generates currents containing heavier fluid propagating within the lighter ambient water as an underflow.

The case of roughness elements at the channel bed is investigated herein. Particularly, this work considers the interaction of density currents with bottom roughness. The rough beds include different configurations of the beam-roughened surfaces. The bed roughness consists of repeated arrays of square cross-section beams, spanning the full channel width and extending along a laboratory channel.

A complete interpretation regarding the influence of bottom roughness on these currents requires analysing the sustained flow (i.e. body) of these currents which is the focus of this experimental research. The continuous-flux density currents are used herein, where there is a continuous supply of intruding dense fluid into the receiving ambient fluid.

1.5 Significance of Research

A wide range of flows are classified as density currents, and it emphasises the importance of studying them. The interaction of density currents with submarine installations (for example porous screens, dykes, oil and gas pipelines, cables) can lead to disastrous damages (Blanchette et al., 2005; Perez-Gruszkiewicz, 2011). A natural turbidity current was captured in Fraser River delta slope (Canada) that was powerful enough to carry a one-tonne observatory platform and sever a heavily armoured cable (Lintern et al., 2016). Theses can justify investigating the interaction of these currents with roughness elements.

One important class of applications is the interaction of the currents with arrays of roughness elements. Natural occurrences of this case include propagation of these currents over a layer of vegetation (e.g. grass, marine plants and trees), and dense gases advancing through wooded or build up zones and turbidity currents travelling over the bottom of reservoirs interacting with a variety of topographic features. In this context, the present research can contribute toward an explanation of the dynamics of density currents in many man-made and natural scenarios. This leads to a better entrainment parametrisation and improved knowledge of mixing in these currents flowing over non-plane surfaces.

Density currents in the form of powder-snow avalanches have been responsible for severe damage to towns situated at the foot of steep slopes (Jóhannesson, 1996). Arrays of barriers can also be used as protective measures on hilly grounds and skirt of the mountains to decelerate powder-snow avalanches (Hopfinger, 1983). Likewise, defence structures (e.g. baffle blocks) can be employed to slow down density currents in rivers.

Density-driven currents are of significant concern as a governing mechanism for reservoir sedimentation. Turbidity currents are the main transport mechanism for the incoming sediments and that they play a vital role in the redistribution of sediments within dam reservoirs through entrainment and deposition of sediments (Hsu et al., 2017). Reservoir sedimentation can block bottom outlets, reduce the capacity of the reservoir and harms the dam power plants (Schleiss et al., 2016). In addition, some environmental problems can be posed by the reservoir sedimentation, for example, its influences on water quality and aquatic life and nutrient supply at the downstream (Ghomeshi, 1995).

The mean yearly loss of reservoirs' storage volume due to sediment deposition is more than increasing volume due to building new dam reservoirs (Oehy, 2003), and the long-term sustainable use of reservoirs is seriously challenged (Batuca and Jordaan Jr, 2000; Chamoun et al., 2017). Annually, 0.5 to 1% of the global storage capacity of dam reservoirs is estimated to be lost due to sedimentation (Basson, 2009). For instance, in Asia, 80% of the useful storage volumes for hydropower production will be lost in 2035, and 70% of the storage capacity used for irrigation will be lost due to sedimentation in 2025 (Basson, 2009). Also, reservoirs in China and Switzerland were reported to have a mean annual loss in their storage capacity of 2.3% (Wang and Chunhong, 2009) and 0.2% (Beyer Portner, 1998), respectively. This means that the reservoirs are non-sustainable and mitigation measures are urgently needed.

Nowadays, the loss of storage capacity of dams is an issue of concern in Malaysia (Luis et al., 2013a). For example, the dead storage for Ringlet Reservoir in Cameron Highland, Malaysia was designed for a useful lifespan of nearly 80 years translating to 20,000 m^3/year of sediment inflow. The sedimentation rate in 1965 was estimated 25,000 m^3/year (Choy and Mohamad, 1990). However, this increased to an average of approximately six folds reaching to 139,712 m^3/year in 2008 (Teh, 2011). An analysis of this reservoir's sedimentation by Luis et al. (2013b) revealed that 34% of the reservoir capacity was taken up in just 35 years of the dam operation. This has left the reservoir with a balance lifespan of 10 years.

To date, most of the focus has been on measures for getting rid of the existing sediment deposits, including allowing dead storage, sediment flushing, hydrosuction removal systems, dredging and heightening of the dam (Wild et al., 2016). Such measures usually provide only short-term solutions and are costly and complicated in terms of implementation. Tackling sedimentation problem and improving reservoir operation requires controlling turbidity currents in dam reservoirs (Fan and Morris, 1992b).

This research studies the interaction of density currents with arrays of roughness elements. Stopping turbidity currents in reservoirs or influencing them in a way that the sediments are not deposited in important zones (e.g. in front of water intake structures and bottom outlets) increases the sustainability of reservoir operation significantly (Asghari Pari et al., 2016; Bühler et al., 2012). Findings of this work can contribute to an enhanced prediction and dealing with control of these currents using arrays of barriers. This can lead to decreasing maintenance costs and increasing useful lifetime of dams and therefore improved reservoir management practices.

All in all, the study of density currents over non-plane surfaces and subsequent increased understanding of this phenomena, have obvious considerable benefits for human and environmental safety purposes and accurate management of various industrial and natural scenarios.

1.6 Thesis Organisation

This thesis structures as follows. In Chapter 1, an introduction is provided on this study involving problem statement, research objectives and scopes and the significance of this experimental laboratory research. The main physical characteristics of density currents are presented in Chapter 2, and the literature regarding dynamics of these currents flowing over different terrains. This covers plane and non-plane surfaces with the emphasis on the effects of roughness arrays on the currents. In Chapter 3, the experimental set-up and measuring facilities are explained. The experiments are described that provide quantitative knowledge in regard to density currents propagating over arrays of roughness. In Chapter 4, the results of the performed experiments concerning the velocity structure of the currents are provided and discussed. In Chapter 5, the experimental findings on concentration structure within the body of density currents and water entrainment into these currents are discussed. In Chapter 6, conclusions of the present study are drawn, and recommendations for future works are presented.

