Countermeasure of Scour around Pier in Steady Current

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ABSTRACT

The experiments on the countermeasures of scours around pier in steady current were conducted in this paper. The factor formations of scour were identified by extensive research of previous paper that related to the project. Scour formations were influence by the strength of the flow, the size of pier, and the sediment condition. From the literature, the project invented a few innovative pier protection measures which are single cross-threaded pier and double-cross threaded pier with variation of cable diameter and thread angle. These cross-threaded piers also tested with collar protection. As the result, the single cross-threaded piers and double cross-threaded piers able to reduce scour in average of 18% and 21% respectively. While, single cross-threaded piers with collar and double cross-threaded piers with collar able to reduce scour in average of 69% and 63% respectively. The single cross-thread pier with collar of 0.1 cable-pier diameter ratio and 15° thread angle outperforms other models with scour reduction of 79%. That shows the cable-pier diameter ratio and thread angle influent the performance of models in scour reduction. The large number of cross-threaded pier with large cable-pier diameter ratio and small thread angle will give the best performance in reducing potential formation of scour depth.

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SYMBOLS

b	=	cable diameter;
D	=	pier diameter;
θ	=	thread angle;
d_{50}	=	median diameter of bed sand;
v	=	mean flow velocity at upstream of pier;
y	=	scour depth of protected pier;
s_0	=	scour depth of unprotected pier;
y_s	=	scour prediction using CSU Equation;
a	=	pier width;
h	=	water depth;
K_1	=	Correction for pier nose shape (round nose=1);
K_2	=	Correction for angle of attack of flow (0°=1);
K_3	=	Correction factor for bed condition (clear-water-1.1);
Fr	=	Froude Number; and
g	=	acceleration of gravity (9.81 m/s^2)
b/D	=	cable diameter to pier diameter ratio

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CHAPTER 1

INTRODUCTION

1.1 Background

Previously, there are many cases of bridge collapse that had been reported which involve losses neither destruction cost nor human life. This structure failure was identified caused by settlement problem at the pier or pile of the bridge. The pier or pile is a structure that supports bridge at the middle of the river. Settlement will happen when the pier loss it bearing capacity at the foundation. Scour that formed around the toe of bridge pier had been a primary reason for settlement to happen. Buloh River Bridge in Malaysia, for example was settled due to scour at piers and was replaced by new bridge (Ng and Razak, 1998).

Generally, scour can be defined as erosion process of sediment at the structure via flow of fluid. For bridge cases, scour happen at the toe of the pier where the river flow eroding the soil around it. This process happen caused by structures that obstruct the river flow pattern. The formation of scour may affect the stability of the pier as the soil around it was carried away by the river current. Thus, prediction of scour depth for this structure is importance to ensure their stability when interacting with current.

Most common method to counter the scour at bridge pier is toe protection. A number of rock or geobag are dump around the toe of pier to protect the sediment form eroding by river flow. Besides toe protection method, a number of researchers attempted to provide solution with flow altering method such as collar attached to piers (Chiew, 1987; 1992; 2003), slots at piers (Kumar et al, 1999), and thread attached at pier (Dey et al 2006). Haque et al (2007) had come out the idea for reducing scours formation by sacrificial piles where a few of pile are located at upstream of pier. The pile will let for erosion and the sediment from it will expect to settle at pier. By this method, the scour hole at the pier will reduce as the strength of the flow reduced by sacrificial pile. The flow pattern around the pier will divert or weaken the strength in order to reduce the scour formation.

1.2 Problem Statement

Toe protection of pier by filling the stone is commonly adopted for prevention of local scour. However, scour at the lee of the pier still exists due to the excessive of flow around the piers. This flow has not been sufficiently dissipated by the friction of toe protection. Besides the structure interaction which resulting the formation of wake vortices at the lee of pier are undermining the soil material. Thus, reduction of local scour rate might be achievable through altering the flow direction when passing around the pier. This research is set to explore the impact of flow redirection on the formation of scour.

1.3 Objective

This research aims at developing a number of innovative solutions on flow altering method to local scour formed in vicinity of a single circular pier subjected to a steady current condition. The usage of cable and collar for scour countermeasure is focused in this study which the models are varies in cable arrangement. The performance characteristics of these solutions are to be assessed through physical modelling approach which scour pattern and scour reduction are observed.

1.4 Scope of Work

This Final Year Research Project was conducted at variety of manner to ensure the objectives of the project are achieved.

<u>Literature Review</u>

For this element of research, book, journal, article and manual on hydraulic field were referred for better understanding on scour formation. Another field of research also had been used for identifying a few aspects such as factor of scour formation, parameter affect the scour formation, and countermeasure of scour around circular pier in current.

<u>Development of Countermeasure for Scour Prevention</u>

The feature design of existing scour countermeasure is invented with the aim to achieve better performance in reducing scour. The modified design was made by referring all previous research works in literature review including the material used. The type of countermeasure was focused on flow altering method only.

Model Construction

The prototype was fabricated with a few designs and variation of dimension after approved by the supervisor. The models were fabricated in the lab with proposed material and dimension. Four type of countermeasure were introduce with mix and match method for different dimension.

Laboratory Set-up

The models were tested in open channel flume. The flume was set-up properly based on previous research as to make the result is comparable such as sediment size and models dimension. However, a few limiting factors based on flume capacity and safety were reconsider while conducting experiment such as flume operating hour, maximum flow rate of discharge and total weight of experiment set-up.

Experiment

The models were tested in a few of series of different type of models with different dimension variation. A few variables were kept constant in this experiment as the time constraint. The experiment of model without countermeasure also was conducted to analysis the feasibility of the experiment with theoretical.

Data Analysis

The performance of models was analysed and interpreted by comparing with unprotected pier. Comparison of these models performance also was done with selected previous type of countermeasure.

Report Writing

The background of this study, objective, experimental set-up and the result of experiment were compiled and wrote in a report. The conclusion and recommendation for this research also recorded into the report.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As the objective of this research to come out the countermeasure of scour, the understanding of scour mechanism must be fully comprehend. The literature review on the mechanism of scour formation in steady current was carried out especially at circular pier. Factor that influent the formation of scour in steady current such as the flow pattern, sediment characteristic, and pier dimension also had been reviewed in this chapter. Research of previous countermeasure on flow altering method also was conducted in order to understand how the mechanism works on reducing scour. Thus, a few aspects can be to take account in producing new innovative of scour countermeasure.

2.2 General Scour Process

Scour is formed when there are structures obstructing the flow pattern. Changes in flow characteristic in terms of velocities may lead to changes in sediment transport capacity. This is due to the disequilibrium between actual sediment transport and the capacity of the flow to transport sediment. Scour is formed by hydraulic adjustment in order to achieve new equilibrium (Hoffmans & Verheij, 1997).

Scour formation is related to the flow formation around the structure. As the flow hits the upstream of a pier, the down-flow, as shown in Figure 2-1, has the tendency to scour the bed. The horseshoe vortex are formed as the consequence of scour where the flow is separated at the edge of upstream scour hole and then rolls to form helical flow. The wake vortices are formed as the separation of flow at the sides of pier where it looks like as a little cyclone. The sediments at the downstream of the pier are lifted by wake vortices and formed downstream scour hole (Heidarpour et al., 2010).

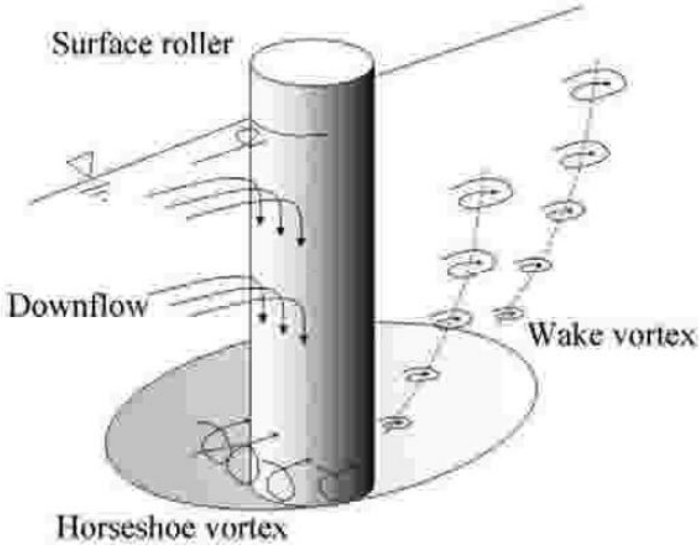


Figure 2-1*: The flow and scour pattern at a circular pier (Retrieve from: Heidarpour et al., 2010)*

2.3 Evaluation Criteria for Scour

In Bridge Scour Manual (2013) that published by Department of Transport and Main Roads of Queensland Government, the equation for pier scour in current are recommended based on Colorado State University (CSU) equation. The ratio of scour depth to water depth is define as

$$\frac{y_s}{h} = 2.0K_1K_2K_3\left[\frac{a}{h}\right]^{0.65} Fr^{0.43}$$

where a = pier width ; h = water depth; K_1= Correction for pier nose shape (***Table 2-1***); K_2= Correction for angle of attack of flow (***Table 2-2***); K_3= Correction factor for bed condition (***Table 2-3***); Fr = Froude Number directly upstream of the pier which define by

$$Fr = \frac{v}{\sqrt{gh}}$$

where v = mean velocity of flow directly upstream of the piers; g = acceleration of gravity (9.81 m/s^2).

Figure 2-2, ***Table 2-1***, and ***Table 2-2*** show the value of correction factor for K_1 and K_2 where it depends on the shape and size of pier, and the angle of attack of the flow while ***Table 2-3*** show the correction factor for K_3 for different bed condition.

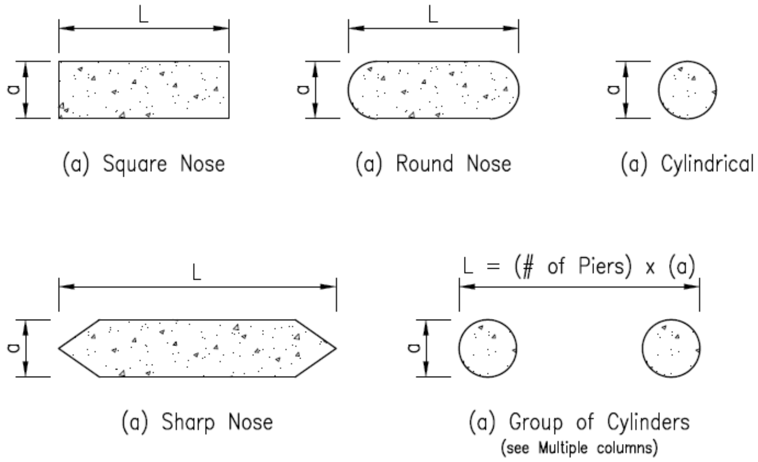


Figure 2-2*: Common piers shapes and correction parameter. (Retrieve from: Bridge Scour Manual, 2013)*

Table 2-1*: Value of K_1 factors*

Shape of Pier nose	K_1
Square nose	1.1
Round nose	1.0
Circular cylinders	1.0
Group of circular cylinders	1.0
Sharp nose	0.9

Table 2-2: *Value for K_2 factors*

Angle	L/a = 4	L/a = 8	L/a = 12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

***Table 2-3**: Values for K_3 factors*

Bed Condition	Dune Height	K_3
Clear-Water Scour	N/A	1.1
Plane bed and Antidune flow	N/A	1.1
Small dunes	3>H>0.6	1.1
Medium dunes	9>H>3	1.2 to 1.1
Large dunes	H>9	1.3

2.4 Scour in Steady Current

As in CSU equation, flow velocity or flow rate plays important role in scour mechanism. When the flow rate increases, the scour depth also increases. Elsebaie (2013) investigated the influence of flow rate and duration of pier exposed to the flow in sandy soil. The ***Figure 2-3*** shows the scour depth increase as the flow rate and duration of pier exposed to the flow increase. The depth of scour will start developing and increase over time. However, the scour depth will stop developing when it reaches equilibrium depth. By increasing the flow rate, the strength of down-flow and horseshoe vortex increased and has ability to scouring the sediment deeper. The reliability of above result was challenged by Chiew and Melville (1987) and Izadinia and Heidarpour (2012) due the flume sidewall effect. The pier diameter should less than 10% of the flume width. The pier diameter in this experiment is about 17% of the width of flume.

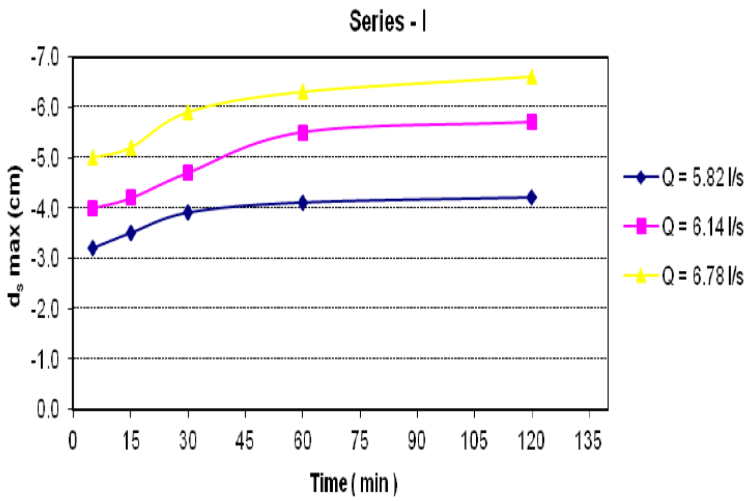


Figure 2-3*: Variation of maximum scour depth with time. (Retrieve from: Elsebaie, 2013)*

By considering the diameter of pier in current-induced scour, Rambabu et al. (2003) investigated the scour depth in cohesive soil. The sediment used in this experiment consisted of 44% clay, 47% silt, and 9% sand. Different from cohesionless sediment, scour in clay takes longer time to achieve equilibrium depth. The resistance of erosion for clay are played by physic-chemical properties that are controlled by attraction of inter-particle surface forces. The ***Figure 2-4*** shows the variation of scour depth by different flow velocity. The equilibrium of scour depth increases as the flow velocity and diameter of pier increase. Pier with large diameter provide larger surface area for flow obstruction, carrying deeper scour depth in front of the pier due to down flow.

