Riprap design at bridge piers with limited scouring

Gholamnabi Khademghaeiny¹, Jalil Abrishami², Amir Reza Zarrati³, Mojtaba Karimaei Tabarestani⁴, Mohammad Mashahir⁵

ABSTRACT

One of the common methods for scour protection around bridge piers is riprap layer. In previous studies, sizing riprap layer was for 100% protection against scouring. However, in many cases limited scour depth around a pier maybe accepted if only smaller riprap sizes are available. In the present work the effects of smaller size of riprap stones than the stable size on the scour depth around a bridge pier is studied. Circular and oval shapes for riprap extent as well as both round and angular stone shape were also tested. All tests were conducted at the threshold of bed sediment motion and the maximum scour depth was measured. The results of these experiments showed that with stone sizes closer to stable riprap material, the efficiency of both round and angular stone shape was identical. As, size of riprap was reduced, deeper scour holes were observed with both round and angular shape material. The results also indicated that increasing

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the extent of the riprap layer from circular to oval with 5 times more riprap volume had insignificant effects on scour hole for angular shape riprap meanwhile reduced the scour hole depth with round shape material. Based on experimental data a method was developed to calculate a smaller riprap size based on an accepted limited scour hole.

**Keywords**: Bridge Piers, Local scour, Riprap protection, Round and angular riprap, limited scouring

1. **Introduction**

Local scour around a pier results from a complex vortex system which forms around the pier. These vortices consist of a horseshoe vortex initiated from the down flow at the upstream face of the pier and wake vortices downstream of the separation point at the sides of the pier [1, 2]. There are many methods to control scouring around bridge piers. These methods include, devices which change the flow pattern to reduce the flow force such as collars [3, and 4], sacrificial piles placed upstream of the pier [5], slots [6] and vanes [7 and 8]. Secondly, methods which increase the streambed resistance such as riprap stones, cable-tied blocks, tetrapods, dolos, etc. [9 to 17].

Previous studies have shown that under clear water conditions, 3 failure mechanisms may occur; 1) shear failure, where riprap stones are entrained by the flow, 2) winnowing failure, where the finer under-laying bed material is eroded from between the riprap stones and 3) edge failure, where scouring at the periphery of the riprap layer undermines the armor stones [9]. In addition, Chiew and Lim [18] (2000) and Chiew [19] (2004) identified another failure mechanism for riprap in live bed condition where the riprap layer is destabilized by the bed forms and bed degradation past the pier.
The application of riprap as an armoring device to protect bridge piers from scouring is common in civil engineering practice. Many experimental researches have been carried out to determine the riprap size and extent around bridge piers [9, 10, 13, 14, 15, 16, 17, 18, 19, 20 and 21]. Most of these studies were conducted in clear water condition and the size of stable riprap layer was only correlated to the approach flow velocity or shear velocity. However, based on large amount of experimental data, Karimaei and Zarrati [13], (2013) and Karimaei et al. [15], (2015-b), presented a new equation including most of the important factors on riprap stability. This equation which can be used for design of stable riprap around aligned and skewed round nose rectangular as well as circular piers is:

\[ N_c = 2.85 \times K_1 \times K_2 \times K_3 \times K_4 \]  

(1)

where \( N_c \) is riprap stability number which indicates the relationship between the flow condition and riprap stone characteristics and can be written as:

\[ N_c = \frac{\rho \cdot U^2}{g \cdot (\rho_s - \rho) \cdot D_{50}} \]  

(2)

where \( U = \) undisturbed upstream depth-averaged flow velocity; \( D_{50} = \) median size of stable riprap stones; \( g = \) gravitational acceleration; \( \rho = \) fluid density; and \( \rho_s = \) riprap stone density. In addition, square root of \( N_c \) is called the Densimetric Particle Froude Number, which was also used by some researchers as an essential parameter affecting scour depth around hydraulic structures [22, and 23]. Comparison of Equation (1) and many other riprap design equations can be found in [13].

