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Effects of Bridge Pier Position in a 180 Degree Flume Bend on Scour Hole Depth

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Abstract: Local scouring around the bridge pier occurs because of flow separation and developing several vortexes around the bridge pier. Such scour hole can cause failure of the bridge especially during the river floods. Because of this several researches, have been conducted during the past three decades in straight flumes. For the case when the bridge piers located in river bend, little information is available. In this study, a series of experimental tests have been conducted in a 180 degree laboratory flume bend with a relative curvature of bend of 4.67. One oblong model pier of width 60 mm and length 180 mm was used for the study in seven different positions of 0, 30, 60, 90, 120, 150 and 180 degree under three different flow conditions were tested. Natural sand with uniform graining of d50 = 2 mm and uniformity factor of 1.7 were used as bed materials. The results of the model study indicated that the maximum depth of scour is highly dependent on the experimental duration. The depth of the scour hole increases as with increasing duration of flow. The extent of scour observed at the pier also increases as the duration of the tests increases. The results of this study showed that, while oblong pier is placed in the bend, the maximum scouring depth is occurs in position of 60 degrees. Also, it was observed that in all positions, increasing the Froude number increases the scouring depth. Measuring depth of scouring based on experimental observation, an empirical relation is developed with high regression coefficient 94%.

Key words: Bridge pier, scour depth, froude number, 180 degree bend, vortex

INTRODUCTION

It has long been established that the basic mechanism causing local scour at bridge piers is the down-flow at the upstream face of the pier and formation of vortices at the base (Muzzammil *et al*., 2004). The flow decelerates as it approaches the pier coming to rest at the face of the pier. The approach flow velocity, therefore, at the stagnation point on the upstream side of the pier is reduced to zero, which results in a pressure increase at the pier face. The associated stagnation pressures are highest near the surface, where the deceleration is greatest and decrease downwards (Melville and Raudkivi, 1977). Figure 1 shows the flow and scour pattern at a circular pier. As shown in this Fig. 1, the strong vortex motion caused by the existence of the pier entrains bed sediments within the vicinity of the pier base (Lauchlan and Melville, 2001). The downflow rolls up as it continues to create a hole and through interaction with the oncoming flow, develops into a complex vortex system. The vortex then extends downstream along the sides of the pier. This vortex is often referred to as horseshoe vortex because of its great similarity to a horseshoe (Breusers *et al*., 1977).

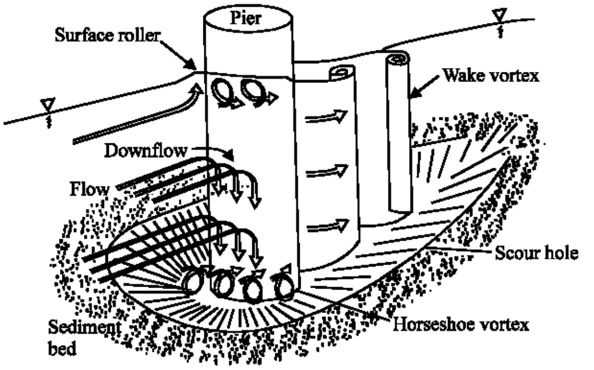

Fig. 1: Illustration of the flow and scour pattern at a circular pier

Thus, the horseshoe vortex developed as a result of separation of flow at the upstream face of the scour hole excavated by the down-flow. The horseshoe vortex itself is a lee eddy similar to the eddy or ground roller downstream of a dune crest (Breusers and Raudkivi, 1991). The horseshow vortex is very effective at transporting the dislodged particles away past the pier.

