Experimental Study on the Effects of Pier Shape and Skew Angle on Pier Scour

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Abstract. Scouring around the bridge piers is one of the reasons for their instability, and in the absence of a suitable solution, it will eventually lead to the destruction of the structure. Therefore, studying the mechanism of scouring and effective parameters on its value is essential. In this study, using a laboratory model, this scouring phenomenon was investigated, and the effect of bridge pier shape and the skew angle between water flow and bridge pier on scouring were investigated. Experiments for four pier shapes, including a rhombus 30° inner-angle, rhombus 60° inner-angle, a cylindrical and an oblong, and three velocities include 0.191, 0.30 and 0.380 m/s, in two modes: parallel and skew-angles between stream and piers. The results show that the depth of scouring depends on the shape of the bridge pier and the angle of its placement in the flow. The best shape of the piers, the smallest scouring around it, is the rhombus 30, rhombus 60, oblong and cylindrical respectively. When the rust-shaped pier was placed in running water, in addition to less flow turbulence, the amount of scouring is also reduced. Also, due to the test with an angle between the stream and the bridge pier, the turbulence of the stream and scouring around the pier of the rhombus30 is lower than the other piers. The shape factor can be used as 1.0 for circular and oblong, and 0.9 for the shape of the rhombus 30 and the rhombus60. By analyzing the experiments, a suitable form for the bridge pier, a rhombus 30° inner-angle was proposed.

1. Introduction
Scouring around the submerged pier is one of the main issues in hydraulics. Due to scouring, a hollow is formed around the bridge pier, which gradually develops to cause instability of the structure and ultimately its destruction in flood (see Figure 1). Due to the collision of water with the pier, the pressure drop from the free surface flow into the bed occurs, and the downward flow is generated. These downstream flows are combined after the collision with the mainstream and create a horseshoe. Horseshoe vortices are more active at the front of the bridge. The rising vortex is caused by the separation of the flow layer from the bridge pier. This type of vortex system acts like a whirlwind and moves sediments from the floor upwards. In other words, the direction of movement of this vortex system is upward. Investigations show that horseshoe vortices and an ascension play a significant role in creating a scrubbing cavity around the bridges [1].
Numerous researchers have studied the scouring around bridge foundations and presented results to face this phenomenon [3-17]. According to Fael, among others, the scouring depth, $d_s$, around submerged pier depends on the slope of the energy line, $S$, acceleration of gravity, $g$ and flow depth, $d$; kinematic viscosity, $\nu$ and fluid density, $\rho$; pier width, $D_p$, density, $\rho_s$, of the sediment, gradation coefficient, $\sigma$, median grain size, $D_{50}$; leveling, and horizontal cross-sectional shape; time, $t$, bed slope, $S_0$, cross-section geometry; and channel width, $B$. The piers’ shape and alignment are typically considered for by the coefficients $K_s$ and $K_\theta$, respectively. For an utterly uniform flow of clear water into a rectangular canal, the floor of which is uniformly composed of sand, the dimensionless scour depth can be expressed as follows [18]:

$$\frac{d_s}{D_p} = \varphi \left( \frac{d}{D_p}, \frac{U}{U_c}, \frac{D_p}{D_{50}}, \frac{U}{\nu}, K_s, K_\theta \right)$$  \hspace{1cm} (1)

In this equation, $U_c$ means the velocity approach for sediment threshold conditions; and average flow velocity is denoted by $U$. It can be used for scouring depth without viscous effects. Related, for example, with the structure suggested Ettema [19], the above equation does not cover the Froude number because this is not agreeable with the concurrent inclusion of flow, $U/U_c$, and $D_p/D_{50}$. For example, on the recommendation of Ettema [19], this equation does not include the Freud number, because the current intensity is not consistent with the current addition $D_p/D_{50}$ and $U/U_c$. According to Melville [20], for constant $U/U_c$, the scour depth becomes this non-dimensional equilibrium:

$$\frac{d_s}{D_p} = \varphi \left( \frac{d}{D_p}, \frac{D_p}{D_{50}}, K_s, K_\theta \right)$$  \hspace{1cm} (2)

