EXPERIMENTAL ANALYSIS OF BRIDGE PIER SCOUR PATTERN

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ABSTRACT

Being an important component of a transportation system, bridge piers needs to be properly designed for scouring around its piers. For proper design of bridge piers, appropriate investigation of scouring patterns is extremely important for various sizes and shapes of such piers. Without having research based knowledge of such patterns, it becomes extremely difficult to predict/minimize the scouring effects ultimately leading to severe pier damages. In this research study, experimental investigation is carried out to find the scouring patterns in terms of scour depth and its extent in lateral direction for circular and square pier models. For this purpose a number of experiments were conducted in the physical modeling laboratory of River Engineering and drainage control, USM, Malaysia. The study shows that the pier scour depth and affected area around pier increase with the increase in pier size. The study further demonstrates that the square pier models results in greater scour depth and area as compared to circular pier models. Magnitudes of scour depths and area with reference to variation in shapes and sizes of piers are also presented in this paper, along with contour maps of scour depths, both on upstream and downstream sides.

KEYWORDS: *Pier scour depth, scour hole dimensions, physical modeling, bridge pier, contour maps, median size of bed material and scour pattern.*

INTRODUCTION

Excessive scouring around the bridge piers can be detrimental leading towards early failure of a bridge structure. Scouring around bridge piers is a major cause of failure, and a major contributor in excessive construction and maintenance costs[1]. Increase in construction and maintenance cost is normally due to over designing for increased depths of foundations and excessive lengths of piers, in the absence of research-based scour prediction models. On the contrary, under prediction of pier scour depth can result in early failures of bridges, which may lead to huge financial and human lives losses. Research-based scour prediction models are essential to avoid such losses and detrimental situations[1]. This study deals with square and circular pier models of various sizes, constructed and tested at physical modeling laboratory of River Engineering and drainage control, USM, Malaysia.

A number of parameters contribute towards variation is scouring area and depths including pier sizes and shapes. Piers are essential structural components of bridges; however, their construction across the flow of water creates hurdles and obstruction to the flow. Such obstructions cause removal of bed material around the piers, termed as scouring around the piers[2]. In this paper scouring reflects the scouring around the piers, unless mentioned otherwise.

Modeling of the scouring phenomena is complex in its nature as a number of factors/parameters affect this phenomenon simultaneously. Due to its complex nature, no single method has been developed that covers all the conditions of flow, sediment, river, and pier characteristics universally[3,4]. This is the reason that less number of mathematical models were developed for predicting scour depth that causes certain bridges to collapse, resulting in adverse impacts including financial loss, increased travel time, and, occasionally, in loss of human life.

To overcome the difficulties involved in pure mathematical modelling, field measurements are sometimes considered as an alternative to assess the actual situation. This is, however, a very difficult task and requires a lot of efforts. Experimental analysis appears as a viable option to address such difficulties where pure mathematical modeling has its limitations. The same approach is adopted in this study to predict pier scour patterns for various sizes and shapes of piers.

Local scour mechanism

When the flow of stream is obstructed by the bridge

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pier, water is divided. Some of the water moves to the downstream along the pier sides while remaining water is deflected downward due to the deceleration at the pier face called down flow. The pressure of down flow reaches maximum at the channel bed causing removal of the sediments. These sediments are then transported by the horse shoe vortex (Figure-1) to the downstream of the pier causing scour hole. Wake vortex is also formed at the downstream of the pier but is weaker than horse shoe vortex. The sediments are deposited at the downstream of the pier and maximum scour depth occurs at the upstream face of the pier. The local scour depth at pier depends on numbers of variables including fluid, flow, bed sediment properties and pier geometry. In this study the focus is on the effects of pier size and shape on pier scour pattern.

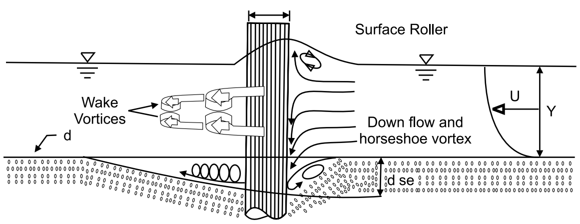


Figure 1: Components of local Scour depth on bridge pier Ettema (1980)[4]

LITERATURE SURVEY

Valuable work to study scour depths around the piers has been executed over the years; however, available studies do not address the objectives set for this study. Review of the important related studies is presented below.

