The Study of Rate of Scour at Cylindrical, Square and Round Nosed Piers

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Authors' contributions

This work was carried out in collaboration between both authors. Author LS designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author SK managed the analyses of the study. Both authors read and approved the final manuscript.

Short Research Article

ABSTRACT

Rate of scour adjacent to piled foundations may result in rapidly loss of skin friction and load bearing capacity of the piles. The piles may be subjected to unplanned bending stresses, from lateral loads and hydrodynamic forces. The knowledge related to the time taken by different piers to achieve a certain scour depth is limited. In this study experiments were conducted using wooden pier models in the re-circulating glass sided tilting flume of 12,5 m length, 300 mm width and 450 mm deep. In all three tests water depth, discharge, and mean approach flow velocity in the channel were kept constant. The flume was filled with cohessionless bed material (artificial sand) average grain diameter of 0.203 mm to a uniform thickness. The scour depths observed from experiments were 30 mm, 16 mm and 14 mm in square, cylindrical and round nosed piers respectively. It was observed that, it takes more time for the cylindrical and round nosed piers to achieve scour depth of 22.2 mm and 20 mm respectively as estimated by Breusers and Raudkivi 1991. The results also showed that: it takes shorter time for a square nosed pier to achieve its empirical scour depth value

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of 26.7 mm. This indicates that the rate of scour depth development in square nosed pier is higher than that of the cylindrical and round nosed piers at a given time.

Keywords: Pier models; approach flow velocity; local scour; maximum scour depth; artificial sand.

1. INTRODUCTION

Local scour at a bridge pier is normally great near the upstream nose of the pier, which may lead to the pier being undermined first at the upstream end and thus tilting. Several studies of bridge failures in the USA in 1973 for 383 bridge failures caused by floods showed that 25 per cent involved pier damage, and 72 per cent involved abutment damage. Furthermore Richardson and Davis studies showed that 1993 flood in the upper Mississippi basin caused 23 bridge failures, of which 14 were from abutment scour, two from pier scour, three from a combination of abutment and pier scour, two from lateral migration, one from debris load and one unattributed [1].

Different laboratory studies have been performed in scour at piers focusing on circular piers and kinematics of fluid around piers. Examples of these studies are investigations of scour at bridge abutment [2], study of the time-dependent clear water scour around circular bridge piers [3], scour around circular and elongated bridge piers with and without pier slot are clarified [4], Experimental investigation of abutment scour in sandy soil [5], and study of sediment motion in scour hole of a circular pier [6]. The experimental findings were compared with those calculated from Breusers and Raudkivi empirical equations for estimating maximum scour depth [7,8,9]. The main objective of this study is to compare the scour at cylindrical, square and round nosed piers with time.

2. EXPERIMENTS

2.1 Experimental Set Up

The experiment was conducted in the re-circulating glass sided tilting flume. The flume had a working length of 12.5 m and a working cross section of 300 mm wide by 450 mm deep. The working section of the flume was made up of a stainless steel bottom and glass sidewalls on both sides. The use of glass provides excellent visibility and allows flow visualizations over the full working height and length of the flume. For the purpose of the experiments, a working section was filled with sand to a uniform thickness of 160 mm and the sand bed section length of 2 m. In this study cohessionless bed material (artificial sand) was used. The sand had coefficient of uniformity of 0.814, mean grain diameter of 0.203mm, and standard deviation of 2.1. The outlet and inlet of the sand bed contained raised sloping ends. The discharge was measured by an electromagnetic flow meter. The pump drew water from a series of interconnected sump tanks standing on the floor and running alongside the flow channel, returned it to the upstream end via an aluminum pipe line which ran directly underneath the flume as shown in Fig. 1.
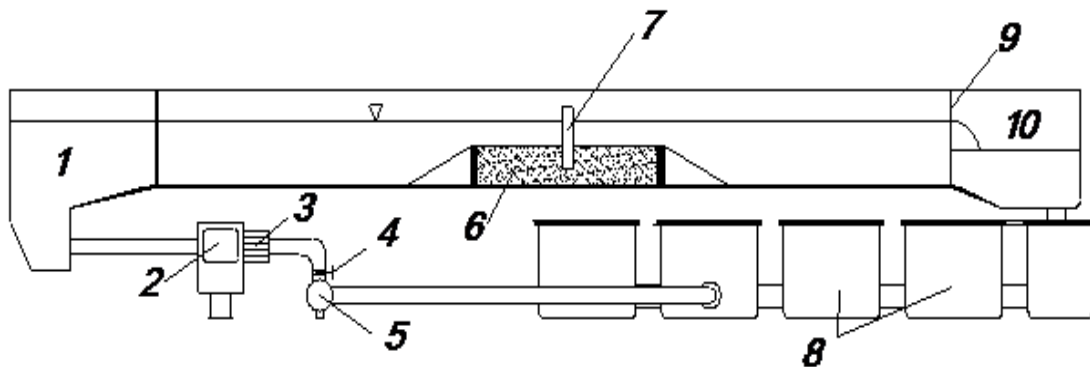