In Equation (1), \( K_1 = \sqrt{D_{50}/B} \) is riprap size adjustment factor where \( B = \) round nose rectangular pier width or circular pier diameter and; \( K_2 = (y/D_{50})^{0.25} \) is flow depth adjustment factor;
$K_3 = \left( \frac{B_1}{B_{\text{eff}}} \right)^{1.5}$ is pier effective width adjustment factor where $B_{\text{eff}}$ is equal to circular pier diameter or projected length of the rectangular pier perpendicular to the flow direction which is defined as $B_{\text{eff}} = L \times \sin \theta + B \times (1 - \sin \theta)$ where $L$ = rectangular pier length and $\theta$ = pier skew angle. For circular as well as aligned rectangular pier, $B_{\text{eff}} = B$. Finally, $K_4$ is collar adjustment factor which is $K_4 = 1$ in the case of no protective collar installation [15]. The accuracy of Equation (1) has been reported in different studies [13, 14, 15 and 16]. For riprap design in clear water condition, winnowing failure can be prevented by using a filter layer between riprap and river deb sediment or placing sufficient riprap thickness. Different studies indicated that a minimum riprap thickness to prevent winnowing failure is $2.5d_{50}$. Finally, riprap edge failure can be prevent by sufficient riprap extent around bridge pier. In the literature, oval and circular shapes for riprap extent around bridge pier were presented. Chiew [9] (1995) suggested that the radius of circular extent for riprap layer can be selected equal to $2.5B$. In addition, investigation by Garde and Ranga Raju, [24] (1977) showed that for oval shape the extension of riprap layer at downstream of bridge pier must be $5B$. Figure (1) shows the definition sketch for riprap cover extent around a circular pier.

In all previous studies, the design of riprap layer accounted for a 100% protection against scour. However, in many cases, a limited scour hole around a pier may be accepted. Therefore, a more economical design may be achieved with smaller riprap size and cover area accepting a limited depth of the scour hole corresponding to the piers foundation depth. In the present work, experiments were carried out in clear water conditions, with different riprap size, shape and extent in order to study the effect of smaller size of riprap stones than the stable size on the scour depth around a bridge pier.
2. Experimental setup

Experiments were conducted in a 12m long, 0.3m wide glass walled horizontal flume. The flume had a 0.15m high and 1.5m long working section in the form of a recess below its bed, which was filled with sediment with median size of the sediment was 0.85mm and density of 2650 (Kg/m$^3$). The geometric standard deviation of bed sediment grading $\sigma_g = \sqrt{d_{84}/d_{16}}$ was 1.2, where $d_{84} = 0.94$ mm and $d_{16} = 0.65$ mm are respectively the size of sediment for which 84% and 16% of material by weight are finer. The value of $\sigma_g$ implies that the sediment sample is uniform. The working section started 6m downstream from the flume inlet where the boundary layer was fully developed. The absolute roughness of the false bed was about 1mm. The pier model was made from a 30 mm diameter clear Perspex tube. The distance between the pier center to the side wall was therefore, 5 times pier diameter. With this distance, the effect of flume side walls was negligible [25].

All tests were conducted at the threshold of bed material motion. The threshold of bed material motion was found by experiment when the pier was not installed. Threshold of material motion was defined as the condition at which finer materials may move, but the elevation of the bed did not reduced not more than 2 to 3 mm during 10 hours test. The ratio of shear velocity ($u_*$) in these experiments calculated from flow depth and energy slope to the threshold shear velocity ($u_{*c}$) calculated from Shields diagram was about 0.93.

The flow depth was measured with a point gauge with 0.1mm accuracy. A rectangular sharp crested weir with a manometer was used to measure the flow discharge at the flume end. The
pier model was scaled and the scour hole depth at the pier perimeter was measured with 1mm accuracy using a periscope installed inside the pier.