The influence of flow shallowness and relative coarseness on designed pier scour depth[5] was investigated. Similarly the influence of densimetric Froude number and separation velocity on scour depth was also determined. All these results were then compared with the methods already in use and were found closer to existing methods. However, this study was not addressing variation of pier sizes and shapes.

Experimental investigation[6] was carried out to predict the time development of local scour around semi integral bridge piers and piles in Malaysia. Both coarse and fine sediments with five different velocities were used for the experimental investigation. It was concluded that pier scour depth increases with increase in time and discharge but decreases with increasing sediment size. The study focused on time, discharge, and sediment size. Again, this study was not aimed at analyzing effects of variation in pier sizes and shapes.

Experimental investigation[7] was conducted to show the effect of pier inclination, flow intensity and blockage ratio on scour depth around cylindrical pile group. It was concluded that scour hole is the main cause of bridge failure. Similarly, increasing the pier size and flow intensity increases the pier scour depth, scour hole surface area and volume. The bridge pier with 10 degrees inclination are much more affective against scouring as compared to piers inclined at 15 degrees.

The characteristics of scour hole[8] around a vertical pier under clear water scour conditions was discussed. From experiments it was seen that the scour hole characteristics depends mainly on Froude number and flow depth. In this research empirical equations are derived for each geometrical parameter of scour hole. The scour parameters calculated from these equations were then compared with the experimental results and were found very close.

A new methodology[9] was proposed for equilibrium pier scour depth analysis and validated it by clear water scour data. This methodology determines the flow condition for given equilibrium pier scour depth. The hypothesis used for the development of this methodology was that the scour hole shape is related to the scour depth. The results obtained using this new methodology was checked with other procedure and was found adequate.

Commonly used pier scour depth measuring formulae[10] were validated using field as well as laboratory data. On the basis of results obtained, it was concluded that[11] predicted pier scour depth reasonably well while the other two formulae presented in[12] and[13] over-predict pier scour depth.

Number of experiments[14] were conducted in a large flume at the USGS research center to study the influence of wash load on pier scour depth. Experiments were conducted using circular pier of three different pier sizes, three different types of cohesion less sediment diameters and a range of flow properties. The results showed that besides other parameters, the equilibrium scour depth also depends on wash load.

Number of experiment were conducted in the hydraulic laboratory at University of Okayama in Japan[15] using circular pier of 0.06m size installed in sediments of d_{50} equal to 1.28mm. On the basis of experimental analysis, a design method for the prediction of time dependent pier scour depth under clear water scour conditions was devised. It was also concluded that equilibrium scour depth is reached when bed shear stress approaches critical shear stress.

The influence of cohesion[16] on scour around circular bridge piers was studied and concluded that, the cohesion affect the geometry, location and extent of the scour hole around bridge piers. This conclusion was made on the basis of the experimental analysis carried out by the author. On the basis of this conclusion a procedure was developed for computing the temporal variation of bridge scour in cohesive soils. It uses the horseshoe vortex characteristics for computing scour around bridge scour.

Experimental analysis was carried out[17] under clear water scour conditions to show the temporal variation of pier scour depth. The experimental results showed that the scour depth increased asymptotically with the increase in time. The results were also used to show the variation of pier scour depth with non-dimensional input independent variables including flow intensity, sediment coarseness ration and flow shallowness. Scour increases linearly with the flow intensity under clear water conditions and reaches maximum at flow intensity equal to one. With the increase in value of flow intensity beyond one, scour decreases for some time before it starts increasing again to reach the second peak point. The second peak is normally smaller than the first peak until the sediments are uniform. This trend has been validated by the laboratory data collected by[4,11,13,18,19] and[20].