REFERENCES

Abad, J. D., Sequeiros, O. E., Spinewine, B., Pirmez, C., Garcia, M. H., and Parker, G. (2011). Secondary current of saline underflow in a highly meandering channel: experiments and theory. *Journal of Sedimentary Research*, 81(11), 787-813.

Adduce, C., Lombardi, V., Sciortino, G., and La Rocca, M. (2010). Laboratory experiments on gravity currents moving on smooth and rough beds. Paper presented at the *River Flow*, Braunschweig, Germany, 605-611.

Adduce, C., Lombardi, V., Sciortino, G., and Morganti, M. (2009). Roughness effects on gravity currents dynamics. Paper presented at the *the Proceedings of the 33rd IAHR Congress, Canada*.

Adduce, C., Sciortino, G., and Proietti, S. (2011). Gravity currents produced by lock exchanges: Experiments and simulations with a two-layer shallow-water model with entrainment. *Journal of Hydraulic Engineering*, 138(2), 111-121.

Alavian, V., Jirka, G. H., Denton, R. A., Johnson, M. C., and Stefan, H. G. (1992). Density currents entering lakes and reservoirs. *Journal of Hydraulic Engineering*, 118(11), 1464-1489.

Altinakar, M., Graf, W., and Hopfinger, E. (1996). Flow structure in turbidity currents. *Journal of Hydraulic Research*, 34(5), 713-718.

Amy, L., Peakall, J., and Talling, P. (2005). Density-and viscosity-stratified gravity currents: Insight from laboratory experiments and implications for submarine flow deposits. *Sedimentary Geology*, 179(1), 5-29.

An, S., and Julien, P. Y. (2014). Three-dimensional modeling of turbid density currents in Imha Reservoir, South Korea. *Journal of Hydraulic Engineering*, 140(5), 05014004.

Asghari Pari, S. A., Kashefipour, S. M., and Ghomeshi, M. (2016). An experimental study to determine the obstacle height required for the control of subcritical and supercritical gravity currents. *European Journal of Environmental and Civil Engineering*, 1-13.

Ashrafian, A., Andersson, H. I., and Manhart, M. (2004). DNS of turbulent flow in a rod-roughened channel. *International Journal of Heat and Fluid Flow,* 25(3), 373-383.

Basani, R., Janocko, M., Cartigny, M. J., Hansen, E. W., and Eggenhuisen, J. T. (2014). MassFLOW-3DTM as a simulation tool for turbidity currents. *From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin*, 587-608.

Basson, G. (2009). Management of siltation in existing and new reservoirs. General Report Q. 89. Paper presented at the *23rd Congress of the CIGB-ICOLD, Brasilia, Brazil*.

Batt, R. L. (2008). *The influence of bed roughness on the dynamics of gravity currents.* University of Leeds.

Batuca, D. G., and Jordaan Jr, J. (2000). *Silting and desilting of reservoirs*: CRC Press.

Best, J., Kirkbride, A., and Peakall, J. (2001). Mean Flow and Turbulence Structure of Sediment-Laden Gravity Currents: New Insights using Ultrasonic Doppler Velocity Profiling. *Particulate Gravity Currents*, 157-172.

Beyer Portner, N. (1998). *Erosion des bassins versants alpins suisses par ruissellement de surface.* École Polytechnique Fédérale de Lausanne. Switzerland.

Bhaganagar, K. (2014). Direct numerical simulation of lock-exchange density currents over the rough wall in slumping phase. *Journal of Hydraulic Research,* 52(3), 386-398.

Birman, V., Martin, J., and Meiburg, E. (2005). The non-Boussinesq lock-exchange problem. Part 2. High-resolution simulations. *Journal of Fluid Mechanics,* 537, 125-144.

Blanchette, F., Strauss, M., Meiburg, E., Kneller, B., and Glinsky, M. E. (2005). High-resolution numerical simulations of resuspending gravity currents: Conditions for self-sustainment. *Journal of Geophysical Research: Oceans,* 110(C12).

Breard, E. C., and Lube, G. (2017). Inside pyroclastic density currents–uncovering the enigmatic flow structure and transport behaviour in large-scale experiments. *Earth and Planetary Science Letters,* 458, 22-36.

Bühler, J., Oehy, C., and Schleiss, A. (2012). Jets Opposing Turbidity Currents and Open Channel Flows. *Journal of Hydraulic Engineering,* 139(1), 55-59.

Bühler, J., Oehy, C., and Schleiss, A. (2013). Jets Opposing Turbidity Currents and Open Channel Flows. *Journal of Hydraulic Engineering,* 139(1), 55-59.

Cantero-Chinchilla, F. N., Dey, S., Castro-Orgaz, O., and Ali, S. Z. (2015). Hydrodynamic analysis of fully developed turbidity currents over plane beds based on self-preserving velocity and concentration distributions. *Journal of Geophysical Research: Earth Surface,* 120(10), 2176-2199.

Cao, Z., Li, J., Pender, G., and Liu, Q. (2015). Whole-process modeling of reservoir turbidity currents by a double layer-averaged model. *Journal of Hydraulic Engineering,* 141(2), 04014069.

Capra, L., Macías, J., Cortés, A., Dávila, N., Saucedo, R., Osorio-Ocampo, S., et al. (2016). Preliminary report on the July 10–11, 2015 eruption at Volcán de Colima: Pyroclastic density currents with exceptional runouts and volume. *Journal of Volcanology and Geothermal Research,* 310, 39-49.