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Table 1: Some equilibrium scour depth prediction equations

Investigator(s)	Equation	Source
Breusers *et al*. (1977) Based on Laursen and Toch (1956)	$y_{se} = 1.35\ K_i b^{0.7} y_0^{0.3}$. where, y_{se} = Equilibrium scour depth, $K_i = 1.0$ for circular pier, b = pier width, y_0 = Flow depth	Hoffmans and Verheij (1997)
Colorado State University (CSU)	$y_{se} = 2.0 K_i\, y_0 F_r^{0.43} \left(\dfrac{b}{y_0}\right)^{0.65}$	Hoffmans and Verheij (1997)
	where, K_i = For a circular pier with clear-water scour, F_r = Froude No.	HEC-18
Shen and Schneider (1969)	$y_{se} = 0.000223 R_b^{0.619}$. where, R_b = Pier Reynolds No.	Dey (1997)

The horseshoe vortex is as a result of scour but is not the cause of scour (Breusers and Raudkivi, 1991). As the scour depth increases, the horseshoe vortex strength diminishes, which automatically leads to a reduction in the sediment transport rate from the base of the pier (Lagasse and Richardson, 2001).

Numerous experimental and numerical studies have been carried out by researchers in an attempt to quantify the equilibrium depth of scour in various types of soil material. Moreover, while a lot of work has been done to develop equations for predicting the depth of scour, researchers have also worked extensively to understand the mechanism of scour.

Estimation of the depth of scour in the vicinity of bridge piers has been the main concern of engineers for years. Therefore, knowledge of the anticipated maximum depth of scour for a given discharge is a significant criterion for the proper design of a bridge pier foundation. In current practice, the design scour depth is chosen to be the maximum equilibrium scour depth achieved for steady flow under the design flow conditions (Gosselin and Sheppard, 1995). A number of studies have been performed with a view to determining the equilibrium scour depth for clear-water scour conditions (Raudkivi and Ettema, 1983). In these studies, the maximum scour depth under steady flow conditions is related to the hydrodynamic and sediment parameters, pier shape and flow intensity. Empirical equations based on the results of such studies are used in the design of bridge pier by way of computing the expected maximum scour depth for a particular flow condition.

Some of the most common equilibrium scour depth predicting equations are shown in Table 1. For a river system, the use of equilibrium scour depths is reasonable since, in many cases, even though the flow is unsteady during storm events, high velocities can persist for long periods of time (Gosselin and Sheppard, 1995). The idea of bed protection and prevention of scour at a pier has attracted a good deal of attention. Reduction of scour depth would mean shallower foundations and reduced cost (Breusers and Raudkivi, 1991).

Majority of researches on scour at spur dike are conducted at a straight flume. In such a case the flow patterns which are mostly the cause of scour would not be the same as the case of straight canal. Therefore, it is the principal objective of this study was to carry out experimental tests on the effect of oblong pier on scour depth at in different positions in a 180 degree river bend. The study reported herein, is based on experiments carried out in the Hydraulic Laboratory at the Islamic Azad University in Ahwaz using a model 180 degree flume bend. The study was confined to uniform cohesionless material and clear-water flow conditions.

MATERIALS AND METHODS

Experimental apparatus: This experiment was conducted in a laboratory flume at Hydraulic Laboratory of Islamic Azad University of Ahwaz. The study was conducted using in a 180 degree laboratory flume bend with a relative radius (Rc/b) was 4.7. The bottom of the flume is made up of an aluminum bottom and plexiglass sidewalls along one side for most of its length to facilitate visual observations. At the end of this flume a control gate was designed to adjust the water surface height at the desired levels (Fig. 2). The study conducted at Hydraulic Laboratory of Islamic Azad University of Ahwaz during September 2007 to September 2008.

In this study, the size of pier was defined to meet the criteria which have been defined by other investigators. Pier diameter should not be more than 10% of flume width to avoid wall effect on scouring (Chiew and Melville, 1987). Melville and Sutherland (1988) defined L/B (L = length of pier and B = width of pier) should not be more than 1/3. So, one oblong model pier of width 60 mm and length 180 mm were used for the study (Fig. 3).

The effects of the grain size and the density of the sediment material are often expressed as a function of the critical flow velocity for the initiation of sediment motion. It was concluded by Breusers and Raudkivi (1991) that ripples usually developed at shear velocities u_* above $0.6\, u_{*c}$ for sediment of size, d50 < 0.7 mm. In this work, the bed sediment consisted of uniform sand, with median diameter d50 = 2 mm and geometric standard deviation $\sigma g = 1.7$.

