Localized scour around setback abutment in compound channel

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**LOCALIZED SCOUR AROUND SETBACK
ABUTMENT IN COMPOUND CHANNEL**

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LOCALIZED SCOUR AROUND SETBACK ABUTMENT IN COMPOUND CHANNEL

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School of Civil and Environmental Engineering

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Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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SUMMARY

This study focused on localized scour formed around 45° wing-wall (WW) setback abutments in a compound channel. Fifty-five long duration scour experiments were carried out to investigate the effects of abutment length, width, degree of flow contraction on the floodplain, flow depth ratio and flow intensity (u/u_c) on the time development of the geometry of scour hole and its characteristics, up to the equilibrium scour conditions. Four different water depths were tested, and different discharges were used for each water depth to achieve various flow intensities under clear water scour conditions. Seven 45° wing-wall models were used in these experiments.

The experimental results showed that a secondary scour hole was formed immediately downstream the rear face of abutment models in some experiments. The longest abutment produces a secondary scour hole earlier compared to the shorter one. The narrowest model does not have a secondary hole. On the other hand, the widest model forms a secondary hole much later. The final shape of scour hole consists of a primary scour hole and a smaller secondary scour hole. The abutment width, floodplain flow depth, abutment length and flow intensity have profound effect on the formation of the secondary scour hole.

The results revealed that the location of maximum scour depth generally occurs slightly downstream of the wing-wall abutment nose. The maximum scour location, R_x is affected by the flow intensity, flow depth, and abutment aspect ratio, (i.e. its length and width). This location is shifted laterally further from the abutment nose as flow intensity decreases for the same abutment aspect ratio. On the other hand. The maximum scour location, R_y is only affected by flow depth, and abutment aspect ratio. However, previous studies suggested that this location is affected only by the relative abutment length.

Generally, it was observed that with an increase in relative abutment length, all dimensions of scour hole and its area and volume increase. Therefore, a shorter abutment

has smaller scour dimensions than the longer one. In addition, for high flow intensity, the values of these characteristics are greater than that of low flow intensity at the same value of abutment aspect ratio.

The abutment width has a significant effect on the characteristics of scour hole, contrary to the findings of previous studies. Generally, with an increase in abutment width, the scour depth and width decrease. Thus, the narrower abutment has larger scour depth and width than the wider one. Conversely, the scour length, area and volume initially increase with an increase in the relative abutment width and then these characteristics reduce significantly with much wider abutment.

The effect of increasing the abutment length on the scour depth and width was found to be greater than on the length of the scour hole. Moreover, the influence of decreasing the abutment width on the scour length was found to be less than on the depth and width of the scour hole.

It was found that the scour width is approximately equal to 3.5 times the floodplain water depth, and this is much wider than the recommended riprap apron extension of two times the floodplain water depth suggested by previous guidelines. Equations are proposed to predict the dimension of scour hole and its area and volume.

Finally, the exponential function was found to be suitable to represent the development of scour hole characteristics with time, and the proposed scour-time equations will be useful to calculate these characteristics when the flow does not last for sufficiently long time to reach its equilibrium scour conditions.

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LIST OF SYMBOLS

A_s	=	Scour area at a specified time
A_{se}	=	Equilibrium scour area
B	=	Width of channel
B_m	=	Width of the main channel
D_*	=	Dimensionless sediment diameter
$d_{15.9}$	=	Grain size of sediment diameter at which 15.9 % of sediment by weight goes through the sieve
d_{50}	=	Median diameter of sediment
$d_{84.1}$	=	Grain size of sediment diameter at which 84.1% of sediment by weight goes through the sieve
d_s	=	Maximum scour depth at a specified time
d_{se}	=	Equilibrium scour depth
F_c	=	Critical Froude number
F_o	=	Densimetric Froude number
F_{oe}	=	Equivalent densimetric Froude number
F_r	=	Upstream Froude number = $\frac{u}{\sqrt{Yg}}$
g	=	Gravitational acceleration

- h_f' = Un-constricted flow depth in the floodplain set by uniform flow downstream of the bridge (flow depth downstream of the abutment in the floodplain)
- K_s = Shape factor
- K_s' = Adjusted shape factor for intermediate abutment
- K_θ = Alignment factor
- K_θ' = Adjusted alignment factor for intermediate abutment
- L = Abutment length
- L_c = Abutment width
- L_e = Equivalent abutment length
- L_s = Maximum length of scour hole measured at 1 cm from the tip of abutment at a specified time
- L_{se} = Maximum length of scour hole measured at 1 cm from the tip of abutment at the equilibrium state
- M = Discharge contraction ratio defined by the ratio of unobstructed discharge in the approach section to the total discharge = $(Q - Q_{\text{obst}}) / Q$
- m = Opening ratio = $((B-L)/B)$
- Q = Total discharge
- Q_a = Flow intercepted by abutment
- Q_{obst} = Discharge obstructed by the abutment in the approach section
- Q_w = Flow related to specific width of channel at end of abutment

- q_{f1} = Flow rate per unit width in the approach section of floodplain
- q_{f0c} = Critical flow rate per unit width in the approach section of floodplain
- R = Radial distance from the centerline of abutment face to the position of maximum scour depth $= \sqrt{R_x^2 + R_y^2}$
- R_e = Reynolds number $= \frac{u y}{\nu}$
- R_x = Normal distance from abutment face to the location of maximum scour depth
- R_y = Distance from the centerline of abutment face to the location of maximum scour depth parallel to flow direction
- S = Specific gravity of sediment
- t = Scour time
- t_e = Equilibrium time of scouring process
- u = Approach velocity of flow
- u_{*1} = Approach flow shear velocity
- u_c = Critical mean velocity for sediment motion
- u_{*c} = Shields critical shear velocity for particle motion
- u_e = Width average velocity
- u_f = Mean flow velocity at the approach section of floodplain
- V_{30} = Volume of scour hole at scour time of 30 hr
- V_s = Scour volume at a specified time

V_{se}	=	Equilibrium scour volume
W_s	=	Width of scour hole measured from the tip of the abutment at a specified time
W_{se}	=	Width of scour hole measured from the tip of the abutment at a specified time
y	=	Approach water depth in rectangular channel
y_f	=	Flow depth of flood plain at the approach section
y_m	=	Flow depth of main channel at approach section
ϕ	=	Angle of repose of sediment
α	=	Angle of attack
θ	=	Angle between the location of maximum scour depth and the centerline of abutment face
θ_c	=	Shields' entrainment function
μ	=	Dynamic viscosity of water
ν	=	Kinematic viscosity of water
ρ	=	Density of water
ρ_s	=	Density of sediment
Δ	=	Specific submerged density $(\rho_s - \rho) / \rho$
σ_g	=	Standard deviation of the sediment size distribution $= (d_{84.1} / d_{15.9})^{0.5}$
γ	=	Specific weight of water

γ_s = Specific weight of sediment

CHAPTER 1 INTRODUCTION

1.1 Background

Flood plains and main channels around bridge foundations are usually subject to the excessive water flowing due to narrowing of water cross section within bridge opening. The motion of sediments from flood plains and main channels by action of moving water can cause erosion or local scour. The rate of scouring is usually high during flood due to large volume of water resulting from rains. Bridges play an essential part for any transportation network. Many bridges are built over streams and rivers. The construction of bridges facilitates the movement of people and goods across river banks. After construction, the foundation may be threatened by localized scour (contraction and local scour) due to a reduction of flow cross section area of water and an increase of local velocities at the bridge location.

Hence, many researchers and scientists have studied scour around bridge foundations as this phenomenon may threaten the stability of the foundations and may cause failure of the bridges. In addition, it may lead to loss of life. It was reported that during the last 30 years, 60% of the thousands of bridge failures in the U.S.A were associated with foundation scour (Shirole, 1991; Lagasse et al., 2007). These failures cause large financial losses in terms of rehabilitation and reconstruction. In 1994 due to flooding from the tropical storm Alberto in Georgia, more than 100 bridges have been reconstructed and renovated, and the cost of these works was US \$130 million (Richardson and Davis, 2001). The FHWA (Federal Highway Administration) remarked that the situation of 20,094 bridges in the U.S.A are found to be susceptible to serious scour (Gee, 2008; Xiong, 2016).

During the last three decades many studies have been done on scour around pier and abutments, such as Melville and Sutherland (1988), Melville (1992, 1995), Sturm (1994, 2006), Lim (1997), Kandasamy and Melville (1998), Oliveto and Hager (2002, 2005), Dey and Barbhuiya (2005), Cardoso and Fael (2010) and Lança et al. (2013). Previous

studies succeeded in reasonably predicting pier scour, but in the case of abutment scour, it seems there is a lack of a generalised formula that can be applied to a wide range of cases, as reported in a recent study by Hong (2012). A comparison between researches on abutment and pier scour shows that the effects of some variables such as abutment aspect ratio or effects of abutment width are still not well defined and understood (Sturm et al., 2011).

Richardson et al. (1993) and Hong (2012) reported that prediction of scour depth using existing equations usually overestimate that of the field observation and this increase the cost of construction of bridges. Moreover, most of the experiments in previous studies were carried out for abutment sited in straight rectangular flumes although natural channels shapes are usually compound (i.e. main channel and one or two floodplains). For the latter there were few studies on scour around abutment terminated in flood plain such as Sturm (1994, 2006), Kouchakzadeh and Townsend (1997), Cardoso and Bettess (1999), Lim and Nugroho (2005). Richardson et al. (1993) pointed out that abutment scour in two-stage channels cannot be determined using the results from rectangular channels. Moreover, Ettema et al. (2010) and Hong (2012) remarked that many predictive formulas for abutment scour overpredict the scour depth, and one reason is that the effects of geometry of channel, particular for compound channel has not been fully accounted for in the predictive equations. Most of the previous studies were conducted on either short or long abutments. However, abutments are usually neither short nor long, but rather intermediate (Mohammadpour, 2012). In addition, Yorozyua (2005) and Ettema et al. (2010) reported that many abutments have shape of spill-through or wing-wall. Also, Sturm et al. (2011) found there is a lack of knowledge regarding scour characteristics around wide abutments.

Link et al. (2008) reported that there is a lack of information related to temporal development of scour hole characteristics (depth, length, width, surface area and volume). Studies on the effects of abutment length and width on the time development of the topography of scour hole are also very limited (Kose, 2007; Yildiz, 2014). In addition, the location of maximum scour depth is an important characteristic of the scour

hole for wing-wall (WW) abutment, and it has not received much attention. When this location occurs far from the abutment tip and moves near to the bankline of the channel, this position may threaten the geotechnical stability of the bank between floodplain and main channel and causes its failure (Ettema et al., 2010). This parameter is especially useful for the design of scour countermeasure (Ballegooy, 2005).

1.2 Objectives

The objectives of the present study are:

- To determine the geometry of scour hole formed around 45° wing-wall setback abutments in compound channel and the effects of abutment length, abutment width, flow intensity and flow depth ratio on the local scour.
- To give better understand regarding the location of the maximum scour depth around 45° wing-wall setback abutments in compound channel under different hydraulic conditions.
- To determine the dimensions of scour hole (length, width, depth, surface area) and its volume around narrow and wide abutments at the equilibrium state using different lengths of wing-wall abutments in the intermediate length category under various flow depth ratio in compound channel.
- To give better understand regarding the temporal development of scour hole characteristics (length, width, depth, surface area and volume) with time.

To achieve the goals, series of long duration scouring experiments were carried out and data from the literature were compiled with data of the present study in the analysis of the controlling parameters.

1.3 Organization of thesis

This thesis comprises five chapters. Chapter 1 deals with the background, objectives and motivation of the present study. Chapter 2 gives a review of previous works regarding the geometry of scour hole, the position of maximum scour depth, scour hole characteristics at the equilibrium state and the temporal development of scour hole characteristics. Chapter 3 outlines the experimental setup, apparatus, material and procedures used to carry out the experiments. The hydraulic conditions of these experiments are also provided. Chapter 4 presents the experimental results from the present and previous studies concerning the geometry of scour hole, the location of deepest point of scour hole, scour hole characteristics at the equilibrium state and the temporal development of scour hole characteristics. Prediction equations are also suggested to estimate the aforementioned characteristics. Chapter 5 summarizes the conclusions drawn from the present study and suggests further investigations for the future work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Scour of alluvial channels is a problem attracted a great attention in hydraulic engineering because it affects the stability of hydraulic structures. Localized scour has led to the collapse of many bridges around their foundations, which consist mainly of pier and abutment, and these collapses typically happened suddenly (see Figure 2.1). Kattel and Eriksson (1998) claimed that bridge scour is a major reason of highway bridge failures in the U.S.A. The “Transportation Research Board” reported in 1997 that there were 488,750 bridges in the Unites States, and the cost for bridge failures due to scour was evaluated at \$30 million/year. In addition, Kandasamy and Melville (1998) mentioned that 60% of the bridge collapses in New Zealand during Cyclone Bola were associated with abutment scour.

Figure 2.1: Failure due to scour around wing-wall abutment photo from NCHRP 24-27(2)

This chapter reviews the state of knowledge regarding the geometry of scour hole, the location of maximum scour depth, the scour hole characteristics (length, width, depth, area and volume), and time development of these characteristics. The current study aims to investigate the aforementioned scour characteristics in compound channel since past studies have focused mainly on the prediction of scour depth around abutment in rectangular channel and few studies have been conducted in compound channels. Through the literature, the relevant findings of previous studies are highlighted and presented in association with the objectives of the present study.

2.2 Definition of scour and its types

Scour can be defined as the removal of alluvial beds and banks by action of flowing water. It can occur naturally or manmade (Breusers and Raudkivi, 1991). Scour can occur at any time and was found to be high during flood period. An illustration of the various types of scour is given in Figure 2.2.

The scour can be divided into (Breusers and Raudkivi, 1991; Melville and Coleman, 2000; Arneson et al., 2012):

- **Local scour**

Scour directly occurs from the presence of structural elements (i.e. piers and abutments) in the flow, and this is because of local changes in flow pattern and turbulence level in the vicinity of these elements.

- **Contraction scour or constriction scour**

This occur when a section of the channel is narrowed either by pier, abutment or natural embankment, so the flow area at the contracted section will decrease, causing increase in flow velocity near these elements.

Figure 2.2: Types of scour which can happen at a bridge (Melville and Coleman, 2000)

- General scour

This include other types of scour that are not covered by the local and contraction scour. It occurs regardless of presence of bridge structure and is related to changes in fluvial or geomorphic or hydrometeorological conditions such as bed degradation.

There is also a different classification of scouring that is applicable in terms of different conditions of sediment transport:

- Clear water scour

This is the case when the approaching flow does not convey any sediment to the scour hole, and the scour will progress until the boundary shear stress of the scour hole is less or equal to the critical shear stress for sediment entrainment.

- Live bed scour

This is the case when the approaching flow continuously feeds the scour hole with sediments, and the scour will continue until the rate of sediment transported into the scour hole equals the rate of sediment leaving it.

Figure 2.3 shows that the maximum scour depth for live bed is smaller than for clear water scour.

Figure 2.3: Variation of scour depth with time for live-bed and clear-water scour (Melville and Coleman, 2000)

2.3 Mechanism of scour

Localized scour refers to the scouring around piers and abutments, and the scour processes are relatively similar (Melville and Colman, 2000). Extensive research on scour around abutments were conducted at the University of Auckland (Wong, 1982; Tey, 1984; Kwan, 1984, 1988; Kandasamy, 1985, 1989; Dongol, 1994; Melville and Coleman, 2000).

Detailed flow around abutments has been measured by Kwan (1988) and reported in Breusers and Raudkivi (1991). The main features of the flow around abutment are sketched in Figure 2.4 and these are:

- a) Surface roller - because of the existence of abutment, water surface slightly increases at the upstream face of abutment.
- b) Downflow - when the flow touches the upstream of abutment the stagnation pressure decreases along the height of abutment causing downflow.
- c) The principal vortex - this is quite similar to the horse shoe vortex at pier. It starts at the upstream head of the abutment, moves towards the bed and sediments are eroded from the entrainment zone.
- d) The wake vortices - after the flow separates at the nose of abutment, wake vortices are formed downstream of the abutment nose as a result of unstable shear layers.

The principal vortex is considered a main agent of the scour process (Barbhuiya and Dey, 2004).

Figure 2.4: Flow structure at wing wall abutment (Breusers and Raudkivi, 1991)

Figure 2.5: Definition sketch of scour hole around abutment

2.4 Geometry of scour hole

The geometry of scour hole is highly affected by flow structure around abutment and properties of sediments (Zhang et al., 2012). In addition, the shape of scour hole has a profound effect on aquatic habitat and stability of bank (Kuhule, 1999). The scour usually starts at the upstream of the abutment nose and as time increases, the scour hole increases in size. However, the location of maximum scour depth depends on the shape of abutment and flow conditions. Therefore, the maximum scour depth is more likely to occur slightly downstream of the abutment nose for wing-wall abutment (Kose, 2007). On the other hand, the maximum scour depth for vertical-wall abutment mostly occurs just upstream of the abutment nose (Oliveto and Hager, 2002). The final shape of scour hole is usually an inverted cone centred at abutment nose (Kose, 2007). Few studies have been conducted regarding the geometry of scour hole around abutment.

Nugroho (2006) reported that there were three different shapes of scour hole formed around vertical-wall setback abutment in compound channel, namely the inverted cone type, the edge-truncated inverted cone type and the extended upstream edge-truncated inverted cone type (See Figures 2.6 to 2.8). First shape consisted of one scour hole which extended only around abutment nose whereas in the second shape, the scour hole extended around abutment nose and touched the flume wall. Finally, the third shape consisted of a smaller secondary scour hole upstream the main scour hole. He remarked that first and second shapes were more likely to occur with relatively deep water depth in flood plain, whereas last shape usually occurred with shallow water in flood plain.

Figure 2.6: Definition sketch of the inverted cone scour hole (Nugroho, 2006)

Figure 2.7: Definition sketch of the edge-truncated inverted cone scour hole (Nugroho, 2006)

Figure 2.8: Definition sketch of the edge-truncated inverted cone scour hole with a secondary upstream edge scoured zone (Nugroho, 2006)

Xiong et al. (2013) studied the effect of abutment width on the topography of scour hole, the surface velocity field and the equilibrium scour depth around vertical-wall abutment sited in rectangular channel which had width of 154 cm. They tested four models and grouped their experiments into four groups to cover different flow conditions for narrow and wide abutments. For each group, two abutment models were used. First one had width of 110 cm, but second one had width of 5 cm. Their experiments had a constant water depth of 10 cm. Groups 1 and 3 had the same flow intensity (i.e. $u/u_c = 0.65$). On the other hand, the length of abutment models of Group 1 was 40 cm and the length of abutment models of Group 3 was 80 cm. Groups 2 and 4 had the same length as Groups 1 and 3, respectively, but they had higher flow intensity (i.e. $u/u_c = 0.9$). They reported that for Groups 1 and 3, there were a smaller scour hole downstream the rear face of abutment, whereas it is clear from Figure 2.9 that for Groups 2 and 4, the smaller scour holes are merged with the primary scour hole which is located at abutment nose. Therefore, for the same wide abutment, the formation of secondary scour hole is highly sensitive to flow intensity. They also measured the stream-wise and span-wise velocities at fixed bed and scoured bed after equilibrium. Finally, they found there was very little difference between scour depths using the wide and narrow models.

Group 1

Group 2

Figure 2.9: Topography of scour hole at the equilibrium state (Xiong et al., 2013)

2.5 Location of maximum scour depth

The location of maximum scour depth is an important characteristic of the scour holes formed around abutment. It refers to the location of severe scour around abutment. It is especially useful for the design of scour countermeasure (Ballegooy, 2005). Therefore, the prediction of this location can reduce the cost of scour countermeasure as the countermeasure can be extended only around this location to cover the dimensions of scour hole. The previous guidelines such as Richardson and Davis (1995), Morales et al. (2008) and Federal Highway Administration (FHWA) (2009) suggested to extend the scour countermeasure around whole perimeter of abutment face (see Figure 2.10). When this location occurs far from the abutment tip and moves near to the bankline of channel, this position threatens the geotechnical stability of the bank between floodplain and main channel which causes its failure (Ettema et al., 2010). Furthermore, the prediction of this location will be useful to estimate the minimum distance required to construct the neighbouring pier and river training works so as to prevent undermining of these structures due to the existence of the severe scour location nearby (Abid and Hong, 2018). This scour characteristic has not received much attention in the past (Tey, 1984; Ballegooy, 2005; Abid and Hong, 2018). Studies on the position of maximum scour depth are presented in this section.

Tey (1984) studied the location of maximum scour depth around 45° wing-wall and 1:1 spill-through abutments in rectangular channel. He concluded that for shallow water depth with high flow intensity (i.e. $y = 5$ cm and $u/u_c = 0.95$), the location moved from a location abreast and perpendicular to the abutment tip to just upstream of the abutment tip during the development of scour. He stated that this was due to the changes of down flow during the progress of scour hole. His conclusion was based on the observation of only three experiments (i.e. two for wing-wall and one for spill-through) which are preliminary to conclude any definitive trend for this location.

Figure 2.10: Definition sketch for the extension of apron around a spill-through in compound channel (Richardson and Davis, 1995)

To observe the position of maximum scour depth around spur dikes under clear water overtopping flow, Kuhnle et al. (1999) conducted experiments on two models. He reported that the ratio between flow depth and abutment height and flow intensity had a significant effect on this location. Higher values of this ratio (i.e. ratio between flow depth and abutment height > 2) moved the position of maximum scour to the wall of channel and caused formation of a secondary scour hole downstream of the spur dikes.

Sturm (2006) did two experiments to investigate the position of maximum scour depth around vertical-wall in compound channel. He stated that for a given water depth when the discharge decreases, this location shifts towards the bankline of channel. In other

words, when flow intensity reduces, the location of maximum scour depth moves further to the centreline of the channel.

Ballegooy (2005) and Melville et al. (2006) observed the location of maximum scour depth around spill-through setback erodible abutment protected by countermeasure (i.e. riprap and cable tied block) in different sizes of compound channels. They defined this location in terms of the radial distance from abutment face to the position of maximum scour depth (R) and the angle (θ). They found that as abutment length increase, the location shifts away from abutment face. In addition, as the apron width increase the scour hole migrates further away from the abutment face. They also remarked that the location is not affected by floodplain width. Finally, they proposed the following equations to predict R and θ as follows:

$$\frac{R}{y_f} = C_1 \left(\frac{L}{y_f} \right)^{0.2} \left(1 + \frac{W}{y_f} \right)^{a_1} \quad (2.1)$$

$$\frac{\theta}{y_f} = C_2 \left(\frac{L}{y_f} \right)^{0.7} \left(1 + \frac{W}{y_f} \right)^{a_2} \quad (2.2)$$

where R is the radial distance from abutment face to the position of maximum scour depth, θ is the angle between the location of maximum scour depth and the centerline of abutment face, L is the abutment length, y_f is the flow depth of the floodplain at the approach section and W is the width of apron. C_1 , C_2 , a_1 and a_2 are constants which rely on protection type. For cable tied block, $C_1 = 1$, $C_2 = 2.2$, $a_1 = 0.9$ and $a_2 = 0.4$, whereas for riprap, $C_1 = C_2 = 4$, $a_1 = 0.4$ and $a_2 = 0.1$.

Zhang et al. (2012) attempted to study the maximum scour location around vertical-wall abutment in rectangular channel. He concluded that scouring which starts at the abutment tip and the maximum scour depth remains at the same location around the abutment tip because of the continuous strong vortex action when the flow intensity is high. On the other hand, for low flow intensity, the flow is relatively weaker, and the vortex formation is further from the abutment face causing the maximum scour location to be deflected more laterally. As result, as the flow intensity decreases, the location of

maximum scour depth shifts further laterally from the abutment nose to the centerline of flume.

Yorozuya and Ettema (2015) experimentally studied the position of maximum scour depth around spill-through setback erodible abutment to check the geotechnical stability of erodible embankment. They used similar coordinates of Ballegooy (2005) and Melville et al. (2006) (see Figure 2.11). They remarked that when this location occurs near to the bankline, it threatens the stability of embankment. In addition, as the relative abutment length increases, the position moves further away from the abutment face. They also found that the location generally occurs at the rear face of abutment nose due to partial failure of erodible abutment at the end of experiments as shown in Figure 2.11. Finally, they compared their data with equation suggested by Melville et al. (2006), but they modified this equation to be applicable for erodible abutment without countermeasure as follows:

$$\frac{R}{y_f} = 4 \left(\frac{L}{y_f} \right)^{0.2} \quad (2.3)$$

Figure 2.11: The position of deepest point of scour hole for erodible spill through abutment (Yorozuya and Ettema, 2015)

2.6 Abutment scour studies

2.6.1 Prediction of scour hole dimensions around abutment in rectangular channels

Early studies associated to abutment scour focused on the prediction of the maximum scour depth, whereas the studies on other dimensions such as scour hole length, width and volume are very limited (Wu, 2014). The latter dimensions are very useful for the estimation of scour countermeasure because the countermeasure can be extended only to cover scour hole length and width instead of covering whole perimeter of abutment face as suggested by the existing guidelines such as Richardson and Davis (1995). This will save the cost of countermeasure extended to other areas around abutment which are not affected by severe scour compared to area around abutment nose.

Laursen (1960) argued the contraction ratio caused by the abutment would not affect local scour if the scour hole did not stretch to the other flume wall. He modified a formula of scour in long contraction and applied to abutment and pier by assuming that the scour width around these structures was roughly 2.75 times the scour depth in a long contraction.