A set of experiments[21] was conducted on circular and square pier models to show the temporal variation of pier scour depth installed in uniform bed. Scour prediction curves were also prepared in terms of different flow and sediment parameters. Contours for scour hole around only the cylindrical pier were plotted. Ansari,[4] conducted large number of experiments to explain the influence of coarser sediments on pier scour depth. It was reported that "the scour process changed abruptly with the variation of sediment gradation in case of clear water scour". This argument was defended by giving the following two reasons. 1) The coarser material filled the grooves at the surface of the scour hole which are the targets of the down flow thus cause to cease the scouring process, 2) Extra energy of down flow is dissipated in the gaps between the coarser sediments thus causing reduction in the pier scour depth.

Similarly empirical relations[11,22,23] were developed on the basis of their experimental analysis.

[20]Worked on the temporal variation of pier scour depth. It was the most comprehensive work. It showed that scour depth increases with the time.

The above literature reveals the importance of experimental analysis for the pier scour depth analysis. Keeping in view the importance of scour depth analysis experimentally, experimental analysis is carried in Malaysia. This research paper presents the results obtained from this experimental analysis. These experiments were carried out to investigate the pier scour depth and its distribution pattern around the pier. Similarly, the effect of pier size and shape on scour pattern is also investigated. The scour pattern is presented in the form of contour maps which will help in finding the extent of remedial measures required for scour reduction.

MATERIAL AND METHODS

All the experiments were conducted in horizontal rectangular open channel of length 6.0 meters, width 0.6 meter, and depth 0.63 meters. Water was supplied to the channel from a constant head circular tank through a 350 mm diameter pipe. The bottom of the channel is made up of steel while sides are of glass as shown in Figure-2. Water to the constant head circular tanks is supplied from the underground water tank located in the laboratory through two centrifugal pumps. The water supplied to the channel is recirculated. A gate is installed at the start for supply of desired quantity of water while a tail gate at the downstream end for controlling depth of water. The pier models are installed in the test section which is filled with sediments of 0.54mm size.

The test section for the installation of the pier model is started from point where the flow is fully developed located at 3.5 m from channel bed identified through Streamflo422 velocity meter (Figure-3a). The test section is constructed by raising parts of the channel upstream and downstream of it with the help of wooden blocks covered with glass or plywood. It is 1.5 meters long, 0.6 meter wide and 0.25 meters deep was filled with sediments of median grain size d_{50}=0.54 mm and standard deviation σ of 1.28. These properties of sediments were obtained from the sieve analysis of the sample.

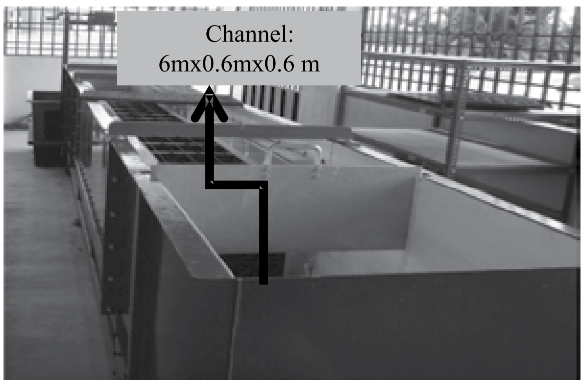


Figure 2: Rectangular Open Channel in Physical Modeling Laboratory of REDAC, USM Malaysia

At the starting section of 0.5 m length honeycombs are placed to dissipate energy of flowing water for development of uniform flow in the channel. A sharp crested triangular weir (Figure-3b) is installed at the downstream end of the channel to trap the sediments that are coming out of the test section and avoid its re-circulation. The flow depth in the channel as well as the scour depth measurements were made through point gauge installed over the channel (Figure-4). The actual discharge is measured by filling the container of known volume and the time required for its filling. The velocity in the channel is measured using an instrument called streamflo422 velocity meter.

The velocities are measured at three horizontal sections i.e. at the middle and at a distance of 10cm from each side wall. Vertically the velocity is measured at 0.2y, 0.6y and 0.8y where "y" is depth of water in the channel.