Cesare, G. D., Schleiss, A., and Hermann, F. (2001). Impact of turbidity currents on reservoir sedimentation. *Journal of Hydraulic Engineering,* 127(1), 6-16.

Chamoun, S., De Cesare, G., and Schleiss, A. J. (2016). Managing reservoir sedimentation by venting turbidity currents: A review. *International Journal of Sediment Research,* 31(3), 195-204.

Chamoun, S., De Cesare, G., and Schleiss, A. J. (2017). Venting of turbidity currents approaching a rectangular opening on a horizontal bed. *Journal of Hydraulic Research,* 1-15.

Chen, G., Fang, X., and Devkota, J. (2016). Understanding flow dynamics and density currents in a river-reservoir system under upstream reservoir releases. *Hydrological Sciences Journal,* 61(13), 2411-2426.

Choi, S.-U., and Garc ı´ a, M. H. (2002). k-ε turbulence modeling of density currents developing two dimensionally on a slope. *Journal of Hydraulic Engineering,* 128(1), 55-63.

Chowdhury, R. A. (2013). *Effect of roughness on density currents.* Master Thesis. The University Of Texas at San Antonio. USA.

Choy, F. K., and Mohamad, F. (1990). Cameron Highlands Hydro Electric Scheme–The Sedimentation Problems. Paper presented at the *Seminar on Hydro Power and Flood Mitigation Projects Without Dams: Prospects and Issues*.

Cortés, A., Rueda, F., and Wells, M. (2014). Experimental observations of the splitting of a gravity current at a density step in a stratified water body. *Journal of Geophysical Research: Oceans,* 119(2), 1038-1053.

Cossu, R., and Wells, M. G. (2012). A comparison of the shear stress distribution in the bottom boundary layer of experimental density and turbidity currents. *European Journal of Mechanics-B/Fluids,* 32, 70-79.

Dai, A. (2013). Experiments on gravity currents propagating on different bottom slopes. *Journal of Fluid Mechanics,* 731, 117-141.

Dallimore, C. J., Imberger, J., and Ishikawa, T. (2001). Entrainment and turbulence in saline underflow in Lake Ogawara. *Journal of Hydraulic Engineering,* 127(11), 937-948.

Diman, C. P., and Tahir, W. (2012). Dam Flooding Caused A Prolonged Flooding. *International Journal of Civil & Environmental Engineering IJCEE-IJENS,* 12(06), 71-75.

Edwards, D., Leeder, M., Best, J., and Pantin, H. (1994). On experimental reflected density currents and the interpretation of certain turbidites. *Sedimentology,* 41(3), 437-461.

Eggenhuisen, J. T., and Mccaffrey, W. D. (2012). The vertical turbulence structure of experimental turbidity currents encountering basal obstructions: implications for vertical suspended sediment distribution in non-equilibrium currents. *Sedimentology,* 59(3), 1101-1120.

Ellison, T., and Turner, J. (1959). Turbulent entrainment in stratified flows. *Journal of Fluid Mechanics,* 6(03), 423-448.

Ermanyuk, E., and Gavrilov, N. (2005a). Interaction of an internal gravity current with a submerged circular cylinder. *Journal of applied mechanics and technical physics,* 46(2), 216-223.

Ermanyuk, E., and Gavrilov, N. (2005b). Interaction of internal gravity current with an obstacle on the channel bottom. *Journal of applied mechanics and technical physics,* 46(4), 489-495.

Ezz, H., Cantelli, A., and Imran, J. (2013). Experimental modeling of depositional turbidity currents in a sinuous submarine channel. *Sedimentary Geology,* 290, 175-187.

Fan, J., and Morris, G. L. (1992a). Reservoir sedimentation. I: delta and density current deposits. *Journal of Hydraulic Engineering,* 118(3), 354-369.

Fan, J., and Morris, G. L. (1992b). Reservoir sedimentation. II: Reservoir desiltation and long-term storage capacity. *Journal of Hydraulic Engineering,* 118(3), 370-384.

Fang, X., and Stefan, H. G. (2000). Dependence of dilution of a plunging discharge over a sloping bottom on inflow conditions and bottom friction. *Journal of Hydraulic Research,* 38(1), 15-25.

Felix, M., and Peakall, J. (2006). Transformation of debris flows into turbidity currents: mechanisms inferred from laboratory experiments. *Sedimentology,* 53(1), 107-123.

Fernandez, R. L., and Imberger, J. (2006). Bed roughness induced entrainment in a high Richardson number underflow. *Journal of Hydraulic Research,* 44(6), 725-738.

Fernandez, R. L., and Imberger, J. (2008). Time-varying underflow into a continuous stratification with bottom slope. *Journal of Hydraulic Engineering,* 134(9), 1191-1198.

Fildani, A., Normark, W. R., Kostic, S., and Parker, G. (2006). Channel formation by flow stripping: Large-scale scour features along the Monterey East Channel and their relation to sediment waves. *Sedimentology,* 53(6), 1265-1287.

Firoozabadi, B., Afshin, H., and Aram, E. (2009). Three-dimensional modeling of density current in a straight channel. *Journal of Hydraulic Engineering,* 135(5), 393-402.

Fragoso, A., Patterson, M., and Wettlaufer, J. (2013). Mixing in gravity currents. *Journal of Fluid Mechanics,* 734, R2.

Garcia, M. (1990). Depositing and eroding turbidity sediment driven flows: Turbidity currents: Project Report, 306, St Anthony Falls, Hydraulics Laboratory. *University of Minnesota: Minneapolis, Minnesota, USA.*

Garcia, M., and Parker, G. (1989). Experiments on hydraulic jumps in turbidity currents near a canyon-fan transition. *Science,* 245(4916), 393-396.