Based on experiments done on rectangular channel, Liu et al. (1961) concluded that the length over flow depth ratio, L/y and the Froude number, F_r were the main factors affecting dimensionless scour depth, and they also suggested the following equations for clear water and live-bed scour.

$$\frac{d_{se}}{y} = 1.1 \left(\frac{L}{y} \right)^{-0.781} F_r^{0.22} \quad \text{vertical-wall abutment} \quad (2.4)$$

$$\frac{d_{se}}{y} = 1.1 \left(\frac{L}{y} \right)^{-0.781} F_r^{0.33} \quad \text{wing-wall abutment} \quad (2.5)$$

They suggested other equations for $\left(\frac{L}{y} \right) > 25$ and Equations (2.4) and (2.5) would become

$$\frac{d_{se}}{y F_r^{0.22}} = 4 \quad \text{and} \quad \frac{d_{se}}{y F_r^{0.33}} = 7.8, \text{ respectively.}$$

where d_{se} = equilibrium scour depth, L = abutment length, y = approach water depth, Froude number,

$$F_r = \text{upstream Froude number} = \frac{u}{\sqrt{gy}}$$

where u = approach velocity of flow, g = gravitational acceleration.

Gill (1972) reported the role of sediment size and flow depth on equilibrium scour depth and did not discuss the effect of abutment length. He observed that the development of scour in coarse sand is less than for fine sand. He also found that contraction ratio and ratio of sediment size to approach depth had a profound effect on maximum scour depth.

Zaghloul (1983) studied the effects of sediment properties, abutment lengths, angles of spur dike and different upstream flow conditions on scour around it. He claimed that scour depth was dramatically affected by the contraction ratio between the unblocked width of channel to total width of channel and upstream Froude number. He also derived a formula to predict the equilibrium scour depth around spur dike by using dimensional analysis and multiple linear regression as follows:

$$\frac{d_{se}}{y} = 2.62 m^{-1} \alpha^{-0.043} F_r^{2/3} \quad (2.6)$$

where m = opening ratio $((B - L)/B)$, B = width of channel, α = angle of attack.

Melville (1992, 1997) used the extensive laboratory data of Auckland University to develop empirical scour relationship based on parameters such as abutment length, shape, alignment, approach water depth, flow intensity, channel alignment and sediment sizes. This attempt is an extension to Melville and Sutherland's (1988) approach for scour around pier. He divided abutment into three types: short abutment (abutment length to flow depth, $L/y < 1$), long abutment ($L/y > 25$) and intermediate abutment ($1 < L/y < 25$). The equations are as follows:

$$d_{se} = 2 K_s L, \text{ for } \left(\frac{L}{y}\right) < 1 \text{ short abutment} \quad (2.7)$$

$$d_{se} = 2 K_{\theta}' K_s' \sqrt{Ly}, \text{ for } 1 < \left(\frac{L}{y}\right) < 25 \text{ intermediate abutment} \quad (2.8)$$

$$d_{se} = 10 K_{\theta} y, \text{ for } \left(\frac{L}{y}\right) > 25 \text{ long abutment} \quad (2.9)$$

where K_s = shape factor, K_{θ} = alignment factor, K_s' = adjusted shape factor for intermediate abutment, K_{θ}' = adjusted alignment factor for intermediate abutment. These factors are given as follows:

Table 2.1: Abutment shape factors proposed by Melville (1992, 1997)

<u>Abutment model shape</u>	<u>Shape factor K_s</u>
Vertical-wall abutment	1.00
Vertical-wall abutment with rounded end	0.75
45° wing-wall abutment	0.75
Spill-through abutment (0.5:1)	0.60
Spill-through abutment (1:1)	0.50
Spill-through abutment (1.5:1)	0.45

$$K_{\theta}' = K_{\theta}, \text{ for } \left(\frac{L}{y}\right) \geq 3 \quad (2.10)$$

$$K_{\theta}' = K_{\theta} + (1 - K_{\theta}) \left(1.5 - 0.5 \frac{L}{y}\right), \text{ for } 1 < \left(\frac{L}{y}\right) < 3 \quad (2.11)$$

$$K_{\theta}' = 1, \text{ for } \left(\frac{L}{y}\right) \leq 1 \quad (2.12)$$

$$K_s' = K_s, \text{ for } \left(\frac{L}{y}\right) \leq 10 \quad (2.13)$$

$$K_s' = K_s + (1 - K_s) \left(0.1 \frac{L}{y} - 1.5\right), \text{ for } 10 < \left(\frac{L}{y}\right) < 25 \quad (2.14)$$

$$K_s' = 1, \text{ for } \left(\frac{L}{y}\right) > 25 \quad (2.15)$$

For long abutment, it was found that, scour depth depends on flow depth, whereas for short abutment, scour depth depends on abutment length. Moreover, for intermediate abutment, scour depth depends on both water depth and abutment length. He assumed vertical-wall abutment is the reference model which means that this model has shape factor of unity. He also assumed that scour depth is not affected by sediments when $\frac{L}{d_{50}} > 50$. The limitation of this investigation is that the prediction using this method is more likely to be overestimated as it depends on enveloping curves which leads to unnecessary cost regarding bridge foundations construction.

Lim (1997) pointed out that the duration required for achieving equilibrium scour depth is long, from 3 days to 8 days for his test conditions and this duration depends also on the flow and properties of sediment. He proposed a semi-empirical formula to predict equilibrium scour depth for clear water scour on the basis of flow and the continuity equation and the geometry of scour hole. It was found that the shear stress of bed increases because of the presence of abutment in the flow, and this is the main reason of scour around abutment. Lim's formula is as follows:

$$\frac{d_{se}}{y} = K_s \{0.9X - 2\} \quad (2.16)$$

$$X = \left\{ \theta_c^{-0.375} F_o^{0.75} \left(\frac{d_{50}}{y} \right)^{0.25} \left[0.9 \left(\frac{L}{y} \right)^{0.5} + 1 \right] \right\} \quad (2.17)$$

$$F_o = \frac{U}{\sqrt{g(S-1)d_{50}}} \quad (2.18)$$

Equation (2.16) is valid for $X > 2.22$ and it gives $\frac{d_{se}}{y} = 0$ when $X = 2.22$

where θ_c = shields' entrainment function, F_o = densimetric Froude number, d_{50} = median diameter of sand, and S = specific gravity of sand.

Lim and Cheng (1998) suggested a semi-empirical formula to predict the equilibrium scour depth for live-bed abutment scour. It relied on flow and sediment mass continuity equation, the geometry of scour hole and flow resistance, as follows:

$$\left(1 + \frac{d_{se}}{2y}\right)^{4/3} = \frac{1 + 1.2 \sqrt{\frac{L}{y}}}{\sqrt{\frac{u_{*c}^2}{u_{*1}^2} \left(\frac{L \tan \phi}{d_{se}} + 1\right)^{2/3} \left(1 - \frac{u_{*c}^2}{u_{*1}^2}\right)}} \quad (2.19)$$

The equation can be reduced to Equation (2.16) mentioned above for clear water scour for $u_{*c}/u_{*1} \geq 1$ where u_{*1} = approach flow shear velocity, u_{*c} = Shields critical shear velocity for particle motion and ϕ = angle of repose of sediment.

Kuhnle et al. (1999) studied the volume and depth of scour around spur dikes under clear water overtopping flow and found that the ratio between flow depth and abutment height had a significant effect on geometry of scour hole. Higher values of this ratio moved the position of maximum scour to the bank of channel. They suggested a formula to predict depth and volume of scour. They depended on the work of Melville (1992) to derive this relationship,

$$\frac{d_{se}}{y} = 1.12 K_M \left(\frac{L}{y}\right)^{(1-\delta)} \quad (2.20)$$

$$\frac{V_{30}}{(d_{30})^3} = 17.106 \left(\frac{L}{y}\right)^{-0.781} \quad (2.21)$$

The range of L/y from 0.5 to 1.6 and y from 0.2 to 0.3, and $K_M = 0.56$ to represent the effect of overtopping flow, V_{30} = volume of scour hole at scour time of 30 hr, d_{30} = maximum scour depth at time of 30 hr.

Oliveto and Hager (2002, 2005) carried out experiments for vertical, sloping abutments and circular piers using six different types of uniform and non-uniform sediments. It was found that the area around abutment face has the maximum shear stress and the maximum scour depth occurred here. They pointed out that the scour depth relies on densimetric Froude number of sediment mixture. They proposed a formula to predict scour depth in terms of time and emphasized that the scour evolution over time is much more significant than equilibrium scour depth.

Kuhnle et al. (2002) used three models of wing-wall abutments and installed them at angles of 45° , 90° , and 135° to the flow direction and they used two contraction ratios of 0.125 and 0.250 (see Figure 2.12). They found that wing-wall with angle of 90° produced the least scour volume, while wing-wall with angle of 135° generated the highest scour volume.

Figure 2.12: Dimensions of spur dike model, angle to flow direction Θ was 45° , 90° , and 135° (Kuhule et al., 2002)

Dey and Barbhuiya (2004) investigated scour around a short abutment ($L/y \leq 1$) for three types of abutments: (vertical-wall, semi-circular and 45° wing-wall) (for uniform and non-uniform sediments). The ratios between stream wise length and span wise length of abutment for the vertical and semi-circular shapes was 2 while it was 3 for the wing wall. They remarked that the equilibrium scour depth reduced with abutment length. The flow depth had a smaller effect on the equilibrium scour depth for higher flow depth compared to lower flow depth as models were short abutments. The sediment gradation had a profound effect on scour depth for non-uniform sediment because an armour layer was formed inside scour hole which reduced scour compared to tests using uniform sediments. The scouring duration of their experiments was 48-50 hr, and

therefore the scour might not have reached equilibrium. They proposed the following equations:

$$\frac{d_{se}}{L} = 5.857 F_o^{0.314} \left(\frac{y}{L}\right)^{0.128} \left(\frac{L}{d_{50}}\right)^{-0.167} \text{ for vertical-wall abutment} \quad (2.22)$$

$$\frac{d_{se}}{L} = 6.484 F_o^{0.312} \left(\frac{y}{L}\right)^{0.101} \left(\frac{L}{d_{50}}\right)^{-0.231} \text{ for } 45^\circ \text{ wing-wall abutment} \quad (2.23)$$

$$\frac{d_{se}}{L} = 7.287 F_o^{0.192} \left(\frac{y}{L}\right)^{0.103} \left(\frac{L}{d_{50}}\right)^{-0.296} \text{ for semi-circular abutment} \quad (2.24)$$

Using data from other sources, they found that there is general agreement that an increase in the approach water depth leads to an increase in the equilibrium scour depth at decreasing rate until limit of water depth. After this limit, scour depth is no longer affected by water depth, as shown in Figure 2.13.

Figure 2.13: Variation of scour depth with flow depth (Barbhuiya and Dey, 2004)

Ong et al. (2004) used dimensional analysis and multiple linear regression analysis to make a model for estimation of equilibrium scour depth around vertical abutment embedded in light weight bed material with specific gravity = 1.05. They found that abutment scour was significantly affected by sediment density and densimetric Froude number,

$$\frac{d_{se}}{y} = \left\{ 1.86 \left(\frac{L}{y} \right)^{0.92} F_o^{1.41} \left(\frac{d_{50}}{y} \right)^{0.32} \left(\frac{\gamma_s - \gamma}{\gamma_s} \right)^{0.4} \right\} \quad (2.25)$$

where γ = specific weight of water, γ_s = specific weight of sediment. To compare results with different shapes, they used K_s = shape factor, K_θ = alignment factor suggested by Melville (1992), so the equation will be

$$\frac{d_{se}}{y} = \left\{ 1.86 K_s K_\theta \left(\frac{L}{y} \right)^{0.92} F_o^{1.41} \left(\frac{d_{50}}{y} \right)^{0.32} \left(\frac{\gamma_s - \gamma}{\gamma_s} \right)^{0.4} \right\} \quad (2.26)$$

Kayaturk (2005) measured the scour depth around vertical-wall abutment in uniform sand with $d_{50} = 1.48$ mm. They used five models having width of 10, 20, 30, 40 and 50 cm and a blockage ratio of 16.7% with three water depth of 10, 12, 14 cm. They found that scour decreases as the abutment width increases especially at shallow water depth.

Fael et al. (2006) experimentally investigated scour characteristics, i.e. length, width, depth and volume around intermediate and long vertical-wall abutment (i.e. $2 < L/y < 100$) using sand and pumice under clear water and live bed conditions (i.e. $0.39 < u/u_c < 1.1$). They pointed out that the scour characteristics for sand was slightly higher than that of pumice under the same flow conditions, although sand and pumice had the same of median size of sediment (i.e. $d_{50} = 1.28$ mm). They also found that these scour characteristics increased with an increase in L/y and u/u_c . Finally, they proposed an equation to estimate the flow intensity required for scour inception at abutment tip because past studies reported this value based on optical observation of scour at abutment tip. The advantage of this study is that their experiments are sufficiently long up to the equilibrium state. On the other hand, Kose (2007) studied scour depth and area and volume of scour at the end of 150 minutes scouring duration. Therefore, he extrapolated

his data to compare them with previous studies which their experiments achieve the equilibrium state such as Melville (1992) and Oliveto and Hager (2002, 2005).

To investigate the scour depth and width around vertical-wall abutment in rectangular channel, Abousedia et al. (2009) conducted experiments using three abutment models in sand with $d_{50} = 0.38$ mm. They found that the equilibrium scour depth relied on the abutment length and Froude number. They also concluded that scour widths were approximately equal to 1.8 times the scour depths.

Yildiz (2014) studied the scour characteristics, i.e. length, width, depth and volume around short and intermediate vertical-wall abutment with rounded edge (i.e. $1 < L/y < 2.5$). He tested his experiments for 8 hours. This is too short to achieve the equilibrium state and might lead to unrealistic results. He concluded that these scour characteristics relied on the abutment length. This is consistent with Melville (1992) for short abutment. In addition, he reported that the effect of abutment length on the scour depth was higher than that of the height of sand ridge downstream scour hole.

Wu and Balachandar (2014, 2015) measured the scour profiles at many sections (three each in the stream-wise and span-wise directions) around semi-circular abutment in uniform sand with $d_{50} = 0.77$ mm. They used three models having radius of 21, 36.5 and 60 mm and two blockage ratios of 7.5% and 10%. They found that scour width and depth decrease as the relative bed coarseness L/d_{50} increases. These characteristics also increase as the approach water depth increases. They suggested that the relative bed coarseness L/d_{50} should be considered as a separated term in the scour prediction equations. The limitations of this study are that they last their experiments for 48 hours which is not long enough to reach equilibrium. In addition, they used only one sediment. Therefore, their suggestion to use relative bed coarseness in the prediction equations is rather preliminary as the experiments does not cover wide range of sediments. Finally, they reported that d_s/L decreases with an increase in L/d_{50} . This trend because d_s is normalized by L and d_s may be small for shorter abutment, while for shorter model d_s/L is higher than of longer one. Although for a given abutment length when sediment size

reduces, d_s/L should be higher. Lee and Sturm (2009) and Heller (2011) also suggested that the effect of L/d_{50} should be considered from point of view of scale effect.

2.6.2 Prediction of scour hole dimensions around set back abutment in compound channels

Most rivers and streams naturally have a compound cross section consisting of main channel and flood plains. Rivers can have one or two flood plains in accordance with their effective discharge and geomorphic changes that occur along the river path. Richardson et al. (1993) commented that the results from rectangle channels could not exactly represent the process of abutment scour in two-stage channels. In addition, the distribution of velocity around abutment in compound channel is different compared to that in rectangular channel (Richardson et al., 1993; Hong, 2012). Morales and Ettema (2013) reported for abutment models with small length in flood plain cannot simulated using abutment models in rectangular channel because of flow interaction between flood plain and main channel. Therefore, some researchers do experiments in two-stage flume to be similar to the natural river. Review shows that studies on scour hole characteristics around setback abutment are limited.

Sturm and Janjua (1994) performed experiments to study scour around abutment terminating in flood plain. They defined two parameters: (a) Froude number ratio (the ratio between upstream Froude number to critical Froude number), (b) discharge contraction ratio (the ratio between discharge per unit width in floodplain at upstream section to contracted discharge per unit width at abutment section). The discharge ratio represents the effect of geometry of channel, and critical Froude number represents the effect of sediment size. They suggested Equation (2.29) based on the aforementioned parameters to predict scour depth. The limitation of this study is that the discharge contraction ratio (i.e. M) is calculated using numerical model. Therefore, the accuracy depends on the efficiency of this model and type of numerical model.

Figure 2.14: Definition sketch of discharge contraction ratio M (Sturm and Janjua, 1994)

$$M = \frac{Q_{m1} + Q_{f1a}}{Q_{m2} + Q_{f2}} \quad (2.27)$$

$$F_C = 2.27 \left(\frac{D_{50}}{y_f} \right)^{6/7} \quad (2.28)$$

$$\frac{d_{se}}{y_f} = 7.7 \left[\frac{F_r}{M F_C} - 0.35 \right] \quad (2.29)$$

where F_r = upstream Froude number, F_C = critical Froude number, y_f = upstream flood plain flow depth.

Melville (1995) divided abutment scour into four types according to the location of abutment in the channel, as shown in Figure (2.15). He conducted experiments on case B. To estimate influence of channel geometry on local scour, he made a comparison between scour in rectangular and two-stage channel having the same width and flow depth in main channel, and he defined a parameter for the approach channel geometry factor K_G which represents the ratio between scour depth in compound channel to scour depth in a rectangular channel under the same condition of flow depth.

Figure 2.15: Types of abutment scour (Melville, 1995)

Kouchakzadeh and Townsend (1997) carried out experiments on four abutment shapes (vertical, semi-circular, wing-wall and spill-through) to study the effect of lateral momentum transfer between main channel and flood plain on local scour of abutments terminating in flood plain (case C in Figure 2.15, according to Melville (1995)). They lasted their experiments only 5 hr duration, which can be considered short time to reach the equilibrium state. It was found that the ratio of Q_a/Q_w which was the ratio between discharge intercepted by abutment and flow related to specific channel width was useful to represent the effect of abutment length, lateral momentum transfer and relative depth on scour depth. The maximum scour depth, in the case of interacting condition was 15-30% higher than case of isolated flood plain condition. They suggested that the prediction model for scour should take into account the ratio of Q_a/Q_w and their proposed equation is as follows:

$$\frac{d_{se}}{y_f} = 13.5 \left[\frac{Q_w}{Q_a} \right] F_a^{1.17} F_c^{-0.25} \quad (2.30)$$

where Q_w = flow related to specific width of channel at end of abutment, Q_a = flow intercepted by abutment.

Cardoso and Bettess (1999) studied the scour around a vertical-wall abutment in two-stage channel where the length of the abutment varies until it is at the interface between flood plain and main channel (cases C and D in Figure 2.15, according to Melville (1995)). They mainly investigated the time development of the scouring processes. The time development of this study is explained in detail in Section 2.7

Lim and Yu (2001) carried out 24 experiments to study scour around abutment terminating in the main channel (case B in Figure 2.15, according to Melville (1995)). They modified the formula of Lim (1997) to predict maximum scour depth scour by introducing two new parameters; the first was width average velocity and the second was equivalent abutment length to add the effect of the two-channel geometry to Lim's (1997) equation, as follows:

$$\frac{d_{se}}{y_m} = 0.9 K_s \left\{ \theta_c^{-0.375} F_{oe}^{0.75} \left(\frac{d_{50}}{y_m} \right)^{0.25} \left[0.9 \left(\frac{L_e}{y_m} \right)^{0.5} + 1 \right] - 2 \right\}. \quad (2.31)$$

$$F_{oe} = \frac{U_e}{\sqrt{g(S-1)d_{50}}} \quad (2.32)$$

$$L_e = L \left\{ 1 - \frac{B_f}{L} \left[1 - \left(\frac{y_f}{y_m} \right)^{0.5} \right] \right\} \quad (2.33)$$

$$U_e = \frac{B_f U_f + (L - B_f) U_m}{L} \quad (2.34)$$

where y_m = flow depth in main channel, F_{oe} = equivalent densimetric Froude number, U_e = width average velocity, L_e = equivalent abutment length, and B_f = width of flood plain.

Based on the experimental and field observations, Ettema et al. (2003, 2010) illustrated that scour in channels with abutments can be divided into five types as follows: (the figures below are extracted from Ettema et al. (2003))

Type 1 – abutment in channels with no floodplains

(1a) local scour on bed of main channel

(1b) local scour and contraction scour on bed of main channel

Type 2 – abutment of different lengths in channels with floodplains

(2a) local scour and contraction scour on bed of main channel

(2b) collapse of main channel bank due to scour

(2c) scour of floodplains

(2d) erosion of embankment of abutment

Figure 2.16: Scour Type 1a - local scour on bed of main channel (Ettema et al., 2003)

Figure 2.17: Scour Type 2a - local scour and contraction scour on bed of main channel (Ettema et al., 2003)

Figure 2.18: Scour Type 2b - collapse of main channel bank due to scour (Ettema et al., 2003)

Figure 2.19: Scour Type 2c - scour of floodplains (Ettema et al., 2003)

Figure 2.20: Scour Type 2d – erosion of embankment of abutment (Ettema et al., 2003)

In types (1a) and (1b), the scour may cause slope stability problem. Type (2a) is very similar to (1a) except in the latter one the channel is rectangle. For type (2b) the stability of the abutment may be threatened by the collapse of the main channel bank. For type (2c) the scour of flood plain may affect the stability of abutment. While for type (2d), the erosion of the embankment may affect the stability of abutment. Finally, they reported that abutment and contraction scour may occur concurrently, and it is often difficult to separate both of them. Therefore, contraction scour should be included in the abutment scour formulation, and this aspect will be discussed in Section 4.6.3 of the present study.

Nugroho and Lim (2006) studied flow distribution and scour around abutment terminating in flood plain case C (Figure 2.15 according to Melville (1995) or case 2c according to Ettema et al. (2003) for three different abutment lengths. They also studied the effect of separation of flow between flood plain and main channel on equilibrium scour depth. It was found that there were three types of scour hole shapes, namely inverted-cone type, edge-truncated inverted cone and extended upstream edge-truncated inverted-cone (see Figures 2.6 to 2.8). They proposed a formula to predict equilibrium scour depth by modifying Lim's equation (1997). They expressed the shear velocity as a function of mean velocity and introduced an adjustment factor α which is a function of flow depth ratio. The proposed equations are as follows:

$$\alpha = 1.54 \left[\frac{y_f}{y_m} \right]^{0.35} \quad (2.35)$$

$$\frac{d_{se}}{y_f} = K_s \left\{ 2.76 \left(\frac{y_f}{y_m} \right)^{0.26} \left(\frac{u_f}{u_c} \right)^{0.75} \left[0.9 \left(\frac{L}{y_f} \right)^{0.5} + 1 \right] - 2 \right\} \quad (2.36)$$

where u_c = critical mean velocity for sediment motion and u_f = mean velocity in the approach section of flood plain.

Sturm (2006) introduced a relationship between flow redistribution (between flood plain and main channel), sediment size, abutment shape, approach velocity and depth in a formula to predict scour depth around setback and bankline abutments using two

different channel shapes (channel A and channel B). Channel A consisted of a narrow main channel and two wide flood plains, while channel B consisted of a narrow main channel and a very wide flood plain. His approach was based on dimensional analysis and flow contraction theory. He applied a least squares regression analysis on his experiment data. The main limitation of these experiments is that the scour time is relatively short, last only for 12 to 16 hr for channel A and 24 to 65 hours for channel B. This time is not enough to reach equilibrium based on the experience of present study (see Chapter 4). The second limitation is that some values of scour depth for spill-through abutments are greater than that of vertical-wall abutments for the same discharge and water depth. This means that the effect of shape factor on his results is not conclusive. The last limitation of this study is that the discharge contraction ratio is calculated using numerical model. Therefore, the accuracy of it depends on the efficiency of this model and type of numerical model (i.e. one dimensional, two dimensional and three dimensional). He proposed the following relationship,

$$\frac{d_{se}}{h_f'} = 8.1 K_{st} (\xi - c_0) \quad (2.37)$$

where $c_0 = 0.4$, $\xi = \frac{q_{f1}}{M q_{f0c}}$ and $K_{st} = 1.52 \frac{\xi - 0.67}{\xi - 0.4}$ (for $0.67 \leq \xi \leq 1.2$) = shape correction factor, h_f' = un-constricted flow depth in the floodplain set by uniform flow downstream of the bridge (flow depth downstream of the abutment in the floodplain), M = discharge contraction ratio defined by the ratio of unobstructed discharge in the approach section to the total discharge = $(Q - Q_{obst}) / Q$, Q = total discharge, Q_{obst} = discharge obstructed by the abutment in the approach section, ξ = dimensionless ratio, q_{f1} = flow rate per unit width in the approach section of floodplain, and q_{f0c} = critical flow rate per unit width in the approach section of floodplain. It should be noted that Hong (2012) and Hong et al. (2015) extended the same approach but they used erodible abutment (i.e. models were moulded from sand) under free, submerged flow and overtopping flow. They concluded the geotechnical stability of embankment should take into consideration in the prediction models of scour depth.

Nyarko and Ettema (2011) experimentally studied the interaction between pier scour and abutment scour to estimate scour pier and abutment when they are located together in the same section. They used two types of abutment: wing-walls and spill-through. It was found that there are no significant increases in abutment scour depth when the pier is present. However, when the pier is close to the spill-slope toe of a spill-through abutment, the abutment scour depth decreases. Another finding is that abutment scour depth increases by less than 10% when a pier is close to a wing-wall abutment. When the pier is near the abutment toe, the scour depth is equal to the abutment scour depth and when the pier is far away from the abutment, the scour depth is equal to scour at the pier in isolation since pier doesn't have any effect on abutment scour.