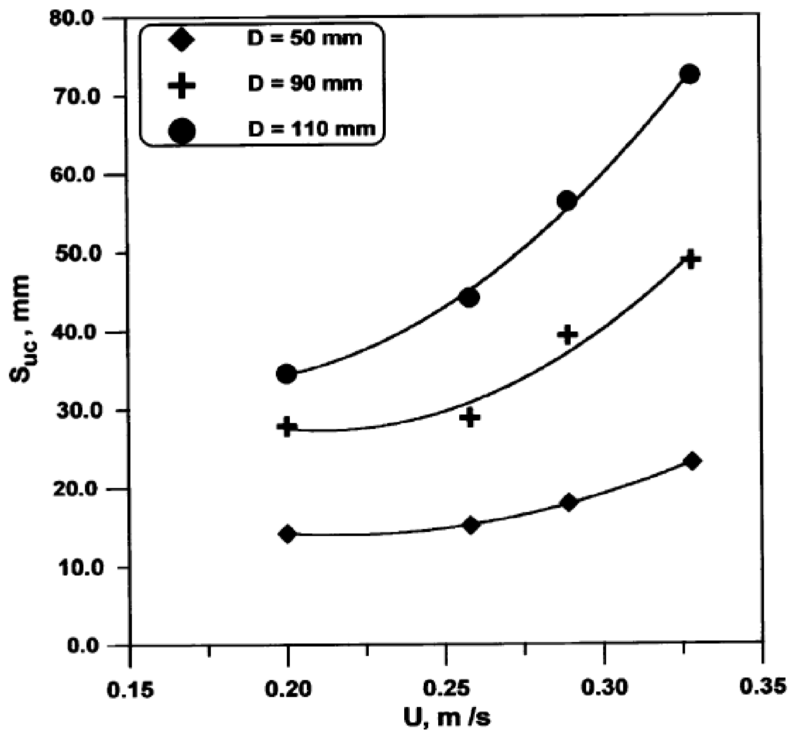


Figure 2-4*: Variation of scour depth with current velocity. (Retrieve from: Rambabu et al., 2003)*

Chen et al (2012) experimentally study on scour for sea-crossing bridge piers in Taiwan that connect between Greater Kinmen and Leiyu Island. A 1:49 scale movable bed model was tested to investigate the greatest magnitude of local scour & potential scour area around sea-crossing bridge group of 28 piles arrangement as shown in ***Figure 2-5***. The model was tested in current flow with speed of 14.3 m/s. For study on a group of pile, the maximum scour depth to pile diameter ratio was about 1.88 for current-alone case as shows in ***Figure 2-6.*** The deepest scours happen in the gap area between second to fourth lines of the group piers from up-coming current side. The scour depth in piles group deeper compare to single pile which scours formation was contributed by the interaction of vortices created around the pile groups and the increment of flow speed between the piles. The high sediment transport induced by the gap flow was lead to the formation of scour. The shedding effect had slow down the vortices strength and makes the few rows behind of pier group not experiencing scour.

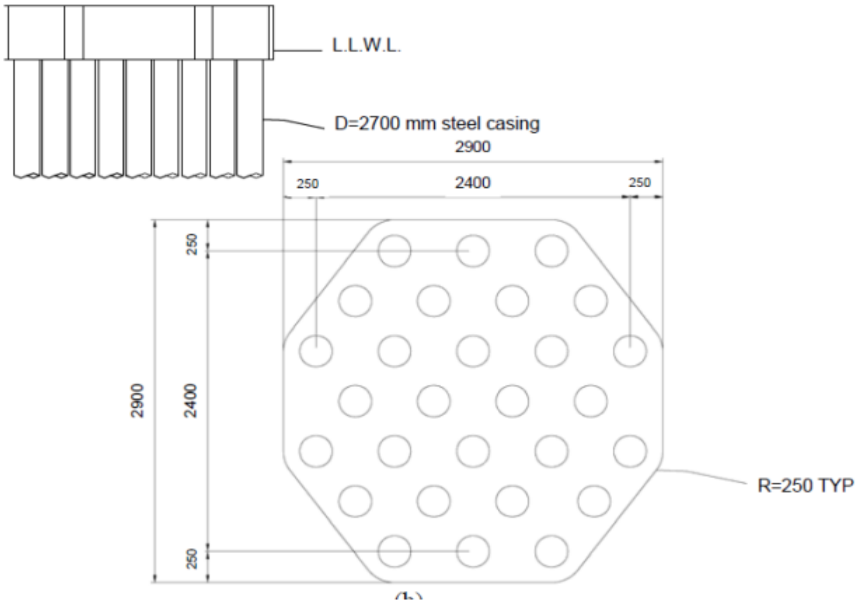


***Figure 2-5**: Piles arrangement of sea-crossing bridge foundation. (Retrieve from: Chen et al (2012))*

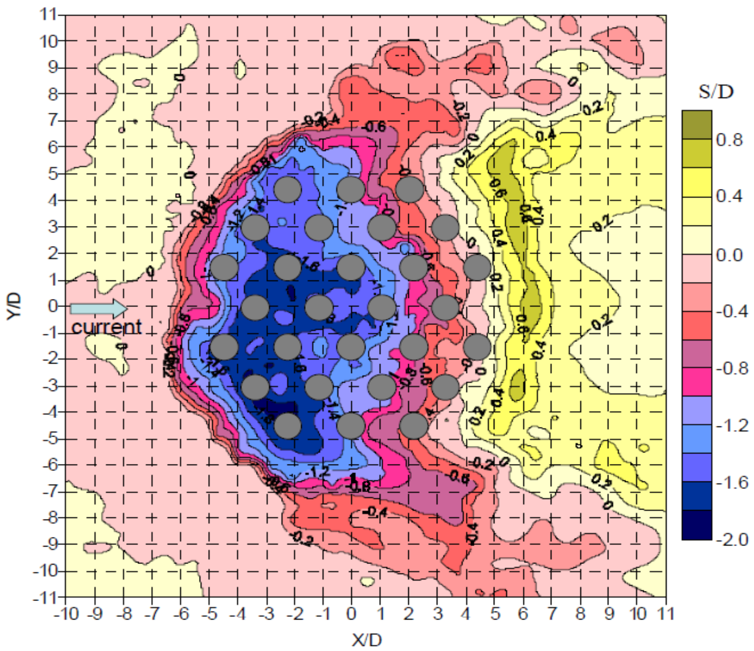


***Figure 2-6**: The potential impact erosion area and scour around group of pile for current-alone case. (Retrieve from: Chen et al (2012))*

2.5 Countermeasure against Scouring

Dey et al. (2006) conducted a research on controlling the scour under current using threaded pile where the helical wires or cables wrapped spirally on the pile. This threaded pile was able to reduce the scour depth by weaken and prevent the formation of down-flow and horseshoe vortex. They adopted three type of threaded pile with different sizes of cable and angle of thread in this study (***Figure 2-7***). **Figure 2-8** shows that variation of scour reduction ratio with different cable to pile diameter ratio for each number of thread and thread angle. Pile with small angle of threaded cable with large size of threaded cable and large numbers of thread able to reduce more scour depth than unprotected pile. The optimum pile design that could reduce scour by 46% is suggested as follow:

- Thread angle of 15°
- Triple number of thread
- Cable diameter to pile diameter ratio (b/D) of 0.1

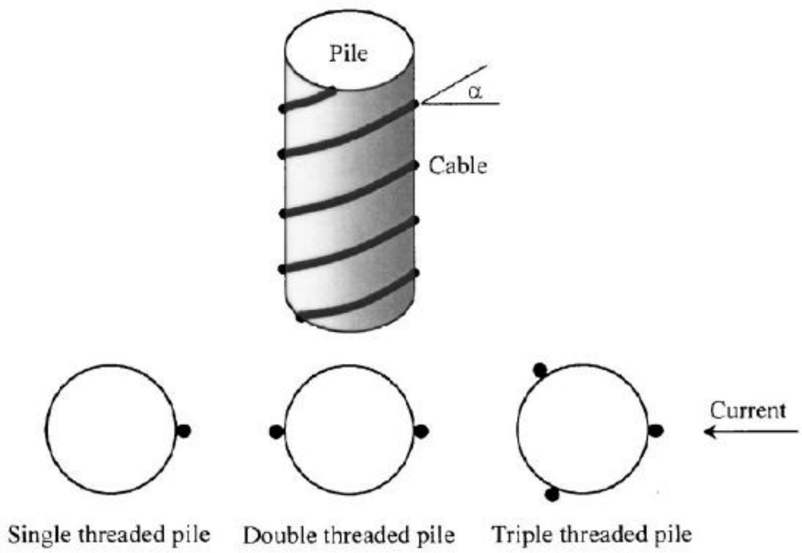


Figure 2-7*: Threaded pile tested under current. (Retrieve from: Dey et al., 2006)*

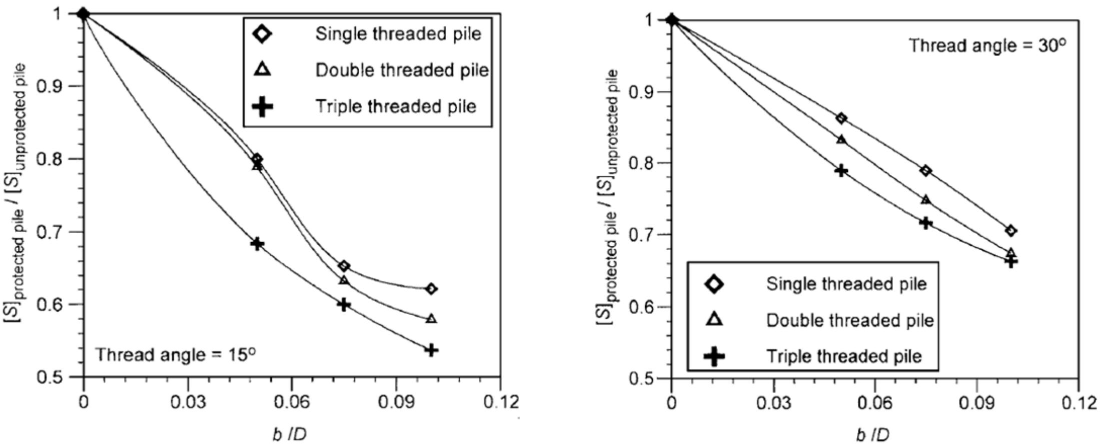


***Figure 2-8**: Variation of non dimensional scour depth with cable-pile diameter ratio b/D for different threaded piles and thread angles under steady current. (Retrieve from: Dey et al., 2006)*

Heidarpour et al. (2010) studied the efficiency of collar in countering the scour formation in group of pile. The collar reduces the scour formation by altering the down-flow from reaching the bed as it was placed at lower elevations. However, the used of collar may induced extension of scour hole at downstream of pile. Heidarpour et al. (2010) tested effectiveness of collar in pier group with a group of two and a group of three of pier in-line arrangement by varying the spacing of pier and the collar size as shown in ***Figure 2-9***. Formations of scour for the pier group with collar were delayed approximately 100 minute, 200 minute and 500 minute for first, second and third pier respectively. ***Figure 2-10*** was comparing time of scour formation for different pile group with and without collar. The scour depth in the pier group of three with spacing and collar size 3 time of pier diameter was reduced by using collar up to 45% at third pier as shown in ***Figure 2-11***. The scour depth was reduced by at third pier because of the sheltering effect of piers in front of it beside the collar had reduced the effect of down-flow and horseshoe vortex in scouring the bed.

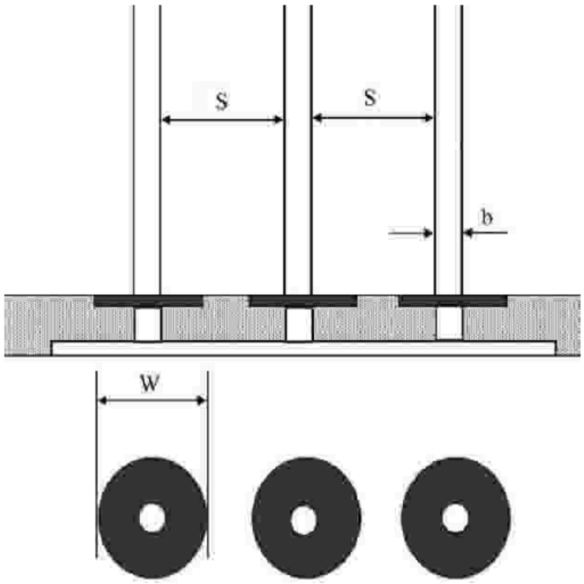


Figure 2-9*: The pier group arrangement in the experiment. Three piers in-line with collar. (Retrieve from: Heidarpour et al., 2010)*

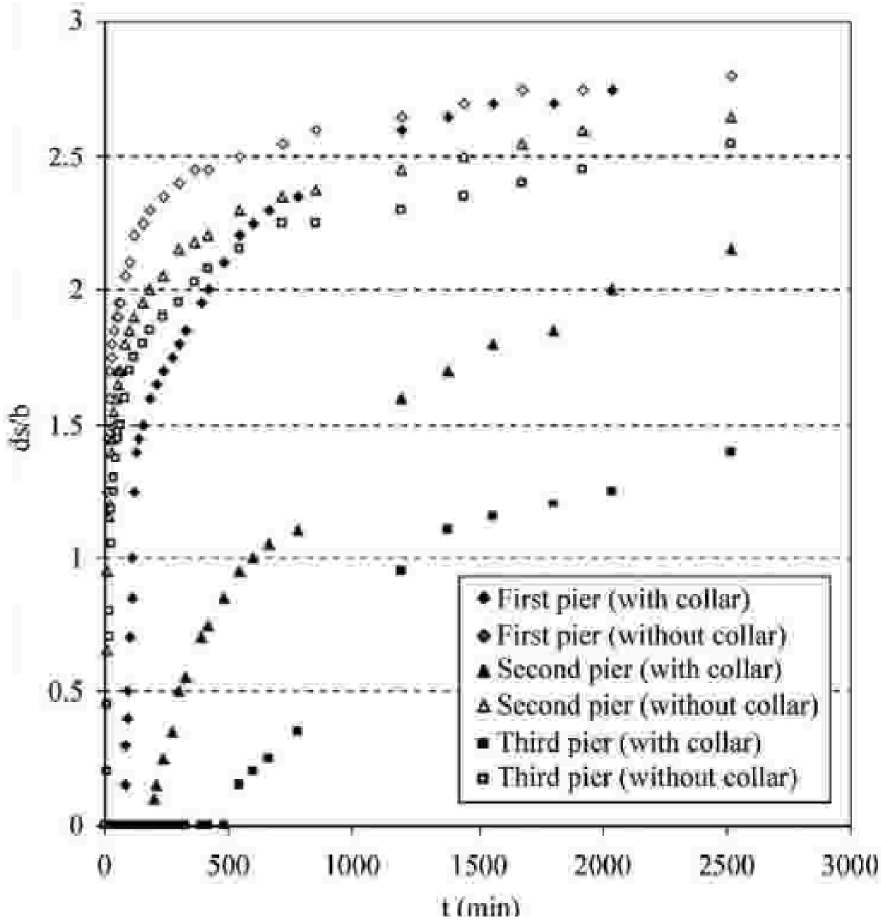


Figure 2-10*: Comparison of scouring depth at group of three piers with and without collar with S/b=3 and w/b=3. (Retrieve from: Heidarpour et al., 2010)*

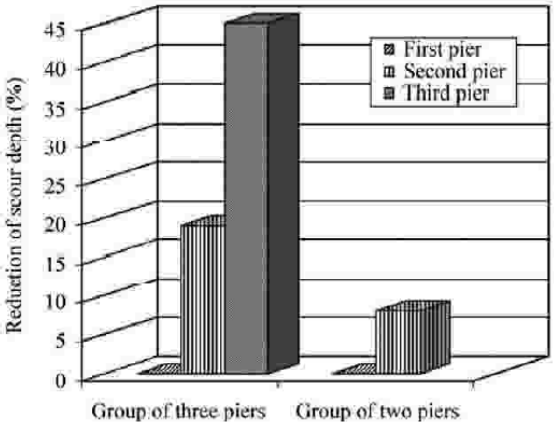
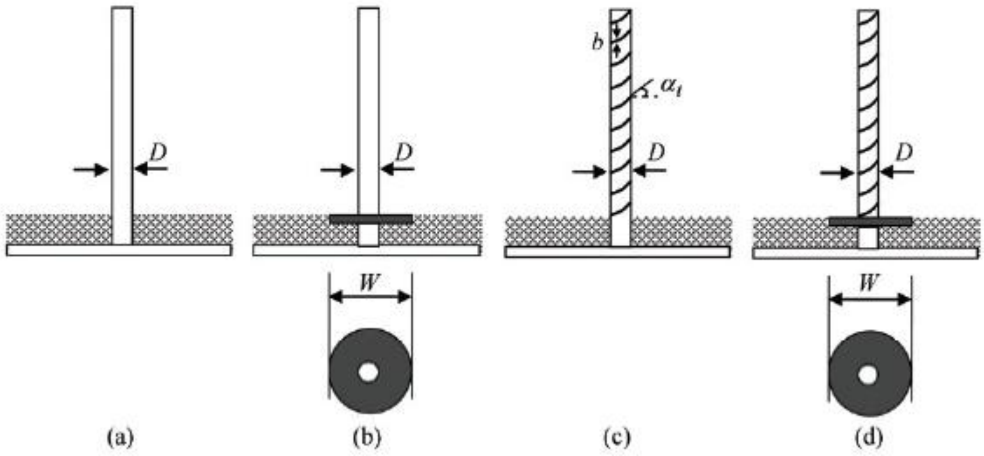


Figure 2-11*: Reduction of scour depth at group of three and two piers with collar with S/b=3, w/b=3. (Retrieve from: Heidarpour et al., 2010)*

Followed the research by Dey et al. (2006) and Heidarpour et al. (2010), Izadinia and Heidarpour (2012) prevented local scouring by using cable and collar on the pile. Various types of pier were tested; (a) single pier without protection, (b) single pier with collar protection, (c) single threaded pier with cable, and (d) single threaded pier with collar protection as shown in ***Figure 2-12***. The experiments of Dey et al. (2006) were run once again as the previous experiments were affected by sediment size and side-wall effects. ***Figure 2-13*** shows the comparison of time of the scour formation for various types of pier. It is clear from the figure that, the threaded pier combined with collar able to delay the formation of scour and reduce the scour depth effectively. The scour depth also can be reduced by decreasing the angle of thread and increasing the cable sizes same as the result from Dey et al. (2006) even the magnitude of scour depth reductions in both experiments were different (***Figure 2-14***) as the result from Dey et al. (2006) are questionable and not reliable (Tafarojnorus, 2010; Izadinia and Heidarpour, 2012). The pier with collar as protection able to reduced the scour depth by 20% while the pier with cable with the best combination of 15° thread angle and cable size to pier diameter ratio (*b/D*) of 0.15 able to reduced by 13%. The scour depth was able to reduce up to 53% by combining the used of collar and the best combination cable size and thread angle.



