UNIVERSITI PUTRA MALAYSIA

MODELLING WATER AND SEDIMENT FLOW IN BRANCHING CHANNEL SYSTEM

NASHWAN KAMAL AL DEEN MOHAMMED

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By

NASHWAN KAMAL AL DEEN MOHAMMED

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

May 2017

DEDICATION

To

My parents

My lovely family, wife and children

&

My siblings

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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May 2017

Chairman: Badronnisa Binti Yusuf, PhD
Faculty: Engineering

Operational problems associated with branching channels and water intakes increase over time due to localised sediment accumulations. The success of branching channel projects depends on the right design to increase the unit discharge and decrease the sediment concentration as much as possible. In addition, a branching channel from rivers and channels affects the bed morphology and causes erosion and sedimentation in the branching junction. There is still a lack of studies on the flow pattern in movable bed branching channel systems for different branching channel angles and bed widths to quantify the amount of water and sediment concentration in the branching channel and investigate its effect on the bed morphology. In this study, the hydraulic performance of differently angled branching channels was compared in an effort to maximise discharge, minimise sediment concentration and decrease its effect on the bed morphology.

The objectives of the study are to investigate the effect of the branching angle and the bed width ratio on the water and sediment flow in the branching channel and scour hole characteristics (scour depth and scour length). The scour hole is formed in the main channel just downstream from the location of the branching channel entrance. This study also investigated the variation in velocity vertically and horizontally at the junction region and determined the total energy loss coefficient across the junction region. The objectives of the study were implemented experimentally using a physical model of 30, 45, 60, 75 and 90° branching channel angles with the main flow direction. In addition, three bed width ratios (30, 40 and 50%) and five total discharges (7.25, 8.5, 9.75, 11, and 12.25 L/s) were investigated for each branching angle scenario. A sand bed with d_{50} of 0.4 mm was used for all the experiments. In order to ensure sediment movement in the main channel at the upstream and to quantify the branching channel sediment concentration, a live-bed condition with flow intensity (V_u/V_c) of 1.1–1.5 was maintained in all experiments.

The results indicated that branching angles of 30° and 45° increased the relative discharge ratios (Q_R) by approximately 5–10% compared with the discharge ratio for the 90° branching angle. The results also indicated that the branching channel sediment concentration and scour depth decreased as the branching channel angle decreased. The branching angles of 30° and 45° reduced the sediment concentrations by an average of 64% and 37%, respectively, compared with the concentration for the 90° branching angle. With respect to scour depth, the branching angle of 30° reduced the scour depth by approximately 14.4-46.7% compared with the scour depth for the 90° branching angle. The main reasons for forming the scour hole are the vortexes generated due to diverting some of the flow towards the branching channel and the downstream branching channel entrance sharp edge.

The 30° branching angle recorded the smaller low velocity region at the beginning of the upstream side wall of the branching channel than other branching angles. Moreover, the velocity distribution in this branching angle is more uniform along the branching channel width than others. The outcomes from this study indicate that a branching angle of 30°– 45° is the best arrangement to increase the branching channel discharge, decrease the branching channel sediment concentration and decrease the scour depth at the junction region. Reducing the amount of branching channel sediment maintains the project efficiency of those depending on the branching channel flow. In addition, a high water unit discharge means a lower initial construction cost for the channel. Moreover, decreasing the scour depth helps to reduce the risks of a scouring effect on the side bank of the main channel or any nearby structures.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMODELAN ALIRAN AIR DAN ENAPAN DI DALAM SISTEM SALURAN BERCABANG

Oleh

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Masalah operasi yang berkaitan dengan saluran bercabang dan tempat masuk air meningkat dengan masa kerana pengumpulan enapan setempat. Kejayaan projek saluran bercabang bergantung kepada reka bentuk yang untuk yang meningkatkan unit kadar alir dan mengurangkan kepekatan enapan sebanyak mungkin. Tambahan lagi, saluran bercabang dari sungai dan saluran menjejas morfologi dasar sungai dan menyebabkan hakisan dan pemendapan di simpang pencabangan. Kajian mengenai corak aliran di dalam sistem pencabangan saluran dasar sungai bergerak bagi sudut pencabangan saluran dan lebar dasar sungai yang berbeza untuk menyatakan kuantiti jumlah air dan kepekatan enapan di dalam saluran bercabang dan menyiasat kesannya ke atas morfologi dasar sungai masih berkurangan. Di dalam kajian ini, prestasi hidraulik saluran pencabangan bersudut berbeza telah dibandingkan dalam usaha untuk memaksimumkan kadar alir, meminimumkan kepekatan enapan dan mengurangkan kesannya ke atas morfologi dasar sungai.