Figure 2.21: Different locations of pier and abutment (Nyarko and Ettema, 2011)

2.7 Time development of scour

The temporal development of scour and the time to achieve equilibrium are very important factors to predict the scour depth at any time (Li, 2005). Sometimes, scour depths do not reach the equilibrium state as the floods may not last for a long time. Consequently, the scour depth is only a fraction of the equilibrium scour depth (Alabi, 2006). Several experimental works to investigate the importance of scour variation with time have been conducted such as Cardoso and Bettess (1999), Coleman et al. (2003), Dey and Barbhuiya (2004), Kose (2007) Ballio (2009, 2010) and Cardoso and Fael (2010). On the other hand, few studies have been investigated on the topographical development of scour hole. Although the topography of scour hole at any time is needed to predict the countermeasure required to protect abutment against scour. In this section, a summary of these investigations is presented.

Figure 2.22: Variation of time and velocity with scour depth (Melville and Coleman, 2003)

The development of live-bed scour and clear water scour is different. From Figure 2.22, for live-bed conditions, scour depth reaches equilibrium at a rate faster than that for clear water conditions. Furthermore, the scour depth for live-bed conditions exhibits an oscillatory behaviour with time due to the movement of sediment from the upstream.

Cardoso and Bettess (1999) studied the scour development with time around rectangular abutment in two-stage channel. Here, two cases of abutment length were considered: 1) abutment terminated in the flood plain, and 2) abutment which extended up to the interface between flood plain and main channel. These cases correspond to case C and, case D according to Melville (1995) (see Figure 2.15), respectively. In case D, the live-bed scour condition happened in the main channel. Hence, the equilibrium scour in case D was reached faster than in case C. Moreover, they found that the scour time development curve can be divided into three parts (an initial phase, principal phase, and the equilibrium phase).

Coleman et al. (2003) investigated the temporal development around a vertical-wall abutment. They defined the time to equilibrium as the time needed for the rate of scour to decrease until it is 5% of the water depth or abutment length within the subsequent 24 hours. This is similar to the definition given by Melville and Chiew (1999) who defined it as the time required to reduce the rate of scour to 5% of pier diameter in the following 24 hours. Using 5% may be sufficient, but it is an arbitrary value. This value may change according to experimental conditions. It was concluded that the equilibrium time depends on flow intensity and relative abutment length.

Dey and Barbhuiya (2004) carried out experiments on three types of abutments (semi-circular, 45° wing-wall and vertical-wall) embedded in uniform and non-uniform sediments under clear water scour conditions. They suggested a semi-empirical model to calculate the change of time with scour depth for short abutment (abutment length/flow depth ≤ 1). The concept of conservation of sediment mass is used as the basis of their methodology. This model is suitable to predict short duration as their experiment lasted only for 48 hrs which is not sufficient to reach equilibrium (Lim,

1997). It was found that the excess abutment Froude number, the ratio of flow depth to abutment length and sediment coarseness (ratio between abutment length and sediment diameter) affected the equilibrium scour depth.

Kose (2007) experimentally investigated the development of scour depth at vertical-wall abutments under clear water conditions using uniform sediment with $d_{50} = 0.9$ mm and 1.8 mm. They suggested a semi-empirical equation to describe the temporal development of scour, and this equation depends on continuity equation of sediment. This study is limited for short abutment and applicable only for short duration models such as Dey and Barbhuiya (2004) which corresponds to the case that flood lasts for short time.

Ballio et al. (2009, 2010) studied the effect blockage ratio on the development of scour depth around vertical-wall abutment. They chose blockage ratios from 0.1 to 0.5. They reported the overall shape of scour development is the same for all experiments and the scour depth increases proportionally with time. They also remarked that the blockage ratio had profound effect during early stage of scour process.

Cardoso and Fael (2010) tried to define an equilibrium time based on experiments done on intermediate and long abutment ($L/y = 9 - 36$) embedded in uniform sand with $d_{50} = 1.28$ mm under clear water scour conditions. Their experiments lasted for a long time (1 week to 3 weeks). They concluded that the equilibrium time depends only on ratio between abutment length and water depth, L/y and relative coarseness, L/d_{50} . This is in contrast to the finding of Coleman et al. (2003) who concluded that the time to reach the equilibrium stage depends on flow intensity.

2.8 Summary

In the aforementioned literature review, the scour around abutments have been discussed, and important parameters affecting on this phenomenon have been reviewed. The literature includes studies on the geometry of scour hole, the location of the maximum scour depth, the scour hole dimensions and its volume and studies on the topographical development of scour hole which are related to the current study. It is observed that the effect of some parameters on scour around abutment such as relative abutment length and flow intensity are well known and agreed by many studies. However, other parameters such as abutment width or abutment aspect ratio and degree of contraction of flow in flood plain are poorly understood and still under investigation. As a result, there is not yet a universally accepted formula to predict scour depth. Proposition of a suitable formula is highly encouraged especially for setback wide abutment in compound channel since this type has not received much attention.

Many researchers studied the scour around vertical-wall abutment sited in rectangular flumes. Moreover, they investigated scour around short and long thin plate vertical abutment. The research on this phenomenon around wide and intermediate length type of abutment is very limited. Previous studies focused only on scour depth formed around abutment. Few researchers studied scour hole dimensions (length, width, depth, area and volume) and the location of maximum scour depth. These scour characteristics are very useful to estimate the cost of scour countermeasure. More importantly, few studies have been conducted on the time development of scour hole topography around setback abutment in compound channel. This aspect is important for floods last for short duration

From the previous review, it can be concluded that there is a limitation concerning the prediction of scour hole characteristics around setback abutment in compound channel using wide abutment with intermediate length type. In addition, a detailed knowledge regarding the topographical development of scour hole around these abutments is still a gap for research. To this end, extensive experiments are conducted in the present study to treat the aforementioned limitation and fill this gap.

CHAPTER 3 EXPERIMENTAL SET-UP AND METHODOLOGY

3.1 Introduction

This chapter describes the experimental setup, apparatus and procedures used to carry out localized scour experiments with seven models of 45° wing-wall (WW) abutment in a compound channel. The laboratory experiments were carried out to measure the characteristics of scour holes (location of maximum scour depth, length, width, depth, surface area and volume of scour hole) formed around a 45° wing-wall (WW) abutment and the time development of these characteristics. The wing-wall abutment was installed in the flood plain of a compound channel. This arrangement is known as a setback abutment (Melville, 1995). The discharge, flow depth, abutment length and width were varied systematically to study the scouring processes around the abutment. Two sets of experiments were done. The first set was aimed measuring the location of maximum scour depth, scour depth, length, width and volume of the scour hole at the equilibrium state. The second set was aimed measuring the dimensions of scour hole, its surface area and volume at different time intervals up to the equilibrium state. Altogether, 55 long duration runs were carried out where the velocity of flow at the flood plain was adjusted to be less than critical velocity for particle motion. Thus, the experiments were conducted under clear water scour conditions.

3.2 Experimental apparatus and bed materials

3.2.1 Flume

The experiments were carried out in a compound flume which had a length of 19 m, a width of 1.6 m, a height of 1 m measured from main channel bed and a longitudinal bed slope of 0.00116, as shown in Figure 3.1. The flume was located at the Hydraulics Modelling Lab, Nanyang Technological University, Singapore. The widths of floodplain and the main channel were 1 m and 0.6 m, respectively. The difference in height between

the floodplain and main channel beds was 0.15 m, as shown in Figures 3.2 and 3.3. At a distance of 11 m from the entrance of the flume, a sand recess of 2.5 m length and 0.4 m depth was installed in the flood plain. This distance was sufficient to ensure that the flow was fully developed. A sediment trap was installed immediately downstream of the sand recess to collect the sediment moved by the flow during the experiments. The sand recess and sediment trip were built-in trenches at the test section in the flume as the main channel and flood plain were made of steel. The water level was adjusted using a tail gate at the end of the flume which was controlled by an electric motor. A sump located below the flume was used to provide water during experiments. A submersible pump was used to pump water continuously during the test to the flume via a header tank which was provided with a perforated steel plate, honey comb and a sponge layer to reduce the turbulence and fluctuation of the incoming flow. The pump capacity was 0.12 m³/s. An electromagnetic flow meter installed on the supply pipe was used to measure the flow rate entering the flume. An electronic panel with an AC inverter was connected to the pump to adjust the rate of discharge. Water was recirculated between the flume and sump.

3.2.2 Abutment models

The 45° wing-wall abutment models were made of 10 mm thick perspex and seven models were constructed. The dimensions of abutment models are listed in Table 3.1. Figures 3.4 and 3.5 show the abutment length, L (i.e. spanwise length) and abutment width, L_c (i.e. streamwise length). Angle 45° for wing wall abutment was commonly used (Yorozuya, 2005; Ettema et al., 2010). The models were fixed to the left side of the flume wall using silicon glue and embedded in the sand recess in the flood plain. The abutment model was placed 0.5 m downstream the leading edge of the sand recess (see Figure 3.6).

Table 3.1: Dimensions of abutment models

Model	Abutment length, L (cm)	Abutment width, L_c (cm)
1	20	20
2	30	30
3	40	40
4	20	5
5	20	80
6	40	5
7	40	80

Figure 3.1: Layout of compound flume

Figure 3.2: The 19 m compound flume

Figure 3.3: Cross section of compound flume at the location of abutment

Figure 3.4: Photo of the 45° wing-wall abutment (Model 3) where L is 40 cm and L_c is 40 cm

Figure 3.5: Plan view of 45° wing-wall abutment model with length, L and width, L_c

Figure 3.6: Photo showing a 45° wing-wall abutment (Model 3) fixed to left side of the flume (abutment length $L = 40$ cm, abutment width $L_c = 40$ cm)

3.2.3 Bed material

Sediments usually consist of different sizes of particles. Sieve analysis test (i.e. gradation test) was carried out for the non-cohesive sediments used in this study. According to the American Society for Testing and Materials (ASTM) C136 (2006). The retained sediments on each sieve were weighted. The cumulative retained and passed weight of sediments are tabulated in Table 3.2. The grain size distribution is a plot between the sieve opening size and cumulative passed of sediments (Dingman, 2009). It can be drawn from first column and last column of Table 3.2. This plot is shown in Figure 3.7. Based on this graph, three characteristics of the sediment were determined. They were $d_{15.9}$, d_{50} and $d_{84.1}$, which corresponded to grain sizes for which 15.9%, 50% and 84.1% of sand weight was finer, respectively. The sand recess of the flood plain was filled with this sand to represent erodible flood plain bed as the flood plain is more likely to be much erodible than the main channel. This sand had a median size (d_{50}) of 0.9 mm

and a standard deviation, $\sigma_g = (d_{84.1}/d_{15.9})^{0.5} = 1.31$. Since $\sigma_g < 1.5$, the sediment was considered uniform (Yang, 1996). For a length of 3 m upstream from the edge of sediment recess, the bed of the flood plain was coated by one layer of the same sand using adhesive glue. This sand layer would help to make the flow fully developed before it reaches the abutment model.

3.2.4 Point gauge

A point gauge was affixed to a carriage as shown in Figures 3.8 and 3.9. This carriage could be moved along the flume and the point gauge could be moved across the flume and vertically into the water. The point gauge was used to measure: (1) water surface level at the approach section, (2) the depth of the scour hole and (3) the topography of scour hole during and at the end of experiment. The accuracy of the point gauge was ± 0.1 mm.

Table 3.2: Sieve analysis of the bed material

Sieve opening size (mm)	Mass of sieve (empty) (g)	Mass of sieve + retained sand (g)	Mass of retained sediment (g)	Cumulative retained (g)	Cumulative retained (%)	Finer (%)
2.0	422.9	423.3	0.4	0.4	0.04	99.96
1.7	398.1	398.3	0.2	0.6	0.06	99.94
1.4	408.3	409.4	1.1	1.7	0.17	99.83
1.18	401.0	479.5	78.5	80.2	8.03	91.97
0.85	356.4	857.9	501.5	581.7	58.23	41.77
0.6	348.1	705.3	357.2	938.9	93.98	6.01
0.5	337.1	374.0	36.9	975.8	97.68	2.32
0.42	326.2	335.3	9.1	984.9	98.59	1.41
0.21	299.0	310.7	11.7	996.6	99.76	0.24
Pan	276.0	278.4	2.4	999.0	100.0	0
Total:			999.0		-	-

Figure 3.7: Grain size distribution of sand

Figure 3.8: 3D view of carriage and point gauge

Figure 3.9: The point gauge installed in the flume

3.3 Measurement of velocity

The depth-averaged velocity at the approach section was measured using a propeller current flow meter and a 3D Acoustic Doppler Velocimeter Profiler. The approach section was chosen to be located at 2 m upstream from the sand recess. The abutment had no effect on flow at this location where there was no change on the water surface at this section due to the presence of abutment model. The discharge in the flume was obtained from the integration of the measured depth averaged velocities over the cross section. The values of discharge for each run were tabulated (see Table 3.3).

3.3.1 Propeller current meter

The 8-mm propeller current meter consists of a probe which can be connected to a display unit via cable as shown in Figures 3.10, 3.11 and 3.12. The probe included a rotating propeller at the end of the probe (see Figures 3.11). The meter was attached to a carriage which was moved along the flume to measure the velocity at various locations and depths. At each location, the propeller was used to measure the point velocity over a 60 second period. The measurement was performed for 5 vertical profiles across the floodplain and 5 vertical profiles across the main channel as shown in Figure 3.13. At each vertical profile, the velocity was measured at 0.2 and 0.8 water depth. The readings from the display unit were converted to velocity in cm/s using a calibrated chart provided by the manufacturer. The chart consisted of two curves, the upper red curve for high value of reading corresponding to high velocity (60-300 cm/s). On the other hand, the lower black one for low value of reading which represents low velocity (5-150 cm/s). The measured velocities were integrated over the cross section to determine the discharge for the main channel and the flood plain. The 8-mm propeller current meter was mainly used for runs with shallow water depth in the flood plain (with water depth less than 5 cm). The accuracy of the propeller current meter was $\pm 1.5\%$.

Figure 3.10: Dimension of 8-mm propeller current meter (all dimensions in mm)

<http://www.nixonflowmeters.co.uk/Portals/25/PDF/streamflo.pdf>

Figure 3.11: The probe of 8-mm propeller current meter includes rotating fan

Figure 3.12: The display unit for the 8-mm propeller current meter

Figure 3.13: Stations of velocity measurements (all dimensions are in cm)

3.3.2 3D Acoustic Doppler Velocimeter profiler (ADVP)

For larger water depth, the flow velocity was measured using ADVP which could be used to measure instantaneous components of velocities in three dimensional directions with a high accuracy of $\pm 0.5\%$. Many researchers such as Song et al. (1994), Rennie et al. (2002), Chen (2014) and Blanckaert (2017) had used ADVP to measure velocity, turbulence and coherent structure of flow. The Acoustic Doppler Velocimeter profiler (ADVP) was a cheaper instrument for velocity measurements compared to Particle Image Velocimeter (PIV) (Emadzadeh, 2014). In addition, Blanckaert and Mclelland (2009) reported that the accuracy of measured turbulence using Doppler Velocimeter profiler (ADVP) was higher than Particle Image Velocimeter (PIV).

The 3D ADVP model used was the Nortek Vectrino – II. It could measure three dimensional velocities and included one 3D down-looking probe which consisted of a transmit transducer and four receivers. The probe was made of titanium and connected to a computer via a fixed cable to display the detected data from this instrument (see Figures 3.14 to 3.16). The working principle of a 3D ADVP based on the Doppler effect theory where a short pulse is released from the transmit transducer and reflected by suspended particles present in water as shown in Figure 3.15 a. The reflected pulse is detected using four receivers and the velocity of flow was calculated by measuring the Doppler shift between the frequencies of the received and transmitted pulses.

The ADVP was fixed on the carriage which could be moved in the x-y directions to measure velocity at various locations of the flume. It could also be moved vertically to measure velocity at different depths. To reduce the noise of measured data, especially near the bottom of flume and to improve the signal-to-noise ratio, air bubble generator was used to provide the seeding material into water in the form of hydrogen bubbles. This generator was an economical accessory and did not produce any pollution on water compared to traditional seeding material (i.e. milk, powder, kaolin clay and vegetable dye). This system had been used by several researchers such as Blanckaert (2003), Blanckaert and Lemmin (2006), Meile et al. (2008) and Emadzadeh (2014). Figures 3.17

and 3.18 show the system which consisted of a DC power source connected to an array of horizontal stainless-steel wires with a diameter of 0.2 mm. These wires were wrapped around a stainless-steel U-shaped frame, which was isolated by a waterproof paint layer to prevent it from participation in the electrolysis process. During measurement, this frame was installed 1.0 m upstream of the ADVP, and this distance appeared to be sufficient far so that the measured velocities would not be affected (Meile et al., 2008).

The depth-averaged velocity at the approach section was measured at a sampling rate of 100 Hz corresponding to 100 samples of velocity components per second as suggested by Garcia (2005), and a sampling time of two minutes. The sampling rate and time were sufficient to reduce the statistical errors of velocity components to the minimum values (Chanson et al., 2007). The sampling volume was 5 cm below the transducer within a cylinder with a height of 3-15 mm (user selectable) and a diameter of 6 mm as shown in Figure 3.15b. The signal-to-noise ratio (i.e. SNR) was approximately 55, the data was considered to be good if SNR was higher than 15 (Nugroho, 2006). Another parameter related to the quality of data collected from ADVP was the correlation of ADVP measurements ratio (i.e. COR) which indicated the consistency between different measurements during each sampling period. The value of COR during measurement was $92 > 70$, this was recommended by Wahl (2003) and Chanson (2008).

The ADVP was used to measure velocities where water depth was greater than 5 cm. The measurement was carried out for one vertical profile at the middle of the floodplain and another one at the middle of the main channel as shown in Figure 3.13. At each vertical profile, the water depth was divided into several intervals. Each interval equalled 1 cm. The measurements of instantaneous velocities started from the bottom of water depth until 5 cm from the water surface, since the ADVP cannot measure velocity above this depth. The measured velocities were integrated over the cross section to obtain the discharge for the main channel and the flood plain.

Figure 3.14 Dimension of Acoustic Doppler Velocimeter profiler (all dimensions in mm) <http://www.nortek-as.com/en/products/velocimeters/vectrino-ii>

Figure 3.15: (a) Configuration of ADV probe and its sampling volume (b) The distance between ADV probe and sampling volume and the height of sampling volume <http://www.nortek-as.com/en/products/velocimeters/vectrino-ii>

Figure 3.16: ADV installed on the carriage

Figure 3.17: The DC power source

Figure 3.18: Dimension of stainless-steel U-shaped frame with horizontal stainless-steel wires

3.4 Measurement of incoming discharge

The discharge entering the flume was controlled using a valve fixed on the inflow pipe to the flume and an AC inverter was connected to the pump to adjust the pump speed. An electromagnetic flow meter (SIEMENS SITRANS F M MAG 6000) was installed in the pipeline upstream of the valve. It was used to measure discharge of water at an ambient temperature (i.e. the temperature of the surrounding air) of -20°C to $+50^{\circ}\text{C}$ up to an accuracy of $\pm 0.2\%$. The measured discharge value was compared with that obtained from integration of the measured velocities the propeller current meter and ADV as described in Sections 3.3.1 and 3.3.2.

3.5 Measurement of flow depth

The water surface at the approach section was measured using the point gauge (see Figures 3.8 and 3.9) which had an accuracy of $\pm 0.1\text{ mm}$ because of some small wave action of water surface. First, the bed levels of the flood plain and main channel were recorded before filling the flume with water. Then the water surface level was measured for each experiment. The water depth was equal to the difference between the bed level and water surface level.

3.6 Measurement of scour dimensions

After the sand bed of the sand recess at the flood plain was levelled, the height of this sand level in the sand recess at the tip of abutment model was recorded using the point gauge. This reading was taken the initial datum level of sand bed. The scour depth between any time intervals was equal to the difference between two records of point gauge reading. For example, the scour depth at 30 minutes from beginning of experiment was equal to the difference between reading of point gauge at 30 minutes and that at beginning of experiment. Likewise, the scour width and length of the scour hole were measured. The scour hole length was measured at 1 cm from the tip of abutment, and the scour hole width was measured from the tip of the abutment.

At the equilibrium scour condition, i.e. after it was observed that there was no more noticeable change of scour profile, the topography of scour hole and the location of the maximum scour depth were also measured using the point gauge. To do this, the water was drained slowly from the scour hole at the end of experiment and the location of maximum scour depth was noted and measured relative to the tip of abutment. For the topography measurement, the scour hole was divided into a grid of 2 cm x 2 cm throughout the scour zone and at each grid point the level of sand bed was measured using the point gauge. The topography data were used to estimate the surface area of the scour hole at the initial bed level and the volume of scour hole using the Surfer 12 software.

3.7 Flow visualization technique

To give better understand regarding the flow features near narrow and wide wing-wall abutments in compound channel, flow visualization using dye injection was carried out for scoured-bed experiment. The dye was released in water upstream the abutment models near to the bed. Photographs were taken to capture the movement of flow around abutment models. The characteristics of flow are presented in Section 4.4.

3.8 Experimental procedure

A total of 55 long duration runs had been carried out. In these experiments 7 models were used to study the effects of abutment length and width, flow depth and discharge on the scour process around the setback 45° WW abutment in a compound channel.

The following procedures were used for each run:

- 1- The abutment model was fixed at the base of sand recess and the sand bed of the recess was levelled carefully to give an initial flat datum surface level. It was then covered using a metal plate to prevent any initial scour before the required discharge was established.

- 2- At the start of the experiment, the tail gate was set sufficiently high, then the flume was filled slowly from downstream of the flume using a small pump at discharge rate less than 1 L/s, so as not to disturb the sand bed.
- 3- The original bed level of sand at the tip of the abutment was recorded using the point gauge (see Figure 3.6).
- 4- The next step was to set the flow to a pre-determined rate and a specific tail water depth. First, the tail gate was lowered slowly while the discharge was increased slowly until the required water depth and discharge were reached. Then the metal sheet was removed. At this point, the experiment was started, and the scour length and width were recorded at different time intervals: 30, 60, 120, 360, 1440, 4320 minutes and when the equilibrium state was reached. The scour depth was recorded every 10 minutes for the first three hours, then the time interval was extended to 1-6 hours up to the equilibrium state.
- 5- Measurements of the water depth and velocity were carried out at the approach section which was located at 2 m upstream of the sand recess.
- 6- The location of the maximum scour depth and scour volume were also measured at the equilibrium state. For Runs 4, 16, 27, 46 and 51, the temporal development of scour holes was also measured at various time intervals: 30, 60, 120, 360, 1440, 4320 minutes and at the equilibrium state. At each time interval, the run was stopped and the dimensions of scour hole (depth, d_s length, L_s and width, W_s) were measured.

Table 3.3 lists the hydraulic conditions of all the experiments conducted for this study.

Table 3.3: Hydraulic conditions of experiments

Run	Model	y_f (cm)	y_m (cm)	y_f/y_m	u_f (cm/s)	u_m (cm/s)	u_c (cm/s)	u_f/u_c	Q (L/s)	Q (actual) (L/s)	Run time (min)
1	1	3.75	18.75	0.20	20.05	30.00	30.80	0.65	37.95	41.40	7740
2	1	3.75	18.75	0.20	25.10	30.50	30.80	0.81	40.40	43.70	11125
3	1	3.75	18.75	0.20	27.30	34.50	30.80	0.88	45.40	49.00	7200
4	1	3.75	18.75	0.20	31.00	36.50	30.80	0.99	50.40	52.40	10080
5	1	6.40	21.40	0.30	21.80	24.20	33.90	0.65	43.00	44.90	7115
6	1	6.40	21.40	0.30	23.90	27.00	33.90	0.71	45.40	50.00	7640
7	1	6.40	21.40	0.30	26.00	28.50	33.90	0.77	50.40	53.10	7920
8	1	6.40	21.40	0.30	30.10	30.20	33.90	0.88	54.60	58.00	8415
9	1	10.00	25.00	0.40	20.60	22.90	36.40	0.57	50.40	54.90	9005
10	1	10.00	25.00	0.40	23.70	25.20	36.40	0.65	56.85	61.50	11305
11	1	10.00	25.00	0.40	32.00	30.00	36.40	0.88	73.85	77.00	11350
12	1	15.00	30.00	0.50	33.50	30.40	38.20	0.88	95.50	104.50	14920
13	2	3.75	18.75	0.20	20.05	30.00	30.80	0.65	37.95	41.40	7200
14	2	3.75	18.75	0.20	25.10	30.50	30.80	0.81	40.40	43.70	10080
15	2	3.75	18.75	0.20	27.30	34.50	30.80	0.88	45.40	49.00	8800

Table 3.3: Hydraulic conditions of experiments, continued.

Run	Model	y_f (cm)	y_m (cm)	y_f/y_m	u_f (cm/s)	u_m (cm/s)	u_c (cm/s)	u_f/u_c	Q (L/s)	Q (actual) (L/s)	Run time (min)
16	2	3.75	18.75	0.20	31.00	36.50	30.80	0.99	50.40	52.40	10080
17	2	6.40	21.40	0.30	21.80	24.20	33.90	0.65	43.00	44.90	8820
18	2	6.40	21.40	0.30	26.00	28.50	33.90	0.77	50.40	53.10	9935
19	2	6.40	21.40	0.30	30.10	30.20	33.90	0.88	54.60	58.00	11340
20	2	10.00	25.00	0.40	20.60	22.90	36.40	0.57	50.40	54.90	8440
21	2	10.00	25.00	0.40	23.70	25.20	36.40	0.65	56.85	61.50	7300
22	2	10.00	25.00	0.40	32.00	30.00	36.40	0.88	73.85	77.00	15540
23	2	15.00	30.00	0.50	33.50	30.40	38.20	0.88	95.50	104.50	15410
24	3	3.75	18.75	0.20	20.05	30.00	30.80	0.65	37.95	41.40	9360
25	3	3.75	18.75	0.20	25.10	30.50	30.80	0.81	40.40	43.70	12960
26	3	3.75	18.75	0.20	27.30	34.50	30.80	0.88	45.40	49.00	14440
27	3	3.75	18.75	0.20	31.00	36.50	30.80	0.99	50.40	52.40	10080
28	3	6.40	21.40	0.30	20.00	23.00	33.90	0.59	40.40	42.33	10940
29	3	6.40	21.40	0.30	21.80	24.20	33.90	0.65	43.00	44.90	9455
30	3	6.40	21.40	0.30	23.90	27.00	33.90	0.71	45.40	50.00	9720

Table 3.3: Hydraulic conditions of experiments, continued.