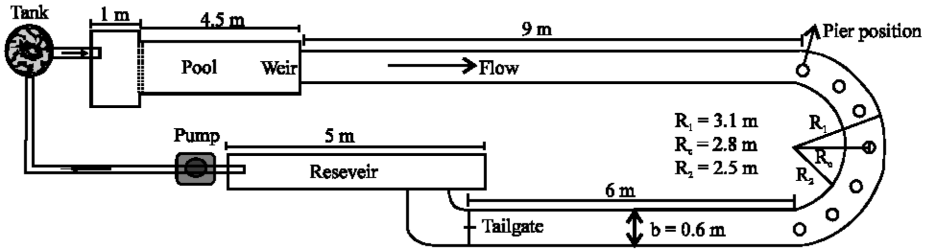

Fig. 2: Schematic illustration of the experimental setup (plan)

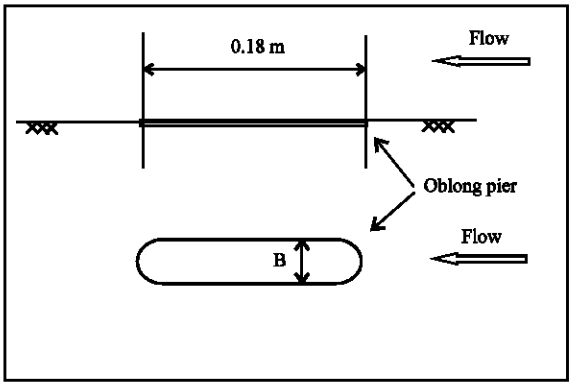

Fig. 3: Schematic illustration of oblong pier

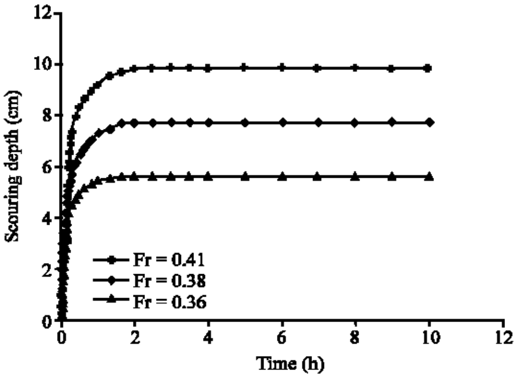

Fig. 4: Equilibrium time in the position of 60 degree

In this study, the experiments were performed under clear-water conditions at three different flow intensities (u_*/u_{*c}) of 0.70, 0.80 and 0.89 (u_* is approach velocity and u_{*c} is critical velocity for sediment movement), corresponding to a shear stress levels of 49, 67 and 80% of the critical shear stress level based on shields stress, respectively. Three different Froude numbers of 0.36, 0.38 and 0.41 were applied in order to investigate the effect of flow conditions on the scouring. All the experimental tests were conducted under the same flow depth. The pier positions were at 0, 30, 60, 90, 120, 150 and 180 degree. A 60 degree triangular weir was used at the upstream section of the flume for flow measuring.

Initially the bed surface was leveled by a plate attached to the carriage mounted on the channel. Then, inlet valve was opened slowly, the discharge increased to a predetermined value so that no scour occurs at the straight reaches of flume. At the end of the experiments, the topography of bed was measured at grids of 2×2 cm around pier oblond nose and at grids of 2×14 cm in the other sections.

Duration of scour test: In this study, to obtain equilibrium time of the experiments, a long time experiment was conducted at Froude number of 0.36, 0.38 and 0.41 and the position of 60 degree. Considering the curves of Fig. 4, approximately 95% of scouring occurs during the first 3 h. Therefore in all our experiments, equilibrium time of 3 h was selected for each test (Fig. 4).

RESULTS AND DISCUSSION

In all experiments, after adjusting the water depth and flow discharge, immediately eddy flows around the piers formed and scouring began with the high rate at upstream. Arisen sediments from scouring cavity, moved toward down stream and after while they reach to the region where the pier effect diminished and the eddy flow effect cannot feel more. Under these conditions, due to the secondary effects transported sediments from scouring cavity moves toward the inner wall and two or more small dune formed near the inner wall. Figure 5a and b show also in this region depends on hydraulic conditions, deposition occurs near the external wall with minimum scouring.