Fig. 1. Schematic illustration of the experimental setup
(1) Inlet tank, (2) digital readout, (3) electromagnetic flow meter, (4) control valve, (5) centrifugal pump, (6) sand bed, (7) pier model, (8) sump tanks, (9) tailgate, (10) discharge tank

The Vernier Hook & Point Gauge was used for the various depth measurements. The gauge was set at 100 mm as the natural ground level (NGL). All the contour profile in the vicinity of the pier were obtained by moving the gauge vertically and horizontally across the flume at different sections, noting the readings on the gauge at each position, and an electromagnetic flow meter was used to measure the flow rate.

In all three piers approach flow velocity, flow depth, pier width and length, size and gradation of the bed material, bed configuration and angle of attack of the approach flow to the pier were the same.

2.2 Flow Condition and Piers Specifications

The artificial sand bed used was having mean grain diameter of 0.203 mm. In all three experiments, water depth in the channel was kept constant at h=47 mm, discharge Q=2.16 l/s and mean approach flow velocity, v=14.01 cm/s.

Pier models of wooden material were used. The geometries of the cylindrical nosed pier had a diameter of 3.4 cm and length of 10.8 cm. The round nosed pier had width of 3.4 cm, length of 10.8 cm and diameter of nose was 3.4 cm, while

the square nosed pier had width of 3.4 cm and a length of 10.8 cm.

2.3 Experimental Procedure

Before each experiment, care was taken to the level of the cohessionless bed material (artificial sand) in the flume. The initial bed elevations were taken randomly to check the leveling of the flume. To start the experiment, the flume was slowly filled with water to the required depth. It should be noted that extra care is required when filling the flume, especially for tests of this nature where no sediment movement is allowed. The pump was then turned on and its speed slowly increased until the desired flow rate had been achieved. At the same time, the tailgate was adjusted so as to maintain the correct depth of flow in the flume.

Throughout the experiment period, the location and magnitude of the point of maximum scour depth was recorded by using the point gauge. The development of the scour hole with time was taken after 3, 5, 8, 10, 20, 30 and 50 minutes.

At the completion of each experiment, the pump was stopped and the tailgate was slowly lowered to allow the water to slowly drain out without disturbing the scour topography as indicated in Fig. 2.

Fig. 2. Round nosed pier picture after the flume dried

The flume bed was then allowed to dry and the final maximum scour depth was recorded using the point gauge. After the experiment the bed elevations were taken and the data obtained were used to draw the contour map of the scour using Surfer Software. The above procedures were repeated for each pier, and the sand was refilled properly so as to remove any prior scour development.

3. RESULTS

In this section we present the results for the three piers. The results were compared with empirical equations for each kind of piers as described in the following sections.

3.1 Cylindrical Nosed Pier

In order to compare the estimated maximum scour depth by empirical equation and that from experiment, Breusers and Raudkivi equations [7] was used.

Breusers and Raudkivi equation predicts maximum scour under clear-water conditions. The equation for cylindrical pier is given by:

$$\frac{y_s}{a} = S_F . K_1 . K_2 . K_5 . K_6 \tag{1}$$

Where:

S$_F$ – factor of safety equal to 1

K$_1$ – correction factor for pier nose shape, whereas for cylindrical nosed pier K$_1$ = 1.5

K$_2$ – correction factor for angle of attack. The factor K$_2$ allows for increase in scour that occurs if the longitudinal axis of the pier is at an angle to the approaching flow. The factor is calculated by Froehlich (1988) formula:

$$K_2 = \left[\cos \alpha + \left(\frac{L}{a} \right) \sin \alpha \right]^{0.62} \tag{2}$$

Where L is the length of the pier measured along its longitudinal axis and α is the angle between the longitudinal axis of the pier and the direction of the approaching flow. For our case L= 10.8 cm, α = 0° and *a* is pier width = 3.4 cm

$$K_2 = \left[\cos 0° + \left(\frac{10.8}{3.4} \right) \cdot \sin 0° \right]^{0.62} = 1$$

The correction factor for flow depth (K$_5$) takes into account the effects of relative water depth on the depth of scour and can be calculated from May and Willoughby equation 1990 [10].