Row	Collar	Cable	Cable diameter (b, mm)	Thread angles (α_t)	b/D
1	Without	Without	–	–	–
2	With	Without	–	–	–
3	Without	With	2	15°;30°;45°	0.05
4	Without	With	4	15°;30°;45°	0.1
5	Without	With	6	15°;30°;45°	0.15
6	With	With	2	15°;30°;45°	0.05
7	With	With	4	15°;30°;45°	0.1
8	With	With	6	15°;30°;45°	0.15

Figure 2-12*: Pile arrangement in Izadinia and Heidarpour experiment. (a) Single pier, (b) pier with collar, (c) single threaded pier, and (d) single threaded pier with collar. (Retrieve from: Izadinia and Heidarpour, 2012)*

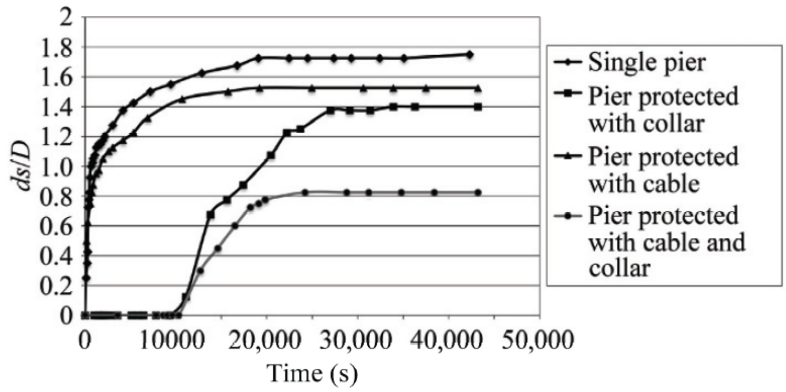


Figure 2-13*: Time development of scouring in upstream of the pier for single pier, pier protected with collar, pier protected with cable, and pier protected with cable and collar simultaneously. (Retrieve from: Izadinia and Heidarpour, 2012)*

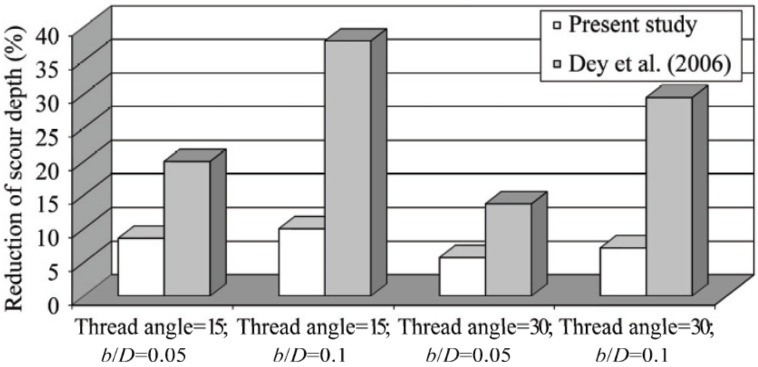


Figure 2-14*: Comparison the results of present study with the results of Dey et al. (2006). (Retrieve from: Izadinia and Heidarpour, 2012)*

2.6 Scour Countermeasure Practices in the Public Work Department (PWD) Malaysia

Based on Ng and Razak (1998), Chiew et. al. (2000) reported that PWD Malaysia had no specific guideline in scour countermeasure for bridge piers. There are not practise for the local authority to estimate the probable scour depth for short and medium bridges even there are various methods available in predicting scour depth. Only piled foundations are commonly adopted in protecting bridges from failure due to scour problem. Besides, by recommendation from the Drainage and Irrigation Department (DID), PWD follow the following specification:

- the bridge structure should cross the river perpendicularly;
- abutment should not protrude into the waterway;
- the number of piers in river should be minimized;
- the shape of bridges piers should, as far as possible, be oval; and
- the pile caps should be buried by at least 1.2m below the expected scoured depth.

where the recommendation is to reduce the obstruction of piers to the river flow. Some remedial action had been taken by PWD to overcome scour problem at constructed bridge piers by replacing scoured material. Ripraps of crushed stone had been commonly used as erosion resistance material for replacement of scoured material.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Extensive model testing was conducted in the Hydraulic Laboratory of UTP to measure the performance of different innovative scour countermeasure. Four types of models which are single cross-threaded piers, double cross-threaded piers, single cross-threaded piers with collar, and double cross-threaded piers with collar were tested with different configuration of thread angle and cable diameter. The procedure and equipment used in this experiment will be explained in detail in this chapter. The measured parameter to measure the performance of models is scour depth of model to scour depth of model without protection.

3.2 Model Scaling

A 30 mm – diameter pier was installed in sand. To neglect flume sidewalls effect so on Chiew and Melville (1987) and Izadinia and Heidarpour (2012) to the scour depth, the pier diameter selected should be less than 10% of the flume width. In this experiment, the pier diameter is about 10% of the flume width.

In order to avoid the effect of the sediment size to the scour depth, the pier diameter to the median grain size (D/d_{50}) should more than 50 (Chiew and Melville, 1987; Izadinia and Heidarpour, 2012). In this experiment, sand sediment with d_{50}= 0.48 mm was used as ***Figure 3-1*** shows the particle distribution size of the sediment. The D/d_{50} for this experiment is 62.5 which is well beyond 50. Therefore, this scale effect can be eliminated from the study.

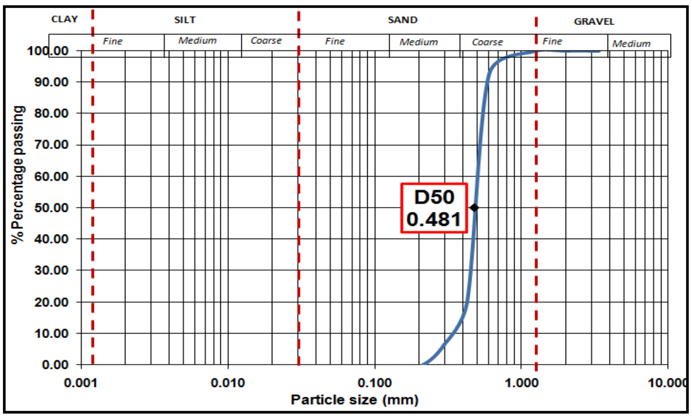


Figure 3-1*: Particle distribution size of the sediment*

3.3 Test Model

Four types of models have been selected, i.e. (a) cross thread cable, (b) double cross thread cable, (c) cross thread cable with a collar, (d) double cross thread cable with a collar as shown in ***Figure 3-2***. The thread angle and cable diameter used for both cross-threaded piers are varying which are 15° and 30°, and 2 mm and 3mm respectively. ***Table 3-1*** shows the properties of the test model in this experiment.

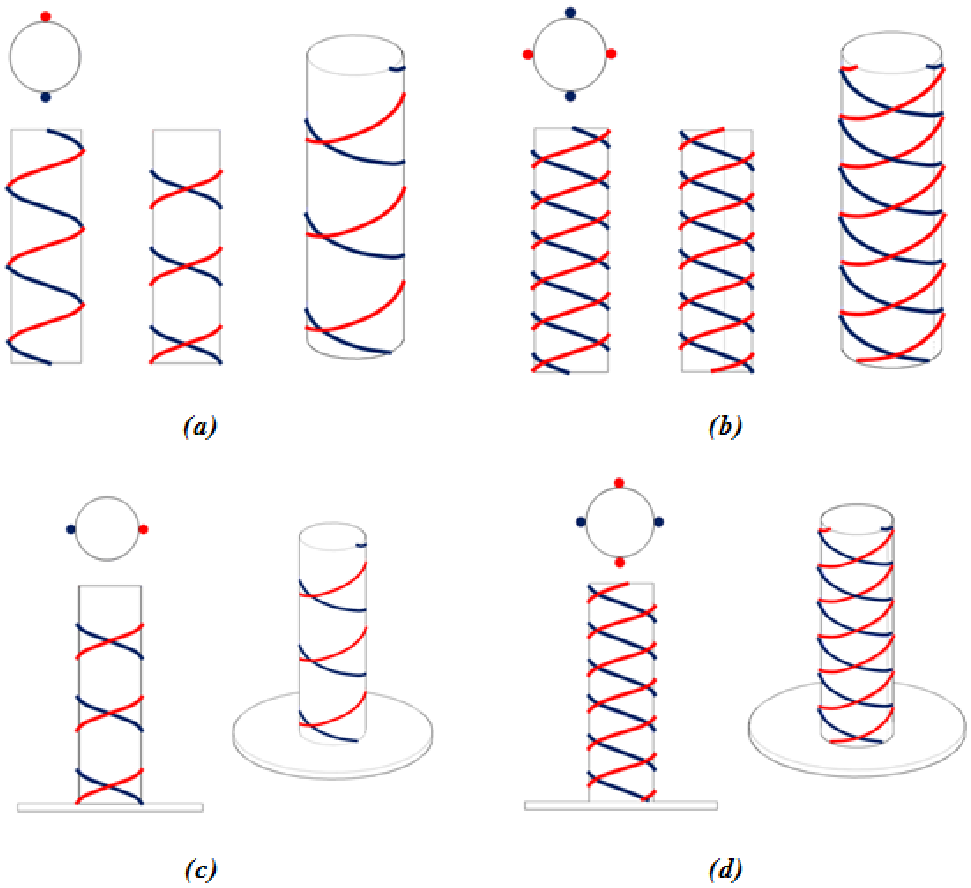


Figure 3-2*: Test models; (a) cross thread cable, (b) double cross thread cable, (c) cross thread cable with a collar, (d) double cross thread cable with a collar.*

Table 3-1*: Properties of models*

	Thread angle, θ	Cable diameter (b, mm)
Single pier without protection	-	-
Cross threaded pier	15°, 30°	2, 3
Cross threaded pier with collar	15°, 30°	2, 3
Double cross threaded pier	15°, 30°	2, 3
Double cross threaded pier with collar	15°, 30°	2, 3

3.4 Test Facilities and Measuring Equipment

The series of tests were conducted in an open channel flume at the Hydraulic Laboratory of UTP. The dimension of the flume is 32 cm width, 10 m length and 48 cm height as shown in ***Figure 3-3***. The flow of water was generated by a pump which the flow rate of water can be controlled using valve. All electrical switching units required for operations are located in the cover of the switch box. Sand filter also required in this experiment as the sediment was used as shown in ***Figure 3-4***. This filter was located at the outlet of flume to avoid small particle of sand from entering the pump system. In order to prevent turbulences flow during the experiment due to the pump forces, a kind of absorber was placed at the upstream of flume. The absorber will absorb the excessive energy and release steady flow for the rest of flume.

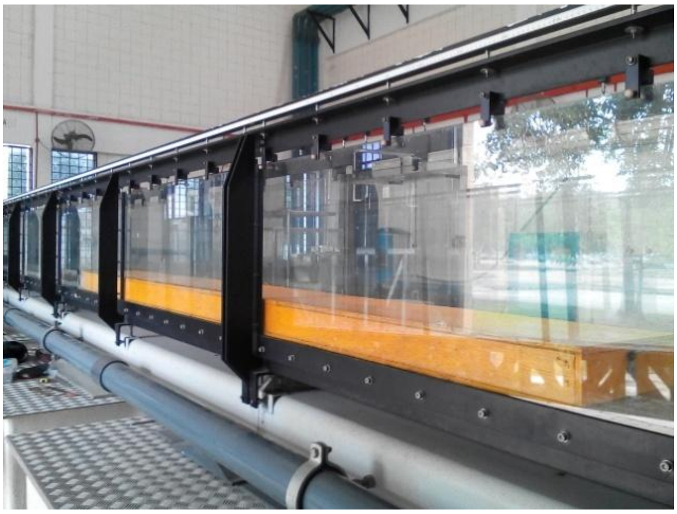


Figure 3-3*: Open channel flume*

Figure 3-4*: Sand filter*

Flow velocity was measured using mini current meter in this experiment as shown in ***Figure 3-5***. This current meter was used because it is small in size and suitable for this availability of flume size. The measured unit for this instrument is in centimetre per second. Point gauge that placed at the top of flume was used for measuring the scour depth as shown in ***Figure 3-6***. The reading of point gauge in this experiment was précised in one decimal place with unit of centimetre.