In the present study, Equation (1) was used for riprap design around bridge pier model with respect to flow condition. Calculations showed that the size of stable riprap stone for a complete protection of the streambed against local scouring was equal to 4.5 mm for the present experimental set up. Based on this result, four sizes of stones equal to 2.5 mm, 3 mm, 4 mm and 4.5 mm were selected as riprap material. Table (1) shows the properties of different riprap stones. As is shown in this table, two series of tests were carried out with two different types of riprap: round and angular stone shape where the shape factor of these grains was 0.7 and 0.425 respectively. Shape factor is defined as \( SF = \frac{e}{\sqrt{ab}} \) where \( a \), \( b \) and \( e \) are the largest, the intermediate and the smallest dimension of a stone measured along three mutually perpendicular axis respectively. The geometric standard deviation of sediment grading \( (\sigma_g) \) for each riprap size was less than 1.3, implying that the sample is uniform.

Two different shapes of riprap extent around the pier were also used: i) circular and ii) oval (Figure 1). The top surface of the riprap layer was leveled with the undisturbed bed elevation. To prevent winnowing failure at the beginning of the experiment, the thickness of riprap layer \( t_r \) in all tests was \( 2.5d_{50} \) [9]. In addition, a screen with a sieve size of 0.3 mm was used between the bed and riprap materials as a filter.

To insert the riprap layer of predetermined cover shape and thickness, a ring with the same extent as the riprap cover was first embedded around the pier model and the bed material inside
the ring was removed. The hole was then filled with riprap and leveled carefully with the approach streambed level. Finally, the ring was removed.

Figure (2) shows time development of maximum scour depth at the upstream face of the pier without any protection and with riprap protection of various sizes and shapes. In this Figure, \( d_{st} \) is scour depth at time \( t \) and \( d_{sf} \) is final scour depth. According to Figure (2), for piers with insufficient riprap protection the rate of scouring was very low after 10 hours and scouring after 24 hours was negligible. This is since riprap stones falling into the scour hole protect it from further scouring. Based on these results all tests were conducted in 24 hours.

3. Number of experiments

After a preliminary test with an unprotected pier, experiments were conducted with four sizes of riprap stones first with circular extension of riprap layer. These tests were carried out with both round and angular shape riprap material. In addition to these eight tests, four additional experiments were performed with smallest and largest round and angular riprap sizes with oval shape extension of riprap layer. All 12 tests were carried out for 24 hours. A summary of all experiments is given in Table (2). In this table \( U/U_c \) is flow intensity parameter which is the ratio of flow velocity to the threshold velocity for the riprap stones. Parameter \( U_c \) was determined using the mean velocity equation for a rough bed [9]:

\[
\frac{U_c}{u_c} = 5.75 \log \left( \frac{R_h}{d_{90}} \right) + 6.25
\]

\[(3)\]

where \( R_h \) is the hydraulic radius. In addition, \( N_c \) in Table (2) was calculated from Equation (2).
4. Experimental results

4.1. Unprotected pier

In a preliminary test, scour depth was measured around the pier without any protection. The test lasted for 10 hours and equilibrium relative scour depth was measured $d_{se}/B = 2.17$ ($d_{se} = 6.5$ cm) at the upstream face of the pier. The equilibrium scour depth was in agreement with the empirical equations (for example Melville and Sutherland [26] 1988). The scour hole around the pier was also symmetric, showing the evenness of flow and correct setup of the experiment.

4.2. Angular riprap stones with circular extent (Table 3)

Table (3) shows the results of experiments with angular shape riprap stone. In this table, equilibrium scour depth ($d_e$), the relative scour depth ($d_s/B$) and the ratio of scour depth to unprotected pier scour depth ($d_s/d_{se}$) are shown. In addition, parameter $K_5$ which is the ratio of parameter $N_c$ for smaller riprap size to design riprap size ($D_{50} = 4.5$ mm) is also shown in this table.