$$K_5 = 0.55 \left(\frac{y_1}{a} \right)^{0.60} \tag{3}$$

For y$_1$/a ≤ 2.7 and K$_5$ = 1.0 for y$_1$/a > 2.7

Where y$_1$ is the local flow depth immediately upstream of the pier which is equal to 4.7 cm

4.7/3.4=1.38 ≤ 2.7; therefore

$$K_5 = 0.55 \cdot \left(\frac{y_1}{a} \right)^{0.60} = 0.55 \cdot \left(\frac{4.7}{3.4} \right)^{0.60} = 0.67$$

The correction factor for mean flow velocity (K$_6$) describes the effect of flow velocity on scour depth and can be determined from:

K$_6$ = 0, for V$_1$/V$_{cr}$ ≤ 0.375

$$K_6 = 1.6 \left(\frac{V_1}{V_{cr}} \right) - 0.6 \tag{4}$$

For 0,375≤ V$_1$/V$_{cr}$ ≤ 1.0

K$_6$ = 1.0 for V$_1$/V$_{cr}$ > 1.0; where V$_1$ = mean approach flow velocity V$_1$ = 14.01 cm/sec and V$_{cr}$ is the critical velocity equal to 18 cm/sec.

V$_1$/V$_{cr}$ =14.01/18 = 0.78 which obey the condition 0.375 ≤ V$_1$/V$_{cr}$ ≤ 1.0; Therefore

$$K_6 = 1.6 \left(\frac{14.01}{18} \right) - 0.6 = 0.65$$

y$_s$ is the maximum scour depth

y = 1x 1.5 x 1 x 0.67 x 0.65 x 3.4 = 2.22 cm = 22.2 mm

The experiment for cylindrical nosed pier was conducted. At the end of experiment that lasted for 60 minutes, the point of maximum scour was located at front edge of the pier. The measured elevation of the maximum scour was 84 mm, meaning that the maximum scour depth equal to 16mm (100 – 84 = 16 mm).
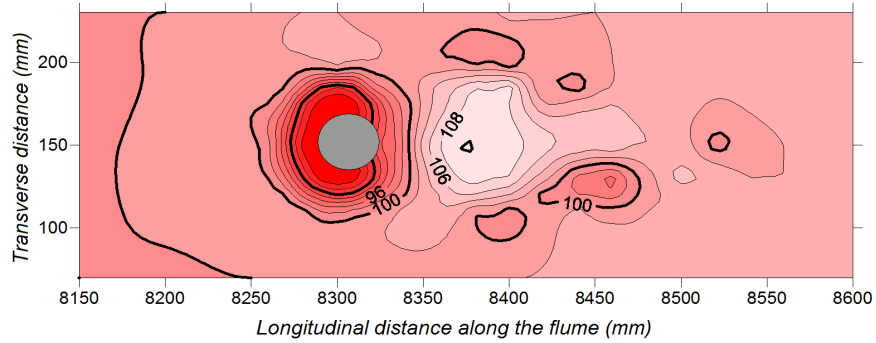
Fig. 3. Contour map of the scour

3.2 Round Nosed Pier

For round nosed pier the maximum scour depth was determined by Breusers and Raudkivi equation given by:

$$\frac{y_S}{a} = S_F \cdot K_1 \cdot K_2 \cdot K_5 \cdot K_6$$

$S_F = 1$; $K_1 = 1.35$

$$K_2 = \left[\cos 0° + \left(\frac{10.8}{3.4}\right) \cdot \sin 0°\right]^{0.62} = 1$$

$$K_5 = 0.55 \cdot \left(\frac{y_1}{a}\right)^{0.60} = 0.55 \cdot \left(\frac{4.7}{3.4}\right)^{0.60} = 0.67$$

$$K_6 = 1.6\left(\frac{14.01}{18}\right) - 0.6 = 0.65$$

y = 1x 1.35 x 1 x 0.67 x 0.65 x 3.4 = 2 cm = 20 mm

The experiment for round nosed pier was conducted. Like the cylindrical nosed pier test, the point of maximum scour after 60 minutes was located at front edge of the pier. The measured elevation of the maximum scour was 86 mm, meaning that the maximum scour depth equal to 14 mm (100 − 86 = 14 mm).