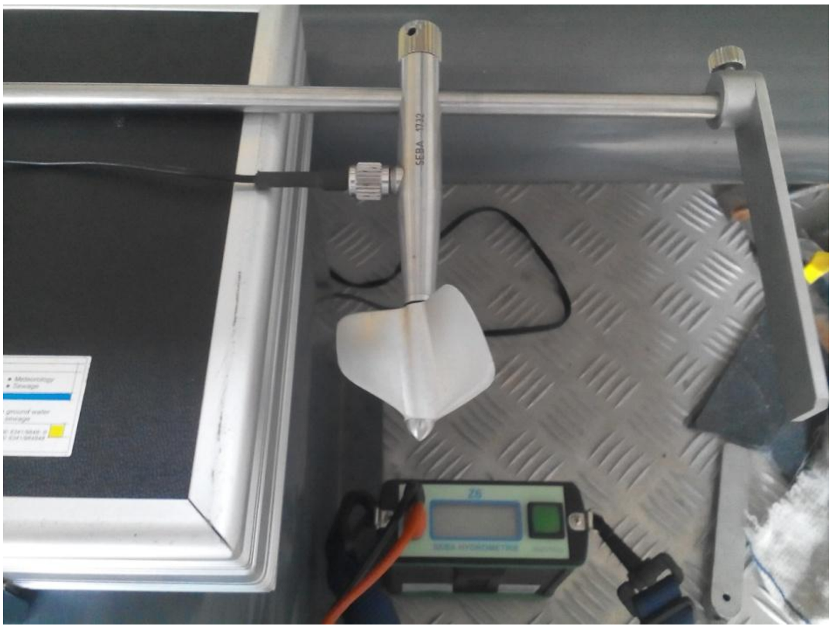


Figure 3-5*: Mini current meter*

Figure 3-6*: Point gauge*

3.5 Laboratory Set-up

The complete set-up of the flume is shown in ***Figure 3-7.*** The pier was located at the mid-length of the flume. The 3 m of false floor was located at upstream of pier followed by 3m of sand with depth of 10 cm. Before the sand sediment was inserted in the flume, 3.5 m long of goetextile was laid down on the flume bed as shown in ***Figure 3-8***. Lastly, 1 m of buffer zone was set-up at the end of flume. ***Figure 3-9*** and ***3-10*** shown the upstream and downstream of the flume respectively

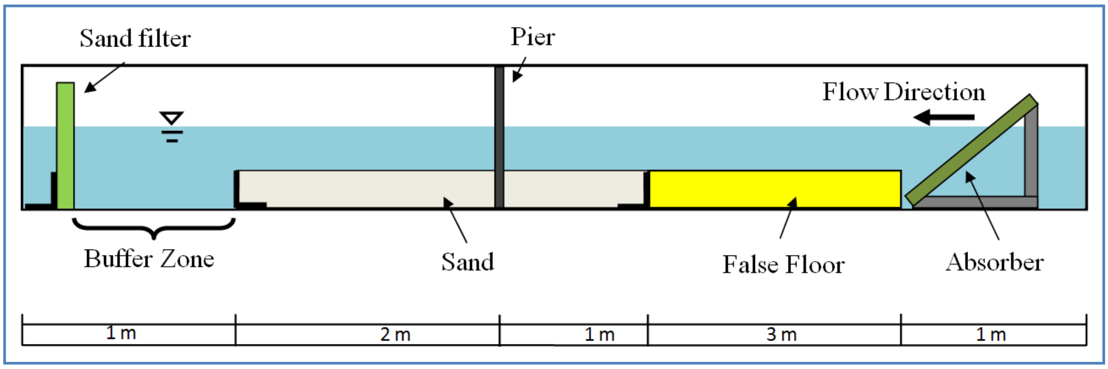


Figure 3-7*: Flume set up in the experiment.*

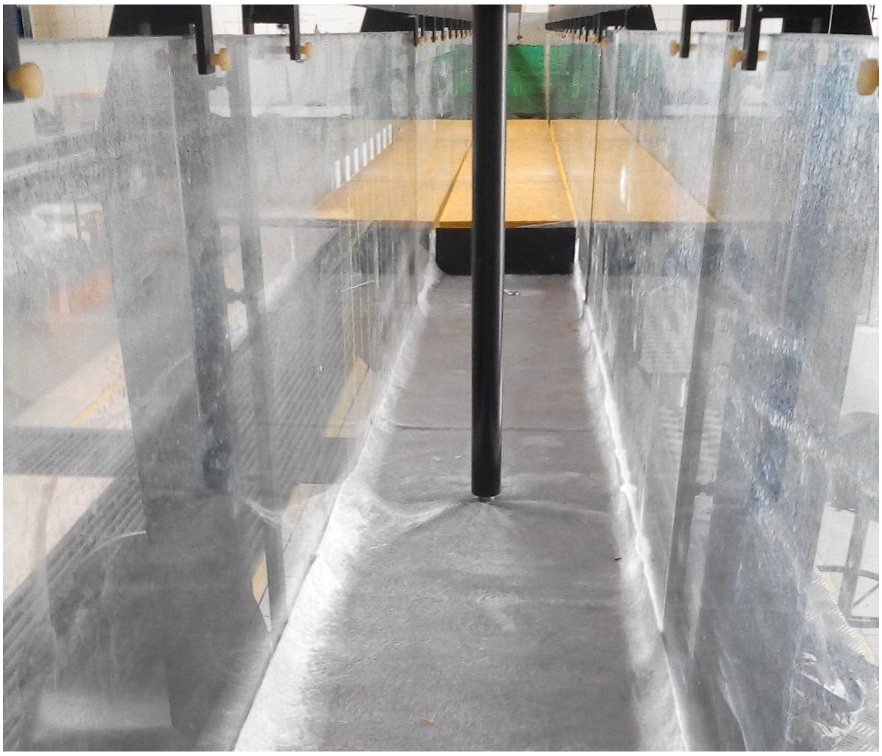


Figure 3-8*: Layer of geotextile*

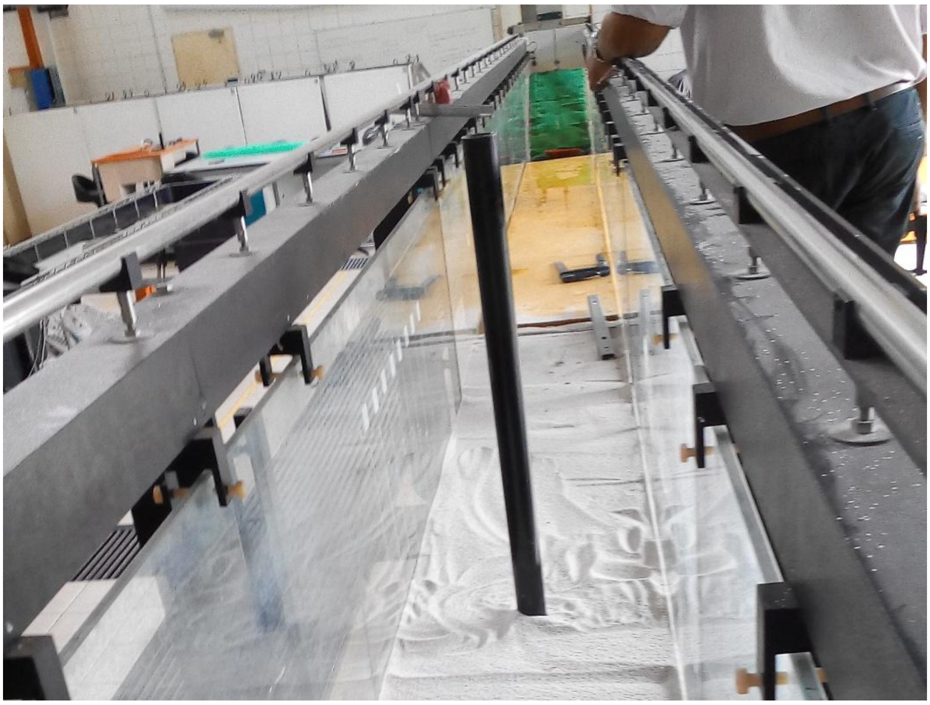


Figure 3-9*: Upstream of the flume*

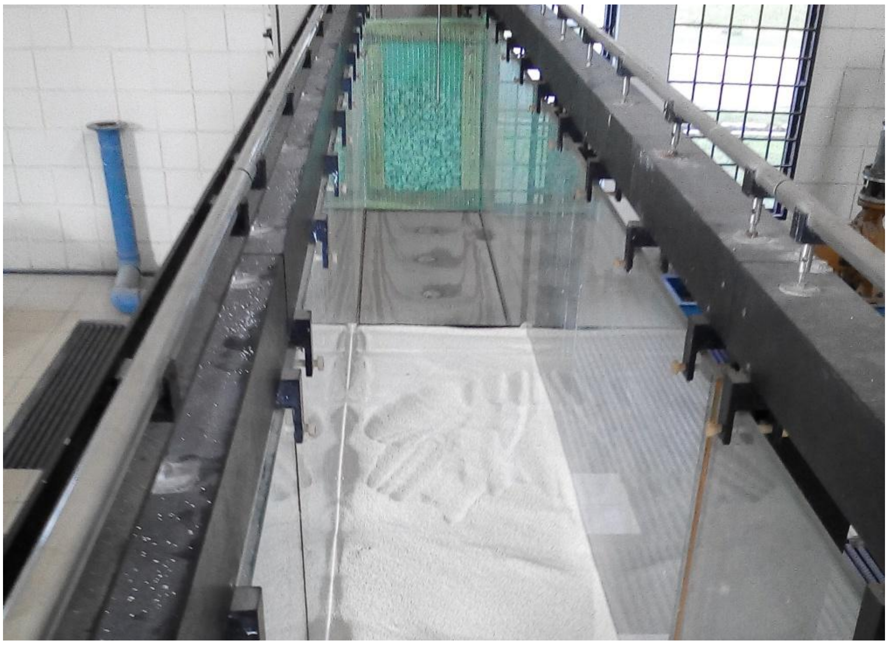


Figure 3-10*: Downstream of the flume*

3.6 Test Programme

***Table 3-2**: Matrix of the experiment.*

Series of Test	Test Condition				Test I.D
Series A	Without Protection	Flow rate 1			A1
		Flow rate 2			A2
		Flow rate 3			A3
Series B	Single Cross-threaded	Flow rate 3	Cable Diameter= 2mm	Thread Angle= 15°	B1
			Cable Diameter= 2mm	Thread Angle= 30°	B2
			Cable Diameter= 3mm	Thread Angle= 15°	B3
			Cable Diameter= 3mm	Thread Angle= 30°	B4
Series C	Double Cross-threaded	Flow rate 3	Cable Diameter= 2mm	Thread Angle= 15°	C1
			Cable Diameter= 2mm	Thread Angle= 30°	C2
			Cable Diameter= 3mm	Thread Angle= 15°	C3
			Cable Diameter= 3mm	Thread Angle= 30°	C4
Series D	Collar protection	Flow rate 3			D1
Series E	Single Cross-threaded with collar	Flow rate 3	Cable Diameter= 2mm	Thread Angle= 15°	E1
			Cable Diameter= 2mm	Thread Angle= 30°	E2
			Cable Diameter= 3mm	Thread Angle= 15°	E3
			Cable Diameter= 3mm	Thread Angle= 30°	E4
Series F	Double Cross-threaded with collar	Flow rate 3	Cable Diameter= 2mm	Thread Angle= 15°	F1
			Cable Diameter= 2mm	Thread Angle= 30°	F2
			Cable Diameter= 3mm	Thread Angle= 15°	F3
			Cable Diameter= 3mm	Thread Angle= 30°	F4

Table 3-2 shows the series of tests were conducted in this research. Experiment of Series A on scour hole around single pier without protection was conducted. The pier was exposed to three different flow rates where the mean velocity and water height at the upstream of the flume was measured. Each experiment run for 30

minutes after the water depth and flow rate was remaining constant. The depth of scour hole at the middle of model was measured. **Figure 3-11** shows the line measurement for scour pattern in this experiment. The experiment results are to be compared with CSU equation.

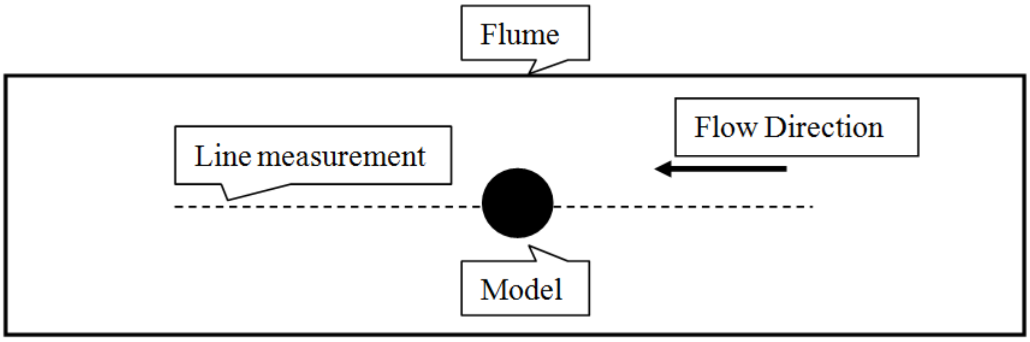


***Figure 3-11**: Line measurement for the experiment (Plan View).*

For Series B, C, D, E and F, the experiment of pier with protection was conducted. Each protected pier will be exposed to the same of flow rate as in Test A1 of 30 m^3/h and water depth of 0.192 m. The scour depth and area from coverage resulted by the models are to be compared with the unprotected pier. Scour reduction for each models are calculated as formula below

$$Scour\ depth\ reduction = 1 - \left(\frac{Maximum\ scour\ depth\ with\ protection, s_0}{Maximum\ scour\ depth\ without\ protection, y}\right) \times 100\%$$

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

The result from experiment of Series A was observed and discussed in this chapter. These results of scour depth recorded are compared with CSU equation due to certain factor that needs to reconsider. The experiment of Series B, C, D, E and F was conducted where the result of scour formation and it pattern are observed. Results are presented according to each models type. Then, performance of the models in reducing scour depth is discussed also in this chapter. Lastly, the comparisons with previous countermeasures are also done here.

4.2 Unprotected pier

This experiment was conducted to analysis the scour formation in set up condition within 30 minute of experiment duration. The cross-section of scour pattern at the middle of the pier with different flow rates are observed as shows in ***Figure 4-1***. The experimental results show scour and sediment deposition occur at the upstream and downstream of the unprotected pier, respectively. At upstream of the pier, the maximum scour depth increases with the increase of water depth and flow velocity. The sediment was disturbed by the flow and became bedload carried away by the water flow. This bedload was deposited as a short distance away from the lee of the pier. The amount of accretion is found directly proportional to the amount of the upstream erosion. This finding is sensible based on the principle of continuity of mass.

The data obtained from the experiment was compared with CSU equation in order to evaluate the scour performance. The ***Figure 4-2*** shows the scour depth with various flow velocities from experimental and theoretical value. The results show that, within 30 minutes of experiment, the scour depth in this experiment does not achieve it equilibrium scour depth. However, the trend of scour formation of experiment is consistent as the theoretical data even the estimated depth are different. As the flow velocity increase, the scour depth also increases. The high value of flow velocity will induce strong down-flows and horseshoe vortices where they able to scour the sediment deeper.