Experimental observations showed that, for riprap with $B/D_{50} = 12$ ($D_{50} = 2.5$ mm), the vortex systems that formed around the pier de-stabilized the riprap stones. At the beginning of the experiment, the down-flow at the upstream face of the pier impinged into the riprap material and removed them towards downstream direction. In addition, at the downstream of the pier, wake vortices lifted and removed the riprap stones from the bed. When some of riprap stones were removed, the bed material was washed out and a scour hole was formed around the pier. With
development of the scour hole, the remaining riprap stones slide into the scour hole, armored it and prevented the hole from further scouring. This test continued for 24 hours after that variation of the scour depth was insignificant (Figure 2). Maximum relative scour depth ($d_s/B$) observed in this experiment was 1.07 at the upstream face of the pier (Table 2). The results showed that though riprap layer failed and scouring occurred around the pier, the final depth of the scour hole, was about 50% less than depth of the scour hole in the pier without any protection.

In the next stage, the riprap size was increased first to $B/D_{50}=10$ ($D_{50} = 3\text{mm}$) and then to $B/D_{50}=7.5$ ($D_{50} = 4\text{mm}$) with $N_c = 2.41$ and 1.81, respectively and experiments were performed with the same flow condition. Similar to the first test, some of riprap stones were removed due to the action of down-flow and vortex systems around the pier. However, the scouring was stopped after riprap stones slide into the scour hole and stabilized it. In these experiments after 24 hours, the final scour depth was 33% and 14% of the scour hole depth of unprotected pier ($d_s/d_{se} = 33\%$ and 14%) for relative riprap size of $B/D_{50}=10$ and 7.5, respectively (Table 3). Figure (3) shows the scour hole around the pier with angular shape riprap stones and circular extent.

After these tests, the stable riprap size was tested with $B/D_{50}=6.67$ ($D_{50} = 4.5\text{mm}$) and $N_c = 1.61$ (Table 2). In this test, the riprap stones around the pier remained stable and no scouring was observed around the pier after 24 hours ($d_s/d_{se} = 0$ in Table 3).

### 4.3. Round shape riprap stones with circular extent (Table 4)

To compare with angular material, the same four sizes of riprap stones, i.e. 2.5mm, 3mm, 4mm and 4.5mm ($N_c = 3.01$ to 1.67) were also tested with round shape material. The shape factor of these materials was between 0.62 and 0.7. In these experiments, the extent of riprap layers and flow condition were similar to tests with angular shape riprap. As is shown in Table (4), with these sizes of riprap stones, $d_s/d_{se}$ was 66%, 39% and 15%, respectively. Similar to angular shape
riprap no scouring was observed with 4.5mm riprap size. A sample of the scour hole around the pier with round shape riprap stones and circular extent is shown in Figure (4).

Comparison between results of experiments with angular and round shape riprap material demonstrates that the efficiency of round material was similar to angular material except in smaller sizes of riprap stones. For 2.5mm riprap stones, the scour depth was about 25% greater in round shape riprap material compared to angular stones. Round shape stone materials are usually available in river deposits. It can therefore, be concluded that, with smaller riprap sizes (higher \( N_c \)), angular shape material could further reduce the scour depth.

4.4. Angular and round shape riprap stones with oval extent (Table 5)

Two more tests were performed with the smallest riprap size of 2.5 mm in oval extent to see the effect of a larger riprap layer on depth of the scour hole. Both angular and round shape material were used in these tests. The oval extent is shown in Figure (1-b) and the results are summarized in Table (5). The results of these tests showed that with angular material, \( d/d_{se} \) was 43% in oval extent, which is close to 49% in circular riprap extent. However, with round shape stone material \( d/d_{se} \) was 43% in oval extent whereas it was 66% in circular extent with the same material showing 35% reduction in the scour depth. It can therefore, be concluded that with smaller riprap size (higher \( N_c \)), if angular shape material is used, larger extent of riprap material do not reduce much the maximum scour depth. However, with round shape material and smaller riprap size, larger extent of riprap layer is needed to reduce depth of the scour hole. The oval extent of the riprap layer used here had 5 times more volume of riprap than the circular extent.

