

CHARACTERISTICS OF DENSITY CURRENT DYNAMICS OVER ROUGH  
CHANNEL BEDS

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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 ( $\lambda/K_r=1, 4, 8, 16, 32, 64$  and  $128$  where  $\lambda$  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 ( $\lambda/K_r=8$ ) 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  $\lambda/K_r=128$  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  $\lambda/K_r=8$ , 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 ( $\lambda/K_r=1, 4, 8, 16, 32, 64$  dan  $128$  di mana  $\lambda$  menunjukkan 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 ( $\lambda/K_r=8$ ) 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 pertambahan lagi jarak elemen kekasaran tersebut. Kekasaran dasar dengan  $\lambda/K_r=128$  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  $\lambda/K_r=8$ , 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.

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## 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
$E_d$	-	Excess density at distance $z$ above the bed
$E_{d_{av}}$	-	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
$We_e$	-	Entrainment velocity
$X$	-	Distance from the inlet gate
$z$	-	Distance above the bed
$z_0$	-	Zero velocity roughness height
$\rho_a$	-	Density of ambient fluid
$\rho_d$	-	Density at depth $z$ above the bed
$\bar{\rho}_d$	-	Average density of the current
$\rho_{in}$	-	Initial density of the current
$\Theta$	-	Bed slope angle
$\Pi$	-	Dimensionless number
$\tau$	-	Bottom shear stress
$\mu_d$	-	dynamic viscosity of the dense fluid at the inlet

$\nu_{in}$	-	Kinematic viscosity of dense fluid at inlet
$\nu$	-	Kinematic viscosity of water
$\lambda$	-	Streamwise spacing between roughness elements
$\lambda/K_r$	-	Roughness parameter

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## **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 widespread 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).

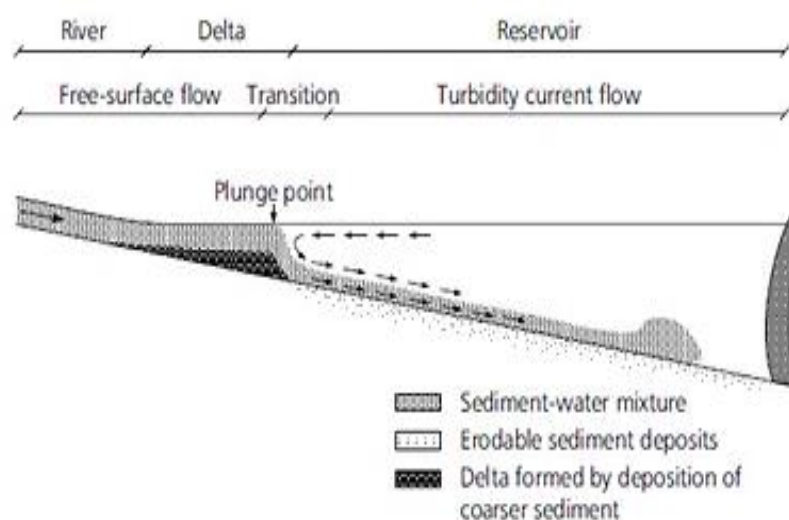


**Figure 1.2** Turbid inflows from a river plunging under seawater in an estuary (Ghomeshi, 2012)

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). These 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<sup>3</sup>/year of sediment inflow. The sedimentation rate in 1965 was

estimated 25,000 m<sup>3</sup>/year (Choy and Mohamad, 1990). However, this increased to an average of approximately six folds reaching to 139,712 m<sup>3</sup>/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.

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