Objektif kajian ini adalah untuk mengkaji kesan sudut pencabangan dan nisbah lebar dasar sungai ke atas aliran air dan enapan di dalam saluran bercabang dan ciri-ciri lubang kerukan (kerukan mendalam dan kerukan panjang). Lubang kerukan terbentuk di dalam saluran utama di hilir berdekatan dengan lokasi masuknya saluran yang bercabang. Kajian ini juga menyiasat perubahan halaju secara menegak dan mendatar di kawasan simpang dan menentukan pekali kehilangan tenaga merentasi kawasan persimpangan tersebut. Objektif kajian ini telah dilaksanakan secara eksperimen dengan menggunakan model fizikal sistem pencabangan saluran 30, 45, 60, 75 dan 90° dari arah aliran utama. Di samping itu, tiga nisbah lebar dasar sungai (30, 40 dan 50%) dan lima jumlah kadar alir (7.25, 8.5, 9.75, 11, dan 12.25 L/s) telah disiasat untuk setiap senario sudut pencabangan. Satu dasar sungai pasir dengan d_{50} 0.4 mm digunakan untuk semua eksperimen. Untuk memastikan pergerakan enapan di hulu saluran utama dan untuk mendapatkan kuantiti kepekatan enapan

saluran, keadaan dasar sungai hidup dengan keamatan aliran (V_u/V_c) antara 1.1 -1.5 dikekalkan di dalam semua eksperimen.

Keputusan menunjukkan bahawa sudut pencabangan 30° dan 45° meningkatkan nisbah kadar alir relatif (Q_R) sebanyak kira-kira 5-10% berbanding dengan nisbah kadar alir untuk sudut pencabangan 90°. Keputusan juga menunjukkan bahawa kepekatan enapan di cabang saluran dan kedalaman kerukan menurun apabila sudut pencabangan saluran berkurangan. Sudut pencabangan 30° dan 45° mengurangkan kepekatan enapan secara purata sebanyak 64% dan 37%, masing-masing, berbanding dengan kepekatan bagi sudut pencabangan 90°. Berkenaan dengan kedalaman kerukan, sudut pencabangan 30° mengurangkan kedalaman kerukan sebanyak kira-kira 14.4-46.7% berbanding dengan kedalam kerokan bagi sudut pencabangan 90°. Sebab-sebab utama pembentukan lubang kerukan adalah putaran yang dijanakan kerana pengalihan sebahagian aliran ke arah saluran yang bercabang dan sisi tajam laluan masuk di hilir saluran cabang.