Because of the flow deviation due to cylindrical pier, water hole formed in upstream which observed in all experiments, but its size vary depends on different pier positions. Some times in downstream this water hole collide with inner wall and cause scouring near the wall bend. If no colliding happens no scouring occurs but sediments deposit. Clearly affecting parameters on water hole size are cylindrical pier position in the bend and the flow rate.

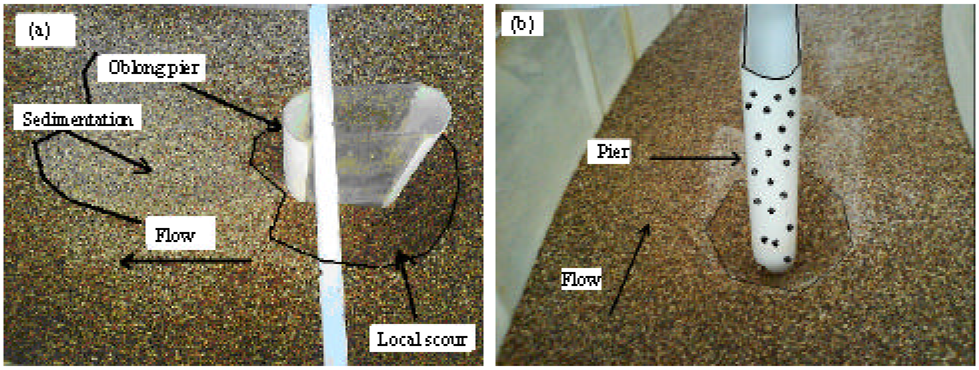

Fig. 5: Scour hole: (a) sedimentation at the downstream and (b) erosion at a location far upstream of the pier