Run	Model	y_f (cm)	y_m (cm)	y_f/y_m	u_f (cm/s)	u_m (cm/s)	u_c (cm/s)	u_f/u_c	Q (L/s)	Q (actual) (L/s)	Run time (min)
31	3	6.40	21.40	0.30	26.00	28.50	33.90	0.77	50.40	53.10	16700
32	3	6.40	21.40	0.30	30.10	30.20	33.90	0.88	54.60	58.00	12000
33	3	10.00	25.00	0.40	15.90	17.30	36.40	0.44	40.40	40.90	7920
34	3	10.00	25.00	0.40	18.20	18.40	36.40	0.50	45.40	45.50	8970
35	3	10.00	25.00	0.40	20.60	22.90	36.40	0.57	50.40	54.90	9375
36	3	10.00	25.00	0.40	23.70	25.20	36.40	0.65	56.85	61.50	9660
37	3	10.00	25.00	0.40	32.00	30.00	36.40	0.88	73.85	77.00	14970
38	3	15.00	30.00	0.50	33.50	30.40	38.20	0.88	95.50	104.50	14460
39	4	3.75	18.75	0.20	27.30	34.50	30.80	0.88	45.40	49.00	8640
40	4	6.40	21.40	0.30	30.10	30.20	33.90	0.88	54.60	58.00	6990
41	4	10.00	25.00	0.40	32.00	30.00	36.40	0.88	73.85	77.00	9885
42	5	3.75	18.75	0.20	27.30	34.50	30.80	0.88	45.40	49.00	10230
43	5	6.40	21.40	0.30	30.10	30.20	33.90	0.88	54.60	58.00	8000
44	5	10.00	25.00	0.40	32.00	30.00	36.40	0.88	73.85	77.00	10800
45	6	3.75	18.75	0.20	27.30	34.50	30.80	0.88	45.40	49.00	8640

Table 3.3: Hydraulic conditions of experiments, continued.

Run	Model	y_f (cm)	y_m (cm)	y_f/y_m	u_f (cm/s)	u_m (cm/s)	u_c (cm/s)	u_f/u_c	Q (L/s)	Q (actual) (L/s)	Run time (min)
46	6	3.75	18.75	0.20	31.00	36.50	30.80	0.99	50.40	52.40	10080
47	6	6.40	21.40	0.30	30.10	30.20	33.90	0.88	54.60	58.00	9860
48	6	10.00	25.00	0.40	32.00	30.00	36.40	0.88	73.85	77.00	15420
49	7	3.75	18.75	0.20	20.05	30.00	30.80	0.65	37.95	41.40	8700
50	7	3.75	18.75	0.20	27.30	34.50	30.80	0.88	45.40	49.00	10085
51	7	3.75	18.75	0.20	31.00	36.50	30.80	0.99	50.40	52.40	10080
52	7	6.40	21.40	0.30	21.80	24.20	33.90	0.65	6.40	21.40	10560
53	7	6.40	21.40	0.30	30.10	30.20	33.90	0.88	54.60	58.00	9860
54	7	10.00	25.00	0.40	23.70	25.20	36.40	0.65	56.85	61.50	10380
55	7	10.00	25.00	0.40	32.00	30.00	36.40	0.88	73.85	77.00	9930

Note: Q (actual) = Discharge obtained from integration of measured velocity profiles over upstream cross section, Q = Discharge measured by electromagnetic flow meter

3.9 Determination of the critical mean velocity for initiation of sediment motion

The critical mean velocity, u_c can be obtained using Strickler equation which was a logarithmic velocity equation (Nugroho, 2006; Xiong, 2016):

$$\frac{u_c}{u_{*c}} = 5.75 \log \left(5.53 \frac{y}{d_{50}} \right) \quad (3.1)$$

where u_{*c} = critical shear velocity which depends on d_{50} of sediment.

To calculate the critical mean velocity, the dimensionless sediment diameter, D_* and the dimensionless critical bed shear stress (Shields number), τ_{*c} were computed as follows (Nugroho, 2006; Hong, 2012):

$$D_* = d_{50} \left(\frac{\Delta g}{\nu^2} \right)^{1/3} \quad (3.2)$$

where ν = kinematic viscosity of water, Δ = Specific submerged density = $\left(\frac{\rho_s - \rho}{\rho} \right)$, ρ_s = density of sediment, ρ = density of water and τ_{*c} is defined as $\frac{u_{*c}^2}{(\Delta g d_{50})}$.

Yalin and Silva (2001) proposed the following equation to calculate the dimensionless critical bed shear stress for $D_* = 0.06 - 430$.

$$\tau_{*c} = 0.13 D_*^{-0.392} e^{-0.015 D_*^2} + 0.045 (1 - e^{-0.068 D_*}) \quad (3.3)$$

Using Equations (3.1) to (3.3), the critical shear velocity for the sediment used is 0.022 m/s and the critical mean velocities are 0.308 m/s, 0.336 m/s, 0.364 m/s and 0.381 m/s for the range of y_f/y_m equal 0.2, 0.3, 0.4 and 0.5, respectively.

The mean flow velocity at the approach section of floodplain for each run was compared with the critical mean velocity to ensure that each run occurred under clear water scour conditions (i.e. $u_f/u_c < 1$).

CHAPTER 4 RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents the results and analysis of the geometry and characteristics of the scour hole formed at a 45° wing-wall setback abutment in a compound channel. The effects of relative abutment length, aspect ratio of abutment, relative sediment coarseness, flow intensity, degree of flow contraction on floodplain, flow depth ratio of floodplain with main channel and scouring time are discussed. The characteristics of scour hole are investigated in terms of its scour depth, length, width, location of maximum scour depth, surface area and volume of scour hole. The time development of these scour hole characteristics up to the equilibrium state is analysed. Proposed formulas to predict these scour hole characteristics are presented in the following sections.

4.2 Dimensional analysis

Local scour around abutment is affected by many parameters and some of which can be categorized into the following six groups (Barbhuiya and Dey, 2004; Nugroho, 2006; Hong, 2012):

- 1- The shape and type of channel (width, cross section and longitudinal slope, side slope between the floodplain and main channel).
- 2- The abutment characteristics (length L , width L_c , shape and alignment).
- 3- Sediment characteristics such as median sediment size d_{50} , standard deviation of grain size σ_g , type of sediment (natural or artificial), angle of repose, density ρ_s and cohesiveness of sediment.
- 4- Approach flow characteristics: mean flow velocity in the floodplain u_f , flow depth on floodplain y_f and main channel y_m and channel roughness, and acceleration of gravity g .
- 5- Fluid characteristics: density ρ , dynamic viscosity μ , and temperature.

- 6- The development of scour over time such as duration of experiments, t and equilibrium scour time, t_e .

It is generally known that scour around abutment is caused by the flow contraction due to the blockage of the abutment and the large-scale turbulence from flow separation at the tip of abutment. Hence, abutment and contraction scour may occur concurrently, and it is often difficult to separate both of them (Benedict, 2003; Mueller and Wagner, 2005; Ettema et al., 2010; Hong, 2012; Yorozya and Ettema, 2015). In this present analysis, the effect of contraction is included in the abutment scour formulation. To this end, the scour hole characteristics at the abutment (see Figures 4.1, 4.2 and 4.9) under clear water scour condition may be written as a function of the following independent variables:

$$\text{Scour hole characteristics } (d_s, L_s, W_s, A_s, V_s, R_x, R_y) = f(y_f, y_m, u_f, u_c, L, L_c, B_m, B_f, d_{50}, \rho_s, \rho, \sigma_g, t) \quad (4.1)$$

where d_s is the maximum scour depth at a specified time; L_s is the maximum length of scour hole measured at 1 cm from the tip of abutment at a specified time; W_s is the width of scour hole measured from the tip of the abutment at a specified time; A_s is the surface area of scour hole at a specified time; V_s is the volume of scour hole at a specified time; R_x is the normal distance from abutment face to the location of maximum scour depth; R_y is the distance from the centerline of abutment face to the location of maximum scour depth parallel to flow direction; y_f and y_m is the flow depth of the floodplain and main channel at the approach section, respectively; u_f is mean flow velocity at the approach section of floodplain; u_c is critical velocity for the initiation of movement of sediment; L is the abutment length; L_c is the abutment width in the flow direction; B_m and B_f is the width of the main channel and the floodplain, respectively; d_{50} is median size of sediment; ρ_s is density of sediment; ρ is density of water; σ_g is standard deviation of the sediment size distribution; and t is the scour time.

For a compound channel, studies have shown that y_f is an appropriate length scale (Sturm, 1994, 2006; Kouchakzadeh and Townsend, 1997). By using the Buckingham π -theorem and choosing u_f , y_f and ρ as the repeating variables, it is shown that

$$\frac{d_s}{y_f} = f\left(\frac{L}{y_f}, \frac{u_f}{u_c}, \frac{L_c}{L}, \frac{y_f}{y_m}, \frac{L}{d_{50}}, \frac{B_f-L}{B_f}, \frac{B_f}{B_m}, \frac{u_f t}{y_f}, \frac{\rho_s}{\rho}, \sigma_g\right) \quad (4.2)$$

The dimensionless terms on the right hand side of Equation (4.2) are also the independent variables for the other scour hole characteristics: $\frac{L_s}{y_f}, \frac{W_s}{y_f}, \frac{A_s}{y_f^2}, \frac{V_s}{y_f^3}, \frac{R_x}{y_f}$, and $\frac{R_y}{y_f}$.

In Equation (4.2), the terms on the right hand side may be explained with respect to the scouring characteristics and processes. For example, $\frac{L}{y_f}$ is related to the interdependence of the abutment length and flow depth on the scour process, $\frac{u_f}{u_c}$ is the flow intensity and a value greater than 1 means live-bed scour, and if it is less than 1, the scouring process takes place under clear water scour condition. The term $\frac{L_c}{L}$ is the aspect ratio of abutment which shows the effect of abutment width on the scouring process, and the review shows that this term has not been extensively studied yet. The term $\frac{y_f}{y_m}$ is the flow depth ratio and it is related to the degree of flow interaction between the floodplain and main channel. For example, the momentum exchange is high if the $\frac{y_f}{y_m}$ ratio is small, and if it is higher than 0.5, it has been shown that the flow in the compound channel behaves like one in the rectangular channel (Knight and Demetriou, 1983). The term $\frac{L}{d_{50}}$ is the relative sediment coarseness. Melville and Coleman (2000) reported that scour depth is unaffected for $\frac{L}{d_{50}} > 50$. Therefore, its effect will be neglected in the present study which has values $(\frac{L}{d_{50}})$ higher than this limit. The term $\frac{B_f-L}{B_f}$ indicates the degree of flow contraction on the scour for setback abutment in the floodplain. This term represents the effect of contraction scour for abutment on floodplain (Ettema et al., 2010; Sturm et al., 2011; Yorozya and Ettema, 2015). The term $\frac{B_f}{B_m}$ represents the relative width of the compound channel, and it has been found that the apparent shear stress increases as this

ratio increases (Knight and Demetriou, 1983). This ratio is kept constant for the present study. Finally, the term $\frac{u_f t}{y_f}$ relates to the temporal development of the scour hole.

The influence of each parameter on the right hand side of Equation (4.2) on characteristics of scour hole is explained in the following sections. Table 4.1 shows the experimental conditions and scour hole characteristics measured for the 55 runs conducted in the present study.

Figure 4.1: Definition of scour hole dimensions: (depth, d_s , length, L_s and width, W_s) at the equilibrium state for abutment model 1

4.3 Geometry of scour hole

Observations showed that the scour starts at the upstream of the abutment tip and as time increases, the scour hole increases in size. The maximum scour depth was observed to migrate slightly downstream of the abutment nose during scour development up to the equilibrium state. This was because the skewed face of the wing-wall shifted the action of the down flow downstream the abutment tip (Kose, 2007). In contrast, the maximum scour depth for vertical-wall abutment mostly occurred just upstream of the abutment nose (Oliveto and Hager, 2002).

The location of maximum scour depth is an important parameter for scour countermeasure and is investigated in detail in Section 4.5. At the end of the experiments, photographs were taken to show the different shapes of scour holes (see appendix).

The final shape of scour hole consists of primary scour hole and a smaller secondary scour hole. The existence of a secondary scour hole depends on the abutment width, floodplain flow depth, abutment length and flow intensity.

Figure 4.3(a) shows that the final shape of scour hole consists of only the primary scour hole for abutment with the narrowest width, but with relatively high flow intensity and water depth (Run 48, model 6, $L = 40$ cm, $L_c = 5$ cm, $u_f/u_c = 0.88$, $y_f/y_m = 0.4$). This is expected as the shifted down flow occurs very near to the wake vortices, which are located near the downstream side of the rear abutment nose. This causes the deepest scour depth to occur for this case compared to a much wider abutment. Bhatia and Setia (2014) also observed that the center of the wake vortices is shifted when the aspect ratio, L_c/L increases from 1 to 2 for vertical-wall abutment. On the other hand, Figure 4.3 (b) shows that the final shape of scour hole consists of a merged primary and secondary scour hole for the widest abutment (Run 55, model 7, $L = 40$ cm, $L_c = 80$ cm, $u_f/u_c = 0.88$, $y_f/y_m = 0.4$).

Figure 4.2: Definition sketch of scour hole: (a) Section A-A shows the scour depth (d_s), (b) Plan view of scour hole shows the length of scour hole (L_s) and width of scour hole (W_s)

Table 4.1: Flow conditions and experimental results of present study

Run	Model	y_f/y_m	u_f/u_c	Q (L/sec)	Run time (min)	t_e (min)	d_{se}/y_f	L_{se}/y_f	W_{se}/y_f	V_{se}/y_f^3	R_x/y_f	R_y/y_f	R/y_f	Location of maximum scour depth
1	1	0.20	0.65	41.40	7740	5155	1.80	17.03	4.69	57.41	0.18	3.12	3.13	Case a
2	1	0.20	0.81	43.70	11125	8815	2.06	19.14	5.23	67.52	0.22	3.12	3.13	Case a
3	1	0.20	0.88	49.00	7200	6820	0.25	1.94	1.40	0.22	0.70	2.00	2.12	Case a
4	1	0.20	0.99	52.40	10080	8640	0.36	2.20	2.60	1.28	0.65	2.00	2.10	Case a
5	1	0.30	0.65	44.90	7115	5195	0.55	3.50	1.65	1.38	0.20	2.20	2.21	Case a
6	1	0.30	0.71	50.00	7640	6200	0.67	4.70	1.80	2.84	0.15	2.15	2.16	Case a
7	1	0.30	0.77	53.10	7920	6600	2.11	18.90	4.55	70.00	0.15	2.00	2.01	Case b
8	1	0.30	0.88	58.00	8415	4435	1.54	13.93	3.57	22.52	0.10	1.33	1.34	Case a
9	1	0.40	0.57	54.90	9005	7235	0.96	5.47	3.01	0.10	0.19	0.40	0.44	Case a
10	1	0.40	0.65	61.50	11305	7885	1.03	6.94	3.55	8.01	0.11	0.08	0.13	Case a
11	1	0.40	0.88	77.00	11350	10630	1.41	8.79	2.58	8.91	0.07	0.03	0.08	Case a
12	1	0.50	0.88	104.50	14920	13495	0.69	3.57	2.56	1.99	0.27	10.67	10.67	Case a
13	2	0.20	0.65	41.40	7200	5865	0.61	3.13	1.70	1.37	0.08	6.25	6.25	Case a
14	2	0.20	0.81	43.70	10080	8230	0.44	2.25	1.34	8.91	0.05	4.00	4.00	Case a
15	2	0.20	0.88	49.00	8800	5885	2.18	8.40	7.63	37.92	2.40	0.27	2.41	Case a

Table 4.1: Flow conditions and experimental results of present study, continued.

Run	Model	y_f/y_m	u_f/u_c	Q (L/sec)	Run time (min)	t_e (min)	d_{se}/y_f	L_{se}/y_f	W_{se}/y_f	V_{se}/y_f^3	R_x/y_f	R_y/y_f	R/y_f	Location of maximum scour depth
16	2	0.20	0.99	52.40	10080	8640	2.08	21.60	5.01	121.55	0.16	4.00	4.00	Case a
17	2	0.30	0.65	44.90	8820	7350	0.58	3.23	3.58	2.67	0.81	2.34	2.48	Case a
18	2	0.30	0.77	53.10	9935	8495	1.20	11.59	5.86	23.27	0.09	2.34	2.34	Case a
19	2	0.30	0.88	58.00	11340	9835	1.30	15.47	2.55	15.26	0.12	2.34	2.35	Case a
20	2	0.40	0.57	54.90	8440	5980	0.29	2.02	1.96	0.40	0.53	1.50	1.59	Case a
21	2	0.40	0.65	61.50	7300	5990	0.46	2.75	2.61	1.20	0.51	1.50	1.58	Case a
22	2	0.40	0.88	77.00	15540	12775	1.16	11.50	2.35	10.70	0.10	1.50	1.50	Case a
23	2	0.50	0.88	104.50	15410	13970	0.94	9.06	2.18	5.81	0.07	1.00	1.00	Case a
24	3	0.20	0.65	41.40	9360	6490	1.17	8.29	5.20	15.93	1.33	5.33	5.50	Case a
25	3	0.20	0.81	43.70	12960	9485	1.39	8.93	5.33	28.44	1.07	5.33	5.44	Case a
26	3	0.20	0.88	49.00	14440	12220	2.00	27.20	4.53	66.18	0.13	5.46	5.47	Case b
27	3	0.20	0.99	52.40	10080	8640	3.20	28.00	7.47	189.63	0.13	5.33	5.33	Case a
28	3	0.30	0.59	42.33	10940	8150	0.81	5.09	4.22	13.16	1.09	3.12	3.31	Case a
29	3	0.30	0.65	44.90	9455	6875	0.73	5.94	2.73	7.63	0.89	3.12	3.25	Case a
30	3	0.30	0.71	50.00	9720	7265	0.89	6.72	2.81	5.82	0.31	3.12	3.14	Case a

Table 4.1: Flow conditions and experimental results of present study, continue.

Run	Model	y_f/y_m	u_f/u_c	Q (L/sec)	Run time (min)	t_e (min)	d_{se}/y_f	L_{se}/y_f	W_{se}/y_f	V_{se}/y_f^3	R_x/y_f	R_y/y_f	R/y_f	Location of maximum scour depth
31	3	0.30	0.77	53.10	16700	12680	1.80	17.03	4.69	57.41	0.18	3.12	3.13	Case a
32	3	0.30	0.88	58.00	12000	6355	2.06	19.14	5.23	67.52	0.22	3.12	3.13	Case a
33	3	0.40	0.44	40.90	7920	4020	0.25	1.94	1.40	0.22	0.70	2.00	2.12	Case a
34	3	0.40	0.50	45.50	8970	5730	0.36	2.20	2.60	1.28	0.65	2.00	2.10	Case a
35	3	0.40	0.57	54.90	9375	6255	0.55	3.50	1.65	1.38	0.20	2.20	2.21	Case b
36	3	0.40	0.65	61.50	9660	8190	0.67	4.70	1.80	2.84	0.15	2.15	2.16	Case b
37	3	0.40	0.88	77.00	14970	12930	2.11	18.90	4.55	70.00	0.15	2.00	2.01	Case a
38	3	0.50	0.88	104.50	14460	12985	1.54	13.93	3.57	22.52	0.10	1.33	1.34	Case a
39	4	0.20	0.88	49.00	8640	5500	0.96	5.47	3.01	0.00	0.19	0.40	0.44	Case c
40	4	0.30	0.88	58.00	6990	5550	1.03	6.94	3.55	8.01	0.11	0.08	0.13	Case c
41	4	0.40	0.88	77.00	9885	8445	1.41	8.79	2.58	8.91	0.07	0.03	0.08	Case c
42	5	0.20	0.88	49.00	10230	5940	0.69	3.57	2.56	1.99	0.27	10.67	10.67	Case a
43	5	0.30	0.88	58.00	8000	6800	0.61	3.13	1.70	1.37	0.08	6.25	6.25	Case a
44	5	0.40	0.88	77.00	10800	8445	0.44	2.25	1.34	8.91	0.05	4.00	4.00	Case a
45	6	0.20	0.88	49.00	8640	7090	2.18	8.40	7.63	37.92	2.40	0.27	2.41	Case c

Table 4.1: Flow conditions and experimental results of present study, continue.

Run	Model	y_f/y_m	u_f/u_c	Q (L/sec)	Run time (mins)	t_e (min)	d_{se}/y_f	L_{se}/y_f	W_{se}/y_f	V_{se}/y_f^3	R_x/y_f	R_y/y_f	R/y_f	Location of maximum scour depth
46	6	0.20	0.99	52.40	10080	8640	3.39	17.01	7.41	102.17	0.40	0.21	0.45	Case c
47	6	0.30	0.88	58.00	9860	8240	2.25	14.45	4.76	51.49	0.08	0.05	0.09	Case c
48	6	0.40	0.88	77.00	15420	13900	2.31	18.40	3.76	55.5	0.15	0.005	0.15	Case c
49	7	0.20	0.65	41.40	8700	7080	0.59	4.77	4.75	4.84	0.67	10.51	10.53	Case c
50	7	0.20	0.88	49.00	10085	8405	1.39	9.49	7.07	37.93	1.65	10.67	10.79	Case a
51	7	0.20	0.99	52.40	10080	8640	2.05	13.63	5.09	61.59	0.13	10.67	10.67	Case a
52	7	0.30	0.65	21.40	10560	9320	0.42	2.61	2.61	0.97	0.78	6.25	6.30	Case a
53	7	0.30	0.88	58.00	9860	8415	1.00	9.41	4.69	12.59	0.23	6.25	6.25	Case a
54	7	0.40	0.65	61.50	10380	9425	0.53	3.40	3.10	1.50	0.60	4.00	4.04	Case a
55	7	0.40	0.88	77.00	9930	8490	1.35	18.05	2.20	9.70	0.18	4.00	4.00	Case a

Note: Run time is the actual time of the experiment, t_e is the time to reach the equilibrium state as defined in Section 4.7.1

Figure 4.3: Scour holes at the equilibrium state (a) Run 48, model 6, $L = 40$ cm, $L_c = 5$ cm (b) Run 55, model 7, $L = 40$ cm, $L_c = 80$ cm

Although Runs 3 and 11 were conducted using the same abutment model, ($L = 20$ cm, at the same flow intensity $u_f/u_c = 0.88$), the final shape of scour hole for Run 3 consisted of a primary scour hole and a separated secondary scour hole at the rear face of the abutment nose. Whereas, the final shape of scour hole for Run 11 consisted of a merged

primary and secondary scour holes (see Figure 4.4). This was probably because Run 11 had higher water depth which caused the rate of scour process higher than that of Run 3. Therefore, the dimensions of primary scour hole were higher, and the primary scour hole merged with the secondary scour hole. In the same way, both Runs 50 and 55 used the same model and flow intensity. The final shape of the scour hole for the former consisted of a primary scour hole. Whereas, the final shape of scour hole for the latter run consisted of a merged primary and secondary scour hole.

Figure 4.4: Scour holes at the equilibrium state (a) Run 3, model 1, $L = 20$ cm, $L_c = 20$ cm (b) Run 11, model 1, $L = 20$ cm, $L_c = 20$ cm

From Figure 4.5, it is clear that the final shape of scour hole for Run 3 consisted of a primary scour hole and a separated smaller secondary scour hole. The final shape of the scour hole for Run 26 originally consisted of a primary and a secondary scour holes, which eventually merged together as scouring progresses. One possible explanation was that Run 26 had longer abutment. Thus, the rate of scour was higher compared to Run 3. This rate of scour increases the dimensions scour hole formed and progressively causes the primary and secondary scour holes to merge.

Figure 4.5: Scour holes at the equilibrium state (a) Run 3, model 1, $L = 20$ cm, $L_c = 20$ cm (b) Run 26, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure 4.6 shows Runs 28 and 32 which used the same model (i.e. model 3) and water depth but with Run 32 tested at higher flow intensity. It can be seen that the final shape of scour hole of Run 28 consisted of only a primary scour hole, whereas Run 32 had merged primary and secondary scour holes. This finding shows that the flow intensity has the ability to form another scour hole (i.e. a secondary scour hole) and also able to merge these scour holes as the scouring progresses to its equilibrium stage.

Figure 4.6: Scour holes at the equilibrium state (a) Run 28, model 3 $L = 40$ cm, $L_c = 40$ cm (b) Run 32, model 3, $L = 40$ cm, $L_c = 40$ cm

4.4 Flow visualization around abutment

Dye injection was used to observe the flow patterns around the narrow and wide abutments (models 6 and 7). It was observed that the flow near the water surface was deflected as it approached the skewed face of 45° wing-wall abutment, as shown in Figures 4.7 and 4.8(a). The deflected flow met the accelerated streamwise flow causing the formation of a surface roller vortex at the abutment tip. The principal vortex was observed at the same place but near to the scour hole bed. On the other hand, a similar vortex was observed at the rear face of the abutment (i.e. wake vortex) due to the expansion of the channel. It should be noted that this wake vortex was formed near the primary vortex for the case of a narrow abutment. The wake vortex was occurred further downstream for a wider abutment. This observation was similar to the findings of Bhatia and Setia (2014). The wake vortex was rather weak and was the main cause for the formation of a smaller secondary scour hole downstream of wide abutment (see Figure 4.8 (b)). Both scour holes had the same inverted cone shape.