Sudut pencabangan 30° mencatatkan kawasan halaju rendah yang libih kecil pada awal dinding hulu saluran bercabang di berbanding sudut-sudut yang lain. Selain itu, agihan halaju untuk sudut pencabangan ini adalah lebih seragam di sepanjang kelebaran saluran bercabang itu berbanding yang lain. Hasil daripada kajian ini mengesyorkan bahawa sudut pencabangan di antara 30°- 45° ialah susunan terbaik untuk meningkatkan kadar alir saluran bercabang, mengurangkan kepekatan enapan saluran bercabang dan mengurangkan kedalaman kerukan di kawasan persimpangan. Mengurangkan jumlah enapan saluran bercabang mengekalkan kecekapan projek yang, bergantung pada aliran saluran ber cabang. Tambahan lagi, kadar alir unit air yang tinggi bermakna lebih kurang kos awal pembinaan saluran. Lebih-lebih lagi, mengurangkan kedalaman kerukan membantu mengurangkan risiko kesan kerukan ke atas tebing sisi saluran utama atau mana-mana struktur berdekatan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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a	Constant of the equation
A	Coefficient from experimental data depending on total discharge from 0 to 1 in Equation (2.16)
b	Exponent of the equation
B_b	Bed widths of the branching channel
B_e	Width of the branching channel entrance
B_m	Bed widths of the main channel
B_r	Bed width ratio = $B_{b/}$ B_m
c	Weir crest shape effect
C_c	Flow contraction coefficient in the branching channel
C_d	Sluice gate coefficient
C_{gb}	Mass sediment concentration in the branching channel
C_{gd}	Mass sediment concentration in the main channel at the downstream
C_m	Coefficient of the branching discharge over side weir
C_{sb}	Volumetric sediment concentration in the branching channel
d_{50}	Medium particles diameter
d_s	Depth of scour
F_*	Dimensionless shear stresses or Shield's parameter
F_{rb}	Froude number in the branching channel
F_{rd}	Froude number in the main channel at the downstream
F_{ru}	Froude number in the main channel at the upstream
g	gravity acceleration
H	Total energy head
H_b	Total energy head in the branching channel
H_d	Total energy head in the main channel at downstream
H_r	Total energy head ratio = H_b/H_u

H_u	Total energy head in the main channel at upstream
K_{12}	Energy loss coefficient between main channel at the upstream and at the downstream
K_{13}	Energy loss coefficient between main channel at the upstream and branching channel
K_{ds}	Relative scour depth = $d_{s\,(\theta°)} / d_{s\,(90°)}$
K_e	Total energy loss coefficient
L	Side weir opening length
l	Length of the vortex
L_s	Length of scour
m	Side slope of the main channel
m_a	Mass involved in the vortexes
n*	Number of the side weir
P_b	Flow power of the branching channel
P_d	Flow power in the main channel at downstream
P_r	Power ratio = $P_{b/}\ P_u$
P_{rd}	Pressure force in the main channel at the downstream conjunction edge
P_{rds}	Pressure force at the downstream branching channel wall
P_{ru}	Pressure force in the main channel at the upstream conjunction edge
P_{rus}	Pressure force at the upstream branching channel wall
P_u	Flow power in the main channel at upstream
q	Unit discharge
Q_b	Water discharge in the branching channel
q_b	Water unit discharge in the branching channel
Q_d	Water discharge in the main channel at the downstream
q_d	Water unit discharge in the main channel at the downstream
Q_r	Discharge ratio = Q_b/Q_u
q_r	Unit discharge ratio = q_b/q_u
Q_R	Relative discharge ratio

q_R	Relative unit discharge ratio compared with the discharge ratio for the 90° branching angle
q_{sb}	Sediment unit discharge in the branching channel
Q_{sb}	Volumetric sediment discharge in the branching channel
Q_{sbt}	Bed main channel sediment discharge at upstream
q_{sd}	Sediment unit discharge in the main channel at the downstream
Q_{slu}	Discharge under the sluice gate
Q_{sst}	Suspended main channel sediment discharge at upstream
Q_{su}	Volumetric sediment discharge in the main channel at upstream
Q_t	Total discharge
Q_u	Water discharge in the main channel at the upstream = Q_t
q_u	Water unit discharge in the main channel at the upstream = q_t
R	Recirculation Region
R^2	Coefficient of determination
R_c	Static pressure recovery coefficient
R_e	Reynold's number
r_{sb}	Bed sediment ratio
r_{ss}	Suspended sediment ratio
R_y	Main channel water depth at the upstream to the downstream = y_u/y_d
S_b	Slope of the branching channel
S_g	Specific gravity of the sand
S_m	Slope of the main channel
S_r	Branching to main sediment ratio
T	Water temperature
U	Velocity of the vortex
U^*	Shear velocity
U^*_c	Critical shear velocity of the particles inception motion
V	Vortex