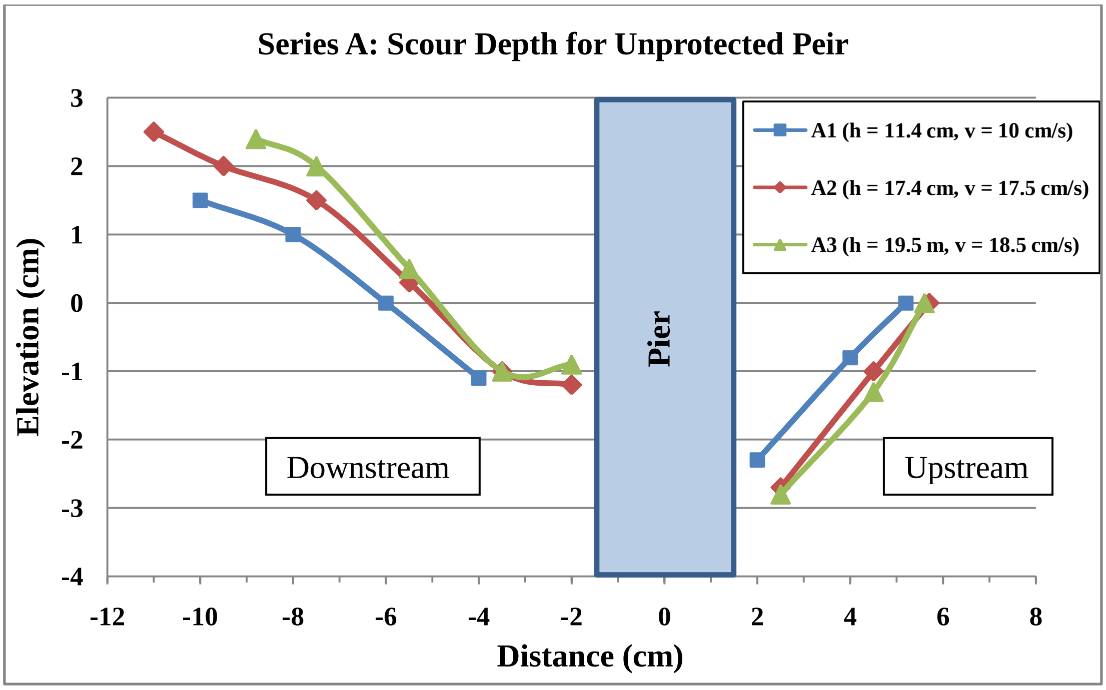


Figure 4-1: *Scour pattern for experiment of Series A*

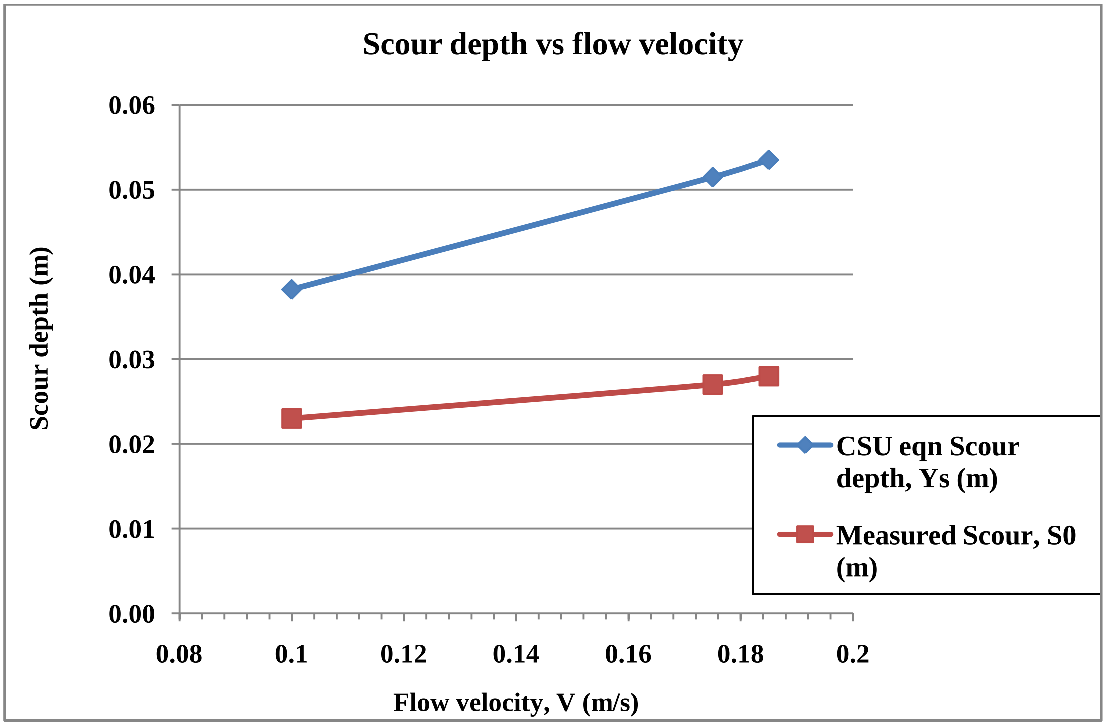


Figure 4-2: *The comparison of experimental scour depth in various flow velocities with theoretical value.*

4.3 Single cross-threaded pier

The cross-section of scour patterns at middle of single cross-threaded pier with varying of cable diameter and thread angel are observed as shows in ***Figure 4-3***. The upstream scour patterns of single cross threaded piers tested are almost resemble to each other regardless of the relative thread width and angle. The maximum scour recorded is approximately 2.6 cm from the original bed level. The downstream bed profiles of piers with thread angles of 15° and 30° for cable diameter to pier diameter ratio (b/D) of 0.067 which Test B1 and B2 cases respectively are similar. A maximum of 0.5 cm of scour depth over a length of 4 cm from the lee side of the piers is observed. As for the Test B3 and B4 of piers with b/D = 0.1, only accretion is seen at the lee of the piers. The pier of thread angle of 15° in Test B3 case tends to trap more sediment. In conclusion, the upstream scour due to the piers of single cross thread is not much affected by the relative thread width and its angle. The downstream scour immediately after the test models is marginal. This is followed by accretion as the distance away from the lee side of the pier increases.

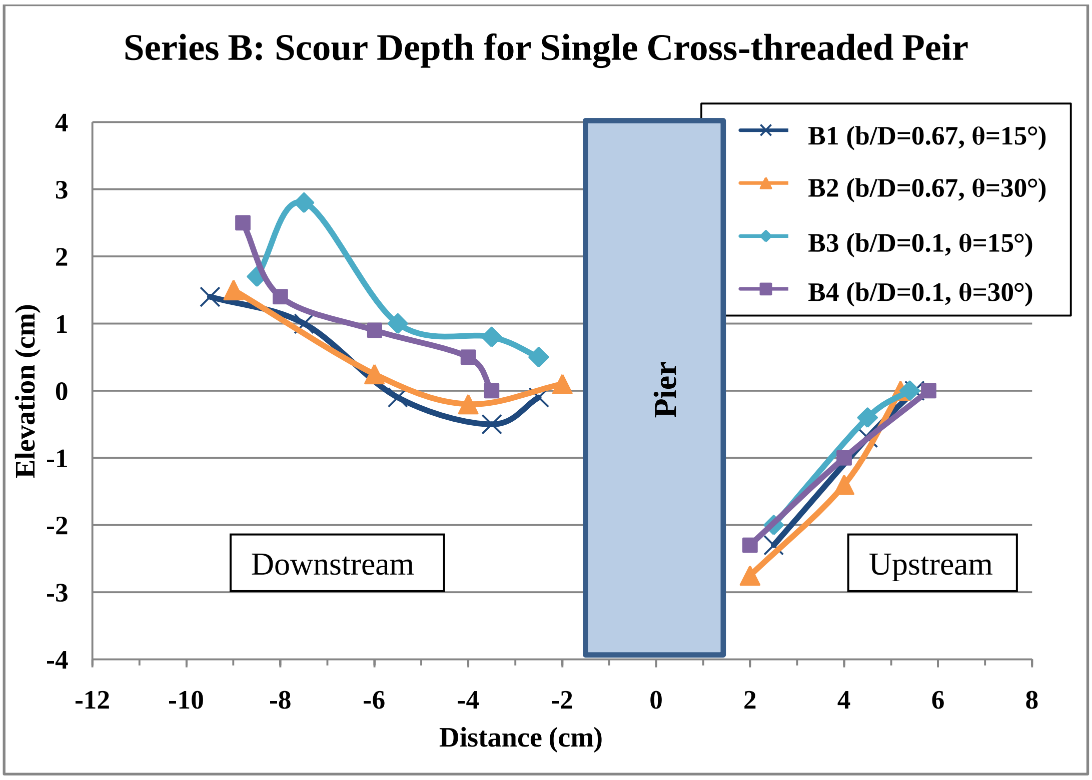


Figure 4-3*: Scour pattern for experiment of Series B*

4.4 Double cross-thread pier

Figure 4-4 shows the cross-section scour pattern at middle of double cross-threaded pier with variation of cable diameter and thread angle. The upstream scour patterns of double cross threaded piers for Test C2, C3 and C4 cases are quite similar. However, the upstream scour depth of Test C1 case is relatively small compared to those of other test cases. The maximum scour depth measured is about 2.3 cm from the flat bed level. The downstream bed profiles of test cases of thread angle of 15° which are Test C1 and C3 cases are closely related to each other, particularly for the zone of accretion which is 6 cm away from the pier. This indicates that the influence of b/D on formation of scour is insignificant. As the thread angle increases to 30° which are Test C2 and C4 cases, the effect of b/D becomes dominant in scour control. Pier of larger b/D tends to pose more sedimentation at its downstream. Similar to the single cross threaded pier, the piers of double cross threads pose scour right in front of the pier, and the scour pattern is not much affected by the relative thread width and its angle. Minimal erosion would be expected immediate after the lee side of the pier.

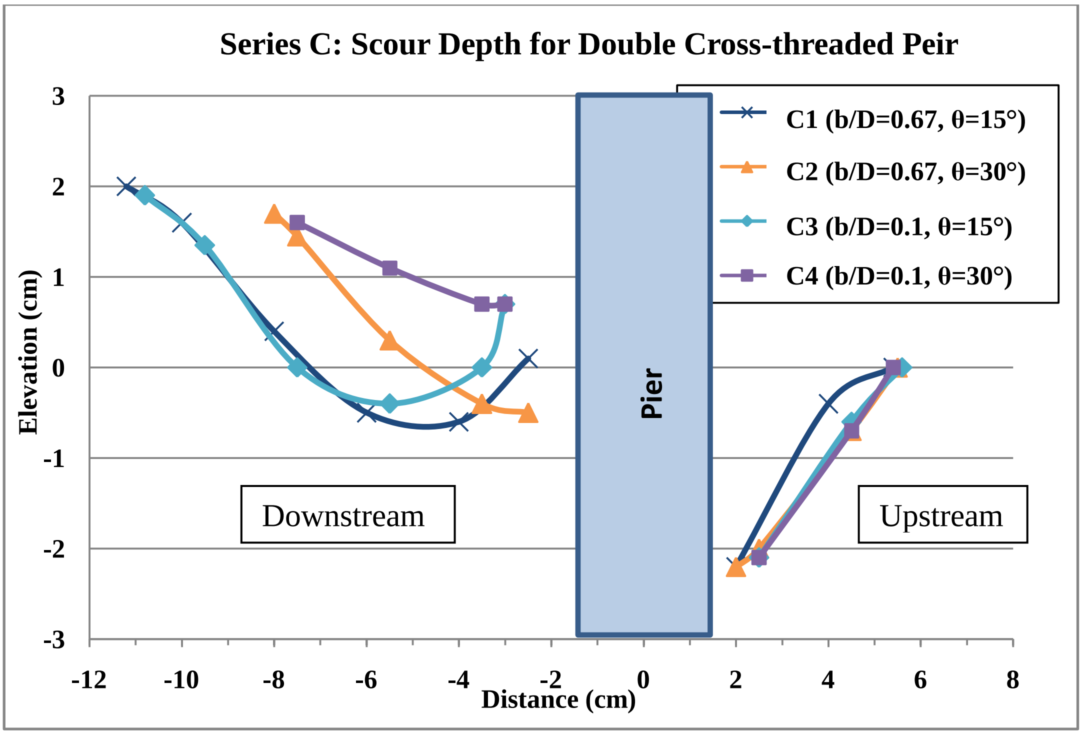


Figure 4-4*: Scour pattern for experiment of Series C*

4.5 Pier with Collar

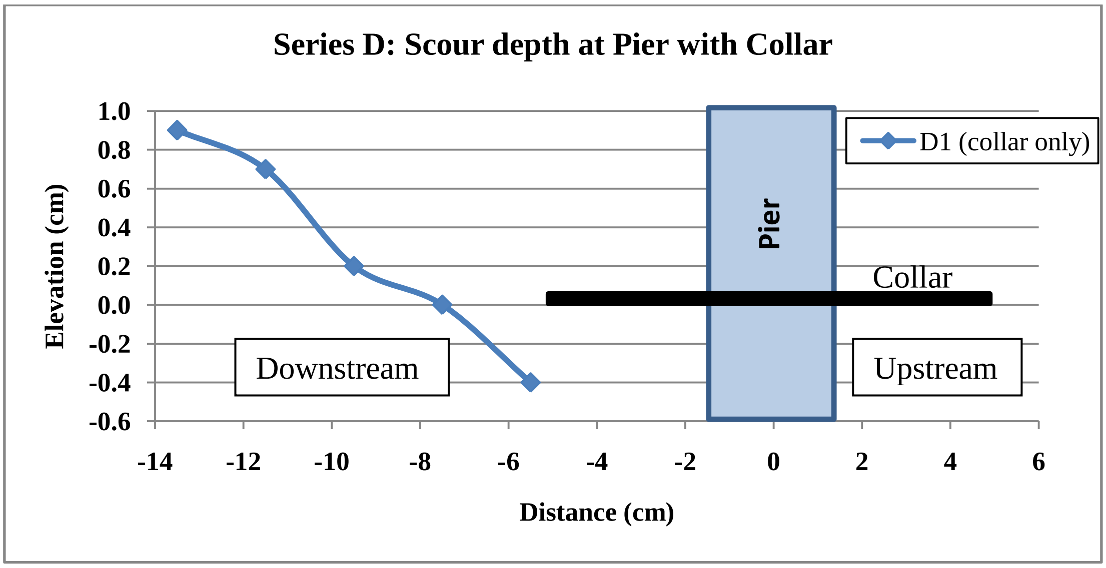


***Figure 4-5**: Scour pattern for experiment of Series D.*

The cross-section of scour pattern at the middle of the pier with collar protection is observed as shows in ***Figure 4-5***. The experimental results show scour and sediment deposition occur at the downstream of the pier. There is no erosion at the upstream of the pier as the sediment is protected by the collar from the down flow. As the separation of the flow at the side of pier, the flow starts to scour the unprotected sediment. The sediments are carried way and start to settle about 8 cm from downstream of the pier.

4.6 Single Cross-threaded Pier with Collar

The cross-section of scour patterns at middle of single cross-threaded pier with collar varying of cable diameter and thread angel are observed as shows in ***Figure 4-6***.The scour hole happen at the downstream of the pier followed by accretion. For b/D = 0.67 which Test E1 and E2 cases, the effect of thread angle are not give much different on the scour pattern. While for b/D = 0.1 which Test E3 and E4 cases, the decreasing of thread angle enhance sedimentation to occur little bit afar by offset of 2 cm. That show, the influence of thread angle to the scour pattern in single cross-threaded pier are significant even there are minimal impact to the changes in scour pattern when it combing with collar.