Figure 4.7: Formation of deflected flow and surface roller and weak vortex for narrow abutment (Run 48, model 6, $L = 40$ cm, $L_c = 5$ cm, $Re = 32000$)

Figure 4.8(a): Formation of deflected flow and surface roller around upstream of a wide abutment (Run 55, model 7, $L = 40$ cm, $L_c = 80$ cm, $Re = 32000$)

Figure 4.8(b): Formation of weak vortex downstream of the rear face of a wide abutment (Run 55, model 7, $L = 40$ cm, $L_c = 80$ cm, $Re = 32000$)

4.5 Location of maximum scour depth

The location of maximum scour depth is an important characteristic of the scour hole for a wing-wall (WW) abutment. Observations of the present study showed that the maximum scour location is generally occurred slightly downstream of the WW abutment nose. This is not the same compared to a vertical-wall (VW) abutment where the maximum scour is observed just upstream of the abutment nose. This difference has not received much attention in the past (Tey, 1984; Ballegooy, 2005). Furthermore, when this location is occurred far from the abutment tip and moves near to the bankline of channel, it threatens the geotechnical stability of the bank between floodplain and main channel which causes its failure (Ettema et al., 2010; Yorozya and Ettema, 2015). Richardson and Davis (1995), Morales et al. (2008) and Federal Highway Administration (FHWA) (2009) suggested that the width of the riprap apron should be extended around the abutment by up to two times the floodplain water depth to protect it from scouring. Based on the present results, this width will be insufficient, especially for flow with low flow intensity because it has been observed that the radial distances (R) of the maximum scour depth location is much higher than two times of floodplain water depth for this case (see Table 4.1). The present study found that the maximum scour location is affected by the flow intensity, flow depth, abutment aspect ratio, (i.e. its length and width) and the shape of abutment.

Figure 4.9 shows a definition sketch of the location of maximum scour depth in terms of R_x and R_y where R_x is the spanwise distance from the abutment face to the location and R_y is the streamwise distance from the centerline of the abutment face to this location, respectively. The radial distance from the centerline of abutment face to the position of maximum scour depth (R) equals $\sqrt{R_x^2 + R_y^2}$. With reference to Figure 4.9, there are three cases for the location of the maximum scour depth with respect to the abutment tip, and they are as follows:

Figure 4.9: Definition sketch of the location of maximum scour depth and its distance from abutment face (R_x) and distance from centerline of abutment face (R_y)

- a) at a location abreast and normal to the abutment tip, and most of present data points fall into this case.
- b) at a location upstream of the abutment tip
- c) at a location downstream of the abutment tip

4.5.1 Time development of location of maximum scour depth

It was observed that for low flow intensity, the location of maximum scour depth, R_x migrates towards the centerline of the flume with the development of time up to the equilibrium state. This finding has a practical implication and may threaten the geotechnical stability of the bankline. The design of countermeasure should take into account this aspect to cover the possible migration of the maximum scour depth. As the width of scour hole will extend further towards the centerline of channel. The time development of this location and scour depth for Run 28 (model 3, $L = 40$ cm, $L_c = 40$ cm) is shown in Figure 4.10. In this figure, the migration scour depth curve is presented in three stages; early stage, intermediate stage and equilibrium stage which is similar in shape to the scour depth development curve. Figures 4.11 and 4.12 show the photograph and measured topography of the scour hole at the equilibrium state, respectively. It is clear that R_x is far from abutment tip and near to the bankline of flume. (case a based on Figure 4.9).

Figure 4.10: Time development of location, R_x and maximum scour depth, d_s for Run 28 ($L = 40$ cm, $L_c = 40$ cm, $u_f/u_c = 0.59$, $y_f/y_m = 0.3$ and run time = 10940 minutes)

Figure 4.11: Photo showing location of maximum scour depth from abutment tip at the equilibrium state for model 3 Run 28

Figure 4.12: Topography of equilibrium scour hole around model 3 ($L = 40$ cm, $L_c = 40$ cm) for Run 28

4.5.2 Effects of L/y_f , L_c/L and u_f/u_c on location of maximum scour depth at equilibrium condition

The runs with $u_f/u_c = 0.57, 0.65, 0.77, 0.81, 0.88$ and 0.99 (see Table 4.1) were used to investigate the effects of abutment length to flow depth ratio, L/y_f , and abutment aspect ratio, L_c/L on the position of maximum scour depth. Generally, Figures 4.13 to 4.14 show that the maximum scour location moves further away from the abutment face with an increase in L/y_f . This trend is supported by the findings of Ballegooy (2005), Melville et al. (2006) and Yorozya and Ettema (2015).

The trend for R_x/y_f in Figure 4.13 shows that for low flow intensity, the values of R_x/y_f are larger than those with higher flow intensity at the same value of L_c/L . This is because for low flow intensity, the maximum scour depth shifts laterally away more from abutment tip. Thus, the distance between abutment face and the maximum scour depth (i.e. R_x) is larger for low flow intensity. This observation is also supported by Sturm (2006) and Zhang et al. (2012). One may conclude that as flow intensity decreases, the location of maximum scour depth shifts further laterally from the abutment nose towards the centerline of flume. Conversely, the data trend for R_y/y_f in Figure 4.14 shows that it does not depend on u_f/u_c .

Based on the finding of Zhang et al.'s (2012) study, one may surmise that in the case of high flow intensity scouring which starts at the abutment tip and the maximum scour depth remains at the same location around this tip because of continuous strong vortex action. On the other hand, for low flow intensity, the flow is relatively weaker, and the vortex formation is further from the abutment face causing the maximum scour location to be deflected more laterally.

Figures 4.13 and 4.14 show that the effect of L_c/L on R_y/y_f is much more than its effect on R_x/y_f . A possible explanation is that for low values of L_c/L (i.e. narrow abutment), the deepest scour point is observed to be migrated to the downstream of abutment nose. This causes the maximum scour depth to be near to the centerline of abutment face.

Thus, the values of R_y/y_f for narrow abutment (for example $L_c = 5$ cm) are much smaller than that of wide abutment (i.e. $L_c = 40$ cm and $L_c = 80$ cm). On the other hand, for a given u_f/u_c , R_x/y_f has no noticeable change when the abutment changes from narrow to much wider one.

Figure 4.13: Variation of R_x/y_f with L/y_f for the present study at different flow intensities and abutment aspect ratios

Figure 4.14: Variation of R_y/y_f with L/y_f for the present study at different flow intensities and abutment aspect ratios

4.5.3 Proposed equations to predict the location of maximum scour depth

To establish the relationship between the location of maximum scour depth and controlling parameters, regression analysis was used. The result showed that the effect of y_f/y_m and L/d_{50} is minimal. Furthermore, it was also noted that Ballegooy (2005) had reported that the position of maximum scour depth is not dependent on $(B_f - L)/B_f$. The following equations are derived as follows:

$$\frac{R_x}{y_f} = 0.06 \left(\frac{L}{y_f} \right)^{0.53} \left(\frac{L_c}{L} \right)^{0.02} \left(\frac{u_f}{u_c} \right)^{-2.76} \quad (4.3)$$

$$\frac{R_y}{y_f} = 0.32 \left(\frac{L}{y_f} \right)^{1.17} \left(\frac{L_c}{L} \right)^{1.69} \quad (4.4)$$

The correlation coefficient (R^2) for Equations (4.3) and (4.4) are 0.91 and 0.92, respectively. The comparisons between measured and calculated values using Equations (4.3) to (4.4) for the present and previous studies are shown in Figures 4.15 to 4.16. The data from Ballegooy (2005) and Sturm (2006) are listed in Tables 4.2 and 4.3. Figures 4.15 and 4.16 show the good agreement of the present data with the proposed equations. As expected, the data of Ballegooy (2005) for spill-through (ST) abutments are underestimated using the suggested equations. The measured values are much higher probably because the Ballegooy's abutment models are erodible models (i.e. models were moulded from sand) and the locations of maximum scour depth are deflected further from abutment face compared to the present solid models. Moreover, Wong (1982) and Tey (1984) found that for the same hydraulic conditions, the width of scour hole for ST abutment (1:1) is higher than that of 45° WW abutment. The sloped face of ST abutment probably shifts the down flow and primary vortex much more from the abutment. As a result, the scour hole is wider because of the enhanced deflected flow and hence causing the location of the maximum scour depth to be shifted more for ST abutment. Ballegooy's (2005) data are multiplied by a factor to take into account for the erodibility effect and shape of abutment model. To this end, the factors are 13 for R_x/y_f and 4 for R_y/y_f , respectively. Similarly, Sturm's (2006) data for vertical wall (VW)

abutments are also underestimated using Equations (4.3) and (4.4) and the multiplying factors are 1.8 for R_x/y_f and 2 for R_y/y_f , respectively. The multiplication factors suggested for ST and VW abutments are based on limited data and it is preliminary at this stage to conclude on the generality of the multiplication factor until more data are available for comparison.

4.5.4 Comparison with formulas of previous studies

To compare the proposed equations with previous formula, Melville et al.'s (2006) equation is chosen, and their equation can be expressed as follows:

$$\frac{R}{y_f} = 4 \left(\frac{L}{y_f} \right)^{0.2} \quad (4.5)$$

This equation is mainly developed to predict the radial distance of the deepest scour point around setback abutment protected with riprap apron. First R_x/y_f and R_y/y_f are calculated using Equations (4.3) to (4.4), and then the radial distance (i.e. R/y_f) is calculated by taking the square root of the sum of $(R_x/y_f)^2$ and $(R_y/y_f)^2$.

Figure 4.17 shows the comparison between the proposed equation and Melville et al.'s (2006) equation for different L/y_f , but at a constant $u_f/u_c = 0.9$ similar to Melville et al.'s test conditions.

In this figure, it is noted that L/y_f is not the only parameter that affects the location of maximum scour depth as suggested by Melville et al. (2006), the parameters u_f/u_c and L_c/L have a significant effect on this location as well. The two former parameters (u_f/u_c and L_c/L) should take into account in any equation to predict this location. As a result, Melville et al. (2006)'s equation cannot represent different flow conditions and aspect ratios of abutment. It is also noticed that for a given u_f/u_c when L_c/L has a high value, its effect starts to diminish (i.e. $L_c/L > 8$). In other words when the value of L_c/L becomes 8, the difference in the calculated R/y_f is small.

Table 4.2: ST Data of Ballegooy (2005) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	R_x cm	R_y cm	L/y_f	u_f/u_c	R_x/y_f	R_y/y_f	Location of maximum scour depth
1	80	160	40	40	10	25	25	62	4	0.90	2.50	6.20	Case c
2	80	160	60	40	10	25	32	78	6	0.90	3.20	7.80	Case c
3	120	120	40	40	10	25	15	38	4	0.90	1.55	3.80	Case c
4	120	120	60	40	10	25	22	50	6	0.90	2.20	5.00	Case c
5	120	120	80	40	10	25	44	79	8	0.90	4.40	7.95	Case c
6	160	80	40	40	10	25	23	45	4	0.90	2.30	4.50	Case c
7	160	80	60	40	10	25	27	50	6	0.90	2.70	5.00	Case c
8	160	80	80	40	10	25	33	61	8	0.90	3.30	6.10	Case c
9	200	40	40	40	10	25	19	47	4	0.90	1.90	4.70	Case c
10	200	40	60	40	10	25	24	54	6	0.90	2.40	5.40	Case c
11	200	40	80	40	10	25	18	58	8	0.90	1.80	5.80	Case c
12	200	40	100	40	10	25	37	66	10	0.90	3.70	6.60	Case c

Table 4.3: VW Data of Sturm (2006) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	R_x cm	R_y cm	L/y_f	u_f/u_c	R_x/y_f	R_y/y_f	Location of maximum scour depth
1	366	15.8	240	15	7.68	23.08	35.0	0.9	31.25	0.42	4.55	0.11	Case c
2	366	15.8	160	15	13.50	28.90	28.0	3.6	26.10	0.49	4.56	0.59	Case c

Note: VW = vertical-wall abutment ST = spill-through abutment

Figure 4.15: Measured R_x/y_f against calculated R_x/y_f using Equation 4.3 for the present and previous studies

Figure 4.16: Measured R_y/y_f against calculated R_y/y_f using Equation 4.4 for the present and previous studies

Figure 4.17: Calculated R/y_f using Equations 4.3, 4.4 and 4.5 at different abutment aspect ratios

4.6 Dimensions of scour hole and its volume at the equilibrium state

The dimensions of the scour hole and its volume are important for scour countermeasures. The countermeasures can be divided into two types: the first is flow alteration based on moving the flow away from the vicinity of abutments, and hence reduces the scour around them, whereas the second one is the armouring technique which is based on using hard materials such as riprap and gabions to prevent the formation of scour near abutments since these materials are less erodible. The dimensions of scour hole and its volume are important for the design of the second type of scour countermeasures as these characteristics translate into the cost of material needed for the protection against scour. Many studies focused only on the measurements of maximum scour depth around abutment, and few studies dealt with scour hole dimensions and its volume (Wu, 2014).

4.6.1 Effects of L/y_f , L_c/L and u_f/u_c on dimensions of scour hole and its volume

The effects of the abutment length to flow depth ratio, L/y_f on scour depth, d_{se}/y_f , length, L_{se}/y_f , width, W_{se}/y_f and volume, V_{se}/y_f^3 at different abutment aspect ratios, L_c/L and flow intensities, u_f/u_c were investigated for varying abutment lengths, flow depths and discharges to cover a range of L/y_f from 1.33 to 10.67, u_f/u_c from 0.57 to 0.99, and abutment aspect ratios, L_c/L from 0.125 to 4.

Figure 4.18 shows d_{se}/y_f plotted against L/y_f for different u_f/u_c and L_c/L with data from the present study and relevant data from Sturm and Janjua (1994), Cardoso and Bettess (1999), Nugroho (2006) and Sturm (2006) (see Tables 4.4 to 4.10). Generally, it is observed that increasing in L/y_f leads to an increase in d_{se}/y_f . In addition, for high flow intensity, the values of d_{se}/y_f are greater than that of low flow intensity at the same value of L_c/L . This is because the rate of scour is higher for high flow intensity. Finally,

Figure 4.18: Variation of d_{se}/y_f with L/y_f for present and previous studies for different flow intensities and abutment aspect ratios

for a given L/y_f and u_f/u_c , d_{se}/y_f decreases with an increase in L_c/L which means narrower abutments have larger scour depth compared to wider ones. This is to be expected as the shifted down flow for the narrower abutment occurs very near to the wake vortices, which are located downstream of the rear abutment nose. This aspect is supported by Briaud et al.'s (2005) rectangular channel experiments using cohesive sediments. They found that for a given contraction ratio, the maximum scour depth for a larger ratio of abutment width to the contracted channel width is less than that for a smaller ratio. Moreover, Afzalimehr et al.'s (2018) flow measurements in scour holes caused by different abutment aspect ratios in rectangular channel reported that abutment models with smaller aspect ratio produced higher scour depth. Finally, Kayaturk's (2005) supported the finding of the present study when his experiments show a 20% reduction in scour depth when L_c/L increased from 0.4 to 2. However, Xiong et al.'s (2013) rectangular data show that abutment width has no noticeable effect on scour depth. This contradicting result is probably because Xiong et al.'s (2013) study did not use a wide enough abutment. The present study using a very wide abutment ($L_c = 80$ cm and $L_c/L = 4$) show that the scour depth reduces as the abutment width increases. This is probably due to the long contraction effect for a very wide abutment width, and it is expected that the flow lost much energy along the abutment side causing the scour depth to be less than other narrower abutment models under similar hydraulic conditions.

Melville's (1992) enveloping equations for solid vertical-wall abutment in rectangular channel is also shown in Figure 4.18. He also assumed that scour depth around setback abutment is equal to scour at rectangular channel for the same hydraulic conditions and abutment shape. However, it seems that Melville's (1992) equation represents the upper limit of all data. Therefore, there is a need to establish a set of new scour prediction equations for setback abutment in compound channel since the data based on rectangular channel are most likely too conservative. It is also noted from data of Sturm (2006) that the scour depth still increases slightly beyond the suggested limit by Melville (1992) beyond $L/y_f = 25$.

Table 4.4: VW Data of Sturm and Janjua (1994) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
1	249	30	58.4	13.0	4.9	25.7	3.3	11.9	0.57	0.22	0.19	0.76	1.77	n.a.
2	249	30	58.4	13.0	5.0	25.8	3.3	11.7	0.64	0.22	0.19	0.76	3.13	n.a.
3	249	30	58.4	13.0	5.2	25.9	3.3	11.2	0.81	0.22	0.20	0.76	3.66	n.a.
4	249	30	58.4	13.0	4.9	25.5	3.3	11.9	0.47	0.22	0.19	0.76	1.31	n.a.
5	249	30	58.4	13.0	7.4	28.2	3.3	7.9	0.45	0.22	0.26	0.76	1.07	n.a.
6	249	30	58.4	13.0	7.3	28.0	3.3	8.0	0.56	0.22	0.26	0.76	2.46	n.a.
7	249	30	58.4	13.0	7.0	27.7	3.3	8.3	0.53	0.22	0.25	0.76	2.23	n.a.
8	249	30	58.4	13.0	7.7	28.5	3.3	7.6	0.42	0.22	0.27	0.76	1.42	n.a.
9	249	30	58.4	13.0	10.6	31.3	3.3	5.5	0.47	0.22	0.34	0.76	1.23	n.a.
10	249	30	58.4	13.0	10.6	31.3	3.3	5.50	0.47	0.22	0.34	0.76	0.99	n.a.
11	249	30	58.4	13.0	10.6	31.3	3.3	5.5	0.42	0.22	0.34	0.76	0.95	n.a.
12	249	30	58.4	13.0	10.3	30.5	3.3	5.7	0.49	0.22	0.34	0.76	1.50	n.a.
13	249	30	116.8	13.0	5.1	25.8	3.3	22.9	0.56	0.11	0.20	0.53	3.18	n.a.
14	249	30	116.8	13.0	5.5	26.3	3.3	21.2	0.45	0.11	0.21	0.53	1.79	n.a.
15	249	30	116.8	13.0	5.4	26.0	3.3	21.6	0.60	0.11	0.21	0.53	3.63	n.a.

Table 4.4: VW Data of Sturm and Janjua (1994) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
16	249	30	116.8	13.0	5.4	26.1	3.3	21.6	0.54	0.11	0.21	0.53	2.92	n.a.
17	249	30	116.8	13.0	7.5	28.2	3.3	15.6	0.39	0.11	0.27	0.53	1.55	n.a.
18	249	30	116.8	13.0	7.3	28.0	3.3	16	0.52	0.11	0.26	0.53	2.82	n.a.
19	249	30	116.8	13.0	7.0	27.7	3.3	16.7	0.54	0.11	0.25	0.53	2.82	n.a.
20	249	30	116.8	13.0	7.5	28.2	3.3	15.6	0.46	0.11	0.27	0.53	1.80	n.a.
21	249	30	116.8	13.0	10.5	31.2	3.3	11.1	0.45	0.11	0.33	0.53	1.86	n.a.
22	249	30	116.8	13.0	10.0	30.7	3.3	11.7	0.40	0.11	0.33	0.53	1.23	n.a.
23	249	30	116.8	13.0	5.4	26.2	3.3	21.6	0.67	0.11	0.21	0.53	3.70	n.a.
24	249	30	154.9	13.0	5.3	26.0	3.3	29.2	0.50	0.08	0.20	0.38	2.59	n.a.
25	249	30	154.9	13.0	5.2	26.0	3.3	29.8	0.47	0.08	0.20	0.38	2.00	n.a.
26	249	30	154.9	13.0	5.3	26.0	3.3	29.2	0.64	0.08	0.20	0.38	3.88	n.a.
27	249	30	154.9	13.0	7.0	27.7	3.3	22.1	0.44	0.08	0.25	0.38	1.63	n.a.
28	259	20	154.9	13.0	7.6	28.3	3.3	20.4	0.41	0.08	0.27	0.40	1.39	n.a.
29	259	20	154.9	13.0	7.6	28.3	3.3	20.4	0.42	0.08	0.27	0.40	1.62	n.a.
30	259	20	154.9	13.0	7.6	28.3	3.3	20.4	0.47	0.08	0.27	0.40	2.10	n.a.

Table 4.4: VW Data of Sturm and Janjua (1994) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
31	259	20	154.9	13.0	7.6	28.3	3.3	20.4	0.56	0.08	0.27	0.40	2.68	n.a.
32	259	20	116.8	13.0	7.6	28.3	3.3	15.4	0.52	0.11	0.27	0.55	2.56	n.a.
33	259	20	116.8	13.0	7.6	28.3	3.3	15.4	0.47	0.11	0.27	0.55	1.99	n.a.
34	259	20	116.8	13.0	7.6	28.3	3.3	15.4	0.43	0.11	0.27	0.55	1.26	n.a.
35	259	20	116.8	13.0	6.8	27.5	3.3	17.1	0.44	0.11	0.25	0.55	1.68	n.a.

Note: VW = vertical-wall abutment

Table 4.5: VW, WW, SC and ST Data of kouchakzadeh and Townsend (1997) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	Shape	t_e (min)
1	38.1	40.6	21.0	9.0	4.2	14.6	0.5	5.00	1.19	0.43	0.29	0.45	2.59	VW	n.a.
2	38.1	40.6	15.0	9.0	3.3	13.7	0.5	4.54	1.07	0.60	0.24	0.61	2.42	VW	n.a.
3	38.1	40.6	9.0	9.0	2.9	13.3	0.5	3.10	1.08	1.00	0.22	0.76	1.86	VW	n.a.
4	38.1	40.6	21.0	4.5	4.2	14.6	0.5	5.00	1.19	0.21	0.29	0.45	2.00	WW	n.a.
5	38.1	40.6	15.0	4.5	3.3	13.7	0.5	4.54	1.07	0.30	0.24	0.61	2.00	WW	n.a.
6	38.1	40.6	9.0	4.5	2.9	13.3	0.5	3.10	1.08	0.50	0.22	0.76	1.79	WW	n.a.
7	38.1	40.6	21.0	9.0	4.2	14.6	0.5	5.00	1.19	0.43	0.29	0.45	1.88	SC	n.a.
8	38.1	40.6	15.0	9.0	3.3	13.7	0.5	4.54	1.07	0.60	0.24	0.61	1.91	SC	n.a.
9	38.1	40.6	9.0	9.0	2.9	13.3	0.5	3.10	1.08	1.00	0.22	0.76	1.72	SC	n.a.
10	38.1	40.6	21.0	4.5	4.2	14.6	0.5	5.00	1.19	0.21	0.29	0.45	1.88	ST	n.a.
11	38.1	40.6	15.0	4.5	3.3	13.7	0.5	4.54	1.07	0.30	0.24	0.61	1.91	ST	n.a.
12	38.1	40.6	9.0	4.5	2.9	13.3	0.5	3.10	1.08	0.50	0.22	0.76	1.45	ST	n.a.
13	38.1	40.6	21.0	9.0	3.8	14.2	0.7	5.53	1.07	0.43	0.27	0.45	3.08	VW	n.a.
14	38.1	40.6	15.0	9.0	3.8	14.2	0.7	3.95	1.02	0.60	0.27	0.61	2.60	VW	n.a.
15	38.1	40.6	9.0	9.0	3.8	14.2	0.7	2.37	0.95	1.00	0.27	0.76	2.03	VW	n.a.

Table 4.5: VW, WW, SC and ST Data of kouchakzadeh and Townsend (1997) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	Shape	t_e (min)
16	38.1	40.6	21.0	4.5	3.8	14.2	0.7	5.53	1.07	0.21	0.27	0.45	2.63	WW	n.a.
17	38.1	40.6	15.0	4.5	3.8	14.2	0.7	3.95	1.02	0.30	0.27	0.61	2.13	WW	n.a.
18	38.1	40.6	9.0	4.5	3.8	14.2	0.7	2.37	0.95	0.50	0.27	0.76	1.79	WW	n.a.
19	38.1	40.6	21.0	9.0	3.8	14.2	0.7	5.53	1.07	0.43	0.27	0.45	2.53	SC	n.a.
20	38.1	40.6	15.0	9.0	3.8	14.2	0.7	3.95	1.02	0.60	0.27	0.61	2.18	SC	n.a.
21	38.1	40.6	9.0	9.0	3.8	14.2	0.7	2.37	0.95	1.00	0.27	0.76	1.71	SC	n.a.
22	38.1	40.6	21.0	4.5	3.8	14.2	0.7	5.53	1.07	0.21	0.27	0.45	2.60	ST	n.a.
23	38.1	40.6	15.0	4.5	3.8	14.2	0.7	3.95	1.02	0.30	0.27	0.61	2.16	ST	n.a.
24	38.1	40.6	9.0	4.5	3.8	14.2	0.7	2.37	0.95	0.50	0.27	0.76	1.58	ST	n.a.