V_b	Velocity of the flow in the branching channel
V_c	Critical velocity of the particles inception motion
V_d	Velocity of the flow in the main channel at the downstream
V_p	Local flow velocity measured by Pitot tube
V_r	Velocity ratio = V_b/V_u
V_u	Velocity of the flow in the main channel at the upstream
V_x	Velocity component towards the main flow
V_y	Velocity component towards the branching flow
V_z	Velocity component normal to the main flow
W	Height of the side weir
W/C	Water content
W_P	Weight of the pycnometer
W_{PS}	Weight of the pycnometer + dry soil
W_{PSW}	Weight of the pycnometer + dry soil + water
W_{PW}	Weight of the pycnometer + water
X	Flow meter reading of the main pump
y	Water depth
y_1	Water depth before the sluice gate
y_2	water depth under the sluice gate
y_b	Water depth in the branching channel
y_d	Water depth in the main channel at the downstream
y_r	Water depth ratio = y_b/y_u
y_u	Water depth in the main channel at the upstream
Z_b	Bed elevation in the branching channel
Z_d	Bed elevation in the main channel at downstream
Z_u	Bed elevation in the main channel at upstream
φ	Main channel contraction angle

β_d	Downstream momentum correction factor
β_u	Upstream momentum correction factor
γ	Water weight density = ρg
γ_s	Bed materials weight density
δ	Strength of the secondary circulation
Δh	Dynamic head = difference between total and static head at the Pitot tube submerged head
θ	Branching angle
$Ø_L$, $Ø_0$	Functions depend on the main channel geometry, Equation (2.8)
ρ	Water density
ρ_s	Bed material density
σ_g	Bed material standard deviation
υ	Water viscosity

CHAPTER 1

INTRODUCTION

1.1 Background

Open channels in irrigation and drainage projects are the most important means to transport water. In many cases, channels need to branch out to secondary channels so that it can feed lateral projects, such as irrigation and the water supply of municipality plants and hydro-power projects (Al Omari, 2009). Therefore, studying the branching channel flow system has a direct application in water resource projects (Meselhe et al., 2016; Ramamurthy et al., 1990). Moreover, branching channel flow or river bifurcations are found in natural rivers as a result of the rivers' dynamics processes (Kleinhans et al., 2013; Redolfi, 2015; Redolfi et al., 2016).

There are many examples of branching channels or river bifurcations in nature, such as the Pannerdense Kop in the lower course of the Rhine River and the bifurcations in the Patia River delta in Colombia (Figure 1.1). Another example of branching flow is the branching of two channels from the Cumberland Marshes, Canada, as shown in Figure 1.2.

Figure 1.1: Patia River Bifurcation (Casas, 2013).

Figure 1.2: Natural Branching Channel Flow from the Cumberland Marshes, Canada.

Man-made branching channels from a channel or river are considered as practical applications of the branching channel flow system. These branching channels vary in their objectives, such as supplying water for the cooling systems of an energy or power station, supplying municipal water, supplying water for irrigation projects, or for any other objectives.

Figure 1.3 shows an example of the branching channel from the Ohio River to supply water to a lateral project (Neary et al., 1999). Other examples of lateral projects, which are supplied with water from the Missouri River in North America by branching channels, are the MidAmerican Energy Company's Council Bluffs Power Station, the Omaha Public Power District-Nebraska City Station, the St. Louis County Water Company to supply municipal water, and the MidAmerican Energy Company's George Neal Station water intake.

Branching channel systems can also be used to capture a portion of the main flow sediment particles (sediment diversion) and subsequently decrease the main flow sediment concentration (Brown et al., 2013; Meselhe et al., 2016).

Miller (2004) gave another example of the practical application of branching channel flow. This is represented by designing and constructing a branching channel through the west bank of the Mississippi River. The branching channel is used to restore the wetlands located in Plaquemines Parish by connecting the Mississippi river with the wetlands (Figure 1.4). This branching channel carries water, sediment and nutrients from the river to the wetlands.