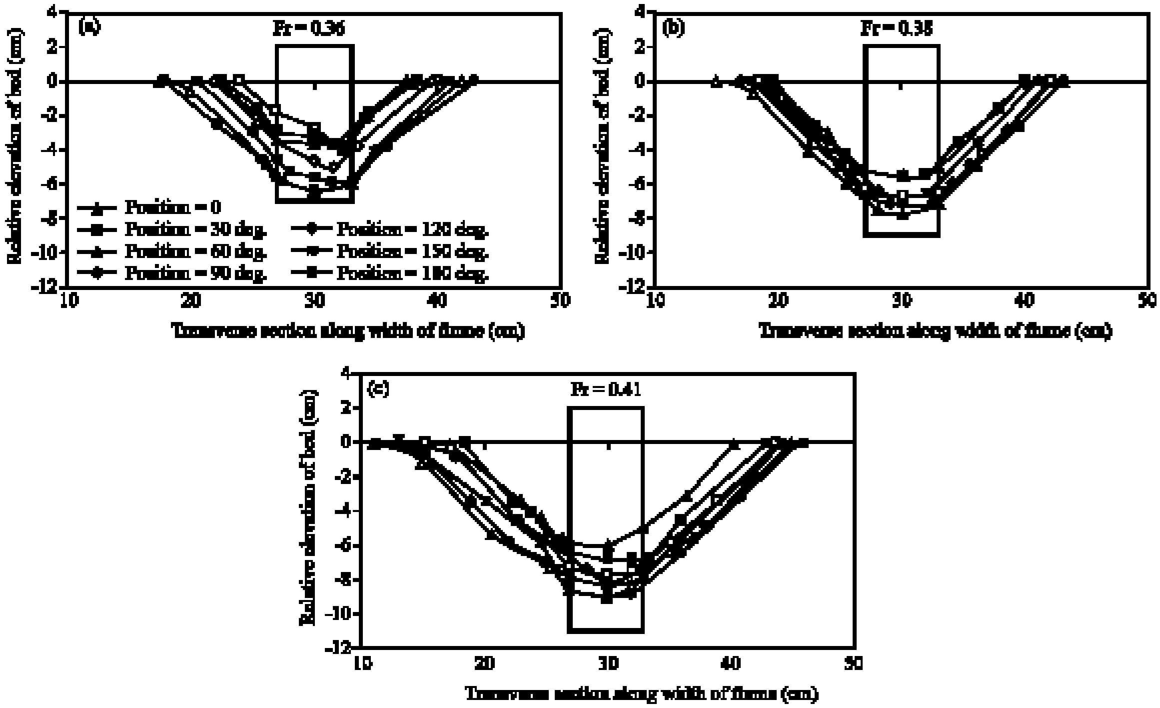

Fig. 6: (a-c) Transverse section of scour profile across the plain pier centre in different positions and for three different flow conditions

Transverse scour profile in different positions for a plain pier: Figure 6a-c show the lateral profile of the scour hole through the centerline of the pier in the positions of 0, 30, 60, 90, 120, 150 and 180 degree for different Froude number conditions. The (0, 0) reference point is at the original bed level at the centerline of the pier. As shown in Fig. 5, the scour profile is symmetrical about the pier. For instance, it is shown that the scour hole extended to a distance of either side of the pier.

To see the effects of different pier position in scour depth, (Fig. 7) was plotted. In this Fig. 8 the maximum measured scour depth has been plotted at different position. As, it can be seen the maximum scour depth at the beginning of bend is lowest and then increases to reach its maximum value at 60 degree position. From this position the scour depth is decreases up to end of bend (180 degree position) which reaches at the same scour depth as it was at the beginning of bend (0 degree position). Experimental results of Melville and Coleman (2000), about flow pattern in 180 degree bend show that the maximum velocity distribution occurs in the angle 60 degrees due to the high power of secondary flow and consequently causes maximum scouring depth in this position.

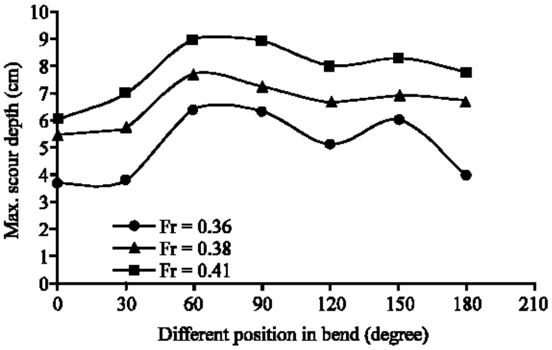

Fig. 7: Maximum scouring depth in different Froude number and positions

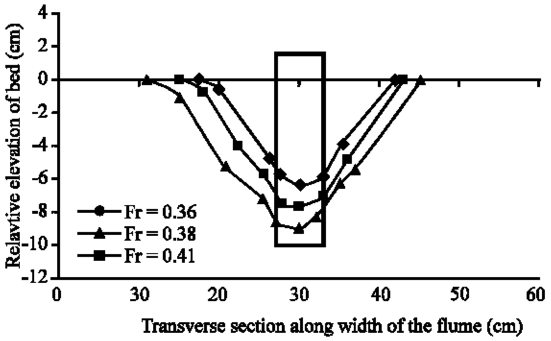

Fig. 8: Transverse section of scour profile across the plain pier centre in different Froude number

The effect of froude number at maximum scour: Figure 8 show, longitudinal and transversal profiles of oblong bridge pier in the position 60 degree with maximum scouring for three different Froude numbers of 0.36, 0.38 and 0.41. Considering Fig. 8 can conclude that overall bed topographical schema is approximately as the same as each other for three froude number but size and depth of the scouring cavity decrease by decreasing the froude number. Also, the sediment pile length in downstream of oblong bridge pier increases rapidly by increasing Froude number due to high power of arising vortex. Furthermore transversal profile shows that there is a direct relation between scouring depth and Froude number which of course is in agreement with previous studies (Melville and Coleman, 2000).