Note: VW = vertical-wall abutment WW = wing-wall abutment SC = semi-circular abutment ST = spill-through abutment

Table 4.6: VW Data of Cardoso and Bettess (1999) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
1	80	156	14.7	3.0	3.1	11.1	0.835	11.9	0.82	0.20	0.28	0.82	3.94	2220
2	80	156	14.7	3.0	7.3	15.3	0.835	11.7	0.77	0.20	0.48	0.82	3.01	7200
3	80	156	27.0	3.0	2.8	10.8	0.835	11.2	0.82	0.11	0.26	0.66	4.54	6060
4	80	156	27.0	3.0	7.8	15.8	0.835	11.9	0.76	0.11	0.49	0.66	3.10	4320
5	80	156	40.0	3.0	2.8	10.8	0.835	7.9	0.83	0.07	0.26	0.50	4.39	1620
6	80	156	40.0	3.0	7.9	15.9	0.835	8.0	0.76	0.07	0.50	0.50	3.11	2700
7	80	156	53.0	3.0	3.7	11.7	0.835	8.3	0.78	0.06	0.32	0.33	5.43	1920
8	80	156	53.0	3.0	8.8	16.8	0.835	7.6	0.83	0.06	0.52	0.33	3.42	1500
9	80	156	66.5	3.0	3.3	11.3	0.835	5.5	0.87	0.04	0.29	0.17	6.64	420
10	80	156	66.5	3.0	6.0	14.0	0.835	5.5	0.89	0.04	0.43	0.17	4.18	720
11	80	156	66.5	3.0	8.4	16.4	0.835	5.5	0.81	0.04	0.51	0.17	3.93	1260

Table 4.7: VW Data of Nugroho (2006) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
1	100	60	20	5.0	3.75	18.75	0.9	5.3	0.82	0.25	0.20	0.80	2.91	n.a
2	100	60	20	5.0	3.75	18.75	0.9	5.3	0.91	0.25	0.20	0.80	2.88	n.a
3	100	60	20	5.0	6.40	21.40	0.9	3.1	0.58	0.25	0.30	0.80	1.56	5760
4	100	60	20	5.0	6.40	21.40	0.9	3.1	0.70	0.25	0.30	0.80	2.39	21000
5	100	60	20	5.0	6.40	21.40	0.9	3.1	0.82	0.25	0.30	0.80	2.91	3180
6	100	60	20	5.0	10.00	25.00	0.9	2.0	0.47	0.25	0.40	0.80	0.55	n.a
7	100	60	20	5.0	10.00	25.00	0.9	2.0	0.57	0.25	0.40	0.80	1.32	10080
8	100	60	20	5.0	10.50	25.50	0.9	1.9	0.61	0.25	0.41	0.80	2.24	31380
9	100	60	20	5.0	10.00	25.00	0.9	2.0	0.80	0.25	0.40	0.80	2.37	7260
10	100	60	20	5.0	15.00	30.00	0.9	1.3	0.78	0.25	0.50	0.80	2.27	26106
11	100	60	35	5.0	3.75	18.75	0.9	9.3	0.66	0.14	0.20	0.65	0.95	10800
12	100	60	35	5.0	3.75	18.75	0.9	9.3	0.82	0.14	0.20	0.65	1.50	n.a
13	100	60	35	5.0	6.40	21.40	0.9	5.5	0.58	0.14	0.30	0.65	3.18	6954
14	100	60	35	5.0	6.40	21.40	0.9	5.5	0.70	0.14	0.30	0.65	1.79	19320
15	100	60	35	5.0	10.00	25.00	0.9	3.5	0.47	0.14	0.40	0.65	3.63	10080

Table 4.7: VW Data of Nugroho (2006) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
16	100	60	35	5.0	10.00	25.00	0.9	3.5	0.57	0.14	0.40	0.65	1.98	10440
17	100	60	50	5.0	3.75	18.75	0.9	13.3	0.66	0.10	0.20	0.50	3.39	4338
18	100	60	50	5.0	3.75	18.75	0.9	13.3	0.82	0.10	0.20	0.50	4.93	2580
19	100	60	50	5.0	6.40	21.40	0.9	7.8	0.58	0.10	0.30	0.50	2.41	2640
20	100	60	50	5.0	10.00	25.00	0.9	5.0	0.47	0.10	0.40	0.50	1.59	9000

Table 4.8: VW Data of Sturm (2006) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
1	366	15.8	80	15.0	3.23	18.63	3.3	24.8	0.52	0.19	0.17	0.78	0.37	n.a.
2	366	15.8	80	15.0	4.11	19.51	3.3	19.5	0.57	0.19	0.21	0.78	0.90	n.a.
3	366	15.8	80	15.0	4.60	20.00	3.3	17.4	0.58	0.19	0.23	0.78	2.39	n.a.
4	366	15.8	80	15.0	5.21	20.61	3.3	15.3	0.61	0.19	0.25	0.78	3.17	n.a.
5	366	15.8	80	15.0	5.88	21.28	3.3	13.6	0.62	0.19	0.28	0.78	3.32	n.a.
6	366	15.8	80	15.0	6.46	21.86	3.3	12.4	0.63	0.19	0.29	0.78	3.54	n.a.
7	366	15.8	160	15.0	3.96	19.36	3.3	40.4	0.46	0.09	0.20	0.56	1.54	n.a.
8	366	15.8	160	15.0	4.36	19.76	3.3	36.7	0.47	0.09	0.22	0.56	2.32	n.a.
9	366	15.8	160	15.0	4.36	19.76	3.3	36.7	0.47	0.09	0.22	0.56	2.02	n.a.
10	366	15.8	160	15.0	5.30	20.70	3.3	30.2	0.48	0.09	0.26	0.56	2.53	n.a.
11	366	15.8	160	15.0	6.13	21.53	3.3	26.1	0.50	0.09	0.28	0.56	3.23	n.a.
12	366	15.8	160	15.0	6.13	21.53	3.3	26.1	0.50	0.09	0.28	0.56	2.89	n.a.
13	366	15.8	160	15.0	6.49	21.89	3.3	24.6	0.50	0.09	0.30	0.56	2.73	n.a.
14	366	15.8	160	15.0	6.86	22.26	3.3	23.3	0.51	0.09	0.31	0.56	3.34	n.a.
15	366	15.8	160	15.0	7.35	22.75	3.3	21.8	0.51	0.09	0.32	0.56	3.85	n.a.

Table 4.8: VW Data of Sturm (2006) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/y_f	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
16	366	15.8	240	15.0	4.05	19.45	3.3	59.2	0.38	0.06	0.21	0.34	2.10	n.a.
17	366	15.8	240	15.0	4.85	20.25	3.3	49.5	0.37	0.06	0.24	0.34	3.19	n.a.
18	366	15.8	240	15.0	5.88	21.28	3.3	40.8	0.37	0.06	0.28	0.34	3.11	n.a.
19	366	15.8	240	15.0	6.61	22.01	3.3	36.3	0.39	0.06	0.30	0.34	3.60	n.a.
20	366	15.8	240	15.0	6.61	22.01	3.3	36.3	0.39	0.06	0.30	0.34	3.13	n.a.
21	366	15.8	240	15.0	7.68	23.08	3.3	31.2	0.42	0.06	0.33	0.34	3.78	n.a.
22	366	15.8	323	15.0	4.69	20.09	2.7	68.9	0.32	0.05	0.23	0.12	4.28	n.a.
23	366	15.8	323	15.0	7.16	22.56	2.7	45.1	0.26	0.05	0.32	0.12	2.51	n.a.
24	366	15.8	323	15.0	6.28	21.68	2.7	51.4	0.29	0.05	0.29	0.12	3.44	n.a.
25	366	15.8	323	15.0	6.67	22.07	2.7	48.4	0.28	0.05	0.30	0.12	3.79	n.a.
26	366	15.8	80	15.0	4.11	19.51	2.7	19.5	0.60	0.19	0.21	0.78	2.60	n.a.
27	366	15.8	80	15.0	4.60	20.00	2.7	17.4	0.61	0.19	0.23	0.78	3.11	n.a.
28	366	15.8	80	15.0	5.21	20.61	2.7	15.3	0.64	0.19	0.25	0.78	3.74	n.a.
29	366	15.8	80	15.0	5.88	21.28	2.7	13.6	0.66	0.19	0.28	0.78	3.62	n.a.
30	366	15.8	160	15.0	4.36	19.76	2.7	36.7	0.50	0.09	0.22	0.56	2.80	n.a.

Table 4.8: VW and ST Data of Sturm (2006) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/y_f	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	Shape	t_e (min)
31	366	15.8	240	15.0	4.85	20.25	2.7	59.3	0.40	2.6	0.21	0.34	3.09	VW	n.a.
32	366	15.8	240	15.0	5.88	21.28	2.7	49.5	0.40	2.6	0.24	0.34	3.83	VW	n.a.
33	366	15.8	240	15.0	6.61	22.01	2.7	40.8	0.39	2.5	0.28	0.34	3.62	VW	n.a.
34	366	15.8	80	15.0	2.68	18.08	1.1	36.3	0.42	2.6	0.30	0.34	4.14	VW	n.a.
35	366	15.8	80	15.0	3.23	18.63	1.1	29.8	0.74	1.7	0.15	0.78	4.33	VW	n.a.
36	366	15.8	80	15.0	4.11	19.51	1.1	24.8	0.77	1.8	0.17	0.78	5.01	VW	n.a.
37	366	15.8	160	15.0	3.54	18.94	1.1	19.5	0.85	1.8	0.21	0.78	4.96	VW	n.a.
38	366	15.8	160	15.0	4.36	19.76	1.1	45.2	0.67	1.7	0.19	0.56	5.25	VW	n.a.
39	366	15.8	160	15.0	5.30	20.70	1.1	36.7	0.71	1.2	0.22	0.56	4.95	VW	n.a.
40	366	15.8	240	15.0	3.08	18.48	1.1	30.2	0.72	1.2	0.26	0.56	5.06	VW	n.a.
41	366	15.8	240	15.0	3.66	19.06	1.1	77.9	0.51	1.2	0.17	0.34	4.64	VW	n.a.
42	366	15.8	240	15.0	4.05	19.45	1.1	65.6	0.53	1.3	0.19	0.34	5.90	VW	n.a.
43	366	15.8	117	15.0	3.57	18.97	3.3	59.3	0.56	2.5	0.21	0.34	6.32	ST	n.a.
44	366	15.8	117	15.0	4.11	19.51	3.3	32.8	0.50	2.4	0.19	0.68	0.34	ST	n.a.
45	366	15.8	117	15.0	5.70	21.10	3.3	28.5	0.57	2.4	0.21	0.68	0.66	ST	n.a.

Table 4.8: ST and WW Data of Sturm (2006) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	Shape	t_e (min)
46	366	15.8	117	15.0	7.01	22.41	3.3	16.7	0.60	0.13	0.31	0.68	2.25	ST	n.a.
47	366	15.8	197	15.0	4.48	19.88	3.3	44.0	0.43	0.08	0.22	0.46	0.96	ST	n.a.
48	366	15.8	197	15.0	5.61	21.01	3.3	35.1	0.46	0.08	0.27	0.46	2.39	ST	n.a.
49	366	15.8	197	15.0	6.43	21.83	3.3	30.6	0.47	0.08	0.29	0.46	3.03	ST	n.a.
50	366	15.8	197	15.0	7.19	22.59	3.3	27.4	0.48	0.08	0.32	0.46	3.14	ST	n.a.
51	366	15.8	237	15.0	4.05	19.45	3.3	58.5	0.37	0.06	0.21	0.35	0.99	ST	n.a.
52	366	15.8	237	15.0	5.09	20.49	3.3	46.6	0.38	0.06	0.25	0.35	2.51	ST	n.a.
53	366	15.8	237	15.0	6.37	21.77	3.3	37.2	0.39	0.06	0.29	0.35	3.01	ST	n.a.
54	366	15.8	237	15.0	7.13	22.53	3.3	33.2	0.42	0.06	0.32	0.35	3.21	ST	n.a.
55	366	15.8	323	15.0	6.34	21.74	3.3	50.9	0.32	0.05	0.29	0.12	4.90	ST	n.a.
56	366	15.8	323	15.0	6.98	22.38	3.3	46.3	0.34	0.05	0.31	0.12	4.54	ST	n.a.
57	366	15.8	323	15.0	8.38	23.78	3.3	38.5	0.33	0.05	0.35	0.12	3.75	ST	n.a.
58	366	15.8	161	15.0	5.3	20.70	3.3	30.4	0.48	0.09	0.26	0.56	0.92	WW	n.a.
59	366	15.8	161	15.0	6.13	21.53	3.3	26.3	0.50	0.09	0.28	0.56	2.28	WW	n.a.
60	366	15.8	161	15.0	6.86	22.26	3.3	23.5	0.51	0.09	0.31	0.56	2.21	WW	n.a.

Table 4.8: WW Data of Sturm (2006) in compound channel, continued.

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	Shape	t_e (min)
61	366	15.8	222	15.0	5.55	20.95	3.3	40.0	0.39	0.07	0.26	0.39	2.47	WW	n.a.
62	366	15.8	222	15.0	6.34	21.74	3.3	35.0	0.41	0.07	0.29	0.39	3.12	WW	n.a.
63	366	15.8	222	15.0	7.35	22.75	3.3	30.2	0.44	0.07	0.32	0.39	3.16	WW	n.a.

Table 4.9: VW Data of Chua (2013) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
1	100	60	50	5.0	12.0	27.0	0.9	4.16	0.49	0.10	0.44	0.50	1.22	2078
2	100	60	50	5.0	10.0	25.0	0.9	5.00	0.54	0.10	0.40	0.50	2.03	8549
3	100	60	50	5.0	12.0	27.0	0.9	4.16	0.41	0.10	0.44	0.50	0.97	9140
4	100	60	50	5.0	9.0	24.0	0.9	5.56	0.47	0.10	0.37	0.50	1.76	4325

Table 4.10: VW Data of Sahroni (2014) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f	t_e (min)
1	100	60	50	5.0	6.40	21.4	0.9	7.81	0.58	0.10	0.44	0.50	2.10	9180
2	100	60	50	5.0	10.0	25.0	0.9	5.00	0.43	0.10	0.40	0.50	1.06	5980

Figure 4.19 illustrates the change of the scour length, L_{se}/y_f against L/y_f based on the experimental results of the present and other studies for various flow intensities and abutment aspect ratios. Generally, the figure shows that L_{se}/y_f increases with an increase in L/y_f . In Section 4.3, it was noted that there are two scour holes formed for large L_c/L (i.e. wide abutment). The present data trend shows that the scour length initially increases for L_c/L from 0.125 to 1, mainly because of the merging of the primary and secondary scour holes. However, when L_c/L increases from 1 to 4, the scour length decreases because the primary and secondary scour holes were separated. This observation is true for runs with high flow intensity (i.e. $u_f/u_c = 0.88$). It is also noted that for a given L/y_f and L_c/L , the trend shows that scour length increases with flow intensity.

In Figure 4.19, Fael et al.'s (2006) long duration scour length data for VW abutment with low L_c/L in rectangular channel were used for comparison as there is no other suitable data in compound channel. Fael et al. (2006) used a similar range of dimensionless abutment length as that in the present study. Yildiz's (2014) rectangular channel data for VW abutment with rounded end were also used, but it should be noted that his experiments were run for only 8 hours which might be too short to reach the equilibrium state (see Tables 4.11 and 4.12). The increasing trend of the present study's data with u_f/u_c is consistent with that of the previous studies.

Figure 4.19: Variation of L_{se}/y_f with L/y_f for present and previous studies for different flow intensities and abutment aspect ratios

Table 4.11: VW Data of Fael et al. (2006) in rectangular channel

Run	B cm	L cm	L_c cm	y cm	d_{50} mm	L/y	u/u_c	L_c/L	$(B - L)/B$	L_{se}/y	W_{se}/y	V_{se}/y^3
1	400	125	2.0	6.6	1.28	18.94	1.04	0.024	0.69	35.47	16.24	2069.59
2	400	109	2.0	6.6	1.28	16.51	1.05	0.027	0.72	35.33	14.65	1669.59
3	400	94	2.0	6.7	1.28	14.03	1.04	0.031	0.76	33.52	12.49	1280.08
4	400	125	2.0	6.9	1.28	18.11	0.8	0.024	0.68	24.81	13.48	575.33
5	400	109	2.0	6.9	1.28	15.80	0.81	0.027	0.73	25.27	12.33	517.49
6	400	94	2.0	7.0	1.28	13.43	0.79	0.031	0.76	21.24	11.21	300.29
7	400	125	2.0	6.6	1.28	18.94	0.63	0.024	0.69	18.26	6.94	118.26
8	400	109	2.0	7.0	1.28	15.57	0.58	0.027	0.73	10.67	5.43	55.39
9	400	94	2.0	7.0	1.28	13.43	0.59	0.031	0.76	7.58	3.76	26.24

Table 4.12: VWRE Data of Yildiz (2014) in rectangular channel

Run	B cm	L cm	L_c cm	y cm	d_{50} mm	L/y	u/u_c	L_c/L	$(B - L)/B$	L_{se}/y	W_{se}/y	V_{se}/y^3
1	150	25.0	10.0	13.5	1.50	1.85	0.90	0.40	0.83	7.56	2.34	15.77
2	150	30.0	10.0	13.5	1.50	2.22	0.90	0.33	0.80	7.84	2.68	23.62
3	150	35.0	10.0	13.5	1.50	2.59	0.90	0.28	0.77	9.54	3.34	38.55

Note: VW = vertical-wall abutment, VWRE = vertical-wall with rounded end abutment

Figure 4.20 shows the change of W_{se}/y_f versus L/y_f for the present and previous studies for different flow intensities and abutment aspect ratios. The available data on scour width for rectangular channels from Fael et al. (2006), Abouseida et al. (2009), Yildiz (2014) and Wu and Balachandar (2015) were also used for comparison. These studies were conducted in rectangular channels with different abutment shapes with scouring duration from 8 to 168 hours (see Tables 4.11 to 4.14). It is generally noticed that increasing in L/y_f leads to an increase in W_{se}/y_f . For a given L/y_f , the scour width increases with an increase in flow intensity. This finding is consistent with the findings of Fael et al. (2006) and Abousedia et al. (2009). Furthermore, W_{se}/y_f decreases as L_c/L increases at constant L/y_f and u_f/u_c . One may conclude that a wide abutment produces smaller scour width compared to the narrower abutment.

It is also noticed that the rate of increase in W_{se}/y_f is gentler at lower values of L/y_f , and is steeper for $L/y_f > 10$. This is probably as a portion of the flow near the abutment nose is diverted and moves away parallel to the upstream face of the longer abutment. This is supported by Kandasamy (1989). This flow component helps to widen the hole. Thus, the rate of increase of scour width is greater for longer abutment compared to shorter one. This part of flow is also not effective to produce down flow, and this is one reason for Melville (1997) to propose that the rate of increase of scour depth is relatively small for long abutment with $L/y_f > 25$.

Fael et al. (2006) and Abousedia et al. (2009) have values of scour width greater than the present study, although some data points have the same L/y_f . As the experiments of these studies were carried out in rectangular channels. It seems that their data form an enveloping curve for all the data. As their experiments carried out in rectangular channels.

Figure 4.20: Variation of W_{se}/y_f with L/y_f for present and previous studies for different flow intensities and abutment aspect ratios

In the present study, it is noticed that the scour width is approximately 3 times the scour depth based on the 55 runs in the present study. This is slightly higher than the 2.75 times used by Laursen (1963) in his analysis. Fael et al. (2006), Abousedia et al. (2009), Yildiz (2014) and Wu and Balachandar (2015) concluded that the scour widths are approximately equal to 2.5, 1.8, 1.6 and 3.3 times the scour depths, respectively, for their data in a rectangular channel. The contradicting result is probably because the previous studies used different abutment shapes. Therefore, the deflected flow on the abutment face is different based on the degree of face inclination. Wong (1982) and Tey (1984) claimed that for the same hydraulic conditions, the width of scour hole for spill-through abutment (1:1) is larger than those of 45° wing-wall abutment. Probably as the sloped face of spill-through abutment shifted the down flow and primary vortex much more away from the face of abutment.

Finally, it is observed that the scour width for the present data is approximately equal to 3.5 times the floodplain water depth. Therefore, the recommendation regarding riprap apron extension suggested by Richardson and Davis (1995), Morales et al. (2008) and Federal Highway Administration (FHWA) (2009) are not sufficient since these studies concluded that the width of the riprap apron should be extended around the abutment by up to two times the floodplain water depth to protect it from scouring. These studies used spill-through abutment models so that their scour widths are different compared to that of the present study.

Table 4.13: VW Data of Abousedia et al. (2009) in rectangular channel

Run	B cm	L cm	L_c cm	y_f cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	$(B_f - L)/B_f$	W_{se}/y_f
1	100	10.0	20.0	12.0	0.38	0.83	0.55	2.00	0.90	1.04
2	100	10.0	20.0	11.9	0.38	0.84	0.55	2.00	0.90	1.09
3	100	15.0	30.0	11.8	0.38	1.27	0.55	2.00	0.85	1.37
4	100	7.5	15.0	12.0	0.38	0.62	0.66	2.00	0.92	1.05
5	100	10.0	20.0	12.0	0.38	0.83	0.66	2.00	0.90	1.19
6	100	10.0	20.0	12.2	0.38	0.82	0.69	2.00	0.90	1.26
7	100	15.0	30.0	12.1	0.38	1.23	0.69	2.00	0.85	1.77
8	100	7.5	15.0	11.9	0.38	0.63	0.75	2.00	0.92	1.20
9	100	10.0	20.0	11.9	0.38	0.84	0.75	2.00	0.90	1.79
10	100	10.0	20.0	12.1	0.38	0.83	0.75	2.00	0.90	1.94
11	100	15.0	30.0	12.1	0.38	1.24	0.75	2.00	0.85	2.13
12	100	7.5	15.0	12.0	0.38	0.62	0.88	2.00	0.92	1.91
13	100	10.0	20.0	12.1	0.38	0.83	0.88	2.00	0.90	2.07
14	100	10.0	20.0	11.5	0.38	0.87	0.95	2.00	0.90	2.68
15	100	15.0	30.0	11.9	0.38	1.26	0.95	2.00	0.85	2.80

Table 4.13: VW Data of Abousedia et al. (2009) in rectangular channel, continued.

Run	B cm	L cm	L_c cm	y_f cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	$(B_f - L)/B_f$	W_{se}/y_f
16	100	7.50	15.0	12.0	0.38	0.62	0.99	2.00	0.92	2.63
17	100	10.0	20.0	11.9	0.38	0.84	0.99	2.00	0.90	2.97
18	100	15.0	30.0	12.0	0.38	1.25	0.99	2.00	0.85	3.05

Table 4.14: Circular-wall Data of Wu and Balachandar (2015) in rectangular channel

Run	B cm	L cm	L_c cm	y cm	d_{50} mm	L/y	u/u_c	L_c/L	$(B - L)/B$	W_{se}/y
1	60.0	6.00	12.00	12.0	0.77	0.50	0.85	2.00	0.90	0.79
2	120.0	6.00	12.00	15.0	0.77	0.40	0.85	2.00	0.95	0.88
3	36.5	3.65	7.30	12.0	0.77	0.30	0.85	2.00	0.90	0.78
4	76.0	3.65	7.30	15.0	0.77	0.24	0.85	2.00	0.95	0.69
5	21.1	2.11	4.22	12.0	0.77	0.17	0.85	2.00	0.90	0.50
6	44.0	2.11	4.22	15.0	0.77	0.14	0.85	2.00	0.95	0.49

Figure 4.21 shows a plot of the volume of scour hole, V_{se}/y_f^3 with L/y_f for the present data and available data from Fael et al. (2006), Kose (2007) and Yildiz (2014) (see Tables 4.11, 4.12 and 4.15). It is generally noted that V_s/y_f^3 increase with an increase in L/y_f . The present data show the scour volume increases initially with an increase in the abutment aspect ratio, L_c/L from 0.125 to 1 mainly because of the merging of the primary and secondary scour holes, but it decreases when L_c/L increases from 1 to 4 simply because the primary and secondary scour holes in the latter are separated. This observation is for high flow intensity (i.e. $u_f/u_c = 0.88$). It is also clear that the scour volume for Fael et al. (2006), Kose (2007) and Yildiz (2014) are higher than that of present study. This is because their experiments were carried out for different shapes of abutment in a rectangular channel. It seems that there is a need to propose relationship for scour hole volume for setback abutment in a compound channel. This will lead to more accurate design of countermeasure, and lower the cost required for protection against scour.

Table 4.15: VW Data of Kose (2007) in rectangular channel

Run	B cm	L cm	L_c cm	y cm	d_{50} mm	L/y	u/u_c	L_c/L	$(B - L)/B$	V_{se}/y^3
1	125	10.0	20.0	8.9	1.80	1.1	0.77	2.0	0.92	9.92
2	125	12.5	20.0	8.9	1.80	1.4	0.77	1.6	0.90	16.48

Figure 4.21: Variation of V_{se}/y_f^3 with L/y_f for present and previous studies for different flow intensities and abutment aspect ratios

4.6.2 Effect of flow depth ratio on dimensions of scour hole and its volume

Figure 4.22 illustrates the relationship of d_{se}/y_f versus the flow depth ratio, y_f/y_m between the depths on the floodplain and main channel. It shows that d_{se}/y_f decreases with an increase in y_f/y_m . This is because the scour depth for shallow water depth is usually less than that for deeper water. The trend is clearer for the narrower abutment models compared to wider ones. This is supported by the trend of scour data from previous studies such as Sturm and Janjua (1994), Nugroho (2006) and Sturm (2006) as depicted in this Figure. It is also observed that for low flow intensity, d_{se}/y_f is smaller than that of high flow intensity at the same value of L_c/L .