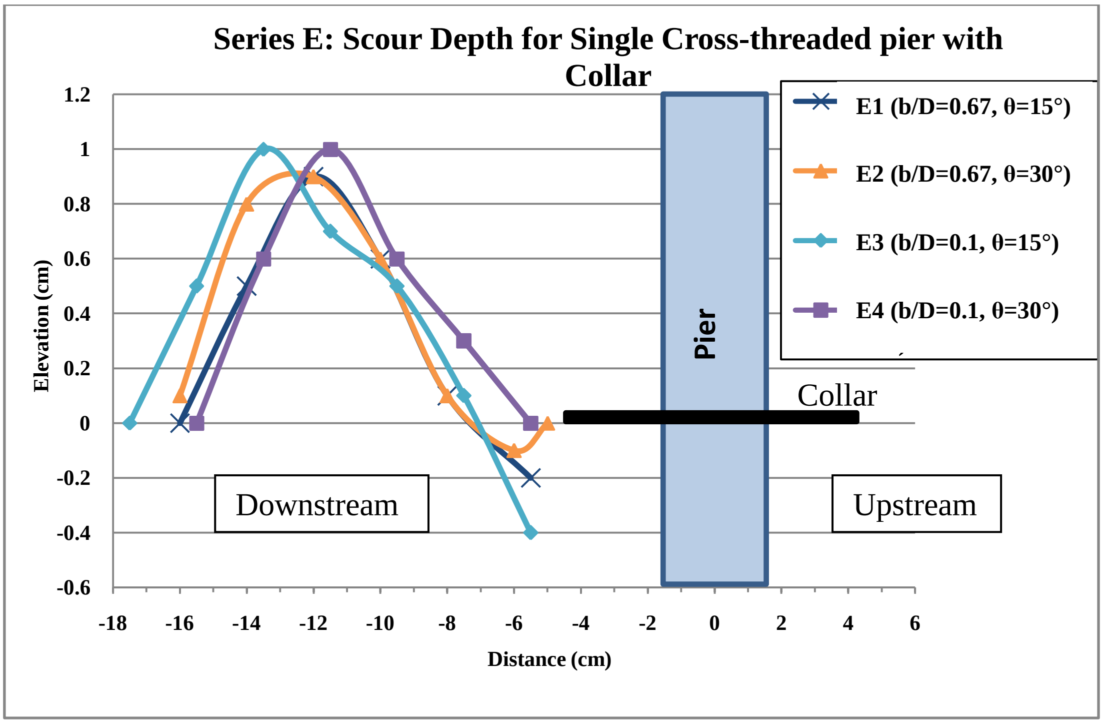


Figure 4-6: *Scour pattern for experiment of Series E*

4.7 Single Cross-threaded Pier with Collar

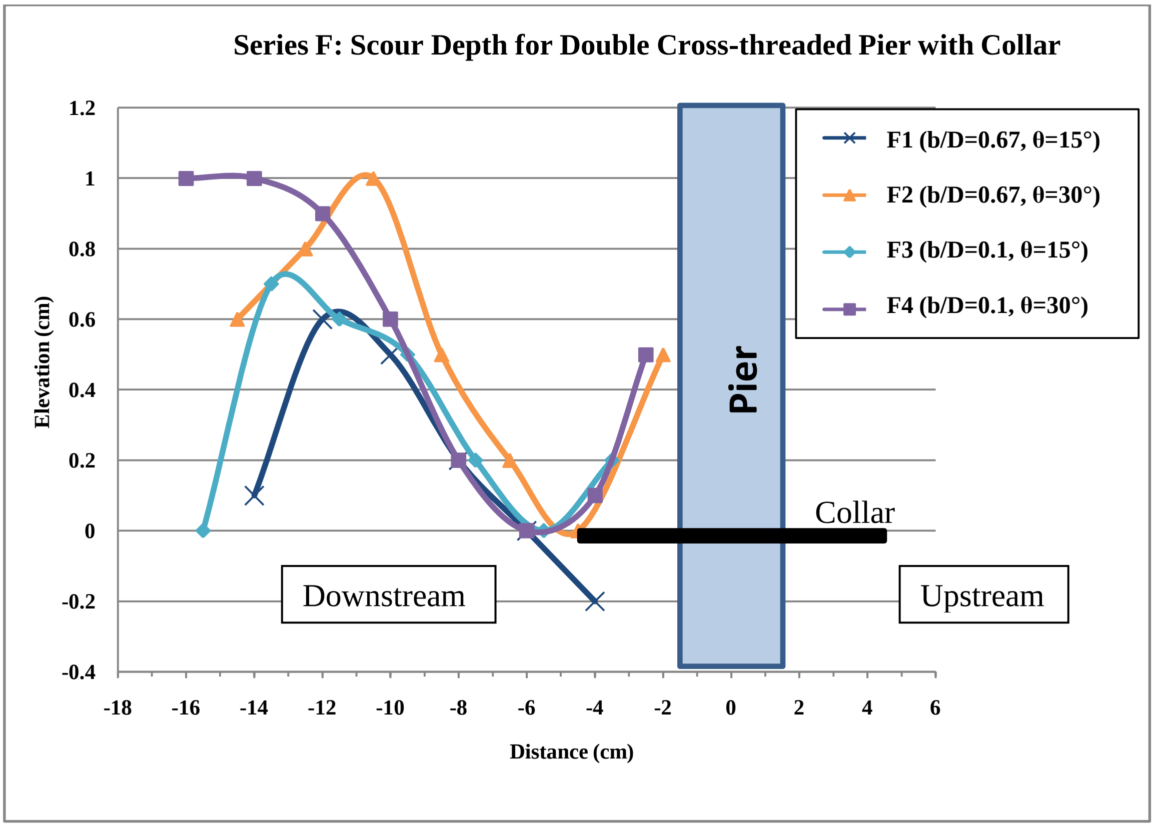


Figure 4-7: *Scour pattern for experiment of Series F.*

Figure 4-7 shows the cross-section scour pattern at middle of double cross-threaded pier with variation of cable diameter and thread angle. Some accretions are observed on the top of collar at the downstream of pier for Test F2, F3 and F4 cases. Only Test F1 case shows the scour hole recorded about 0.2 cm beside the collar at the downstream of the middle of pier. For the thread angle of 15°, the b/D = 0.1 which is Test F3 case enhance longer accretion zone compare to b/D = 0.067 which is Test F1 cases with different of 1.5 cm. Same for the thread angle of 30°, the Test F4 case which b/D = 0.1 accrete more sediment at the downstream of pier compare to Test F2 cases which is b/D = 0.067. That show, the variation of cable diameter give significant effect to the scour pattern for double cross-threaded pier with collar protection.

4.8 Performance of Models

The maximum of scour depth each test case from Series B, Series C, Series E and Series F are compared with maximum of scour depth from Series A which the water depths are same for all experiments. ***Table 4-1*** shows the summary result of scour reduction for all models of single cross-threaded pier and double cross-threaded pier with and without collar protection.

Table 4-1*: Summary of the scour reduction result.*

Model type	Cable diameter, b (mm)	Thread angle, θ (°)	Scour depth, y (cm)	Scour depth reduction (%)
Single Cross-thread without Collar	2	15	2.3	17.9
	2	30	2.5	10.7
	3	15	2.1	25.0
	3	30	2.3	17.9
Double Cross-thread without Collar	2	15	2.2	21.4
	2	30	2.2	21.4
	3	15	2.2	21.4
	3	30	2.25	19.6
Single Cross-thread with Collar	2	15	1.1	60.7
	2	30	1.1	60.7
	3	15	0.8	71.4
	3	30	0.6	78.6
Double Cross-thread with Collar	2	15	1.1	60.7
	2	30	1.1	60.7
	3	15	1	64.3
	3	30	0.9	67.9

Note: Maximum scour depth for unprotected pier is 2.8 cm. Maximum scour depth for pier with collar is 1.1 cm.

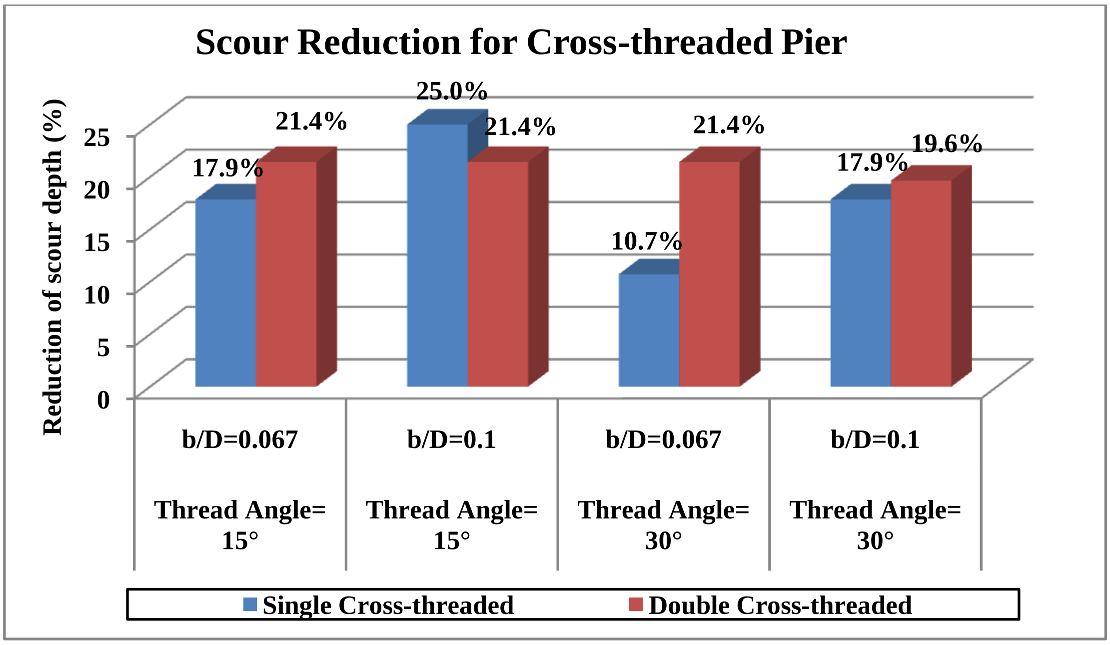


Figure 4-8*: Scour reduction of single and double cross-threaded pier without collar models.*

The comparison of scour reduction for single cross-threaded pier and double cross-threaded pier without collar protection are show in ***Figure 4-8***. In general, the cross-threaded piers help to reduce the upstream scour at varying rates. The 15^o thread angle piers outperform the unthreaded pier by 17.9% to 25%, and the efficiency improves with the increase of b/D value. The double threaded pier serve as a better flow damper when b/D = 0.067. However, this observation is invisible for the test cases of b/D. For the 30^o thread angle piers, those of b/D = 0.1 proves to be a more efficient design in reducing scour depth, particularly for the double cross-threaded piers. Generally, the double cross-thread piers offer higher efficiency in reducing scour problem at its upstream. It outperforms the single threaded piers by an average of 10%. However, the performance of double cross-thread pier becomes less compare to single cross-thread pier when the large cable size and small thread angle are used. This can be explains by the arrangement of the thread become too dense and it have tendency to act as a bigger pier. The finding shows that the number of threads on piers (i.e. single thread and double thread) does give an impact to scour control. Increasing the number of threads will increase the overall efficiency. This can be explained by the fact that the strength of downward flow of the double crossed thread is reduced by large number of cable that obstructs it. In conclusion, scour problem at pier can be reduced by the use piers of double threads of larger width and of smaller thread angle.

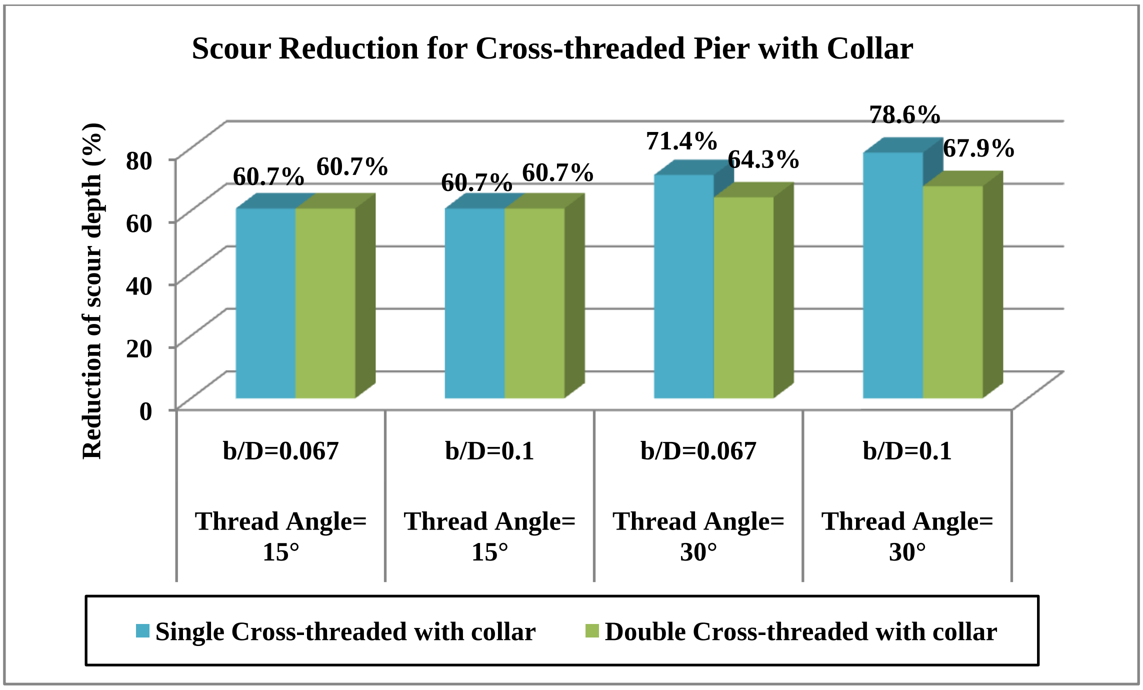


Figure 4-9: *Scour reduction of single and double cross-threaded pier with collar models.*

The percentages of scour reduction of single and double cross-threaded with collar protection are show in ***Figure 4-9*** above. In generally, the average scour reduction of the cross-threaded pier with collar protection is about 65.6 % as the scour reduction of pier with collar protection only is 60.7%. From the result, the single cross-threaded piers give better result compare to double cross-threaded pier with average different of 5%. For the thread angle of 15°, both models give same results which indicate the cable diameter does not affect much in reducing scour. However, when the thread angle is increase into 30°, the cable diameters affect much the performance of the models in scour reduction which maximum scour reduction of combination 30° thread angle and 0.1 cable-pier diameter ratio. The greater cable size, the more scour will reduce. The arrangement of cable for thread angle of 15° is too denser compare to thread angle of 30° which make models have tendency to act as bigger piers and ineffective on reducing the flow strength. The same thing happen when the number of thread is increased from single to double cross-threaded. Thus, the ideal combination will be single cross-threaded pier with large cable diameter and large thread angle. When comparing the model without collar and with collar protection, the models with collar protection are much better. This is because the collar can prevent the down-flow from scouring the sediment while the threaded cable only able to reduce the strength of the down-flow.

4.9 Comparison with Previous Countermeasure

A comparison of reduction ratio with cable–pier diameter ratio b/D for different thread piers of previous study and present study with different thread angles are show in ***Figure 4.6***. Reduction ratio is obtained by performing a relative comparison between scour due to threaded piers and unprotected pier. A coefficient that is approaching unity means that the threaded piers fail to overcome the scour problem.