In the laboratory condition, usually, $U/U_c \approx 1.0$ to maximize the scour depth, e.g., in cases of clear water scouring. According to Melville, in the case where the ratio of the diameter of the base to the average diameter of the sediment particles is more than 20 to 25. $(D/D_{50} \geq 20-25)$, the particle size of the substrate is ineffective on the scour depth. Lee and Storm also set the minimum value for $D/D_{50}$ of 20. A type of pier shape factors, $K_s$, was recommended by other researchers based on minimal laboratory data. In the Eq. (3) which the $K_\theta$ is the multiplying effect for the angle between flow and pier.

$$K_\theta = \left( \cos \theta + \frac{1}{D_p} \sin \theta \right)^{0.65}$$  \hspace{1cm} (3)
Where $D_p$ is the pier width, $\theta$ is the angle of the stream, and $L$ is its length. $K_\theta$ only can be used when the $\theta$ is greater than 5 degrees and $2 \leq L/D_p \leq 16$. This study experimentally investigates the scouring around bridge piers with different shapes defined by $L/D_p \leq 4$. The effects of pier shape and skew angle on pier scour are respectively evaluated [20-26].

2. Materials and Methods
Experiments were performed under the conditions of varying the shape of the bridge piers and skew angle to explore their effects on scour depth. For each test, approach velocity, water depth, and scour depth of sediment bed were measured.

2.1. Test Material
All tested pier was made of stainless steel. To eliminate the effect of the flume walls on local scour, the diameter of the pier should not be greater than 10% of the channel width. The per diameter or thickness was 5 ~ 6.25 cm. The channel width ratio to the bridge diameter of the bridge $B/D_p$ varied from 16 to 20. These results were consistent with the Breusers [27]. They suggested that the scour contraction for $B/D_p$ values is less than 2.0 -2.5. Ballio [28], also said that the scour contraction is zero for $B/D_p \geq 10$ values. Therefore, there is no contraction effect in the experiments.

There were four different shapes for tests including, rhombus30 (The inner-angle 30°), rhombus60 (The inner-angle 60°), oblong and cylinder (see Figure 2). The pier situated in the sedimentary bed was composited by uniform sands.

![Fig. 2. Piers with different shapes](image-url)
The sediment size distribution was obtained by sieve analysis, which is illustrated in Figure 3. Its mean size $d_{50}$ was and gradation factor $\sigma_g=(d_{50}/d_{16}+d_{84}/d_{50})/2$. Before conducting sieve analysis, sediment samples were dried in the oven at 105 °C. Then, the sample was homogeneous, and impurities such as small stones, fibers, and snail shells were cleaned. A sieve with a width of 1.0 mm mesh was used to sift dried samples.

![Fig. 3. The sediment size distribution](image1)

2.2. Test flume

Experiments were performed in a cyclic two-layer flume with 13 m length, 1.20m height, and 1 m width (Figure 4) at the coastal engineering laboratory of Shanghai Jiao Tong University. The flume was divided into two layers by a 0.25 m layer, which created a channel with a length of 11 meters and a height of 0.75 m. At the bottom flume, two pumps were installed to create the flow of water at the desired velocity. There were installed two plates in the input and output section of the flume, to prevent turbulence. During the period of testing the pumps were working, the water was running on the upstream section and dropped to the bottom floor at the downstream part, and then driven by the submersible pumps to the upstream part from the tunnel. This cycle was repeated in the whole period to create constant water flow with the set velocity. The length of flume found to be sufficient to provide stable flow conditions in the flume. The flow depth was 28 cm in each test, which was controlled by the gadget. The velocities were 0.191, 0.300 and 0.380 m/s and flow discharge was 53.5, 84 and 106.4 l/s, respectively. The upper floor was covered horizontally and without slope with the sediment of 20 cm thickness. The surface of the bed was measured at three different levels and flattened slowly.