Figures 4.23 to 4.25 shows the relationship of L_{se}/y_f , W_{se}/y_f and V_{se}/y_f^3 with y_f/y_m . In general, it is found that L_{se}/y_f , W_{se}/y_f and V_{se}/y_f^3 decrease with increasing y_f/y_m . Therefore, these characteristics have a similar decreasing trend as scour depth. The trend of scour length is not as clear as the trend of scour depth and width with y_f/y_m . This is because the scour depth and width are affected mainly by the principal vortex whereas the scour length may be affected by the combined action of the principal vortex, surface roller and wake vortices along the scour hole (Abdelaziz and Lim, 2017). It is also noticed that for the same model, the values of L_{se}/y_f , W_{se}/y_f and V_{se}/y_f^3 for high flow intensity are higher than that of low flow intensity. Figures 4.23 to 4.25 are plotted using the present data as there are no suitable data from previous studies on effect of flow depth ratio.

Figure 4.22: Variation of d_{se}/y_f with y_f/y_m for present study and previous studies at different flow intensities and abutment aspect ratios

Figure 4.23: Variation of L_{se}/y_f with y_f/y_m for present study at different flow intensities and abutment aspect ratios

Figure 4.24: Variation of W_{se}/y_f with y_f/y_m for present study at different flow intensities and abutment aspect ratios

Figure 4.25: Variation of V_{se}/y_f^3 with y_f/y_m for present study at different flow intensities and abutment aspect ratios

4.6.3 Effect of degree of flow contraction on flood plain on dimensions of scour hole and its volume

Figures 4.26 to 4.29 show plots of d_{se}/y_f , L_{se}/y_f , W_{se}/y_f and V_{se}/y_f^3 with the flow contraction ratio, $(B_f - L)/B_f$ for the present study. The term $(B_f - L)/B_f$ represents the effect of contraction scour for abutment on floodplain and some studies have suggested that the effect of contraction scour should be included in the abutment scour prediction formulas since abutment and contraction scour may occur concurrently (Ettema et al., 2010; Sturm et al., 2011; Yorozya and Ettema, 2015). However, Melville and Coleman (2000) disagreed and reported that the two types of scour should be independent. Richardson et al. (1993) and Hong (2012) remarked that one possible reason why many prediction equations did not calculate the scour depth accurately is due to the assumption of independence of abutment and contraction scour.

From these figures, it is generally found that these scour characteristics decrease with an increase in $(B_f - L)/B_f$. This is in contrast to the trend of these scour characteristics with L/y_f . In other words, for a given flood plain width, increase in abutment length leads to increase in these scour characteristics. However, the trend for scour width is not so clear compared to the trend for scour depth, length and volume. It is seen that the values of d_{se}/y_f , L_{se}/y_f , W_{se}/y_f and V_{se}/y_f^3 for shallow water depth are higher than that of deep water depth. Another observation from these figures is that the scour characteristics increase with an increase in flow intensity. As the rate of scour process is higher for higher flow intensity.

Figure 4.26: Variation of d_{se}/y_f with $(B_f - L)/B_f$ for present study at different flow intensities and fixed abutment aspect ratio

Figure 4.27: Variation of L_{se}/y_f with $(B_f - L)/B_f$ for present study at different flow intensities and fixed abutment aspect ratio

Figure 4.28: Variation of W_{se}/y_f with $(B_f - L)/B_f$ for present study at different flow intensities and fixed abutment aspect ratio

Figure 4.29: Variation of V_{se}/y_f^3 with $(B_f - L)/B_f$ for present study at different flow intensities and fixed abutment aspect ratio

4.6.4 Proposed equations to predict the dimensions of scour hole and its volume

To find the best relationships of d_{se}/y_f , L_{se}/y_f , W_{se}/y_f and V_{se}/y_f^3 with the independent parameters of the right hand side of Equation (4.2), regression analysis was performed on data from the present study, Nugroho (2006), Chua (2013) and Sahroni (2014). The last three studies were conducted in the Hydraulics Modelling Lab, Nanyang Technological University, and used vertical-wall abutments in the same flume as the present study. The proposed equations for the scour hole dimensions and volume around solid abutments under clear water scour conditions can be expressed as follows:

$$\frac{d_{se}}{y_f} = 0.86 K_s \left(\frac{L}{y_f} \right)^{0.27} \left(\frac{L_c}{L} \right)^{-0.40} \left(\frac{u_f}{u_c} \right)^{1.65} \left(\frac{y_f}{y_m} \right)^{-0.37} \left(\frac{B_f - L}{B_f} \right)^{-0.14} \quad (4.6)$$

$$\frac{L_{se}}{y_f} = 4.52 \left(\frac{L}{y_f} \right)^{0.03} \left(\frac{L_c}{L} \right)^{-0.13} \left(\frac{u_f}{u_c} \right)^{3.20} \left(\frac{y_f}{y_m} \right)^{-0.03} \left(\frac{B_f - L}{B_f} \right)^{-2.89} \quad (4.7)$$

$$\frac{W_{se}}{y_f} = \left(\frac{L}{y_f} \right)^{0.31} \left(\frac{L_c}{L} \right)^{-0.11} \left(\frac{u_f}{u_c} \right)^{0.99} \left(\frac{y_f}{y_m} \right)^{-0.33} \left(\frac{B_f - L}{B_f} \right)^{-1.24} \quad (4.8)$$

$$\frac{V_{se}}{y_f^3} = \left(\frac{L}{y_f} \right)^{0.73} \left(\frac{L_c}{L} \right)^{-0.43} \left(\frac{u_f}{u_c} \right)^{6.23} \left(\frac{y_f}{y_m} \right)^{-0.16} \left(\frac{B_f - L}{B_f} \right)^{-5.5} \quad (4.9)$$

The correlation coefficient (R^2) for Equations (4.6) to (4.9) are 0.88, 0.97, 0.97 and 0.93, respectively. It should be noted from Equation (4.6) that K_s is the shape factor suggested for different abutment models. This factor is drawn from the comparison between different model shape having the same hydraulic condition and model dimensions (i.e. the abutment length and width). The suggested shape factors are presented in Table 4.16. These factors are applied for $0.4 < u_f/u_c < 0.99$, $1 < L/y_f < 30$, and $0.04 < L_c/L < 4$.

Table 4.16: The suggested abutment shape factors

<u>Abutment model shape</u>	<u>Shape factor K_s</u>
Vertical-wall abutment	1.00
45° wing-wall abutment	0.70
Semi-circular abutment	0.70
Spill-through abutment (1:1)	0.60
Spill-through abutment (2:1)	0.60

Equation (4.6) shows that u_f/u_c and L_c/L have significant effects on scour depth. A possible reason is that scour depth is more sensitive to u_f/u_c compared to other dimensionless parameters (Coleman et al., 2003). Moreover, when L_c/L reduces, the down flow occurs very near to the wake vortices which are located near the downstream of the rear abutment nose. As a result, the largest scour depth occurs for the case with the narrowest abutment.

It should be noted that Equations (4.7) and (4.9) predict scour hole length, width and volume for 45° wing-wall abutment since these equations are based only on the data of the present study. There is no other suitable data found in literature and hence no shape factor is suggested for these equations. From these equations, it is clear that $(B_f - L)/B_f$ and u_f/u_c have the highest impact compared to other parameters since they have the highest exponents. However, L/y_f has a small effect on the scour hole length. This is because the scour depth and width are affected mainly by the principal vortex whereas the scour length may be affected by the combined action of the principal vortex, surface roller and wake vortices along the scour hole (Abdelaziz and Lim, 2017).

The comparisons between measured and calculated values using Equation (4.6) for the present and previous studies are shown in Figure 4.30. As expected, the few data points of Ballegooy (2005) for spill-through abutments are underestimated probably because the models used were erodible. These data are presented in Table 4.17. On the other hand, some data points of Kouchakzadeh and Townsend (1997), Sturm and Janjua (1994) Sturm (2006) are overestimated probably due to short duration of some of their experiments (from 5 hours to 10 hours) which may be too short to reach the equilibrium state. The comparisons between measured and calculated values using Equations (4.7) to (4.9) for the present data are shown in Figures 4.31 to 4.33.

It is also useful to estimate the interrelationship between the scour hole dimensions in terms of the scour depth as the most readily available data are scour depth. Regression analysis is applied on the data to establish the best relationships between scour hole dimensions and its volume with scour depth. The following equations in terms of d_{se}/y_f can be obtained with a correlation coefficient (R^2) of 0.9, 0.85 and 0.93 for Equations (4.10) to (4.12), respectively:

$$\frac{L_{se}}{y_f} = 7.37 \left(\frac{d_{se}}{y_f} \right)^{1.12} \quad (4.10)$$

$$\frac{w_{se}}{y_f} = 3.33 \left(\frac{d_{se}}{y_f} \right)^{0.57} \quad (4.11)$$

$$\frac{V_{se}}{y_f^3} = 8.59 \left(\frac{d_{se}}{y_f} \right)^{2.59} \quad (4.12)$$

Figures 4.34 to 4.36 show that Equations (4.10) to (4.12) predict the values of scour hole characteristics with a reasonable agreement compared to the experimental results. The advantage of these equations is that usually maximum scour depth data are available for the purpose of design, and these equations can be used as a guide to predict the geometrical characteristics of the scour hole, especially the volume required for the sake of protection against scour. These dimensions will translate into the cost of countermeasure needed.

Table 4.17: ST Data of Ballegooy (2005) in compound channel

Run	B_f cm	B_m cm	L cm	L_c cm	y_f cm	y_m cm	d_{50} mm	L/y_f	u_f/u_c	L_c/L	y_f/y_m	$(B_f - L)/B_f$	d_{se}/y_f
1	80	160	40	10.0	10	25	0.82	4	0.90	4.0	0.40	0.50	2.00
2	80	160	60	10.0	10	25	0.82	6	0.90	4.0	0.40	0.25	3.55
3	120	120	40	10.0	10	25	0.82	4	0.90	4.0	0.40	0.67	1.80
4	120	120	60	10.0	10	25	0.82	6	0.90	4.0	0.40	0.50	2.50
5	120	120	80	10.0	10	25	0.82	8	0.90	4.0	0.40	0.33	3.15
6	160	80	40	10.0	10	25	0.82	4	0.90	4.0	0.40	0.75	2.05
7	160	80	60	10.0	10	25	0.82	6	0.90	4.0	0.40	0.63	2.90
8	160	80	80	10.0	10	25	0.82	8	0.90	4.0	0.40	0.50	3.15
9	200	40	40	10.0	10	25	0.82	4	0.90	4.0	0.40	0.80	2.00
10	200	40	60	10.0	10	25	0.82	6	0.90	4.0	0.40	0.70	2.60
11	200	40	80	10.0	10	25	0.82	8	0.90	4.0	0.40	0.60	2.90
12	200	40	100	10.0	10	25	0.82	10	0.90	4.0	0.40	0.50	3.25

Figure 4.30: Measured d_{se}/y_f against calculated d_{se}/y_f using Equation 4.6 for the present and previous studies

Figure 4.31: Measured L_{se}/y_f against calculated L_{se}/y_f using Equation 4.7 for the present study

Figure 4.32: Measured W_{se}/y_f against calculated W_{se}/y_f using Equation 4.8 for the present study

Figure 4.33: Measured V_{se}/y_f^3 against calculated V_{se}/y_f^3 using Equation 4.9 for the present study

Figure 4.34: Measured L_{se}/y_f against calculated L_{se}/y_f using Equation 4.10 for the present study

Figure 4.35: Measured W_{se}/y_f against calculated W_{se}/y_f using Equation 4.11 for the present study

Figure 4.36: Measured V_{se}/y_f^3 against calculated V_{se}/y_f^3 using Equation 4.12 for the present study

4.7 Time development of scour hole characteristics

4.7.1 Time development of scour depth

Scour around obstacle such as pier and abutment is a time dependent process. The scour depth around abutment may not reach the equilibrium state because flow usually does not last long enough during flood event to reach this state. Thus, the scour depth generated from flow hydrograph is smaller than the equilibrium scour depth. As a result, the time development of scour depth is important to predict scour depth at any time shorter than the equilibrium time.

The scour depth around the abutment increases with time until it reaches the equilibrium state. The initial rate of scour is very high and then it starts to decrease with the development of scour hole size as time progresses. Finally, this scour rate will reduce appreciably in an asymptotical manner until there is no noticeable change to the scour size and this is the equilibrium state. Hence, the relationship between the scour depth and time or the scour depth development curve can be divided into three states, namely the initial, the principal and the equilibrium states. The time to reach the equilibrium has been defined differently by various researchers. For example, Cardoso and Bettess (1999) defined it as the time when the slope of the line of scour development curve equals to zero. Coleman et al. (2003) “assumed the equilibrium time as the time when rate of scour reduces to 5% of the flow depth or the smallest foundation length (abutment length or pier diameter) in the succeeding 24-hour period”. However, this ratio is questionable if the scour depth reduces to any ratio less than 5%. In this study, the time of equilibrium is defined as the time when the rate of increase of scour depth is less than or equal to 1 mm for the following 24-hour period. The scale of 1 mm is the smallest length on the point gauge and the 24-hour period is deemed a sufficiently long period to observe the change in scour development and ensure that this change is no longer significant. In the present study, the time of equilibrium is also tested using the criterion of Cardoso and Bettess (1999) to ensure that the equilibrium state occurs. Figures 4.37 to 4.39 show the scour depth development curves for Runs 27, 31 and 35. These runs

were conducted using the same models under the same discharge (i.e. model 3, $Q = 52.4$ L/s), but they have different water depths of $y_f/y_m = 0.2, 0.3$ and 0.4 . The figures show that the curves can be divided into three phases, as explained before.

Figure 4.37: Scour depth development curve for Run 27 (model 3, $L = 40$ cm, $L_c = 40$ cm, $u_f/u_c = 0.99$, $y_f/y_m = 0.2$ and run time 10080 minutes)

Figure 4.38: Scour depth development curve for Run 31 (model 3, $L = 40$ cm, $L_c = 40$ cm, $u_f/u_c = 0.77$, $y_f/y_m = 0.3$ and run time 16700 minutes)

Figure 4.39: Scour depth development curve for Run 35 (model 3, $L = 40$ cm, $L_c = 40$ cm, $u_f/u_c = 0.57$, $y_f/y_m = 0.4$ and run time 9375 minutes)

From Figures 4.37 to 4.39, t_e can be estimated, and then the graphs of dimensionless scour depth, d_s/d_{se} against dimensionless time, t/t_e can be plotted, as shown in Figures 4.40 to 4.42. These plots provide an estimate of the scour depth as a fraction of the equilibrium scour depth and its corresponding time as a fraction of the equilibrium time. The t_e has been estimated from the time development curves of all 55 experiments conducted in this study, and these curves are presented in the Appendix. It is clear that the curves almost have similar shape and they can be described using exponential function. In addition, it is generally observed that when the time, t/t_e is approximately equal to 25%, the scour depth is about 80% of the equilibrium scour depth. This is supported by Nugroho's (2006) finding.

Figure 4.40: Dimensionless scour depth against dimensionless time for Run 27 (model 3, $L = 40$ cm, $L_c = 40$ cm, $u_f/u_c = 0.99$, $y_f/y_m = 0.2$ and run time 10080 minutes)

Figure 4.41: Dimensionless scour depth against dimensionless time for Run 31 (model 3, $L = 40$ cm, $L_c = 40$ cm, $u_f/u_c = 0.77$, $y_f/y_m = 0.3$ and run time 16700 minutes)

Figure 4.42: Dimensionless scour depth against dimensionless time for Run 35 (model 3, $L = 40$ cm, $L_c = 40$ cm, $u_f/u_c = 0.57$, $y_f/y_m = 0.4$ and run time 9375 minutes)

4.7.2 Equilibrium time of scouring process, t_e

In the present study, the 55 experiments have been conducted under clear water conditions and each run lasted several days so that the scour development curve can be analysed for the time to reach the equilibrium state (Lim, 1997; Coleman et al., 2003). The equilibrium time, t_e is defined as the time when the rate of increase of scour depth is less than or equal to 1 mm for the following 24-hour period, (see Section 4.7.1).

With reference to Equation (4.2), reproduced below, it can be seen that the dimensionless scour depth d_{se} and t_e are interdependent in the functional relationship.

$$\frac{d_{se}}{y_f} = f\left(\frac{L}{y_f}, \frac{u_f}{u_c}, \frac{L_c}{L}, \frac{y_f}{y_m}, \frac{L}{d_{50}}, \frac{B_f - L}{B_f}, \frac{B_f}{B_m}, \frac{u_f t_e}{y_f}, \frac{\rho_s}{\rho}, \sigma_g\right) \quad (4.2)$$

Many studies such as Melville and Chiew (1999), Coleman et al. (2003) and Cardoso and Fael (2010) pointed out that d_{se} and t_e are interdependent. Therefore, both of them should rely on the same independent parameters. As a result, Equation (4.2) can be written for the analysis of the equilibrium scour time as follows:

$$\frac{u_f t_e}{y_f} = f\left(\frac{L}{y_f}, \frac{u_f}{u_c}, \frac{L_c}{L}, \frac{y_f}{y_m}, \frac{L}{d_{50}}, \frac{B_f - L}{B_f}, \frac{B_f}{B_m}, \frac{\rho_s}{\rho}, \sigma_g\right) \quad (4.13)$$

In section 4.1, the effects of $\frac{L}{d_{50}}, \frac{B_f}{B_m}, \frac{\rho_s}{\rho}, \sigma_g$ on scour depth have been discussed and found to be negligible. Likewise, these terms should have similar effect for t_e . So, Equation (4.13) can be reduced to the following terms:

$$\frac{u_f t_e}{y_f} = f\left(\frac{L}{y_f}, \frac{u_f}{u_c}, \frac{L_c}{L}, \frac{y_f}{y_m}, \frac{B_f - L}{B_f}\right) \quad (4.14)$$

Figure 4.43 shows the relationship between $u_f t_e / y_f$ against L / y_f for different u_f / u_c and L_c / L with data from the present study and pertinent data from Cardoso and Bettess (1999), and Nugroho (2006) (see Tables 4.6 to 4.7). It is noted that these studies conducted the experiments for a sufficient long period to reach the equilibrium state. In general, it is clear that as L / y_f increases, $u_f t_e / y_f$ increases except for few points. In addition, for high flow intensity, the values of $u_f t_e / y_f$ are greater than that of low flow

intensity for the same L_c/L . This trend is similar to the trend of scour depth with L/y_f . Conversely, the figure shows that $u_f t_e/y_f$ does not have clear trend with L_c/L . Therefore, it is decided to discard this term from the regression analysis as it seems that it does not have a significant effect on $u_f t_e/y_f$.

Figure 4.43: Variation of $u_f t_e/y_f$ with L/y_f for present study for different flow intensities and abutment aspect ratios

Figure 4.44 illustrates the relationship of $u_f t_e/y_f$ versus the flow depth ratio, y_f/y_m for the present study. It is generally observed that $u_f t_e/y_f$ decreases with an increase in y_f/y_m . In addition, the values of $u_f t_e/y_f$ for high flow intensity are higher than that of low flow intensity. This is similar to the trend of d_s/y_f with y_f/y_m .

Figure 4.45 shows plot of $u_f t_e/y_f$ with $(B_f - L)/B_f$ for the present study. It is generally found that an increase in $(B_f - L)/B_f$ leads to a decrease in $u_f t_e/y_f$. This is reasonable as the abutment length increases, the time to reach the equilibrium state increases. It should be noted that this trend is not as clear as the trend of scour depth with $(B_f - L)/B_f$.

Figure 4.44: Variation of $u_f t_e / y_f$ with y_f / y_m for present study at different flow intensities and abutment aspect ratios

Figures 4.45: Variation of $u_f t_e / y_f$ with $(B_f - L) / B_f$ for present study at different flow intensities and fixed abutment aspect ratio

4.7.3 Proposed equation to predict the equilibrium time of scouring process

Regression analysis was performed on data from the present study to get the best relationship between $u_f t_e / y_f$ and the independent parameters of the right side of Equation (4.14). The proposed equation for the dimensionless time of scour depth around 45° wing-wall setback abutment in compound channel can be expressed as follows:

$$\frac{u_f t_e}{y_f} = 1.26 \times 10^6 \left(\frac{L}{y_f} \right)^{0.27} \left(\frac{u_f}{u_c} \right)^{1.99} \left(\frac{y_f}{y_m} \right)^{-0.38} \left(\frac{B_f - L}{B_f} \right)^{-0.121} \quad (4.15)$$

The correlation coefficient (R^2) for Equation (4.15) is 0.99.

A comparison between the measured and calculated values using Equation (4.15) for the present and previous studies is shown in Figure 4.46. The present data agree well with the equation. As expected, a few data points of Nugroho (2006) for vertical-wall abutments are underestimated probably because the time to reach the equilibrium state for vertical-wall abutments is longer than that of 45° wing-wall. On the other hand, some data points of Cardoso and Bettess (1999) are overestimated probably due to short duration for some of their experiments (from 7 hours to 72 hours) which may be too short to reach the equilibrium state.

Many studies pointed out that the temporal development of scour around obstacle under clear water scour condition could be described using an exponential function (Breusers et al., 1977; Franzetti et al., 1982; Melville and Chiew, 1999; Coleman et al., 2003; Cheng et al., 2016). As a result, the relationship between d_s / d_{se} against t / t_e may be written as follows:

$$\frac{d_s}{d_{se}} = 1 - \exp \left(-m \left(\frac{t}{t_e} \right)^n \right) \quad (4.16)$$

where d_s = scour depth at a specified time, t , d_{se} is the equilibrium scour depth, t_e is the time to reach the equilibrium state for scour process, m and n are constants

By applying regression analysis on the data from the time development curves of the present study, it was found that m and n are 2.58 and 0.25, respectively.

Figure 4.46: Comparison of measured $u_f t_e / y_f$ against calculated $u_f t_e / y_f$ using Equation 4.11 for the present study and data from Cardoso and Bettess (1999) and Nugroho (2006)

A comparison between the measured and calculated d_s / d_{se} against t / t_e curves using Equations (4.16) for the present study is shown in Figures 4.47 to 4.53. Generally, it can be seen the data agree well with this equation. It is also observed that there is a notable difference between the measured and calculated values for experiments with shallow water depth (i.e. Runs 2, 4, 7, 14, 18, 39, 52, 53). This is probably because the primary and secondary vortices for shallow water depth are relatively weaker, and the equilibrium time is reached faster than those with deep water depth.

Figures 4.47: Measured and calculated d_s/d_{se} versus t/t_e curves for abutment model 1 ($L = 20$ cm, $L_c = 20$ cm)

Figures 4.48: Measured and calculated d_s/d_{se} versus t/t_e curves for abutment model 2 ($L = 30$ cm, $L_c = 30$ cm)

Figures 4.49: Measured and calculated d_s/d_{se} versus t/t_e curves for abutment model 3 ($L = 40$ cm, $L_c = 40$ cm)

Figures 4.50: Measured and calculated d_s/d_{se} versus t/t_e curves for abutment model 4 ($L = 20$ cm, $L_c = 5$ cm)

Figures 4.51: Measured and calculated d_s/d_{se} versus t/t_e curves for abutment model 5 ($L = 20$ cm, $L_c = 80$ cm)

Figures 4.52: Measured and calculated d_s/d_{se} versus t/t_e curves for abutment model 6 ($L = 40$ cm, $L_c = 5$ cm)

Figures 4.53: Measured and calculated d_s/d_{se} versus t/t_e curves for abutment model 7 ($L = 40$ cm, $L_c = 80$ cm)

A comparison between the measured and calculated d_s/d_{se} against t/t_e curves using Equations (4.16) for Nugroho's (2006) data is shown in Figure 4.54. These data show reasonably good match with the proposed equation. To obtain the calculated d_s/d_{se} against t/t_e curves for Nugroho's data, d_{se} was calculated first using Equation (4.6), and then t_e was calculated using Equation (4.15). Finally, d_{se} and t_e are substituted into Equations (4.16) for various time intervals, t to get d_s .

Figures 4.54: Measured and calculated d_s/d_{se} versus t/t_e curves for Nugroho's (2006) data

4.7.4 Time development of scour hole length, width, area and volume

The topographical development of the scour holes was measured at seven-time intervals: 30, 60, 120, 360, 1440, 4320 and 10080 minutes for five runs (i.e. Runs 4, 16, 27, 46 and 51). These data are presented in Table 4.18

The results show that the scour starts at a location upstream of the abutment nose. As the time increases, the scour hole increases in size. Figures 4.55 to 4.57 show that a secondary scour hole forms immediately downstream of the rear face of abutment models 1, 2 and 3 for Runs 4, 16, 27, respectively. The longest abutment (model 3) develops a secondary hole earlier ($t = 1440$ minutes) compared to the shortest one (models 1 and 2 with $t = 4320$ minutes). The narrowest model 6 (Figure 4.58), which has the same abutment length as models 3 and 7, does not have a secondary hole. On the other hand, the widest model 7 (Figure 4.59) with $L_c = 80$ cm, develops a secondary hole much later at $t = 4320$ minutes.