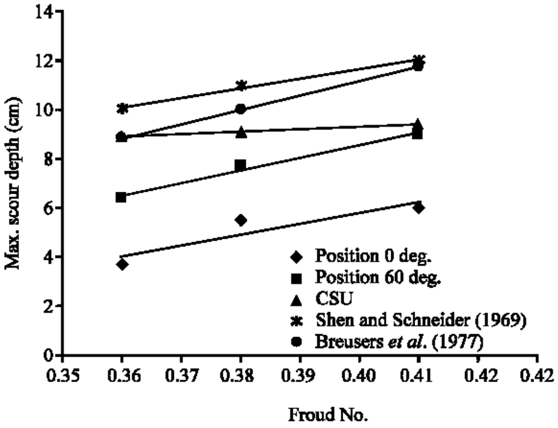

Fig. 9: The comparison of regression analysis of the present study data with Shen and Schneider, (1969) and Breusers *et al.* (1977) and Colorado State University (CSU)

Table 2: Measured maximum scour depth in mm

	Position of pier in 180 degree bend						
Froude No.	0	30	60	90	120	150	180
0.36	37	38	64	63	51	60	40
0.38	55	58	77	72	67	69	67
0.41	60	70	90	89	80	83	78

Comparison of measured and predicted scour depth: Several of the common equilibrium scour depth prediction equations as published in the literature were used to compute the equilibrium scour depth to be expected for the test conditions applicable to the 115 mm pier. The reason for the analysis is to evaluate the usefulness of some of the renowned equations in the literature with a view of testing how reasonably they can predict the equilibrium scour depth based on the flow and sediment conditions used in this study. The results of measured scour depth at various positions and different Froude numbers are shown in Table 2.

Figure 9 shows comparison of regression analysis of the present study data with results of study of Shen and Schneider (1969) and Breusers *et al.* (1977) and Colorado State University (CSU). For this comparison, a good agreement can be found between the results of this study with work of Breusers *et al.* (1977) with R2 = 0.96. The adjusted equation was re-written as:

$$\frac{\text{dsmax}}{B} = \left(2\left(\frac{u}{u_c}\right) - 1\right)\left(2\tanh\left(\frac{y}{B}\right)\right)(Fr + k) \qquad (1)$$

Where:

ds max = Maximum of scour depth

B = Pier diameter

u = Velocity

u_c = Critical velocity

y = Water depth

K = Coefficient of position in bend with clear-water scour (Table 3)

Fr = Froude number

Table 3: Coefficient of position in bend with clear-water scour

Position of bend (degree)	K
0	0.10
30	0.15
60	0.36
90	0.34
120	0.25
150	0.30
180	0.21

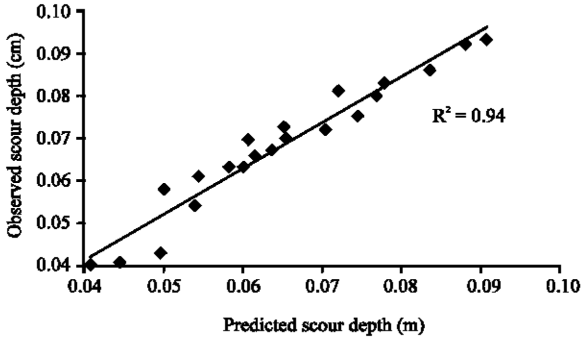

Fig. 10: Comparison of measured and predicted scour depth

with regression coefficient of 0.94. Figure 10 shows the comparison of calculated values with use to Eq. 1 and tested values of relative maximum scour depth. It is evident that Eq. 1 predicts the maximum scour depth with acceptable accuracy.

CONCLUSIONS

In this study, the temporal development of scour at oblong pier was experimentally studied using a physical hydraulic model. The study was performed under clear-water conditions using a uniform cohesionless bed material and oblong pier.

The results of the model study indicated that the maximum depth of scour is highly dependent on the experimental duration. The depth of the scour hole increases as the duration of the increased flow that initiates the scour increases. The extent of scour observed at the pier also increases as the duration of the tests increases.

The results of this study showed that, while oblong pier is placed in the bend, the maximum scouring depth is alternatively and maximum scouring occurs in position of 60 degrees. Also, it was observed that in all positions, increasing the Froude number increases the scouring depth.

The results of this study showed that, Breusers *et al.* (1977) equation made the modified equation fit well to the data from the present study when compared with the original equation.

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