Garcia, M. H. (1994). Depositional turbidity currents laden with poorly sorted sediment. *Journal of hydraulic engineering,* 120(11), 1240-1263.

García, M. H. (1993). Hydraulic jumps in sediment-driven bottom currents. *Journal of Hydraulic Engineering,* 119(10), 1094-1117.

Gerber, G., Diedericks, G., and Basson, G. (2010). Particle image velocimetry measurements and numerical modeling of a saline density current. *Journal of hydraulic engineering,* 137(3), 333-342.

Ghomeshi, M. (1995). *Reservoir sedimentation modelling.* PhD Dissertation. University of Wollongong. Australia.

Ghomeshi, M. (2012). Understanding and Managing Turbidity Currents in Dam Reserviors. Iran: Khouzestan Water and Power Authority.

Gonzalez-Juez, E., Constantinescu, S., and Meiburg, E. (2007). A study of the interaction of a gravity current with a square cylinder using two-dimensional numerical simulations. Paper presented at the *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*.

Gonzalez-Juez, E., and Meiburg, E. (2009). Shallow-water analysis of gravity-current flows past isolated obstacles. *Journal of Fluid Mechanics,* 635, 415-438.

Gonzalez-Juez, E., Meiburg, E., and Constantinescu, G. (2009a). Gravity currents impinging on bottom-mounted square cylinders: flow fields and associated forces. *Journal of Fluid Mechanics,* 631, 65-102.

Gonzalez-Juez, E., Meiburg, E., and Constantinescu, G. (2009b). The interaction of a gravity current with a circular cylinder mounted above a wall: Effect of the gap size. *Journal of Fluids and Structures,* 25(4), 629-640.

Gray, T., Alexander, J., and Leeder, M. R. (2006a). Longitudinal flow evolution and turbulence structure of dynamically similar, sustained, saline density and turbidity currents. *Journal of Geophysical Research: Oceans (1978–2012),* 111(C8).

Gray, T., Alexander, J., and Leeder, M. R. (2006b). Longitudinal flow evolution and turbulence structure of dynamically similar, sustained, saline density and turbidity currents. *Journal of Geophysical Research: Oceans*, 111(C8).

Guo, Y., Wu, X., Pan, C., and Zhang, J. (2011). Numerical simulation of the tidal flow and suspended sediment transport in the Qiantang Estuary. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 138(3), 192-202.

Gyüre, B., and Jánosi, I. M. (2003). Stratified flow over asymmetric and double bell-shaped obstacles. *Dynamics of Atmospheres and Oceans,* 37(2), 155-170.

Hacker, J., Linden, P., and Dalziel, S. (1996). Mixing in lock-release gravity currents. *Dynamics of Atmospheres and Oceans,* 24(1), 183-195.

Haghabi, A. H. (2004). *Effect of bed slope on velocity and concentration profiles in density currents.* PhD Dissertation. Shahid Chamran University of Ahvaz. Iran.

Haghabi, A. H., Ghomeshi, M., and Kashefipour, S. M. (2008). Investigation on Hydraulic Characteristics of Density Currents in Reservoirs. *Journal of Irrigation Science and Engineering,* 30(4B), 14.

Hallberg, R. (2000). Time integration of diapycnal diffusion and Richardson number-dependent mixing in isopycnal coordinate ocean models. *Monthly Weather Review,* 128(5), 1402-1419.

Hallworth, M. A., Huppert, H. E., Phillips, J. C., and Sparks, R. S. J. (1996). Entrainment into two-dimensional and axisymmetric turbulent gravity currents. *Journal of Fluid Mechanics,* 308, 289-311.

Hamilton, P. B., Strom, K. B., and Hoyal, D. C. (2015). Noninvasive Methods for Hydraulic Characterization of Density Currents with Application to Submarine Fan Experiments. *Journal of Hydraulic Engineering,* 141(1).

Härtel, C., Meiburg, E., and Necker, F. (2000). Analysis and direct numerical simulation of the flow at a gravity-current head. Part 1. Flow topology and front speed for slip and no-slip boundaries. *Journal of Fluid Mechanics,* 418, 189-212.

He, Z., Zhao, L., Lin, T., Hu, P., lv, Y., Ho, H.-C., et al. (2017). Hydrodynamics of Gravity Currents Down a Ramp in Linearly Stratified Environments. *Journal of Hydraulic Engineering,* 143(3), 04016085.

Hoffmann, G., Nasr-Azadani, M. M., and Meiburg, E. (2015). Sediment wave formation caused by erosional and depositional turbidity currents: A numerical investigation. *Procedia IUTAM,* 15, 26-33.

Hopfinger, E. (1983). Snow avalanche motion and related phenomena. *Annual review of fluid mechanics,* 15(1), 47-76.

Horner-Devine, A., and Chickadel, C. C. (2017). Lobe-cleft instability in the buoyant gravity current generated by estuarine outflow. *Geophysical Research Letters,* 44(10).

Hosseini, S., Shamsai, A., and Ataie-Ashtiani, B. (2006). Synchronous measurements of the velocity and concentration in low density turbidity currents using an Acoustic Doppler Velocimeter. *Flow Measurement and Instrumentation,* 17(1), 59-68.

Hsu, S. M., Tseng, C. M., and Lin, C. C. (2017). Antecedent Bottom Conditions of Reservoirs as Key Factors for High Turbidity in Muddy Water Caused by Storm Rainfall. *Journal of Hydraulic Engineering,* 143(1), 05016006.

Huang, H., Imran, J., and Pirmez, C. (2005). Numerical model of turbidity currents with a deforming bottom boundary. *Journal of Hydraulic Engineering,* 131(4), 283-293.

Huppert, H. E., and Simpson, J. E. (1980). The slumping of gravity currents. *Journal of Fluid Mechanics,* 99(04), 785-799.