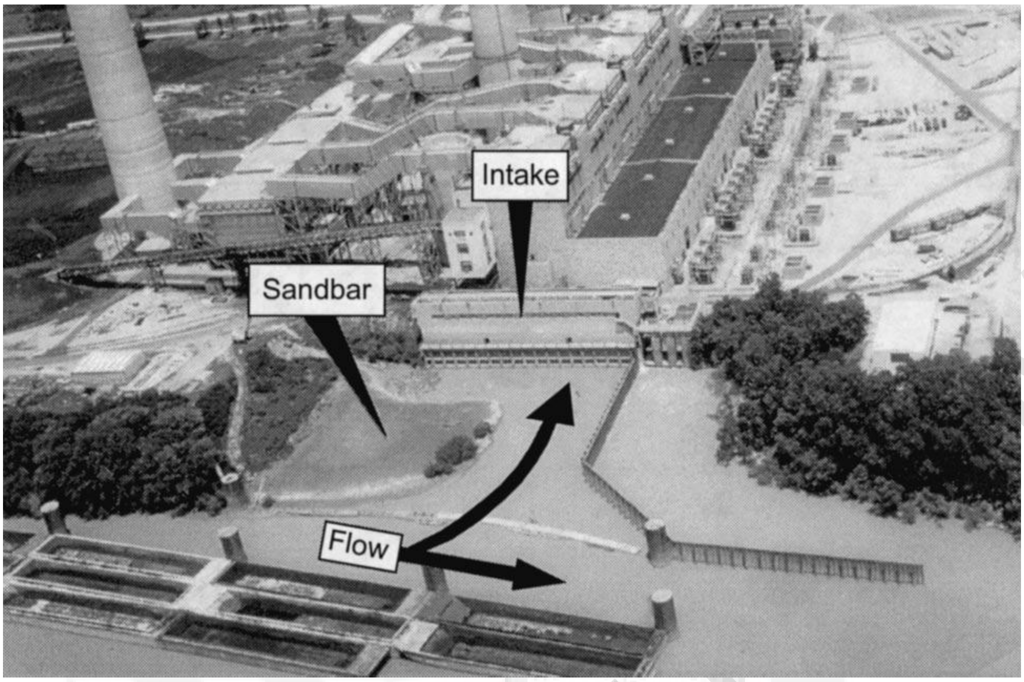

Figure 1.3: Lateral Water Intake from the Ohio River (Neary et al., 1999).

Figure 1.4: Branching Channel through the West Bank of the Mississippi River (Miller, 2004).

Branching channel flow has been studied in recent decades e.g. (Bulle, 1926; Grace & Priest, 1958; Taylor, 1944) and still attracts the attention of water resources engineering researchers as it commonly exists in many water engineering related projects and depends on many variables. Due to the complexity of branching flow, involving many interlinked factors, generalisation of the phenomena involved is very difficult to achieve (Lama et al., 2002).

1.2 Problem Statement

The problem of the branching sediment flow always accompanies the branching channel system (Moradinejad et al., 2017; Raudkivi, 1993) . Over time, branching channels may experience a decrease in their hydraulic efficiency due to an accumulation of sediment particles, for instance, by building up the sediment within the branching channel bed from the Ohio River, as shown in Figure 1.3 (Neary et al., 1999). The sediment concentration in the branching channel is higher than the concentration in the main channel. The branching channel receives more water from the main channel's lower layers where the sediment particles are concentrated (Barkdoll, 2004). The main channel's upper layers have higher momentum and tend to continue downstream past the branching channel while the lower momentum in lower layers are easily diverted to the branching channel (Herrero et al., 2015; Neary & Odgaard, 1993; Omidbeigi et al., 2009).

The sediment particles may block filters and damage water pumps in the water supply and hydropower systems. In addition, irrigation network systems, especially when these systems depend on irrigation by drops or sprinkler systems, always need sediment-free water to prevent their nozzles from blockage or damage. Rehabilitation efforts often require the accumulated sediment to be dredged from the branching channels at a high cost.