3.3 Square Nosed Pier

Emperical scour depth for square nosed pier was computed using the Breusers and Raudkivi equation as:

$$\frac{y_S}{a} = S_F \cdot K_1 \cdot K_2 \cdot K_5 \cdot K_6$$

$S_F = 1$; $K_1 = 1.8$

$$K_2 = \left[\cos 0° + \left(\frac{10.8}{3.4}\right) \cdot \sin 0°\right]^{0.62} = 1$$

$$K_5 = 0.55 \cdot \left(\frac{y_1}{a}\right)^{0.60} = 0.55 \cdot \left(\frac{4.7}{3.4}\right)^{0.60} = 0.67$$

$$K_6 = 1.6\left(\frac{14.01}{18}\right) - 0.6 = 0.65$$

y = 1x 1.8 x 1 x 0.67 x 0.65 x 3.4 = 2.67 cm = 26.7 mm

Experiment for Square nosed pier was performed. At the end of test (after 60 minutes), the point of maximum scour depth was not located directly in front of the pier on flume axis line as it was observed in previous two tests, but was located at the front corners of pier. The measured elevation of the maximum scour was 70 mm, meaning that the maximum scour depth equal to 30 mm (100 − 70= 30 mm).

The results for maximum scour depth values obtained from experiments and the Emperical maximum scour depth values estimated by Breusers and Raudkivi (1991) equation are indicated in Table 1. The data for development of scour with time are given in Fig. 6.

Table 1. Experimental scour depth versus empirical equation data

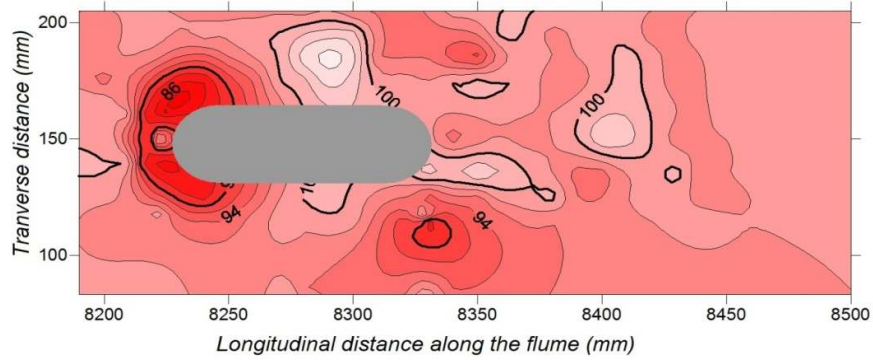| Piers shape	Experimental scour depth (mm)	Breusers and Raudkivi (1991) empirical Equation (mm)
Cylindrical pier	16	22.2
Round nosed pier	14	20
Square nosed pier	30	26.7