Bridge Pier Models

Three different shapes (circular, square and sharp

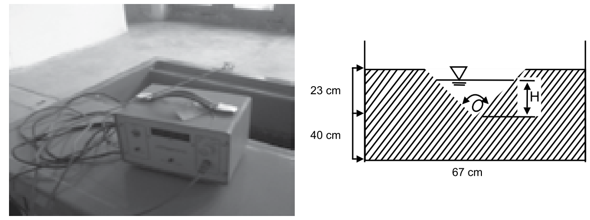


Figure 3: a). Streamflo422 velocity meter, b) Sharp Crested Weir

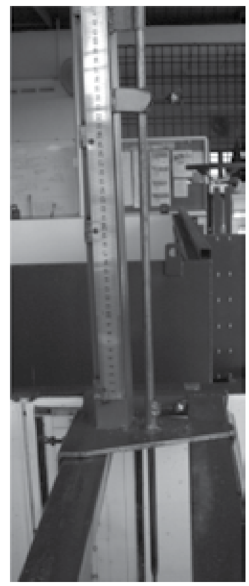


Figure 4: Vertical Point Gauge

edged) and sizes (5cm, 4cm and 3cm) of pier models are used in this study as listed in Table-1 and are shown in Figure-5. The range of all the variables used in the experimental analysis is shown in Table-2.

The objective is to compare the scour pattern for various sizes and shapes of pier models. In total, nine experiments were conducted.

OBJECTIVES OF THE RESEARCH

The main objectives of this research work are:

- To investigate the effect of pier size and shape on the pier scour depth
- To draw contour maps for the area affected by scouring around the bridge pier.

Experimental Procedure

The experiments were conducted in an open channel shown in Figure-2. In order to remove the air voids from the sediments, water is allowed to stay over the test section for about an hour. The pier models of different sizes and shapes are installed in the test section one by one for each experiment. Each pier model is installed at a distance of 0.5 meter from the upstream edge of the test section and equidistant from the channel sides. The pier was supported with the help of a wooden plank from the top. After pier installation, the test section is properly compacted and the surface is made smooth and uniform as shown in Figure-6.

Table 1: Different pier models used in experiments

Experiment-No	1	2	3	4	5	6	7	8	9
Pier Shape	Circular			Square			Sharped edged		
Pier Size (m)	0.03	0.04	0.05	0.03	0.04	0.05	0.03	0.04	0.05

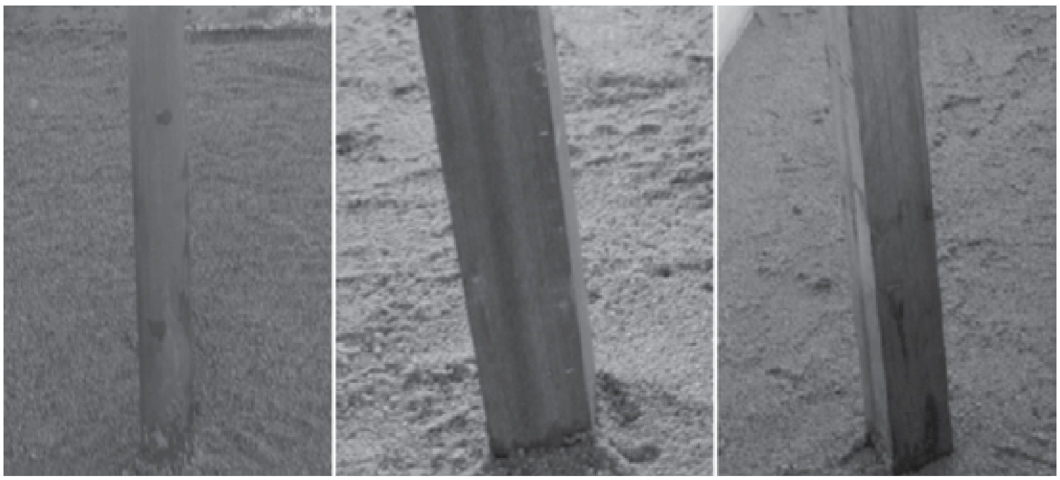


Figure 5: Three pier models used in this study (1. Circular 2. Square 3. Sharp edged)

Table 2: Range of independent variables and results obtained from the Experimental analysis for scour pattern investigation