Islam, M. A., and Imran, J. (2008). Experimental modeling of gravity underflow in a sinuous submerged channel. *Journal of Geophysical Research: Oceans (1978–2012),* 113(C7).

Islam, M. A., and Imran, J. (2010a). Vertical structure of continuous release saline and turbidity currents. *Journal of Geophysical Research: Oceans (1978–2012),* 115(C8).

Islam, M. A., and Imran, J. (2010b). Vertical structure of continuous release saline and turbidity currents. *Journal of Geophysical Research: Oceans,* 115(C8).

Ismail, H., Viparelli, E., and Imran, J. (2016). Confluence of density currents over an erodible bed. *Journal of Geophysical Research: Earth Surface*, 121(7), 1251-1272.

Ito, M., and Saito, T. (2006). Gravel waves in an ancient canyon: Analogous features and formative processes of coarse-grained bedforms in a submarine-fan system, the lower Pleistocene of the Boso Peninsula, Japan. *Journal of Sedimentary Research,* 76(12), 1274-1283.

Jacobson, M., and Testik, F. (2013). On the concentration structure of high-concentration constant-volume fluid mud gravity currents. *Physics of Fluids (1994-present),* 25(1), 016602.

Jiang, Y., and Liu, X. (2017). Experimental and numerical investigation of density current over macro-roughness. *Environmental Fluid Mechanics*, 17(1), 1-20.

Jóhannesson, T., Lied, K., Stefan, M., and Frode, S. (1996). An Overview of the Need for Avalanche Protection Measures in Iceland. Iceland: Icelandic Meteorological Office.

Johnson, C. G., Hogg, A. J., Huppert, H. E., Sparks, R. S. J., Phillips, J. C., Slim, A. C., et al. (2015). Modelling intrusions through quiescent and moving ambients. *Journal of Fluid Mechanics,* 771, 370-406.

Jung, J., and Yoon, H. (2016). Effect of scour depth on flow around circular cylinder in gravity current. *Ocean Engineering*, 117, 78-87.

Kaheh, M., Ghomeshi, M., and Musavi Jahromi, S. H. (2012). Experimental Investigation on the Frontal Velocity of Gravity Currents over Rough Beds. *Journal of Irrigation Science and Engineering*, 35(1), 9.

Karamzadeh, N. (2004). *Experimental study on water entrainmnt in density currents.* Master Thesis. Shahid Chamran University of Ahvaz. Iran.

Kashefipour, S., Kooti, F., and Ghomeshi, M. (2010). Effect of reservoir bed slope and density current discharge on water entrainment. Paper presented at the

Environmental Hydraulics, Two Volume Set: Proceedings of the 6th International Symposium on Enviornmental Hydraulics, Athens, Greece, 23-25 June 2010, 195.

KEM. (2012). Portable Density/Specific Gravity Meter DA-130N Operation Manual. Japan: Kyoto Electronics Manufacturing CO., LTD.

Keshtkar, S., Ayyoubzadeh, S. A., Firoozabadi, B., and Kordi, E. (2011). Experiments on Turbidity Current Regimes in a Straight Open Channel. Paper presented at the *World Environmental and Water Resources Congress 2011@ sBearing Knowledge for Sustainability*, 4047-4064.

Khavasi, E., Afshin, H., and Firoozabadi, B. (2012). Effect of selected parameters on the depositional behaviour of turbidity currents. *Journal of Hydraulic Research,* 50(1), 60-69.

Kneller, B., Bennett, S., and McCaffrey, W. (1997). Velocity and turbulence structure of density currents and internal solitary waves: potential sediment transport and the formation of wave ripples in deep water. *Sedimentary Geology,* 112(3), 235-250.

Kneller, B., and Buckee, C. (2000). The structure and fluid mechanics of turbidity currents: a review of some recent studies and their geological implications. *Sedimentology,* 47(s1), 62-94.

Kneller, B., and McCaffrey, W. (1999). Depositional effects of flow nonuniformity and stratification within turbidity currents approaching a bounding slope: deflection, reflection, and facies variation. *Journal of Sedimentary Research,* 69(5).

Kneller, B. C., Bennett, S. J., and McCaffrey, W. D. (1999). Velocity structure, turbulence and fluid stresses in experimental gravity currents. *Journal of Geophysical Research: Oceans (1978–2012),* 104(C3), 5381-5391.

Kostic, S. (2011). Modeling of submarine cyclic steps: Controls on their formation, migration, and architecture. *Geosphere,* 7(2), 294-304.

Kostic, S., and Parker, G. (2003). Progradational sand-mud deltas in lakes and reservoirs. Part 1. Theory and numerical modeling. *Journal of Hydraulic Research,* 41(2), 127-140.

Kostic, S., and Parker, G. (2006). The response of turbidity currents to a canyon–fan transition: internal hydraulic jumps and depositional signatures. *Journal of Hydraulic Research,* 44(5), 631-653.

Koti, F. (2010). *Interaction of reservoir bed slope and density current discharge on water entrainment.* Master Thesis. Shahid Chamran University of Ahvaz.

Kubo, Y. s. (2004). Experimental and numerical study of topographic effects on deposition from two-dimensional, particle-driven density currents. *Sedimentary Geology*, 164(3), 311-326.

Kubo, Y. s., and Nakajima, T. (2002). Laboratory experiments and numerical simulation of sediment-wave formation by turbidity currents. *Marine Geology*, 192(1), 105-121.

La Rocca, M., Adduce, C., Sciortino, G., and Pinzon, A. B. (2008). Experimental and numerical simulation of three-dimensional gravity currents on smooth and rough bottom. *Physics of Fluids (1994-present)*, 20(10), 106603.