Table 4.18: Results of relative scour depth, length, width, surface area and volume of scour hole for Runs 4, 16, 27, 46 and 51 at different scour time ($y_f/y_m = 0.2$, $B_f/B_m = 0.6$, $u_f/u_c = 0.99$, $u_f = 0.3$ m/s, $u_c = 0.31$ m/s)

Run	Model	Time (min)	L_s/y_f	W_s/y_f	A_s/y_f^2	V_s/y_f^3	$u_f t/y_f$
4	Model 1	30	4.00	2.53	22.75	4.71	14400
4	Model 1	60	4.45	2.72	23.80	4.90	28800
4	Model 1	120	4.66	2.98	26.52	5.11	57600
4	Model 1	360	5.01	3.33	30.60	5.34	172800
4	Model 1	1440	6.50	3.60	54.40	11.10	691200
4	Model 1	4320	18.18	4.13	74.14	23.84	2073600
4	Model 1	10080	19.20	4.80	78.09	37.33	4838400
16	Model 2	30	5.12	2.53	24.89	5.50	14400
16	Model 2	60	5.79	2.74	25.96	6.10	28800
16	Model 2	120	6.11	3.06	28.01	6.45	57600
16	Model 2	360	6.48	3.47	34.97	10.08	172800
16	Model 2	1440	9.60	4.16	60.44	14.46	691200
16	Model 2	4320	19.57	4.32	114.56	42.11	2073600
16	Model 2	10080	21.60	5.01	163.00	121.55	4838400
27	Model 3	30	8.67	2.67	40.38	12.08	14400

27	Model 3	60	11.20	3.20	59.86	18.26	28800
27	Model 3	120	12.40	3.68	91.63	30.52	57600
27	Model 3	360	14.67	4.00	107.84	51.27	172800
27	Model 3	1440	16.00	4.80	199.93	103.37	691200
27	Model 3	4320	25.07	6.67	224.94	150.06	2073600
27	Model 3	10080	28.00	7.47	230.99	186.97	4838400
46	Model 6	30	8.48	3.52	64.55	20.04	14400
46	Model 6	60	9.68	3.95	73.32	31.95	28800
46	Model 6	120	10.88	4.24	77.52	52.69	57600
46	Model 6	360	11.52	4.93	93.58	64.69	172800
46	Model 6	1440	13.81	5.68	122.10	82.11	691200
46	Model 6	4320	15.04	6.43	171.30	90.72	2073600
46	Model 6	10080	17.01	7.41	191.23	102.16	4838400
51	Model 7	30	5.39	2.93	12.95	4.38	14400
51	Model 7	60	5.81	3.41	20.98	6.85	28800
51	Model 7	120	6.24	3.49	27.80	15.76	57600
51	Model 7	360	8.32	4.29	29.90	20.32	172800
51	Model 7	1440	9.81	4.64	40.18	24.47	691200
51	Model 7	4320	10.69	4.75	64.49	32.99	2073600
51	Model 7	10080	13.63	5.09	107.82	61.60	4838400

Figure 4.55: Topography of scour hole for Run 4 around model 1 ($L = 20$ cm, $L_c = 20$ cm) at (a) 30 minutes (b) 60 minutes (c) 120 minutes (d) 360 minutes (e) 1440 minutes (f) 4320 minutes (g) 10080 minutes. All dimensions are in cm

Figure 4.56: Topography of scour hole for Run 16 around model 2 ($L = 30$ cm, $L_c = 30$ cm) at (a) 30 minutes (b) 60 minutes (c) 120 minutes (d) 360 minutes (e) 1440 minutes (f) 4320 minutes (g) 10080 minutes. All dimensions are in cm

Figure 4.57: Topography of scour hole for Run 27 around model 3 ($L = 40$ cm, $L_c = 40$ cm) at (a) 30 minutes (b) 60 minutes (c) 120 minutes (d) 360 minutes (e) 1440 minutes (f) 4320 minutes (g) 10080 minutes. All dimensions are in cm

Figure 4.58: Topography of scour hole for Run 46 around model 6 ($L = 40$ cm, $L_c = 5$ cm) at (a) 30 minutes (b) 60 minutes (c) 120 minutes (d) 360 minutes (e) 1440 minutes (f) 4320 minutes (g) 10080 minutes. All dimensions are in cm

Figure 4.59: Topography of scour hole for Run 51 around model 7 ($L = 40$ cm, $L_c = 80$ cm) at (a) 30 minutes (b) 60 minutes (c) 120 minutes (d) 360 minutes (e) 1440 minutes (f) 4320 minutes (g) 10080 minutes. All dimensions are in cm

Figures 4.60 and 4.61 show the change of scour length, L_s and scour width, W_s against time, t . Generally, it is observed that the dimensions of the scour hole increase with time, and the shorter abutment has smaller scour dimensions than the longer one. On the other hand, the narrower abutment has larger scour dimensions (except the scour length,) than the wider one. An increase of the abutment length from 20 cm to 40 cm causes the latter scour length at the equilibrium state to be 45% longer and the scour width to be 64% wider than the former. On the other hand, a decrease of the abutment width from 80 cm to 5 cm causes the latter scour length at the equilibrium state to be 25% longer and the scour width to be 50% wider than the former. However, the model with abutment width of 40 cm generates the longest scour length at the equilibrium state. This is because of the merging of the primary and secondary scour hole at the equilibrium state. The results show that the influence of increasing the abutment length has more effect on scour width than on scour length. This is because the scour width is affected mainly by the principal vortex whereas the scour length may be affected by the combined action of the principal vortex, surface roller and wake vortices along the scour hole (Abdelaziz and Lim, 2017).

Similarly, the effect of decreasing the abutment width on the width of the scour hole is greater than on scour length.

Figure 4.60: Variation of scour length with time

Figure 4.61: Variation of scour width with time

Figure 4.62 shows the variation of the scour surface area, A_s with t . It is clear that the surface scour area increases as time increases. An increase of the abutment length from 20 cm to 40 cm caused the latter scour area at equilibrium to be 195% larger than the former. On the other hand, an increase of the abutment width from 5 cm to 80 cm caused the latter scour area at equilibrium to be 56% smaller than the former. Although the surface area around model 3 is less than that of model 6 at the beginning of scour process, the reverse happened at the equilibrium state because of the formation of secondary scour hole around model 3 which caused it to have a scour surface area to be larger than that of model 6.

Figure 4.63 shows the variation of the scour volume, V_s with t for different abutment lengths and widths. An increase of the abutment length from 20 cm to 40 cm caused the latter scour volume at equilibrium to be 400% more than the former. On the other hand, an increase of the abutment width from 5 cm to 80 cm caused the latter scour volume at equilibrium to be 60% less than the former. It is observed that the initial rate of change of scour volume for model 6 is higher than model 3, but after a longer scouring duration (beyond 1440 minutes), the rate of change of scour volume for model 3 starts to exceed that of model 6. Figures 4.62 and 4.63 showed that experiments lasted for short time may result in unrealistic estimation of scour hole area and volume especially for narrow and wide abutment.

Figure 4.62: Variation of scour area with time

Figure 4.63: Variation of scour volume with time

From Figures 4.60 to 4.63, it is clear that the shapes of the graphs have a similar trend. Therefore, the temporal change of scour hole length, width, area and volume may be described using an exponential function. As a result, the dimensionless relationships between these characteristics and time can be written as follows; for scour length

$$\frac{L_s}{L_{se}} = 1 - \exp \left(-a_3 \left(\frac{t}{t_e} \right)^{a_4} \right) \quad (4.17)$$

where L_s scour length at a specified time, t , L_{se} is the equilibrium scour length, t_e is the time to reach the equilibrium scour state, a_3 and a_4 are constants. By applying regression analysis on the present data, these constants are $a_3 = 2.08$ and $a_4 = 0.31$, respectively. Similarly, for scour width,

$$\frac{W_s}{W_{se}} = 1 - \exp \left(-a_5 \left(\frac{t}{t_e} \right)^{a_6} \right) \quad (4.18)$$

where W_s scour width at a specified time, t , W_{se} is the equilibrium scour width, a_5 and a_6 are constants. By applying regression analysis on the present data, the constants are $a_5 = 2.53$ and $a_6 = 0.23$, respectively. For scour surface area,

$$\frac{A_s}{A_{se}} = 1 - \exp \left(-a_7 \left(\frac{t}{t_e} \right)^{a_8} \right) \quad (4.19)$$

where A_s scour area at a specified time, t , A_{se} is the equilibrium scour area, a_7 and a_8 are constants. By applying regression analysis on the present data, the constants are $a_7 = 2.21$ and $a_8 = 0.41$, respectively. Lastly, for the scour volume,

$$\frac{V_s}{V_{se}} = 1 - \exp \left(-a_9 \left(\frac{t}{t_e} \right)^{a_{10}} \right) \quad (4.20)$$

where V_s scour volume at a specified time, t , V_{se} is the equilibrium scour volume, a_9 and a_{10} are constants. By applying regression analysis on the present data, the constants are $a_9 = 1.34$ and $a_{10} = 0.44$, respectively.

Figures 4.64 to 4.67 show comparisons between the measured and calculated values using Equations (4.17) to (4.20). The data agree well with the predicted values using these equations.

For these series of tests, the surface area of scour was also measured and a regression analysis on these data at the equilibrium state gives the following equation

$$\frac{A_s}{y_f^2} = \left(\frac{L}{y_f} \right)^{0.55} \left(\frac{L_c}{L} \right)^{-0.13} \left(\frac{B_f - L}{B_f} \right)^{-0.65} \quad (4.21)$$

It should be noted that $\left(\frac{y_f}{y_m} \right)$ and $\left(\frac{u_f}{u_c} \right)$ remained constant for these sets of experiments. Therefore, these terms are not included in Equation (4.21). The correlation coefficient (R^2) for Equation (4.21) is 0.97. Note that predictive equations (Equations 4.7 to 4.9) for scour length, width and volume have been presented earlier.

Figure 4.68 show a comparison between the measured and calculated values using Equation (4.21) for the present data and previous studies. The agreement is acceptable. However, it can be seen that Kose's (2007) scour area data are overestimated. This is probably because of the short duration of Kose's (2007) tests. In addition, Fael et al.'s (2006) data points with low flow intensity of less than 0.63 are overestimated using the proposed equation. In Figure 4.68 it should be noted that the data from Fael et al. (2006) and Kose (2007) were conducted in rectangular channels.

Figure 4.64: Measured and calculated L_s/L_{se} versus t/t_e curves for Runs 4, 16, 27 and 51

Figure 4.65: Measured and calculated W_s/W_{se} versus t/t_e curves for Runs 4, 16, 27 and 51

Figure 4.66: Measured and calculated A_s/A_{se} versus t/t_e curves for Runs 4,16, 27 and 51

Figure 4.67: Measured and calculated V_s/V_{se} versus t/t_e curves for Runs 4, 16, 27 and 51

Figure 4.68: Measured A_s/y_f^2 against calculated A_s/y_f^2 using Equation 4.21 for the present study

CHAPTER 5 CONCLUSIONS AND RECOMANDATIONS

5.1 Introduction

This study investigates localized scour formed around 45° wing-wall setback abutments in compound channel. A total of 55 long scouring duration experiments were conducted to study the effects of relative abutment length, aspect ratio of abutment, flow intensity, degree of flow contraction on floodplain, flow depth ratio of flood plain with main channel on the location of maximum scour depth and the dimensions of scour hole and its volume. In addition, the temporal development of these characteristics with time was also investigated. This chapter presents the main conclusion of the present study.

5.2 Geometry of scour hole

Generally, the results showed that the scour starts at the upstream of the abutment nose and as time increases, the scour hole increases in size. The maximum scour depth is observed to migrate slightly downstream of the abutment nose during the scour development up to the equilibrium state. This is because the skewed face of the wing-wall shifts the action of the down flow. A secondary scour hole forms immediately downstream the rear face of abutment models in some experiments. The longest abutment forms a secondary hole earlier compared to the shortest one. The narrowest model does not have a secondary hole. On the other hand, the widest model generates a secondary hole much later.

The final shape of scour hole consists of a primary scour hole and a smaller secondary scour hole. The existence of secondary scour hole depends on the abutment width, floodplain flow depth, abutment length and flow intensity.

For quite wide abutments with relatively low flow intensity under shallow flow condition (for example, with $L_c/L = 1$, $y_f/y_m = 0.2$ and $u_f/u_m < 0.81$), the final shape of scour hole consists of only a primary scour hole. In addition, for narrow abutment (for

example, with $L_c/L = 0.125$ and $L_c/L = 0.25$) regardless of abutment length and water depth, the final scour hole consists of only a primary scour hole.

For all abutment models with relatively high flow intensity under shallow flow conditions (for example, with $y_f/y_m = 0.2$ and $u_f/u_m = 0.99$ except for $L_c/L = 0.125$ and $L_c/L = 2$), the final shape of scour hole consists of a primary and a secondary scour holes, but both holes merged together eventually as scouring progresses.

For quite wide abutments with relatively low flow intensity under deep flow conditions (for example, with $L_c/L = 1$, $y_f/y_m = 0.4$ and $u_f/u_c < 0.88$), the final scour hole consists of only a primary scour hole, whereas for wider abutment with relatively low flow intensity under deep flow conditions (for example, with $L_c/L = 2$, $y_f/y_m = 0.4$ and $u_f/u_m < 0.88$), the final scour hole consists of merged primary and secondary scour holes because the latter model are wider.

For a given abutment model and water depth, when u_f/u_c changes from 0.65 to 0.88, the flow intensity has the ability to form another scour hole (i.e. a secondary scour hole) and also able to merge the primary and secondary scour holes as the scouring progresses to its equilibrium stage. This depends on abutment width. Similarly, for a given abutment model and flow intensity, when y_f/y_m changes from 0.2 to 0.4, the flow depth ratio has the same ability to form a secondary scour hole and the ability to merge it with the primary scour hole.

5.3 Location of maximum scour depth

Observations on the location of deepest point of scour hole showed that it generally occurs slightly downstream of the WW abutment nose which is different compared to a vertical-wall (VW) abutment where it occurs just upstream of the abutment nose (Oliveto and Hager, 2002). The results showed there are three cases for the location of the maximum scour depth with respect to the abutment tip, i.e. at a location abreast and normal to the abutment tip, at a location upstream of the abutment tip and at a location downstream of the abutment tip.

The maximum scour location, R_x is affected by the flow intensity, flow depth, abutment aspect ratio, (i.e. its length and width) and the shape of abutment. The location is larger as flow intensity decreases for the same abutment aspect ratio, L_c/L . This is because for low flow intensity, the maximum scour depth shifts further laterally from the abutment tip and migrates towards the bankline. This finding has a practical implication and may threaten the geotechnical stability of the bankline. The results showed the radial distances (R) of the maximum scour depth location is much higher than two times the floodplain water depth. As a result, the guidelines regarding riprap apron extension suggested by Richardson and Davis (1995), Morales et al. (2008) and Federal Highway Administration (FHWA) (2009) are not sufficient as it is recommended that the width of the riprap apron should be extended around the abutment by up to two times the floodplain water depth to protect it from scouring. In general, it was observed that the maximum scour location for narrow abutment is much smaller than that of wide abutment. Equations are proposed to predict the maximum scour location (i.e. Equations (4.3) and (4.4)) which included the relative abutment length, flow intensity and abutment aspect ratio. This is an important finding as Melville et al. (2006) concluded that this location depends only on the relative abutment ratio.

5.4 Dimensions of scour hole and its volume

Generally, it was observed that an increase in relative abutment length leads to an increase in all dimensions of scour hole and its area and volume. Therefore, the shorter abutment has smaller scour dimensions than the longer one. In addition, for high flow intensity, the values of these characteristics are greater than that of low flow intensity at the same value of L_c/L . This is because the rate of scour is higher for high flow intensity.

The experimental results showed that the abutment width has profound effect on the characteristics of scour hole, contradicting the findings of previous studies. Generally, an increase in abutment width leads to a reduction in scour depth and width. However, the scour length, area and volume initially increase with increase in the relative abutment width and then these characteristics reduce significantly with much wider abutment. Thus, the narrower abutment has larger scour depth and width than the wider one. As result, abutment width should be taken into account in prediction formulas for scour hole dimensions and its volume.

.The effect of increasing the abutment length on the length of the scour hole is less than that on scour depth and width. In addition, the influence of decreasing the abutment width on the depth and width of the scour hole is greater than that on the scour length.

It was found that the scour width is approximately equal to 3.5 times the floodplain water depth, and this is much wider than the recommended riprap apron extension of two times the floodplain water depth suggested by earlier studies. This aspect can be a new suggestion for riprap apron extension around 45° wing-wall setback abutments in compound channel. As prior studies made their suggestions based on spill-through abutment models.

It was found that dimensions of scour hole and its volume for setback abutment in compound channel are more likely to be less than of abutment in rectangular channel under the same flow conditions. Therefore, the prediction equations of the present study

are useful to predict scour around setback abutment in compound channel and the corresponding countermeasure required.

The proposed equations to predict the dimensions of scour hole and its volume (i.e Equation (4.6) to (4.9)) showed that the flow intensity (u_f/u_c), abutment aspect ratio (L_c/L), and the contraction ratio, $((B_f - L)/B_f)$ are important parameters for setback abutments in compound channel.

5.5 Time development of scour hole characteristics

It was found that scour depth and equilibrium time of scouring process are interdependent, and the latter does not have a clear trend with aspect ratio of abutment. The results showed that it is important to conduct long scouring duration experiments so that the effect of the secondary scour hole, which does not occur during the early stage of scouring, can be observed. The development of scour hole characteristics with time can be represented using an exponential function, and the proposed scour-time equations will be useful to calculate the scour when the flow does not last for sufficiently long time to reach its equilibrium scour conditions.

5.6 Recommendations

The present study used 7 abutment models but only one sediment size was used. It is recommended that different sizes of sediment should be used to investigate the effect of relative sediment coarseness and size distribution on the characteristics of scour hole. The effect of channel geometry such as the slope of bankline on these characteristics should be taken into account for future investigation. In addition, the effect of different shape of abutment models such as vertical-wall and spill-through and different alignment of these abutment models should be considered for any future research to better understand these characteristics and add to the data base collected. Finally, the flow patterns within the evolving scour hole around narrow and wide abutment with different shape of abutment models are areas that need to be explored.

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APPENDIX

Figure A.1: Scour depth development curve for Run 1

Figure A.2: Scour holes at the equilibrium state after 7740 minutes for Run 1, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.3: Scour depth development curve for Run 2

Figure A.4: Scour holes at the equilibrium state after 11125 minutes for Run 2, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.5: Scour depth development curve for Run 3

Figure A.6: Scour holes at the equilibrium state after 7200 minutes for Run 3, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.7: Scour depth development curve for Run 4

Figure A.8: Scour holes at the equilibrium state after 10080 minutes for Run 4, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.9: Scour depth development curve for Run 5

Figure A.10: Scour holes at the equilibrium state after 7115 minutes for Run 5, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.11: Scour depth development curve for Run 6

Figure A.12: Scour holes at the equilibrium state after 7640 minutes for Run 6, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.13: Scour depth development curve for Run 7

Figure A.14: Scour holes at the equilibrium state after 7920 minutes for Run 7, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.15: Scour depth development curve for Run 8

Figure A.16: Scour holes at the equilibrium state after 8415 minutes for Run 8, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.17: Scour depth development curve for Run 9

Figure A.18: Scour holes at the equilibrium state after 9005 minutes for Run 9, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.19: Scour depth development curve for Run 10

Figure A.20: Scour holes at the equilibrium state after 11305 minutes for Run 10, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.21: Scour depth development curve for Run 11

Figure A.22: Scour holes at the equilibrium state after 11350 minutes for Run 11, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.23: Scour depth development curve for Run 12

Figure A.24: Scour holes at the equilibrium state after 14920 minutes for Run 12, model 1, $L = 20$ cm, $L_c = 20$ cm

Figure A.25: Scour depth development curve for Run 13

Figure A.26: Scour holes at the equilibrium state after 7200 minutes for Run 13, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.27: Scour depth development curve for Run 14

Figure A.28: Scour holes at the equilibrium state after 10080 minutes for Run 14, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.29: Scour depth development curve for Run 15

Figure A.30: Scour holes at the equilibrium state after 8800 minutes for Run 15, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.31: Scour depth development curve for Run 16

Figure A.32: Scour holes at the equilibrium state after 10080 minutes for Run 16, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.33: Scour depth development curve for Run 17

Figure A.34: Scour holes at the equilibrium state after 8820 minutes for Run 17, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.35: Scour depth development curve for Run 18

Figure A.36: Scour holes at the equilibrium state after 9935 minutes for Run 18, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.37: Scour depth development curve for Run 19

Figure A.38: Scour holes at the equilibrium state after 11340 minutes for Run 19, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.39: Scour depth development curve for Run 20

Figure A.40: Scour holes at the equilibrium state after 8440 minutes for Run 20, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.41: Scour depth development curve for Run 21

Figure A.42: Scour holes at the equilibrium state after 7300 minutes for Run 21, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.43: Scour depth development curve for Run 22

Figure A.44: Scour holes at the equilibrium state after 15540 minutes for Run 22, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.45: Scour depth development curve for Run 23

Figure A.46: Scour holes at the equilibrium state after 15410 minutes for Run 23, model 2, $L = 30$ cm, $L_c = 30$ cm

Figure A.47: Scour depth development curve for Run 24

Figure A.48: Scour holes at the equilibrium state after 9360 minutes for Run 24, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.49: Scour depth development curve for Run 25

Figure A.50: Scour holes at the equilibrium state after 12960 minutes for Run 25, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.51: Scour depth development curve for Run 26

Figure A.52: Scour holes at the equilibrium state after 14440 minutes for Run 26, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.53: Scour depth development curve for Run 27

Figure A.54: Scour holes at the equilibrium state after 10080 minutes for Run 27, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.55: Scour depth development curve for Run 28

Figure A.56: Scour holes at the equilibrium state after 10940 minutes for Run 28, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.57: Scour depth development curve for Run 29

Figure A.58: Scour holes at the equilibrium state after 9455 minutes for Run 29, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.59: Scour depth development curve for Run 30

Figure A.60: Scour holes at the equilibrium state after 9720 minutes for Run 30, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.61: Scour depth development curve for Run 31

Figure A.62: Scour holes at the equilibrium state after 16700 minutes for Run 31, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.63: Scour depth development curve for Run 32

Figure A.64: Scour holes at the equilibrium state after 12000 minutes for Run 32, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.65: Scour depth development curve for Run 33

Figure A.66: Scour holes at the equilibrium state after 7920 minutes for Run 33, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.67: Scour depth development curve for Run 34

Figure A.68: Scour holes at the equilibrium state after 8970 minutes for Run 34, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.69: Scour depth development curve for Run 35

Figure A.70: Scour holes at the equilibrium state after 9375 minutes for Run 35, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.71: Scour depth development curve for Run 36

Figure A.72: Scour holes at the equilibrium state after 8640 minutes for Run 36, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.73: Scour depth development curve for Run 37

Figure A.74: Scour holes at the equilibrium state after 14970 minutes for Run 37, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.75: Scour depth development curve for Run 38

Figure A.76: Scour holes at the equilibrium state after 14460 minutes for Run 38, model 3, $L = 40$ cm, $L_c = 40$ cm

Figure A.77: Scour depth development curve for Run 39

Figure A.78: Scour holes at the equilibrium state after 8640 minutes for Run 39, model 4, $L = 20$ cm, $L_c = 5$ cm

Figure A.79: Scour depth development curve for Run 40

Figure A.80: Scour holes at the equilibrium state after 6990 minutes for Run 40, model 4, $L = 20$ cm, $L_c = 5$ cm

Figure A.81: Scour depth development curve for Run 41

Figure A.82: Scour holes at the equilibrium state after 9885 minutes for Run 41, model 4, $L = 20$ cm, $L_c = 5$ cm

Figure A.83: Scour depth development curve for Run 42

Figure A.84: Scour holes at the equilibrium state after 10230 minutes for Run 42, model 5, $L = 20$ cm, $L_c = 80$ cm

Figure A.85: Scour depth development curve for Run 43

Figure A.86: Scour holes at the equilibrium state after 8000 minutes for Run 43, model 5, $L = 20$ cm, $L_c = 80$ cm

Figure A.87: Scour depth development curve for Run 44

Figure A.88: Scour holes at the equilibrium state after 10800 minutes for Run 44, model 5, $L = 20$ cm, $L_c = 80$ cm

Figure A.89: Scour depth development curve for Run 45

Figure A.90: Scour holes at the equilibrium state after 8640 minutes for Run 45, model 6, $L = 40$ cm, $L_c = 5$ cm

Figure A.91: Scour depth development curve for Run 46

Figure A.92: Scour holes at the equilibrium state after 10080 minutes for Run 46, model 6, $L = 40$ cm, $L_c = 5$ cm

Figure A.93: Scour depth development curve for Run 47

Figure A.94: Scour holes at the equilibrium state after 9860 minutes for Run 47, model 6, $L = 40$ cm, $L_c = 5$ cm

Figure A.95: Scour depth development curve for Run 48

Figure A.96: Scour holes at the equilibrium state after 15420 minutes for Run 48, model 6, $L = 40$ cm, $L_c = 5$ cm

Figure A.97: Scour depth development curve for Run 49

Figure A.98: Scour holes at the equilibrium state after 8700 minutes for Run 49, model 7, $L = 40$ cm, $L_c = 80$ cm

Figure A.99: Scour depth development curve for Run 50

Figure A.100: Scour holes at the equilibrium state after 10085 minutes for Run 50, model 7, $L = 40$ cm, $L_c = 80$ cm

Figure A.101: Scour depth development curve for Run 51

Figure A.102: Scour holes at the equilibrium state after 10080 minutes for Run 51, model 7, $L = 40$ cm, $L_c = 80$ cm

Figure A.103: Scour depth development curve for Run 52

Figure A.104: Scour holes at the equilibrium state after 10560 minutes for Run 52, model 7, $L = 40$ cm, $L_c = 80$ cm

Figure A.105: Scour depth development curve for Run 53

Figure A.106: Scour holes at the equilibrium state after 9860 minutes for Run 53, model 7, $L = 40$ cm, $L_c = 80$ cm

Figure A.107: Scour depth development curve for Run 54

Figure A.108: Scour holes at the equilibrium state after 10380 minutes for Run 54, model 7, $L = 40$ cm, $L_c = 80$ cm

Figure A.109: Scour depth development curve for Run 55

Figure A.110: Scour holes at the equilibrium state after 9930 minutes for Run 55, model 7, $L = 40$ cm, $L_c = 80$ cm