Variables	Maximum (m)	Median (m)	Minimum (m)
b (m)	0.050	0.030	0.030
Y(m)	0.104	0.030	0.010
V(m/s)	0.433	0.176	0.048
d50 (m)	0.00055	0.00035	0.00035
ds (m)	0.080	0.039	0.021
Length (m)	0.2750	0.1100	0.0510
Width (m)	0.2300	0.1000	0.0420

After preparing the bed at the test section, the water is allowed to flow in the channel. The flow depth is adjusted by using the tailgate. All the experiments were conducted under clear water conditions for maximum scour depth. The approach flow velocity is calculated by using streamflo422 while the critical velocity is calculated by using equation[23] for flow intensity calculations. The flow depth is measured by point gauge while the discharge is measured by using the procedure mentioned above.

Since the objective of this experimental study is to investigate the variation of pier scour depth and its pattern with pier size and shape, therefore all the other

Figure 6: Flat, uniform and compacted test section before start of the experiment

parameters were kept constant (discharge of 12.8 liters per second, time sixteen (16) hours and flow depth 8.2 cm). The time is decided on the basis of equation[17] developed for the calculation of time to reach equilibrium. After the completion of each experiment, the water is allowed to drain out of the channel and different readings are taken. The maximum scour depth upstream, downstream and on both sides of the pier are measured. Similarly, the scour hole dimensions (Length and width) are also measured. Similarly, data is also collected for the development of contour maps. This data include three dimensions for each point including measurements along the length and width of channel and scour depth. All these dimensions are taken with respect to some common reference point i.e. the extreme upstream point of scour hole. The lateral distances are measured with respect to right side wall of the channel while the scour depth is measured from the initial flat-bed level at the start of each experiment. After measuring and recording all the required data, the pier model is replaced and the surface is leveled before the start of the next experiment. The same procedure is repeated for all nine experiments.

RESULTS AND DISCUSSIONS

Experimental investigation of scour pattern is carried out in this study. In all the experiments it is observed that the scouring started immediately after the start of flow. It is also observed that the scouring process started at the upstream of the pier propagating downstream along the pier sides resulting in formation of scour hole at upstream and deposition of the sediments on the pier downstream. Initially the rate of sediments removal is high but with the passage of time, it goes on decreasing until it reaches equilibrium. The scour hole developed for all the three shapes of pier models are shown in Figure 7.

All the results obtained from the experimental analysis are shown in Table-3.

DISCUSSION ON RESULTS

The results obtained from the experimental investigation and presented in Table-3 above are used for analysis and extracting different conclusions. The effect

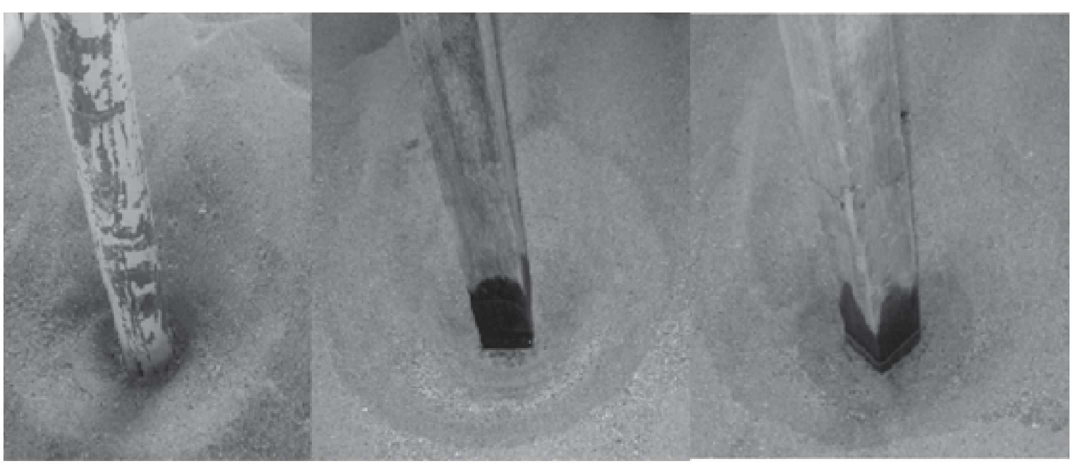


Figure 7: Resultant Scour hole shapes for three different types of pier models used in the experiments