Laanearu, J., Cuthbertson, A. J. S., and Davies, P. A. (2014). Dynamics of dense gravity currents and mixing in an up-sloping and converging vee-shaped channel. *Journal of Hydraulic Research*, 52(1), 67-80.

Lai, S. Y., Gerber, T. P., and Amblas, D. (2016). An experimental approach to submarine canyon evolution. *Geophysical Research Letters*, 43(6), 2741-2747.

Lai, Y. G., Huang, J., and Wu, K. (2015). Reservoir turbidity current modeling with a two-dimensional layer-averaged model. *Journal of Hydraulic Engineering*, 141(12), 04015029.

Lane-Serff, G., Beal, L., and Hadfield, T. (1995). Gravity current flow over obstacles. *Journal of Fluid Mechanics*, 292, 39-53.

Leonardi, S., Orlandi, P., Djenidi, L., and Antonia, R. (2004). Structure of turbulent channel flow with square bars on one wall. *International journal of heat and fluid flow*, 25(3), 384-392.

Leonardi, S., Orlandi, P., Smalley, R., Djenidi, L., and Antonia, R. (2003). Direct numerical simulations of turbulent channel flow with transverse square bars on one wall. *Journal of Fluid Mechanics*, 491, 229-238.

Li, G., Piper, D. J., Campbell, D. C., and Mosher, D. (2012). Turbidite deposition and the development of canyons through time on an intermittently glaciated continental margin: The Bonanza Canyon system, offshore eastern Canada. *Marine and Petroleum Geology*, 29(1), 90-103.

Lintern, D. G., Hill, P. R., and Stacey, C. (2016). Powerful unconfined turbidity current captured by cabled observatory on the Fraser River delta slope, British Columbia, Canada. *Sedimentology*, 63(5), 1041-1064.

Lowe, R. J., Rottman, J. W., and Linden, P. (2005). The non-Boussinesq lock-exchange problem. Part 1. Theory and experiments. *Journal of Fluid Mechanics,* 537, 101-124.

Luis, J., Sidek, L., Desa, M., and Julien, P. (2013a). Sustainability of hydropower as source of renewable and clean energy. Paper presented at the *IOP Conference Series: Earth and Environmental Science,* 012050.

Luis, J., Sidek, L. M., Desa, M. N. B. M., and Julien, P. Y. (2013b). Hydropower Reservoir for Flood Control: A Case Study on Ringlet Reservoir, Cameron Highlands, Malaysia. *Journal of Flood Engineering,* 4(1), 87-102.

Middleton, G. V. (1993). Sediment deposition from turbidity currents. *Annual Review of Earth and Planetary Sciences,* 21, 89-114.

MJK. (2009). MagFlux Electromagnetic Flow Meter Installation and User Manual. Denmark: MJK Automation.

Monaghan, J. (2007). Gravity current interaction with interfaces. *Annu. Rev. Fluid Mech.,* 39, 245-261.

Morris, S. A., and Alexander, J. (2003). Changes in flow direction at a point caused by obstacles during passage of a density current. *Journal of Sedimentary Research,* 73(4), 621-629.

Nakajima, T., and Satoh, M. (2001). The formation of large mudwaves by turbidity currents on the levees of the Toyama deep-sea channel, Japan Sea. *Sedimentology,* 48(2), 435-463.

Nasr-Azadani, M., Hall, B., and Meiburg, E. (2013). Polydisperse turbidity currents propagating over complex topography: comparison of experimental and depth-resolved simulation results. *Computers & Geosciences,* 53, 141-153.

Nasr-Azadani, M., and Meiburg, E. (2014). Turbidity currents interacting with three-dimensional seafloor topography. *Journal of Fluid Mechanics,* 745, 409-443.

Nasr-Azadani, M. M., and Meiburg, E. (2011). TURBINS: an immersed boundary, Navier–Stokes code for the simulation of gravity and turbidity currents interacting with complex topographies. *Computers & Fluids,* 45(1), 14-28.

Negretti, M. E., Zhu, D. Z., and Jirka, G. H. (2008). The effect of bottom roughness in two-layer flows down a slope. *Dynamics of Atmospheres and Oceans,* 45(1), 46-68.

Neufeld, J. (2002). *Lobe-Cleft patterns in the leading edge of a gravity current.* Master Thesis, University of Toronto.

Nogueira, H. I., Adduce, C., Alves, E., and Franca, M. J. (2012). The influence of bed roughness on the dynamics of gravity currents. Paper presented at the *River Flow*.

Nogueira, H. I., Adduce, C., Alves, E., and Franca, M. J. (2013). Analysis of lock-exchange gravity currents over smooth and rough beds. *Journal of Hydraulic Research,* 51(4), 417-431.

Nogueira, H. I., Adduce, C., Alves, E., and Franca, M. J. (2014). Dynamics of the head of gravity currents. *Environmental Fluid Mechanics,* 14(2), 519-540.

Normark, W. R., Piper, D. J., Posamentier, H., Pirmez, C., and Migeon, S. (2002). Variability in form and growth of sediment waves on turbidite channel levees. *Marine Geology,* 192(1), 23-58.

Nortek. (2013). Comprehensive Manual. Norway: Nortek AS.

Nourmohammadi, Z., Afshin, H., and Firoozabadi, B. (2011). Experimental observation of the flow structure of turbidity currents. *Journal of Hydraulic Research,* 49(2), 168-177.

Oehy, C. (2003). *Effects of obstacles and jets on reservoir sedimentation due to turbidity currents*: Laboratoire de Constructions Hydrauliques, Ecole Polytechnique Federale Lausanne.

Oehy, C., and Schleiss, A. (2001). Numerical modelling of a turbidity current passing over an obstacle–Practical application in the Lake Grimsel, Switzerland. Paper presented at the *Proceedings of the 2001 International Symposium on Environmental Hydraulics*, 6.