5. Design of smaller riprap with scour hole
Equation (1) predicts riprap stones to account for a 100% protection against scour around the pier. However, present experimental data was used to determine a smaller riprap size based on an accepted limited scour hole. Therefore, Equation (1) can be rewritten as:

\[ N_c = 2.85 \times K_1 \times K_2 \times K_3 \times K_4 \times K_5 \]  

(4)

where \( K_5 \) is the scour depth adjustment factor for riprap design which can be found from the Table (3) to (5) based on \( d_s/d_{se} \). In the present experimental data, this parameter was calculated as a ratio of parameter \( N_c \) for smaller riprap size to the design riprap size \( (D_{50} = 4.5 \text{ mm in the present study}) \). Experimental results showed that the value of \( K_5 \) can be calculated based on 3 different conditions: 1) for round and angular shape riprap with oval extent (Table 5); 2) for angular shape riprap with circular extent (Table 3); 3) for round shape riprap with circular extent (Table 4). Figure (5) shows the variation of \( K_5 \) with \( d_s/d_{se} \) for these three conditions. Based on regression analysis of experimental data following equations were determined for calculation of \( K_5 \).

\[
K_5 = \begin{cases} 
1.861 \left( \frac{d_s}{d_{se}} \right) + 1 & \text{Round and angular shape riprap with oval extent} \\
1.559 \left( \frac{d_s}{d_{se}} \right) + 1 & \text{Angular shape riprap with circular extent} \\
1.216 \left( \frac{d_s}{d_{se}} \right) + 1 & \text{Round shape riprap with circular extent}
\end{cases}
\]  

(5)

From present experimental data, the range of \( d_s/d_{se} \) in above equations should be \( 0 \leq d_s/d_{se} < 0.7 \). In addition, as is shown in Figure (5), the accuracy of these equations in predicting experimental data are very high with regression coefficient almost equal to 1.
Two examples are presented here to illustrate how the present method can be used to estimate the riprap size finer than the calculated stable size based on considered scour hole. Table (6) summarizes the measured undisturbed upstream flow depth ($y$) and velocity ($V$) as well as pier width ($B$) at two bridges one over Homochitto River and another over Brazos River. These conditions are assumed to be design conditions for the respective sites in the case studies. The details of these bridge sites can be found in Chiew (1995) [9]. From Table (6), stable riprap sizes were calculated for these two bridges by using Equation (4). Results showed that the stable riprap size ($d/d_{se} = 0$) with $\rho_s = 2650$ Kg/m$^3$ in these two bridge sites were calculated about 155 mm and 56 mm respectively. Now, the question is that what will be the riprap size, if a limited scour hole equal to $d/d_{se} = 0.1$, 0.2, 0.3 and 0.5 is considered as a design criteria. Table (7) shows the results of riprap size based on angular or round shape riprap stone and oval or circular riprap extent. Results showed that in both examples for oval extent riprap layer by considering 50% of equilibrium scour depth at the bridge site, the stable riprap size can be decreased for about 40%. In this case, for circular extent, the riprap size can be decreased for about 37% and 32% for angular and round shape stones respectively. It is therefore, possible for design engineers to decide on the riprap size based on economical and/or construction restrictions.

6. Conclusion

Determination of riprap layer based on an accepted limited scouring may be economical in engineering designs. In the present study, the scour depth around riprap stones smaller than stable riprap size was studied, experimentally. The effect of riprap particle shape and extent around a cylindrical bridge pier on the scour hole depth was also investigated. Tests were conducted with 4 sizes of riprap stones with relative size $B/D_{50}$ between 6.67 and 12. All experiments were conducted at the threshold of sediment material motion.
Based on the test results, if a finer stone is used for protection of the streambed around the pier though some riprap material are washed away and scour hole is developed. However, the remaining stones slide into the scour hole and armor it. Therefore, the scour hole is stabilized and its final depth will be less than the equilibrium scour depth for the unprotected pier depending on the riprap size.