Table 3: Summary of Results obtained from the experimental investigation

Exp. No	Y (m)	V (m/s)	Pier shape	b (cm)	d50 (mm)	Scour depth ds (cm)	Length L (cm)	Width W (cm)	Time (hours)
1	0.082	0.264	Circular	5.0	0.54	7.0	22.5	22.5	16
2	0.082	0.264	Circular	4.0	0.54	5.9	19	19	16
3	0.082	0.264	Circular	3.0	0.54	4.8	17	17	16
4	0.082	0.264	Square	5.0	0.54	8.5	28	28	16
5	0.082	0.264	Square	4.0	0.54	7	23.5	23.5	16
6	0.082	0.264	Square	3.0	0.54	5.7	19.7	18.7	16
7	0.082	0.264	Sharp Edged*	5.0	0.54	8.3	25.3	25.9	16
8	0.082	0.264	Sharp Edged*	4.0	0.54	6.4	21.5	21.8	16
9	0.082	0.264	Sharp Edged*	3.0	0.54	5.0	18.3	18.7	16

*sharp edged mean square pier with the sharp edge facing flow

of pier shape and size on the pier scour pattern including scour depth and scour hole dimensions is investigated and presented below.

Variation of scour depth with Pier Size and Shape

To investigate the variation of scour depth with pier sizes and shapes, plots are drawn by keeping all other variables constant as shown in Figure 8. It shows three different curves drawn one each for circular, square and sharp edged pier models. Figure-8 shows that pier scour depth increase with the increase in pier size for all pier shapes. It is also concluded that for the same pier size, and flow and sediment properties, square pier model resulted in higher pier scour depth as compared to the other pier shapes followed by the sharp edged pier.

Variation of scour hole dimensions with Pier Size and Shape

Experimental analysis also investigated the variation of scour hole dimensions with pier size and shape. Figures- 9 & 10 below shows the variation of length and width of scour hole with pier size and shape respectively. These Figures show that with the increase in pier size, the length as well as width of scour hole increases. Similarly, under the same conditions of flow and sediment properties, both length and width of scour hole for square pier model is maximum followed by the sharp edged pier model while the circular pier model

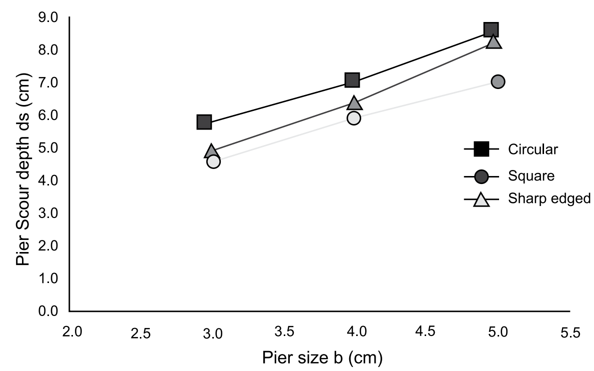


Figure 8: Pier scour depth variation with pier shape and pier size

gave minimum values for both.

Contour map for pier scour around pier models

To investigate the scour pattern around the pier after the scouring takes place, contour maps are drawn from the results obtained from the experiments. The contour maps drawn for 4cm and 5 cm size of all pier models are shown and discussed below. These contour maps are drawn for the area affected by scouring around pier including upstream and downstream and sides of pier. Figure-11 shows the contour maps drawn for pier models of different shapes and 4cm size, while Figure-12 shows the contour maps for the same pier models but size of 5cm. In both the figures Part-A represents contour map for circular pier model, Part-B represents contour map