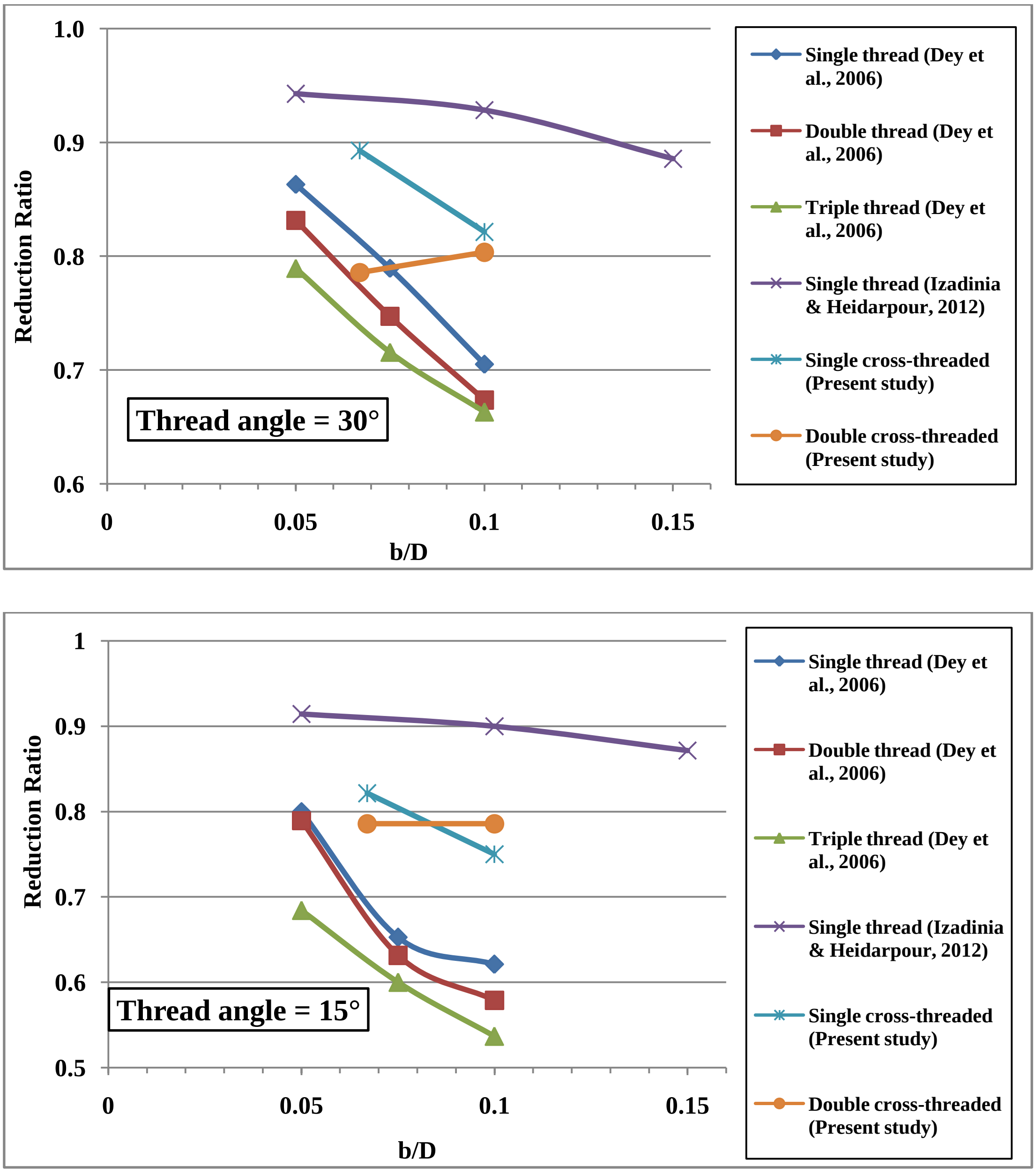


Figure 4-10*: Variation of reduction ratio with cable-pier diameter ratio (b/D) for different type of model and thread angles under steady current.*

Generally, the performances of Dey et al. (2006) much better than present study and performance of present study is better than Izadinia and Heidarpour (2012). However, the results from Dey et al. (2006) are questionable where the Izadinia and Heidarpour (2012) were conducting back the experiment as they believe Dey et al. (2006) experiment was affected by flume sidewall effect. By extrapolating the performance of single thread pier from Izadinia and Heidarpour (2006) for double and triple thread pier, the models from present study can be comparable and might be better than previous study. However, the experiment for double and triple thread pier need to conduct once again for better comparison.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

From the literature review, the scour depth was depended on the strength of the flow, pier size and sediment condition all the time. The strong flow will induced strong vortices that involve in scouring the sediment. Large surface area of obstructing the flow also induces large vortices in forming scour. The strength of sediment in resist the erosion also affects the scour depth. The scour depth will keep increase over time until it reach equilibrium depth where the strength of vortices is equal to the resistance of sediment to erosion.

As the result, the scour formation for unprotected pier was conducted. The result shows the same trend as CSU equation as it does not achieved equilibrium depth. The availability of laboratory facilities and time constraint does not effort the experiment to conduct in longer period.

By considering the accretion pattern at the lee of pier, the cross-threaded models are able to alter the flow direction around the pier. The scour pattern for single cross-threaded are influence by cable diameter. The pattern for cable-pier diameter ratio (b/D) of 0.067 is different from b/D of 0.1. The variation of thread angle just changes the magnitude of accretion pattern of respective cable diameter. Vice versa for double cross-threaded models, the scour pattern much influence by thread angle. The patterns for thread angle 15° are different from thread angle 30°. By increasing the cable diameter, the sedimentation at lee of pier also increase with particular thread angle.

The models that were tested in this experiment able to reduce scour at the upstream of pier by weaken the strength of flow-down from scouring the sediment. The models also enhance the more accretion at the lee of pier as the strength of wake vortices is reduced.

For overall performance of tested models without collar protection, single cross-thread piers were able to reduce scour about 18% and double cross-thread pier with 21%. While tested models with collar protection, single cross-thread piers were able to reduce scour about 69% and double cross-thread pier with 63%. However, correct matching of cable diameter and thread angle will optimize the performance of the models. The maximum scour reduction that was recorded is single cross-threaded pier with collar of 0.1 cable-pier diameter ratio and 30° thread angle able to reduce about 79% of potential scour hole.

As the time constrain, only a few combination of countermeasure able to test in this experiment. For future study, more combination of countermeasure and flow velocities is recommended for better comparison of performance study. Specifically for this study, double and triple thread pier of Dey et al. (2006) also need conduct back as feature comparison of the single and double cross-threaded pier. Besides that, the constructability, durability and commercial value aspect of this countermeasure also can be future study.

For the accuracy and precision of the result, some improvements in measured instrument are suggested. Eco-sounder or bed profiler is recommended for future experiment. These instruments able to give more accurate and faster digital bed profile compare to point gauge. The usage of point gauge may lead to parallax error where the eye not perpendicular to the measurement scale and the point gauge not placed correctly on the bed surface as it penetrate into the sediment. Besides, the usage of point gauge is time consuming. By using eco-sounder of bed profiler, the bed profile also be observed by vary of time without stopping the flow and saving much time. Acoustic Doppler Current Profiler (ADCP) also suggests being use instead of using mini current meter for measuring the velocity. This instrument is able to plot current pattern around the models in three directions which are x, y and z. Thus, the better understanding of flow pattern around the models can be obtained.

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APPENDIX

Experimental Result: Series A

Measurement

Test no.	Test I.D	Pier Diameter, D (mm)	Flowrate (m3/h)	Water depth, h (cm)	Measured Upstream Velocity, v (cm/s)	Measured Scour Width, W (cm)	Measured Scour Length, L (cm)	Measured Max. Scour Depth, $y_{1.u}$ (cm)
1	A1	30	11.23	11.4	10	9.9	12.2	2.4
2	A2	30	24.33	17.4	17.5	11.3	16.7	2.7
3	A3	30	32.85	19.5	18.5	10.4	14.4	2.8

CSU Equation Calculation

Test I.D	Water depth, Y1 (m)	mean Velocity, V1 (m/s)	Pier Length,L (m)	Pier Width,a (m)	Fr	a/Y1	K1	K2	K3	CSU eqn Scour depth, Ys (m)	Measured Scour, S0 (m)
A1	0.114	0.1	0.03	0.03	0.09456	0.2632	1	1	1.1	0.038	0.023
A2	0.174	0.175	0.03	0.03	0.13395	0.1724	1	1	1.1	0.051	0.027
A3	0.195	0.185	0.03	0.03	0.13376	0.1538	1	1	1.1	0.054	0.028

Scour Bed Profile

A1 (h = 11.4 cm, v = 10 cm/s)				A2 (h = 17.4 cm, v = 17.5 cm/s)			
Length Distance (cm)	Distance (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	Distance (cm)	Depth (cm)	Elevation (cm)
15	2	7.7	-2.3	15	2.5	7.3	-2.7
17	4	9.2	-0.8	17	4.5	9	-1
18.2	5.2	10	0	18.2	5.7	10	0
9	-4	8.9	-1.1	10.5	-2	8.8	-1.2
7	-6	10	0	9	-3.5	9	-1
5	-8	11	1	7	-5.5	10.3	0.3
3	-10	11.5	1.5	5	-7.5	11.5	1.5
				3	-9.5	12	2
				1.5	-11	12.5	2.5

A3 (h = 19.5 m, v = 18.5 cm/s)			
Length Distance (cm)	Distance (cm)	Depth (cm)	Elevation (cm)
15	2.5	7.2	-2.8
17	4.5	8.7	-1.3
18.1	5.6	10	0
10.5	-2	9.1	-0.9
9	-3.5	9	-1
7	-5.5	10.5	0.5
5	-7.5	12	2
3.7	-8.8	12.4	2.4

Picture Scour Pattern

Scour hole during experiment

Scour hole during experiment

Experimental Result: Series B

Measurement

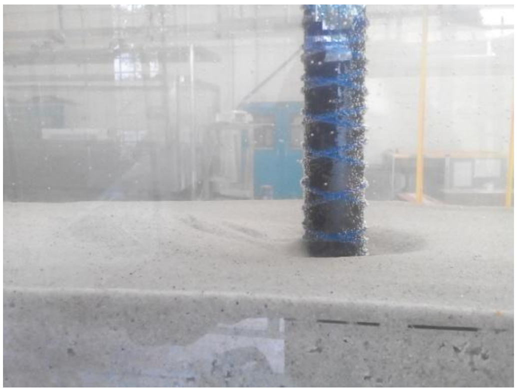
Test I.D	Cross-threaded	Collar	Cable Diameter, b (mm)	Pier Diameter, D (mm	Thread Angle, θ (°)	b/D	Flowrate (m3/h)	Water depth, h (cm)	Measured Upstream Velocity, v (cm/s)	Measured Scour Width, W (cm)	Measured Scour Length, L (cm)	Measured Max. Scour Depth, $y_{1,s}$ (cm)	Reduction Ratio, y1,s/y1,u	Efficiency, 1-(y1,s/y1,u) x 100%
B1	single	no	2	30	15	0.067	34.28	19.95	18.5	10.7	15	2.3	0.82	17.86
B2	single	no	2	30	30	0.067	35.99	20	18	10.2	14.2	2.5	0.89	10.71
B3	single	no	3	30	15	0.100	34.54	19.8	18	10.2	13	2.1	0.75	25.00
B4	single	no	3	30	30	0.100	34.26	20	19	10.8	14.6	2.3	0.82	17.86

Scour Bed Profile

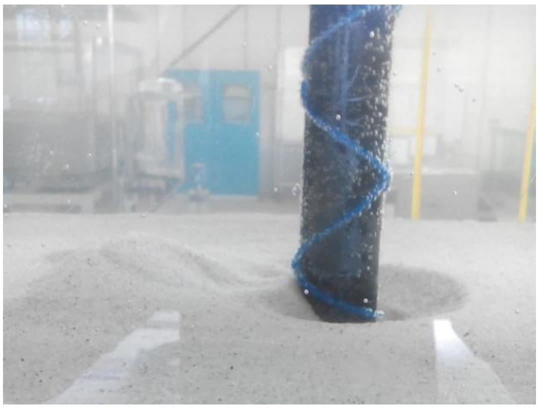
B1 (b/D = 0.067, θ = 15°)				B2 (b/D = 0.067, θ = 30°)			
Length Distance (cm)	Distance (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	Distance (cm)	Depth (cm)	Elevation (cm)
15	2.5	7.7	-2.3	15	2	7.25	-2.75
17	4.5	9.3	-0.7	17	4	8.6	-1.4
18	5.5	10	0	18.2	5.2	10	0
10	-2.5	9.9	-0.1	11	-2	10.1	0.1
9	-3.5	9.5	-0.5	9	-4	9.8	-0.2
7	-5.5	9.9	-0.1	7	-6	10.25	0.25
5	-7.5	11	1	4	-9	11.5	1.5
3	-9.5	11.4	1.4				

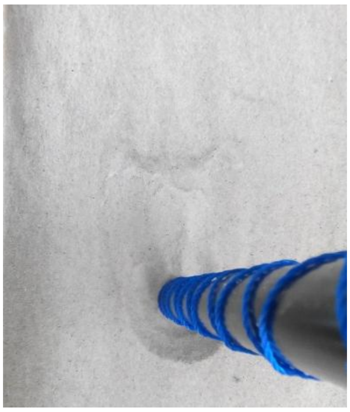
B3 (b/D = 0.1, θ = 15°)				B4 (b/D = 0.1, θ = 30°)			
Length Distance (cm)	Distance (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	Distance (cm)	Depth (cm)	Elevation (cm)
15	2.5	8	-2	15	2	7.7	-2.3
17	4.5	9.6	-0.4	17	4	9	-1
17.9	5.4	10	0	18.8	5.8	10	0
10	-2.5	10.5	0.5	9.5	-3.5	10	0
9	-3.5	10.8	0.8	9	-4	10.5	0.5
7	-5.5	11	1	7	-6	10.9	0.9
4	-8.5	11.7	1.7	4.2	-8.8	12.5	2.5

Scour Pattern: B1 (b/D = 0.067, θ = 15^{o})

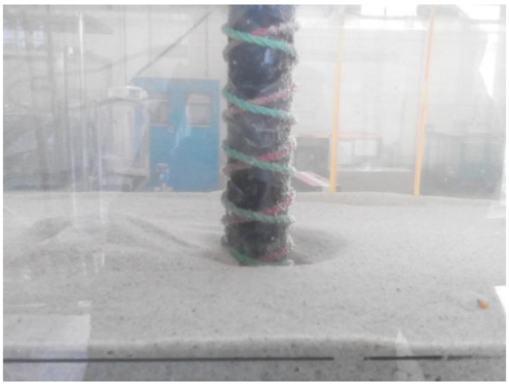


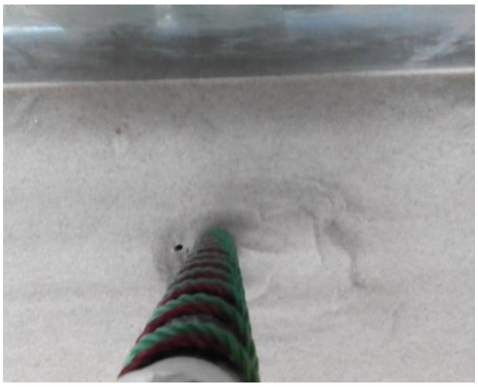
Scour Pattern: B2 (b/d = 0.067, θ = 30^{o})

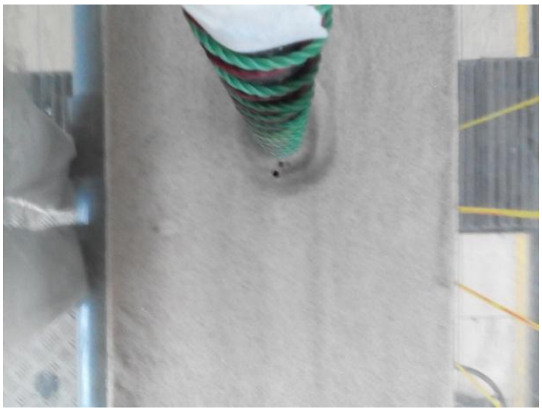




Scour Pattern: B3 (b/d = 0.1, θ = 15^o)







Scour Pattern: B4 (b/d = 0.1, θ = 30^o)