Oehy, C. D., De Cesare, G., and Schleiss, A. J. (2010). Effect of inclined jet screen on turbidity current. *Journal of Hydraulic Research,* 48(1), 81-90.

Oehy, C. D., and Schleiss, A. J. (2007). Control of turbidity currents in reservoirs by solid and permeable obstacles. *Journal of Hydraulic Engineering,* 133(6), 637-648.

Ooi, A., Zgheib, N., and Balachandar, S. (2015). Direct Numerical Simulation of Three-dimensional Gravity Current on a Uniform Slope. *Procedia Engineering,* 126, 372-376.

Oshaghi, M. R., Afshin, H., and Firoozabadi, B. (2013). Experimental investigation of the effect of obstacles on the behavior of turbidity currents. *Canadian Journal of Civil Engineering,* 40(4), 343-352.

Ottolenghi, L., Adduce, C., Inghilesi, R., Armenio, V., and Roman, F. (2016). Entrainment and mixing in unsteady gravity currents. *Journal of Hydraulic Research,* 54(5), 541-557.

Özgökmen, T. M., and Fischer, P. F. (2008). On the role of bottom roughness in overflows. *Ocean Modelling,* 20(4), 336-361.

Parker, G., Fukushima, Y., and Pantin, H. M. (1986). Self-accelerating turbidity currents. *Journal of Fluid Mechanics,* 171, 145-181.

Parker, G., Garcia, M., Fukushima, Y., and Yu, W. (1987). Experiments on turbidity currents over an erodible bed. *Journal of Hydraulic Research,* 25(1), 123-147.

Perez-Gruszkiewicz, S. E. (2011). Reducing underwater-slide impact forces on pipelines by streamlining. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 138(2), 142-148.

Perry, A. E., Schofield, W. H., and Joubert, P. N. (1969). Rough wall turbulent boundary layers. *Journal of Fluid Mechanics,* 37(02), 383-413.

Peters, W. D. (1999). *Rough-surface gravity current flows.* PhD Dissertation. University of New Brunswick, Department of Mechanical Engineering. Canada.

Peters, W. D., and Venart, J. (2000). Visualization of rough-surface gravity current flows using laser-induced fluorescence. Paper presented at the *Proceedings of 9th international symposium of flow visualization, Edinburgh, Scotland*.

Pickering, K. T., Hodgson, D. M., Platzman, E., Clark, J. D., and Stephens, C. (2001). A new type of bedform produced by backfilling processes in a submarine channel, late Miocene, Tabernas-Sorbas basin, SE Spain. *Journal of Sedimentary Research,* 71(5), 692-704.

Poudeh, H. T., Emamgholizadeh, S., and Fathi-Moghadam, M. (2013). Experimental study of the velocity of density currents in convergent and divergent channels. *International Journal of Sediment Research,* 28(2), 254-259.

Ross, A. N., Linden, P., and Dalziel, S. B. (2002). A study of three-dimensional gravity currents on a uniform slope. *Journal of Fluid Mechanics,* 453, 239-261.

Rottman, J. W., and Simpson, J. E. (1983). Gravity currents produced by instantaneous releases of a heavy fluid in a rectangular channel. *Journal of Fluid Mechanics,* 135, 95-110.

Rottman, J. W., Simpson, J. E., Hunt, J., and Britter, R. (1985). Unsteady gravity current flows over obstacles: some observations and analysis related to the Phase II trials. *Journal of Hazardous Materials,* 11, 325-340.

Rusello, P. (2009). A practical primer for pulse coherent instruments. *Nortek technical note No.: TN-027.*

Samasiri, P., and Woods, A. W. (2015). Mixing in axisymmetric gravity currents. *Journal of Fluid Mechanics,* 782, R1.

Schleiss, A. J., Franca, M. J., Juez, C., and De Cesare, G. (2016). Reservoir sedimentation. *Journal of Hydraulic Research,* 54(6), 595-614.

Sequeiros, O. E. (2008). *Bedload transport, self acceleration, downstream sorting, and flow dynamics of turbidity currents.* PhD Dissertation. University of Illinois at Urbana-Champaign. USA.

Sequeiros, O. E., Spinewine, B., Beaubouef, R. T., Sun, T., García, M. H., and Parker, G. (2010). Characteristics of velocity and excess density profiles of saline underflows and turbidity currents flowing over a mobile bed. *Journal of Hydraulic Engineering,* 136(7), 412-433.

Shehni Karamzadeh, N., Mahmoudian Shoushtari, M., and Ghomeshi, M. (2013). Experimental study on water entrainment into density currents. Paper presented at the *9th International River Engineering Conference*, Iran.

Simpson, J. E. (1999). *Gravity currents: In the environment and the laboratory*: Cambridge University Press.

Soler, M., Colomer, J., Serra, T., Casamitjana, X., and Folkard, A. (2017). Sediment deposition from turbidity currents in simulated aquatic vegetation canopies. *Sedimentology*.

Stacey, M. W., and Bowen, A. J. (1988). The vertical structure of density and turbidity currents: theory and observations. *Journal of Geophysical Research: Oceans (1978–2012),* 93(C4), 3528-3542.

Stagnaro, M., and Pittaluga, M. B. (2014). Velocity and concentration profiles of saline and turbidity currents flowing in a straight channel under quasi-uniform conditions. *Earth Surface Dynamics,* 2(1), 167.

Stashchuk, N., and Hutter, K. (2003). Modelling the gravity current flowing from the Bosphorus to the Black Sea. *Geophysical & Astrophysical Fluid Dynamics,* 97(1), 1-24.

Strauss, M., and Glinsky, M. E. (2011). Turbidity current flow over an obstacle and phases of sediment wave generation. *arXiv preprint arXiv:1108.5048*.