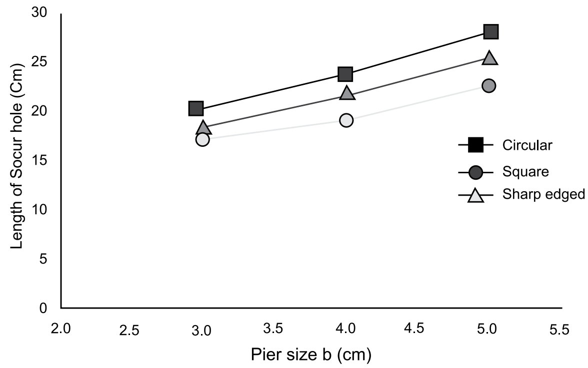


Figure 9: Variation of Length of Scour Hole with variation in Pier size and Shape

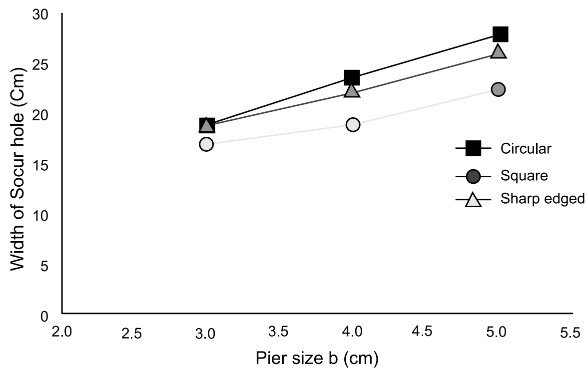


Figure 10: Variation of Width of Scour Hole with variation in Pier size and Shape

for square pier model and Part-C for sharp edged pier model. From the literature review, it was observed that contour maps are drawn for circular pier only and that was also for the scour hole region only but in this study, the contour maps are drawn for the first time for all three types of pier models for scour hole as well as the area affected upstream, and downstream sediment deposition thus investigating all the area around pier affected by scouring process.

These contour maps will also help to reflect the effect of pier size and shape on the shape and orientation of the scour hole. From these contour maps, the following observations and findings can be extracted.

- The contour lines for circular pier models are almost circular in shape while for the other two models, scour holes are elongated along the width of channel because of its sharp edges which causes more disturbances and hence more scour along the sides of the pier model. But for the downstream sediment deposition region, all the models follow the same pattern that is elongated along the channel length,

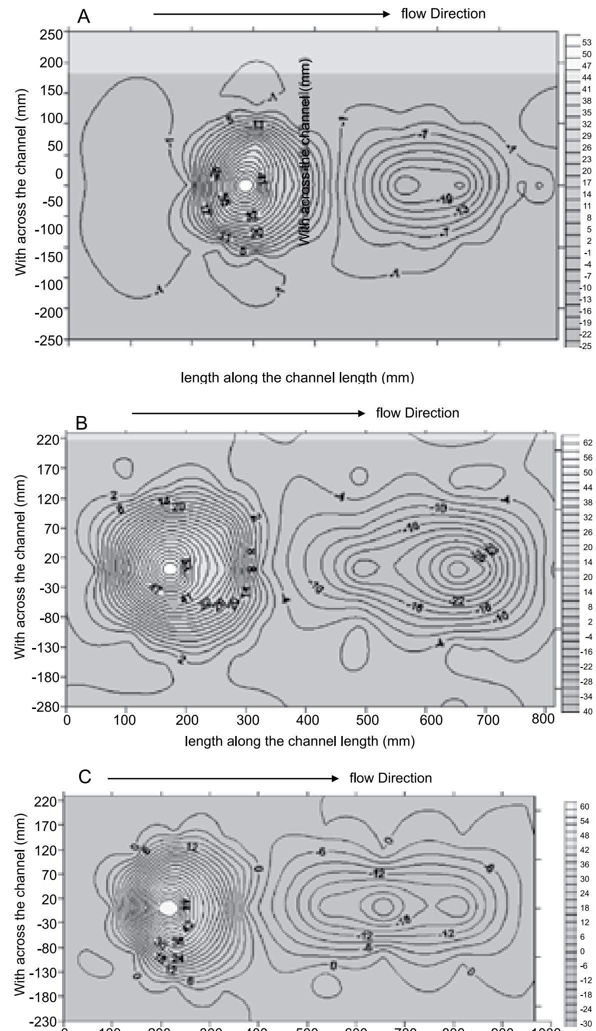
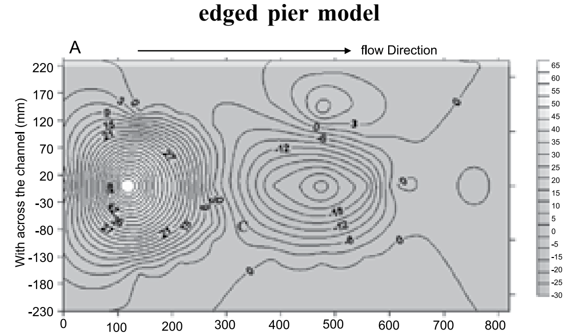