Experiments showed that with coarser material (smaller $B/D_{50}$) closer to the stable riprap size the efficiency of round and angular material was identical. With finer riprap sizes for example $B/D_{50} = 12$, scour depth was about 17% greater in round shape riprap material compared to angular shape stones. Experimental results also showed that for angular shape riprap stones by decreasing stable riprap size which is for 100% scour protection for about 2 times, the scour depth increased for about 50% of equilibrium scour depth. However, for this condition, about 66% of equilibrium scour depth happened for round shape stones.

Finally, based on experimental data a new modification factor was applied to the equation presented by Karimaei and Zarrati, [15] (2015-b) in order to calculate a smaller riprap size based on an accepted limited scour hole.

References


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Fig. (4) Scour hole around pier with round shape riprap material and circular extent (Black line shows the boundary of the scour hole)

Fig. (5) Variation of $K_5$ with $d/d_{se}$ for different riprap conditions
<table>
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Table (3) Scour depth results with angular shape riprap stones and circular extent

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Table (4) Scour depth results with round shape riprap and circular extent

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<td>39</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>7.5</td>
<td>1.88</td>
<td>1.0</td>
<td>15</td>
<td>1.13</td>
</tr>
<tr>
<td>4.5</td>
<td>6.67</td>
<td>1.67</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Table (5) Scour depth results with round and angular shape riprap and oval extent

<table>
<thead>
<tr>
<th>Riprap shapes</th>
<th>$D_{50}$ (mm)</th>
<th>$N_c$</th>
<th>$d_s$ (cm)</th>
<th>$d/d_{se}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular</td>
<td>2.5</td>
<td>2.89</td>
<td>2.8</td>
<td>43</td>
</tr>
<tr>
<td>Round</td>
<td>2.5</td>
<td>3.01</td>
<td>2.8</td>
<td>43</td>
</tr>
<tr>
<td>Angular</td>
<td>4.5</td>
<td>1.61</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Round</td>
<td>4.5</td>
<td>1.67</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table (6) Field conditions at selected bridge sites [9]

<table>
<thead>
<tr>
<th>Bridge site</th>
<th>y (m)</th>
<th>U (m/s)</th>
<th>B (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homochitto River</td>
<td>3.8</td>
<td>2</td>
<td>2.44</td>
</tr>
<tr>
<td>Brazos River</td>
<td>10.4</td>
<td>1.1</td>
<td>3.50</td>
</tr>
</tbody>
</table>
Table (7) Riprap size with different conditions for bridge site over Homochitto and Brazos River
(in meter)

<table>
<thead>
<tr>
<th>$d_s/d_{se}$</th>
<th>For oval extent</th>
<th>For angular shape and circular extent</th>
<th>For round shape and circular extent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Homochitto River</td>
<td>Brazos River</td>
<td>Homochitto River</td>
</tr>
<tr>
<td>0.0</td>
<td>0.155</td>
<td>0.056</td>
<td>0.155</td>
</tr>
<tr>
<td>0.1</td>
<td>0.135</td>
<td>0.049</td>
<td>0.138</td>
</tr>
<tr>
<td>0.2</td>
<td>0.120</td>
<td>0.044</td>
<td>0.124</td>
</tr>
<tr>
<td>0.3</td>
<td>0.108</td>
<td>0.039</td>
<td>0.114</td>
</tr>
<tr>
<td>0.5</td>
<td>0.091</td>
<td>0.033</td>
<td>0.098</td>
</tr>
</tbody>
</table>
Fig. (1) Definition sketch for riprap cover extent
Fig. (2) Time development of scouring with and without protection and with different riprap material (circular extent)
Fig. (3) Scour hole around the pier with angular shape riprap and circular extent (Black line shows the boundary of the scour hole)
Fig. (4) Scour hole around pier with round shape riprap and circular extent (Black line shows the boundary of the scour hole)
Fig. (5) Variation of $K_s$ with $d_s/d_{se}$ for different riprap conditions

**Technical brief**

Gholamnabi Khademghaeiny received both his BSc in Civil Engineering and MSc in Hydraulic Structure from Ferdowsi University of Mashhad. He is currently working in Project Management sector at consultant engineering companies.

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