The mechanisms of the sediment transport in river bifurcations are still not well understood. Therefore, attempts of managing the branching channel sediment flow are still considered as a challenge (Sassi et al., 2013). Researchers have previously investigated various strategies for reducing sediment in branching channels, with a focus on using submerged vanes in front of the entrance to the branching channel (Beygipoor et al., 2013; Michell et al., 2006; Neill et al., 1997; Yalin Wang et al., 1996). The use of submerged vanes to control and redirect the upstream sediment downstream in the main channel is potentially costly and may adversely affect navigation of the main channel (Barkdoll et al., 1999). While, designing the branching channels and water intakes for municipal use should be stable and maintain the navigation of the main channel (Kleinhans et al., 2013). Moreover, it may inadvertently direct ice to the branching channel (Yushi Wang et al., 2014). The effectiveness of the submerged vanes is also limited based on flow conditions (effective approach for a unit discharge ratio up to 20-30%). The limitations of using submerged vanes to control the branching channel sediment flow display the importance of investigating alternative approach to control and manage of the branching channel sediment by choosing an appropriate branching angle, which can effectively reduce the branching channel sediment discharge.

Although bed morphology is considered as an essential element of the design of a branching channel (Xu et al., 2016), most of the studies related to branching channel flow have been carried out with the rigid boundary condition, e.g. (Mignot et al., 2014;

Mignot et al., 2013; Momplot et al., 2017), while most of the branching channel flow studies with a movable bed condition focused only on branching channel flow with a branching angle of 90°, e.g. (Barkdoll et al., 1999; Herrero et al., 2015). Al Omari (2009) and Casas (2013) reported that the effect of the branching angle of 30° and 60° on sediment transport in the branching channel system is lacking and should be taken into account in a future studies.

In addition, the branching channel can affect the main channel flow, alter the channel bed mechanics and change the bed morphology. The change of the bed topography and the turbulence of the flow in the region of the branching channel junction, besides the boundary friction, contribute to the energy loss. Furthermore, the branching channel leads to the formation of erosion and sedimentation regions at the branching channel junction (Allahyonesi et al., 2008). Some researchers have reported the formation of scour downstream of the channel junction (Barkdoll et al., 1999; Casas, 2013). Up to now, to our knowledge, no explicit studies investigating the effect of the branching channel flow with different branching angles and bed width ratios on the scour depth and the scour length have been done.

Therefore, there is a real need to investigate the branching channel discharge and sediment concentration, with the movable bed condition, for a wide range of branching angles and different bed width ratios.

Quantifying branching channel water discharge and sediment concentration and investigating the characteristics of the scour hole for different scenarios of branching angle and bed width ratio help to find the best arrangement of the branching channel that can increase the discharge and decrease the sediment concentration in the branching channel.

1.3 Objectives of the Study

The main objective of this study is to investigate experimentally the water and sediment flow and bed morphology in a branching channel system to compare the hydraulic performance of differently angled branching channels in an effort to maximise discharge, minimise sediment concentration, and reduce scour hole. The specific objectives of this study can be listed as follows:

1. To quantify the water and sediment flow in a branching channel and to compare the results for various branching angles and bed width ratios.
2. To investigate the characteristics of the scour hole (scour depth and scour length) forming at downstream of the main channel due to the branching channel system.
3. To investigate the variation in velocity vertically and horizontally at the junction region of the branching channel system.
4. To determine the total energy loss coefficient across the junction region in the branching channel system.

1.4 Significance of the Study

This study provides more insight on the effect of a wide range of branching angles and bed width ratios on the water and sediment flow in branching channels, as well as on the scour depth, scour length, velocity distribution and total energy loss coefficient.

The findings are useful in designing and managing channel systems with branching channels. Studying the flow behaviour in the branching channel and flow diversion location is important for water management (Yousefi et al., 2011) and for sedimentation management downstream of the diversion (Baker et al., 2011).

In designing and managing branching channel systems, water resources engineers strive to maximise the water discharge while minimising the cross-sectional area and associated construction and operation costs. In hydropower projects for example, the generated energy amount has a direct relationship with the water discharge (Lazzaro et al., 2013). In systems with high sediment laden, the main challenge is to decrease the sediment entering the branching channel while maximising the branching channel water discharge. A high sediment concentration leads to an increment in the operation cost and a decrement in operational efficiency. For example, in the water supplying plants, a higher concentration of sediment means a higher filtration cost. The findings from this study offer an alternative approach in sediment control in a branching channel system through appropriate selection of branching angles and bed width ratios.