![Fig. 4. Flume](image2)
2.3. Flow velocity measurement

Pure water was added gradually at a slow speed to the flume in order to prevent the movement of sediment until a depth that was desirable. Then, a pump was switched on to start flowing water flow. In the first instance, the flow rate was small, and then it gradually increased to the designated value. The velocity profile with 128 sampling points in the flume was measured by Ultrasonic Doppler velocimeter (UDV) device. The UDV has a measuring range of 0.001 to 4.5 m/s and an accuracy of 0.0001 m/s. The resolution of the measurements is 0.0001 m/s, and the precision of the UDV is 0.1%.

2.4. Scour depth measurement

The scour depth was monitored with the help of ultrasonic Doppler velocimeter (UDV). As the UDV probe can detect the bed surface position, a set of UDV probe was beamed to the deepest location of the scour hole at the lateral side of the pier. The scour depth at any instant moment can be obtained from the detected bed surface signals. The experiment run was stopped until the detected bed surface ceased changing, and the water was slowly released out of the flume. Then, the elevations on the scour surface were measured immediately in three flow sections. For each section, five permanent positions were measured by a point gage. The scour depth was obtained from the comparison of the values before and after scouring of the bed.

3. Results and Discussion

3.1. Time for scour depth development

Laboratory observations indicate that the pier scouring started from the front of the pier and then extended to the lateral sides of the bridge pier, and after a while, the scouring reached the leeside of the pier. Figure 5 shows Time for scour depth development for tests run 1. The depth of the scour hole was very low after 5 hours running. Therefore, 5 hours was regarded as the time of stability of the scouring depth for this test. Generally, the pier shapes, which have the lowest scouring depth, are for the pier of the rhombus 30, rhombus 60, oblong and cylindrical. The best type of scouring and the lowest scour was related to the rhombus 30, which did not have much fluctuation after initial scouring and also had the least scouring. If there is a skew-angles pier, the scour is more than the parallel current.

![Fig. 5. Time for scour depth development](image)

3.2. Maximum scour depth

Table 1 shows a summary of the test conditions and results. Froude's numbers were 0.12, 0.18, and 0.23, respectively. Reynolds number for all tests were larger than 38000, which tells the flows in the flume were turbulent.
Table. 1. Experiments details

| Test | Shape | \(D_p\) (mm) | L/D\(p\) | B/D\(p\) | d/D\(p\) | \(D_p/D_{50}\) | \(\theta\) (°) | Velocity (m/s) | \(d_s\) (mm) |
|------|-------|-------------|---------|---------|--------|-------------|--------|---------------|----------|
| 1    | C     | 50.6        | -       | 19.76   | 5.53   | 194.62      | -      | 0.191         | 46.46    |
| 2    | C     | 50.6        | -       | 19.76   | 5.53   | 194.62      | -      | 0.300         | 59.845   |
| 3    | C     | 50.6        | -       | 19.76   | 5.53   | 194.62      | -      | 0.380         | 56.027   |
| 4    | O     | 50.6        | 3.7     | 19.76   | 5.53   | 194.62      | 0      | 0.191         | 33       |
| 5    | O     | 50.6        | 3.7     | 19.76   | 5.53   | 194.62      | 0      | 0.300         | 72.025   |
| 6    | O     | 50.6        | 3.7     | 19.76   | 5.53   | 194.62      | 0      | 0.380         | 54       |
| 7    | R30   | 60          | 3.73    | 16.66   | 4.66   | 230.77      | 0      | 0.191         | 8.348    |
| 8    | R30   | 60          | 3.73    | 16.66   | 4.66   | 230.77      | 0      | 0.300         | 29.956   |
| 9    | R30   | 60          | 1.77    | 16.66   | 4.66   | 230.77      | 0      | 0.380         | 30.665   |
| 10   | R60   | 60          | 1.77    | 16.66   | 4.66   | 230.77      | 0      | 0.300         | 42       |
| 11   | R60   | 60          | 1.77    | 16.66   | 4.66   | 230.77      | 0      | 0.380         | 37.5     |
| 12   | O     | 85.9        | 2.1     | 11.64   | 3.25   | 330.38      | 15     | 0.191         | 39       |
| 13   | R30   | 59.4        | 3.64    | 16.83   | 4.71   | 228.46      | 15     | 0.191         | 22       |
| 14   | R60   | 58.1        | 1.76    | 17.21   | 4.81   | 223.46      | 15     | 0.191         | 25.008   |