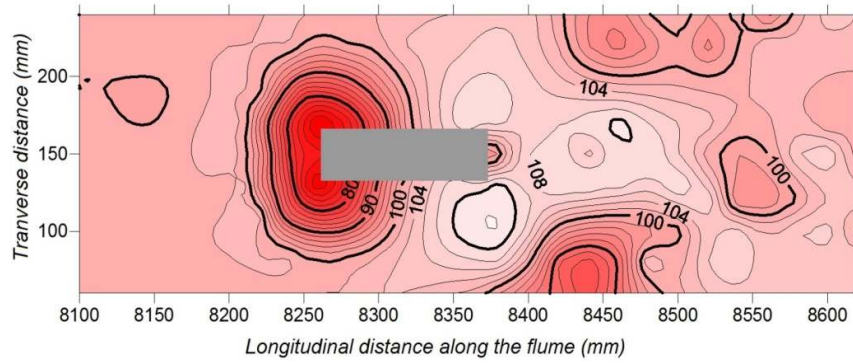**Fig. 4. Contour map of the scour**

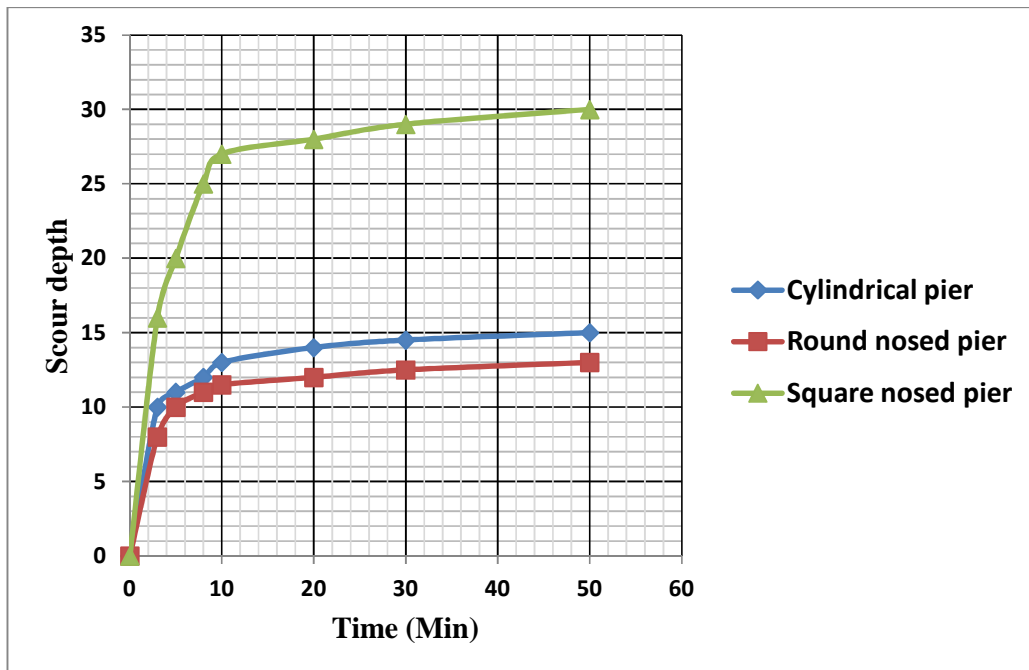**Fig. 5. Contour map of the scour**

Fig. 6. Development of scour depth vs time for Cylindrical, Round and Square nosed piers

4. DISCUSSION AND CONCLUSION

The data from all three experiments were used for the analysis of the effect of pier shape on the development of the scour depth. The largest recorded value of maximum scour depth was 30 mm that even exceeded the value determined by Breusers and Raudkivi (1991) empirical Equation of 26.7 mm, this is because sediments were very fine therefore were easily washed away and develop maximum scour depth in short time. This value was recorded at the square nosed pier. Maximum scour depth values of 16 mm and 14 mm were recorded for the cylindrical and round nosed piers respectively. However, it should also be noted that the scour depths from the two tests for round and cylindrical nosed piers had not reached their maximum of 20 mm and 22.2 mm given by Breusers and Raudkivi (1991) empirical Equation by the time the tests were stopped since equilibrium conditions were not reached.

The scour depth increased with time for all three tests. The results also indicate that the scour development was very much similar for all three tests during the first minute. From there onwards the difference in scour depths between the three tests started to increase rapidly and later gradually until the respective maximum scour depths was achieved at the end of the tests. It was observed that, it takes more time for the cylindrical and round nosed piers to achieve maximum value of scour depth estimated by Breusers and Raudkivi empirical equation which are 22.2 mm and 20 mm respectively than the time taken by square nosed pier to achieve maximum estimated scour depth value obtained by Breusers and Raudkivi empirical equation which is 26.7 mm. Therefore the rate of scour depth development in square nosed pier is higher than that of the cylindrical and round nosed piers at a given time.

This study was done by using cohessionless bed material (artificial sand), it is important to conduct study on local scour by using cohesive bed materials (e.g clay soil).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Richardson EV, Davis SR. Evaluating scour at bridges, Fourth Edition Hubert; 2001.
2. Abdallah Mohamed Y, Mohamed Abdel-Aal G, Hemdan Nasr-Allah T, Awad A Shawk. Experimental and theoretical investigations of scour at bridge abutment; King Saud University; 2013.
3. Aysegul Ozgenc Aksoy, Gokcen Bombar, Tanıl Arkis, Mehmet Sukru Guney. Study of the time-dependent clear water scour around circular bridge piers. Civil Engineering Department, Dokuz Eylul University, Turkey. 2017;4800-058.
4. Azevedo ML, Leite FC, Lima MMCL. Experimental study of scour around circular and elongated bridge piers with and without pier slot. Portugal; 2014.
5. Abou-Seida, Mostafa TMS, Isaeed, GH, Elzahry EFM. Experimental investigation of abutment scour in sandy soil. Faculty of Engineering (Shoubra), Benha University, Egypt. J. Appl. Sci. Res. 2009;5(1):57–65.
6. Alessio Radice, Chau K Tran. Study of sediment motion in scour hole of a circular pier. Faculty of Hydrology and Water Resources, Water Resources University, Vietnam; 2012.
7. Breusers HNC, Raudkivi AJ. Scour (Hydraulic engineering), Rotterdam: Balkema; 1991.
8. Emmet M Laursen, Arthur Toch. Scour around bridge piers and abutments; 1956.
9. Leo C van Rijn. Principles of Sediment Transport in Rivers, estuaries and coastal Seas; 1993.
10. May RWP, Willoughby IR. Local scour around large obstructions, Wallingford, Oxfordshire; 1990.

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