Figure 11: Contour maps for the experimental data collected in Malaysia for 4cm pier model where (A) Circular pier model, B) Square pier model, C) Sharp edged pier model



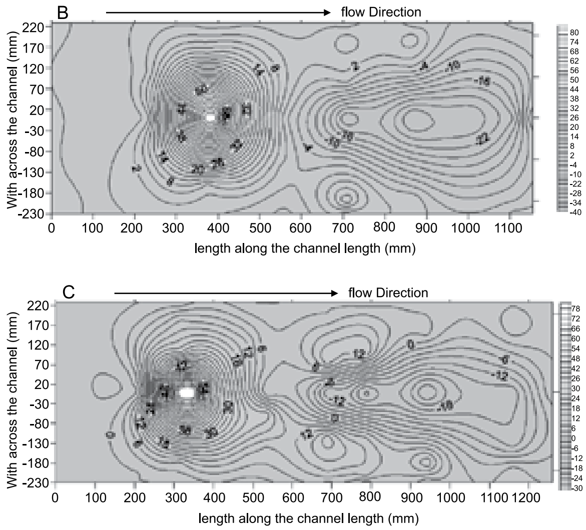


Figure 12: Contour maps for the experimental data collected in Malaysia for 5cm pier model where (A) Circular pier model, B) Square pier model, C) Sharp edged pier mode.

- The contour lines for the square pier models were closer to each other as compared to the other two followed by the sharp edged pier and then by the circular pier showing deeper scouring for the earlier.

- From figures 11 and 12, it is clear that there forms a ridge at the downstream end of the pier resulting from the transport of sediment by flow of water. The height of this ridge is greater for square pier model followed by sharped edge and then circular.

- It is clear from the contour maps for different pier shapes that the contour maps for the sharped edge pier model are very much irregular as compared to the other two models because of the extra disturbance caused by the sharped edges.

- Contour maps shown in figures 11 &12 strengthen the argument that the scour depth is greater for square pier model as compared to the other two but the total area affected in both cases is much greater for Sharped edge pier model followed by square pier model and then circular.

CONCLUSIONS

In this study, the experimental analysis is carried out in Malaysia to check not only the variation of scour pattern around the bridge pier with the variation in pier size and shape but also the area affected by the scouring process. Nine numbers of experiments were conducted three each for circular, square and sharp edged pier models. On the basis of the results obtained from the experimental analysis the following conclusions can be made

Under the same condition of flow, sediments and pier geometry, square pier models resulted in maximum pier scour depth and larger scour holes as compared to the other models. Similarly, greater size pier resulted in more pier scour depth and larger scour holes validating the work done by the earlier researchers.

The contour maps for scour hole and the area around it were drawn for the first time, giving a clear picture of the extent of remedial measures required for the scour depth prevention. Previously it was drawn only for circular pier covering only the scour hole portion ignoring the area around it.

From the contour maps, it was concluded that not only the pier scour depth but the scour hole dimensions for square pier models is very large as compared to the circular model, thus seriously threatening the stability of bridges but the overall area affected by the sharp edged pier model is much more greater as compared to the other two models.

The sediment deposited on downstream of the pier model was investigated for the first time because it also plays a very important role specially in case there is another pier located just at its downstream.

Thus on the basis of this research it is concluded that among the three pier shapes presented here, the circular pier is the most suitable pier shape for use in bridges construction while the other two pier models required a lot of scour prevention measure for its safety.

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