Experimental Result: Series C

Measurement

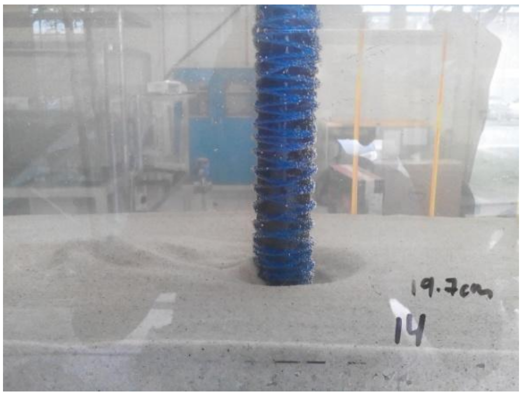
Test no.	Test I.D	Cross-threaded	Collar	Cable Diameter, b (mm)	Pier Diameter, D (mm	Thread Angle, θ (°)	b/D	Flowrate (m3/h)	Water depth, h (cm)	Measured Upstream Velocity, v (cm/s)	Measured Scour Width, W (cm)	Measured Scour Length, L (cm)	Measured Upstream Max. Scour depth, $y_{1,d}$ (cm)	Reduction Ratio, y1,d/y1,u	Efficiency, 1- (y1,s/y1,u) x 100%
1	C1	double	no	2	30	15	0.067	34.56	19.7	18.5	10.1	16.6	2.2	0.79	21.43
2	C2	double	no	2	30	30	0.067	32.61	20	17.5	9.5	13.5	2.2	0.79	21.43
3	C3	double	no	3	30	15	0.100	32.61	19.8	17.5	11	16.4	2.2	0.79	21.43
4	C4	double	no	3	30	30	0.100	34.14	19.95	19.5	10.3	13	2.25	0.80	19.64

Scour Bed Profile

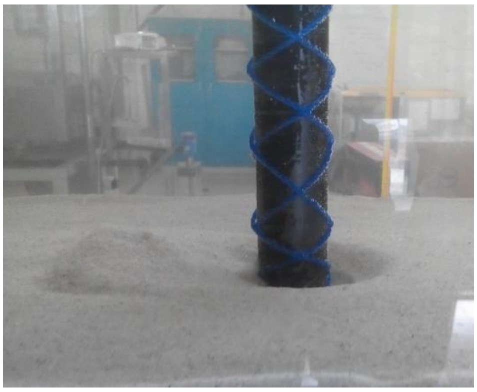
C1 (b/D = 0.067, θ = 15°)				C2 (b/D = 0.067, θ = 30°)			
Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)
15	2	7.8	-2.2	14.5	2	7.8	-2.2
17	4	9.6	-0.4	15	2.5	8	-2
18.4	5.4	10	0	17	4.5	9.3	-0.7
10.5	-2.5	10.1	0.1	18	5.5	10	0
9	-4	9.4	-0.6	10	-2.5	9.5	-0.5
7	-6	9.5	-0.5	9	-3.5	9.6	-0.4
5	-8	10.4	0.4	7	-5.5	10.3	0.3
3	-10	11.6	1.6	5	-7.5	11.45	1.45
1.8	-11.2	12	2	4.5	-8	11.7	1.7

C3 (b/D = 0.1, θ = 15°)				C4 (b/D = 0.1, θ = 30°)			
Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)
15	2.5	7.9	-2.1	15	2.5	7.9	-2.1
17	4.5	9.4	-0.6	17	4.5	9.3	-0.7
18.1	5.6	10	0	17.9	5.4	10	0
9.5	-3	10.7	0.7	9.5	-3	10.7	0.7
9	-3.5	10	0	9	-3.5	10.7	0.7
7	-5.5	9.6	-0.4	7	-5.5	11.1	1.1
5	-7.5	10	0	5	-7.5	11.6	1.6
3	-9.5	11.35	1.35				
1.7	-10.8	11.9	1.9				

Scour Pattern: C1 (b/D = 0.067, θ = 15^o)

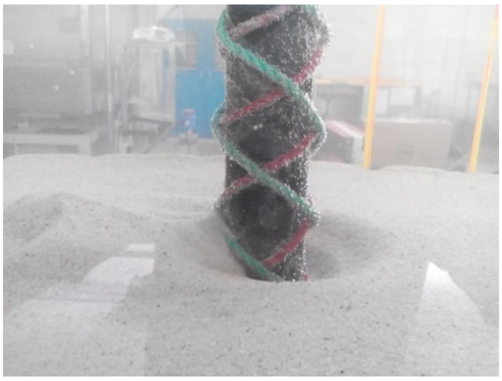


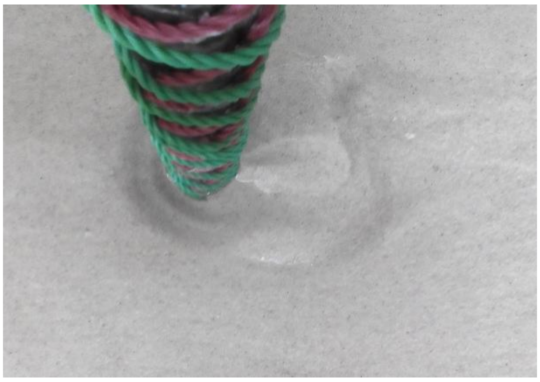
Scour Pattern: C2 (b/D = 0.067, θ = 30^o)



Scour Pattern: C3 (b/D = 0.1, θ = 15^o)

Scour Pattern: C4 (b/D = 0.1, θ = 30^o)





Experimental Result: Series D

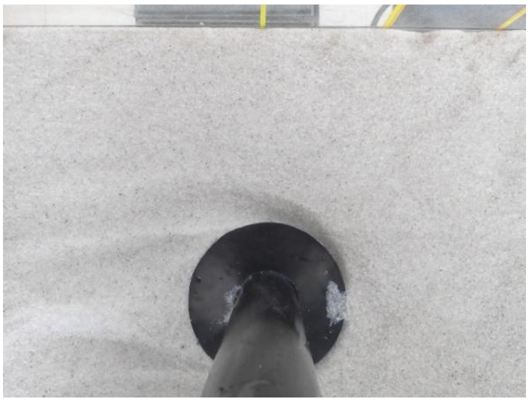
Measurement

Test no.	Test I.D	Cross-threaded	Collar	Cable Diameter, b (mm)	Pier Diameter, D (mm	Thread Angle, θ (°)	b/D	Flowrate (m3/h)	Water depth, h (cm)	Measured Upstream Velocity, v (cm/s)	Measured Max. Scour depth, $y_{1,d}$ (cm)	Reduction Ratio, y1,c/y1,u	Efficiency, 1-(y1,s/y1,u) x 100%
1	D1	no	yes	0	30	0	0	30.99	19.3	15.3	1.1	0.39	60.71

Scour Bed Profile

D1 (collar only)			
Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)
15	2.5	10	0
17	4.5	10	0
17.9	5.4	10	0
7	-5.5	9.6	-0.4
5	-7.5	10	0
3	-9.5	10.2	0.2
1	-11.5	10.7	0.7
-1	-13.5	10.9	0.9

Scour Pattern: D1 (collar only)



Experimental Result: Series E

Measurement

Test no.	Test I.D	Cross-threaded	Collar	Cable Diameter, b (mm)	Pier Diameter, D (mm	Thread Angle, θ (°)	b/D	Flowrate (m3/h)	Water depth, h (cm)	Measured Upstream Velocity, v (cm/s)	Measured Scour Width, W (cm)	Measured Max. Scour depth, $y_{1,d}$ (cm)	Reduction Ratio, y1,sc/y1,u	Efficiency, 1-(y1,s/y1,u) x 100%
1	E1	Single	yes	2	30	15	0.067	32.59	19.3	18	13	1.1	0.39	60.71
2	E2	Single	yes	2	30	30	0.067	33.94	19.3	18.3	13.1	1.1	0.39	60.71
3	E3	Single	yes	3	30	15	0.100	33.2	19.2	18.3	13.5	0.8	0.29	71.43
4	E4	Single	yes	3	30	30	0.100	34.76	19.2	18	14.2	0.6	0.21	78.57

Scour Bed Profile

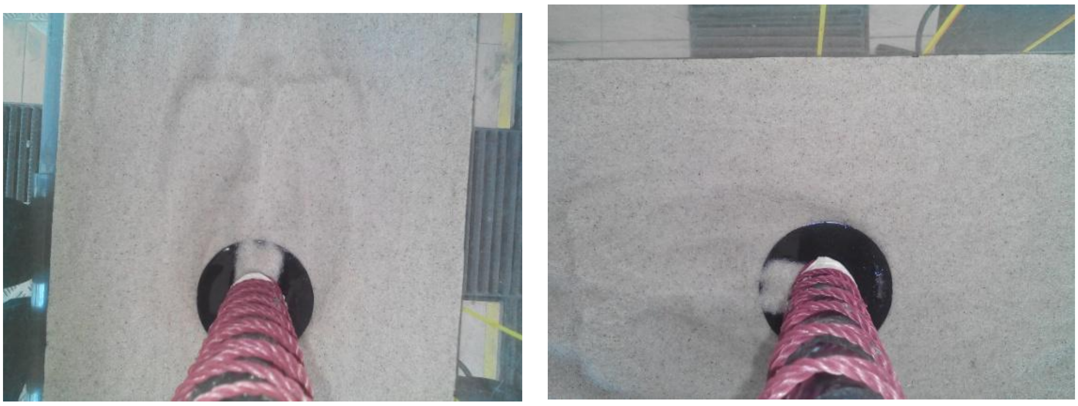
E1 (b/D = 0.067, θ = 15° with collar)				E2 (b/D = 0.067, θ = 30° with collar)			
Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)
15	2	10	0	14.5	1.5	0	-10
17	4	10	0	15	2	0	-10
18.4	5.4	10	0	8	-5	10	0
7.5	-5.5	9.8	-0.2	7	-6	9.9	-0.1
5	-8	10.1	0.1	5	-8	10.1	0.1
3	-10	10.6	0.6	3	-10	10.6	0.6
1	-12	10.9	0.9	1	-12	10.9	0.9
-1	-14	10.5	0.5	-1	-14	10.8	0.8
-3	-16	10	0	-3	-16	10.1	0.1

E3 (b/D = 0.1, θ = 15° with collar)				E4 (b/D = 0.1, θ = 30°with collar)			
Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)
15	2.5	10	0	15	2.5	10	0
17	4.5	10	0	17	4.5	10	0
7	-5.5	9.6	-0.4	17.9	5.4	10	0
5	-7.5	10.1	0.1	7	-5.5	10	0
3	-9.5	10.5	0.5	5	-7.5	10.3	0.3
1	-11.5	10.7	0.7	3	-9.5	10.6	0.6
-1	-13.5	11	1	1	-11.5	11	1
-3	-15.5	10.5	0.5	-1	-13.5	10.6	0.6
-5	-17.5	10	0	-3	-15.5	10	0

Scour Pattern: E1 (b/D = 0.067, θ = 15^{o} with collar)

Scour Pattern: E2 (b/D = 0.067, θ = 30^{o} with collar)

Scour Pattern: E3 (b/D = 0.1, θ = 15^{o} with collar)



Scour Pattern: E4 (b/D = 0.1, θ = 30^{o} with collar)

Experimental Result: Series F

Measurement

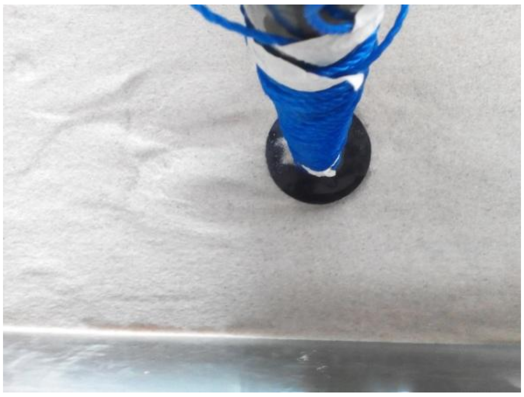
Test no.	Test I.D	Cross-threaded	Collar	Cable Diameter, b (mm)	Pier Diameter, D (mm	Thread Angle, θ (°)	b/D	Flowrate (m3/h)	Water depth, h (cm)	Measured Upstream Velocity, v (cm/s)	Measured Scour Width, W (cm)	Measured Max. Scour depth, $y_{1,d}$ (cm)	Reduction Ratio, y1,sc/y1,u	Efficiency, 1-(y1,s/y1,u) x 100%
1	F1	Double	yes	2	30	15	0.067	29.7	19.1	17.5	14	1.1	0.39	60.71
2	F2	Double	yes	2	30	30	0.067	30.28	19.2	18	14.7	1.1	0.39	60.71
3	F3	Double	yes	3	30	15	0.100	29.62	19.2	17.5	13.7	1	0.36	64.29
4	F4	Double	yes	3	30	30	0.100	30.17	19.3	18		0.9	0.32	67.86

Scour Bed Profile

F1 (b/D = 0.067, θ = 15° with collar)				F2 (b/D = 0.067, θ = 30° with collar)			
Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)
17	6	10	0	15	3.5	10	0
15	4	10	0	12	0.5	10	0
9	-2	10	0	9.5	-2	10.5	0.5
7	-4	9.8	-0.2	7	-4.5	10	0
5	-6	10	0	5	-6.5	10.2	0.2
3	-8	10.2	0.2	3	-8.5	10.5	0.5
1	-10	10.5	0.5	1	-10.5	11	1
-1	-12	10.6	0.6	-1	-12.5	10.8	0.8
-3	-14	10.1	0.1	-3	-14.5	10.6	0.6

F3 (b/D = 0.1, θ = 15° with collar)				F4 (b/D = 0.1, θ = 30°with collar)			
Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)	Length Distance (cm)	L axis (cm)	Depth (cm)	Elevation (cm)
17	4.5	10	0	15	2	10	0
15	2.5	10	0	10.5	-2.5	10.5	0.5
9	-3.5	10.2	0.2	9	-4	10.1	0.1
7	-5.5	10	0	7	-6	10	0
5	-7.5	10.2	0.2	5	-8	10.2	0.2
3	-9.5	10.5	0.5	3	-10	10.6	0.6
1	-11.5	10.6	0.6	1	-12	10.9	0.9
-1	-13.5	10.7	0.7	-1	-14	11	1
-3	-15.5	10	0	-3	-16	11	1

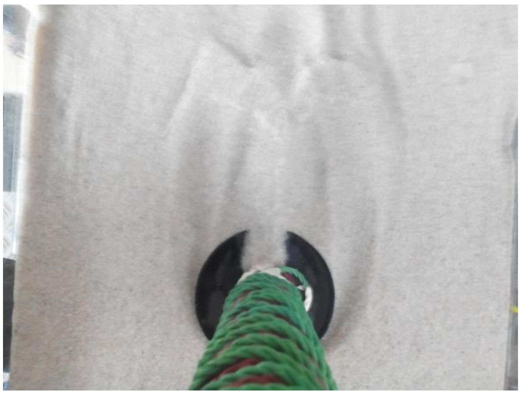
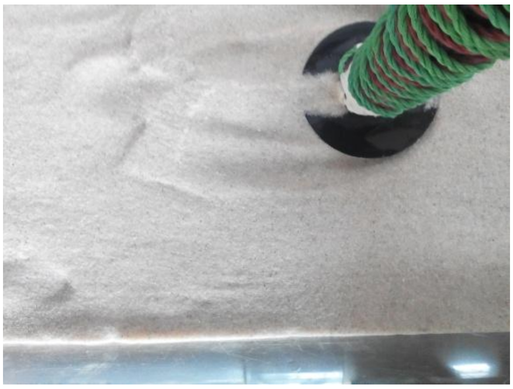
Scour Pattern: F1 (b/D = 0.067, θ = 15° with collar)

Scour Pattern: F2 (b/D = 0.067, θ = 30° with collar)

Scour Pattern: E3 (b/D = 0.1, θ = 15° with collar)

Scour Pattern: E4 (b/D = 0.1, θ = 30° with collar)