Talling, P., Peakall, J., Sparks, R., Cofaigh, C. Ó., Dowdeswell, J., Felix, M., et al. (2002). Experimental constraints on shear mixing rates and processes: implications for the dilution of submarine debris flows. *Geological Society, London, Special Publications,* 203(1), 89-103.

Tanino, Y., Nepf, H., and Kulis, P. (2005). Gravity currents in aquatic canopies. *Water resources research*, 41(12).

Teh, S. H. (2011). *Soil erosion modeling using RUSLE and GIS on Cameron highlands, Malaysia for hydropower development*. Master Thesis. The School for Renewable Energy Science. Iceland.

Tokyay, T., and Constantinescu, G. (2015). The effects of a submerged non-erodible triangular obstacle on bottom propagating gravity currents. *Physics of Fluids*, 27(5), 056601.

Tokyay, T., Constantinescu, G., Gonzalez-Juez, E., and Meiburg, E. (2011). Gravity currents propagating over periodic arrays of blunt obstacles: Effect of the obstacle size. *Journal of Fluids and Structures*, 27(5), 798-806.

Tokyay, T., Constantinescu, G., and Meiburg, E. (2012). Tail structure and bed friction velocity distribution of gravity currents propagating over an array of obstacles. *Journal of Fluid Mechanics*, 694, 252-291.

Tokyay, T., Constantinescu, G., and Meiburg, E. (2014). Lock-exchange gravity currents with a low volume of release propagating over an array of obstacles. *Journal of Geophysical Research: Oceans*, 119(5), 2752-2768.

Tokyay, T. E. (2010). *A LES study on gravity currents propagating over roughness elements*. University of Lowa. USA.

TPS. (2012). Model WP-84 Conductivity, TDS, Salinity, Temp Meter User Manual. Australia: TPS Pty Ltd.

Tsakiri, M., Prinos, P., and Koftis, T. (2016). Numerical simulation of turbulent exchange flow in aquatic canopies. *Journal of Hydraulic Research*, 54(2), 131-144.

Turner, J. (1986). Turbulent entrainment: the development of the entrainment assumption, and its application to geophysical flows. *J. Fluid Mech*, 173(431), 71.

Turner, J. S. (1979). *Buoyancy effects in fluids*: Cambridge University Press.

Ungarish, M. (2007). A shallow-water model for high-Reynolds-number gravity currents for a wide range of density differences and fractional depths. *Journal of Fluid Mechanics*, 579, 373-382.

Ungarish, M., and Zemach, T. (2005). On the slumping of high Reynolds number gravity currents in two-dimensional and axisymmetric configurations. *European Journal of Mechanics-B/Fluids*, 24(1), 71-90.

Wåhlin, A., Darelius, E., Cenedese, C., and Lane-Serff, G. (2008). Laboratory observations of enhanced entrainment in dense overflows in the presence of submarine canyons and ridges. *Deep Sea Research Part I: Oceanographic Research Papers*, 55(6), 737-750.

Wang, Z.-y., and Chunhong, H. (2009). Strategies for managing reservoir sedimentation. *International Journal of Sediment Research*, 24(4), 369-384.

Wild, T. B., Loucks, D. P., Annandale, G. W., and Kaini, P. (2016). Maintaining sediment flows through hydropower dams in the Mekong River Basin. *Journal of Water Resources Planning and Management*, 142(1), 05015004.

Woods, A. W., and Bursik, M. I. (1994). A laboratory study of ash flows. *Journal of Geophysical Research: Solid Earth (1978–2012)*, 99(B3), 4375-4394.

Woods, A. W., Bursik, M. I., and Kurbatov, A. V. (1998). The interaction of ash flows with ridges. *Bulletin of Volcanology*, 60(1), 38-51.

Wynn, R. B., and Stow, D. A. (2002). Classification and characterisation of deep-water sediment waves. *Marine Geology*, 192(1), 7-22.

Wynn, R. B., Weaver, P. P., Ercilla, G., Stow, D. A., and Masson, D. G. (2000). Sedimentary processes in the Selvage sediment-wave field, NE Atlantic: new insights into the formation of sediment waves by turbidity currents. *Sedimentology*, 47(6), 1181-1197.

Xiao, Y., Yang, F., Zhou, Y., and Chen, W. (2015). 1-D numerical modeling of the mechanics of gravity-driven transport of fine sediments in the Three Gorges Reservoir. *Lake and Reservoir Management*, 31(2), 83-91.

Xu, J., Noble, M., and Rosenfeld, L. K. (2004). In-situ measurements of velocity structure within turbidity currents. *Geophysical Research Letters*, 31(9).

Xu, X., Chang, Y. S., Peters, H., Özgökmen, T. M., and Chassignet, E. P. (2006). Parameterization of gravity current entrainment for ocean circulation models using a high-order 3D nonhydrostatic spectral element model. *Ocean Modelling*, 14(1), 19-44.

Yaghoubi, S., Afshin, H., Firoozabadi, B., and Farizan, A. (2017). Experimental Investigation of the Effect of Inlet Concentration on the Behavior of Turbidity Currents in the Presence of Two Consecutive Obstacles. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 143(2), 04016018.

Yilmaz, N. A., Testik, F. Y., and Chowdhury, M. R. (2014). Laminar bottom gravity currents: friction factor–Reynolds number relationship. *Journal of Hydraulic Research*, 52(4), 545-558.

Zhao, L., Yu, C., and He, Z. (2016). A Multi-Phase Mathematical Model for Gravity Currents. Paper presented at the *World Environmental and Water Resources Congress 2016*, 433-441.

Zhu, J., Lee, C., Chen, G., and Lee, J. (2006). PIV observation of instantaneous velocity structure of lock release gravity currents in the slumping phase. *Communications in Nonlinear Science and Numerical Simulation*, 11(2), 262-270.