Most of the previous studies on branching channels were limited to branching channel flow with rigid boundary and branching angle of 90°, despite the facts that the natural branching channel systems have always occurred with movable boundary and at various branching angles depending on the bank stability relative to the flow strength (Kleinhans et al., 2013). Therefore, this study on the branching channel with movable bed and at various angles is significant as it provides better understanding of the complex branching channel system in the nature.

In a branching channel system, the formations of scours and sedimentations are also the main concerns as they affect the stability of the main channel banks and any crossing structures if any. Knowledge of the locations and the characteristics of scours helps engineers to select a suitable conjunction location, which is at a safe distance from other nearby hydraulic structures. In a case if a crossing bridge accompanying the branching junction area is required to connect roads on the different banks, the scour location and depth due to branching flow are important factors that need to be taken into account in the design of piers for the bridge besides the scour results from the pier itself.

Moreover, the study gives comprehensive understandings on the velocity distribution and total energy loss coefficient at the junction region at a much wider range of branching angles and bed width ratios. The velocity distribution provides essential information on the vortexes and turbulence characteristics at the channel junction.

1.5 Scope and Limitations

The scope of this research is to investigate experimentally a branching channel flow system with a sand bed condition. The experimental work includes five branching angles (30°, 45°, 60°, 75° and 90°), three branching to main channel bed width ratios (30%, 40% and 50%) and five different total discharges for each case (7.25 L/s, 8.5 L/s, 9.75 L/s, 11 L/s and 12.25 L/s). The datasets are used to quantify and compare the different cases in terms of the branching channel water and sediment flow, scour depth, velocity distribution and total energy loss coefficient.

There are many variables that can be taken into account in the investigation of branching channel flow, but it is difficult to consider all of them. In this study, one type of bed material, sand soil with a medium diameter of 0.4 mm, specific gravity of 2.53 and standard deviation of 1.46 is used. Water and sediment are re-circulated during the experiment by collecting water at the ends of both the main and branching channels and pumping it to the upstream main channel and re-circulating again. A live bed load condition of the main channel at upstream with a velocity to threshold velocity of the sand movement of 1.1–1.5 is considered during the experiments to get an appropriate amount of sediment load into the branching channel to measure. The flow is subcritical with a Froude number around 0.3 for all the experiments.

Investigation the velocity distribution horizontally and vertically is limited only to highlight the flow-dividing pattern and the low and high velocity region not for developing a velocity model. The model scale is limited according to the available main channel flume, 12.5 m long and 0.313 m wide, and the space available for the fabricated branching channel flume, 2.75 m long, in the hydraulic laboratory at the Faculty of Engineering, Universiti Putra Malaysia.

1.6 Thesis Layout

This thesis is composed of five chapters. Chapter One, as shown above, presents a background about branching channel flow and its applications, the problems accompanying the flow phenomena, and the objectives of the study, together with the significance, scope and limitations of the current research.

Relevant literature is reviewed in Chapter Two. This Chapter extensively reviews the flow characteristics and the variables governing the flow in branching channels, the effect of the branching channel’s physical characteristics, such as the branching angle and bed slope, and the sediment transport behaviour in the branching channel flow system. The Chapter also reviews some case studies of practical applications of branching channels and previous modelling types, dimensions and specifications of branching channel flow. Finally, there is a summary of the literature review and the research gaps related to branching channel flow studies.

Dimensional analysis of the parameters governing the branching channel water discharge, sediment discharge, the scour depth, scour length and the total energy loss coefficient in the branching flow system are demonstrated in the third Chapter. Chapter Three also includes a description of the physical model of the branching channel system, the preparation of the experimental work, facilities, data collection, calibration of laboratory apparatus and the programme of experiments.

The results of the experiments are presented and discussed as graphs, tables and / or empirical equations for each objective of the study individually in Chapter Four. Chapter Four also includes a comparison between different cases and their effect on the flow phenomena. Finally, Chapter Five presents a summary and conclusions of the study, as well as suggestions for some work in the future.

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