C – Circular, O – Oblong, R30- Rhombus (The inner-angle 30°), R60- Rhombus (The inner-angle 60°)

3.3. Shape effect on scouring

The shape factor is introduced to consider the effect of pier shape on the maximum scour depth. The shape factor for circular shape \(k_s=1.0\) at the condition \(\theta=0\). For all the tests, the shapes factors are illustrated in Figure 6. Compare with existing results, including Melville [22] and Richardson [31]; it can be concluded that the circle and oblong are almost behavioural since \(K_s\) is equal in both.

![Fig. 6. Shape factor at the equilibrium, \(K_s\).](image)

As noted above, it can be concluded that this base shape acts as a circular pier. However, due to the existence of the length-to-width ratio, these conditions change when the angle is present, and the ratio of L/D\(p\) acts as a different function. That means the length to width ratio varies, resulting in a scouring effect.

3.4. Pier alignment factor

The foundation alignment factor, \(K_\theta\), is the operating principle of the pier level, in other words, the angle of the pier, the ratio of pier scouring with a shape, planted at a tilting angle between the bridge and the flow, \(\theta\) and scouring at the same pier for the angle \(\theta=0^\circ\). It should be noted that \(\theta=15^\circ\), eventually \(\theta=0^\circ\), which means that this configuration may be used through appropriate shape factors. The base alignment factors in these experiments are shown in Figure 7. As indicated, the ratio of L/D\(p\) to the pier-level factor is a direct proportion. It is clear that Equation 3 represents a prediction of \(K_\theta\) for L/D\(p\)=4.0, while it
estimates the $K_\theta$ for the interval $L/D_p = [0.5, 1.36]$. The shape of the hole is the same for each $\theta$, including the $\theta=0^\circ$. As a result, the scour depth at an oblong pier necessarily reflects the effect of both shapes and $\theta$, and the shape factor, such as the alignment factor, is an inevitable concept. The related to the scour equilibrium at any time and is calculated on piers with a small $L/D_p$ ratio based on derived derivatives for the cylinder pier. Compare with existing results of other researchers and Equation (3) It can be seen that with $\theta=15^\circ$, the scouring process increases. Except in the case of $D/D_p=4.8$, the scour depth was less observed. This change is close to Zhao and Sheppard’s research [32].

4. Conclusion
The present study concentrates on the impact of pier shape, attacking angle on Pier Scouring, which is done for four different bridge shapes. Experiments were carried out in a rectangular channel, covered with sand evenly and without washed waves, in a uniform, clear water flow. It can be concluded that for $L/D_p \leq 4$:

1. The shape factor, $K_s$, can be used as $K_s=1.0$ for circular and oblong, and $K_s=0.9$ for the shape of the rhombus30 and the rhombus60. This number is confirming the robustness of the experimental results reported by other researchers [30].

2. For values of $L/D_p < 4$, the $K_s$ and $K_\theta$ are the same and should not be ignored.

3. The effect of the geometry stays on the skewed pier, although the corresponding coefficient dwells in the limited range around 1.

4. For $\theta=0^\circ$, the effect of $L/D_p$ on $K_\theta$ is negligible and does not change much in $K_\theta$.

5. Despite the two diamond shapes, it was observed that the $L/D_p$ is inversely proportional to scouring.

6. The depth scour, and $L/D_p$ have an inversely proportional ratio.

Acknowledgments
This work was financially supported by National Natural Science Foundation of China, Grant No.: 51779137. Title: Experimental study on the local scour of bridge piers subject to vibration loadings in unidirectional flow, fund.

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