Experimental Investigation of the Debris Configurations Effects on the Scour Hole Morphology at Circular Bridge Piers

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Abstract. The hydraulic conditions and river bed morphology at bridge piers get extremely changed with debris accumulations. In this study, a series of tests were conducted to understand the scour hole geometry behaviour during debris accumulation at circular bridge pier. Three groups of rectangular debris were tested under clear water condition with 27 tests. The most dangerous shapes from these groups were specified and the effects of debris thickness, width and length were elaborated. The results show that the scour depth, width and length increased as the percentage of obstructed area of debris to the flow area increased. Hence, the modification factor of scour hole dimensions increased. The study concluded that the modification debris coefficient for scour hole depth, width and length increased to 2.397, 2.308 and 2.145 when the obstructed area of debris to the flow area increases from 2.07% to 26.89%, respectively. More notifications should be considered in protection work around bridge piers subjected to debris accumulation.

1. Introduction
Accumulation of debris with stationary case around bridge piers is one of the serious problems that should be considered in scour and bed morphology analysis. The debris jam around bridge piers changes the flow field behavior and increases the obstruction area as compared with single pier, which lead to an increase in the acceleration of scour process at river bed within affected area near piers. Considering this case, the possibility of bridge failure increases. Many studies considered this problem and tried to introduce comprehensive understanding of this issue. Melville and Dongol (1992), studied the effect of cylindrical debris accumulation around single circular pier with downstream extension. The maximum scour depth was obtained with 3.6 times pier diameter. The study derived an equation that modeled the effect of debris by the effective pier diameter estimation. Also, a design curve was obtained to relate the floating debris with circular shapes. The National Cooperative Highway Research Program (NCHRP), carried out a study about the effect of debris accumulation around rectangular bridge piers. The study investigated different geometry locations, shapes, roughness and porosity. According to the study, the maximum scour can be observed with debris at the surface location. Also, the effect of debris roughness and porosity was not significantly obvious on the scour process (Lagasse, P. F, et al. (2010). Pagliara and Carnacina (2011), studied the influence of wood debris accumulation on bridge pier scour in order to present the temporal evolution of scour with obstructed debris area up to 12%. Ebrahim Rahimi, et al. (2016), investigated the effect of debris shapes and geometry on the pier groups. The results stated that the highest scour depth related to rectangular shapes. According to Pagliara and Carnacina (2012), the flow field with debris accumulation significantly differ. In addition, the accumulation of debris with 5% obstructed area
increase the velocity and turbulence near the pier with considerable changes. However, the maximum velocities were located near debris accumulation. The dune morphology in the presence of debris generates significant turbulence, single and multiple dunes can be located with different flow intensities (Pagliara and Carnacina, 2014). Al-Khafaji, et al. (2016), investigated the effect of floating debris on local scour. Different debris shapes were studied by physical and mathematical model using the HEC-RAS software. The results showed that the debris have conspicuous effect on scour phenomena and the HEC-RAS model was not efficient enough to represent the problem. Mohsen Ebrahimi et al. (2018), investigated the accumulation of debris around sharp nose piers that were already used in old bridges (masonry piers) with shallowest effect considerations. Results of this investigation indicated that the effect of debris reduced the scour depth near the bed locations. Due to the lack of literatures that take into account the scour hole morphology in the presence of debris, this study aims to investigate the effect of rectangular debris accumulations near cylindrical pier with new experimental investigation and to specify the most dangerous geometry. Maximum scour depth, width and length of scour hole was analyzed under clear water conditions and new debris modification coefficient was introduced with respect to isolated cylinder pier.

2. Materials and Methods

2.1 Flume Characteristics

The experimental works were executed in the special hydraulic lab prepared by the research team and hydraulic engineering advisors. The lab and the other hydraulic facilities were installed in the University of Karbala. A horizontal rectangular flume with closed recirculating system of 9.1 m length with sump and head tanks were used for performing the tests, see Figure 1. The channel was made from steel frame with highly transparent polyethylene wall of 7 m length, 0.7 m width and 0.5 m depth. The two sump tanks dimensions are 1.6 m length, 1.36 m width and 0.7 m depth, while the head tank dimensions are 1.4 m length 0.7 m width and 0.8m depth, which was supplied with two steel mesh to reduce the turbulence of supplying water. The water was supplied from the sump tank using an electrical pump with a discharge capacity of upto 25 l/s. The discharge was measured by pre calibrated volumetric flow meter of 0.2 l/s precision and adjusted by control and pay pass valves. A false bottom with 2.5 m length, 0.22 m depth and 0.7 m width was used to simulate the scoured zone and a cylindrical aluminum pier of 0.031 m at the center of working section zone. An up stream ramp of steel box made (1.3 m length, 0.7 m width and 0.22 m depth) and filled with a thin layer of concrete to provide the required transition to the working section.

![Figure 1. Experimental flume.](image)

To keep the same roughness at the upstream and downstream, another steel box (0.7 m×0.7 m×0.7 m) was fixed at the end of working section and covered with the same concrete layer thicken. The required flow depth was adjusted by the tail gate at the end of the flume. A digital point gauge, of 0.01 mm precision, was installed on a trolley steel equipment to measure the maximum scour. In addition, another digital caliper with the same precision was used to measure the maximum transverse and longitudinal scour hole in working section.
2.2 Sediment Characteristics and Hydraulic Conditions

The scoured zone was represented by non-cohesive sand material of mean diameter, $d_{50} = 0.716$ mm, while the geometric standard deviation of sample was uniform $\sigma/d = 1.283$, so the effect of ripples formation and armoring can be neglected (Raudkivi and Ettema, 1983; Raudkivi, 1986), the grain size distribution as shown in Figure 2. All tests were carried out under clear water conditions with flow intensity $\nu/v_c = 0.92$. The critical flow velocity for initiation of motion ($v_c$) was estimated with respect to $d_{50} = 0.716$ mm according to Melville (1997).

The ratio of flow depth ($Y$) to pier diameter ($D$) was selected to get the required hydraulic condition for maximum scour in the presence of debris and isolated pier ($2.6 \leq Y/D \leq 4$), so the depth was kept within 10 cm ($3.226D$) which satisfied the maximum effect on scour depth with debris accumulation (Melville and Dongol, 1992). Also, the pier diameter (3.1 cm) was chosen to eliminate the coarseness and side wall effect ($25 \leq D/d_{50} \leq 130$) and ($D/B \leq 0.1$), where $B$ is the channel width, $\rho$ is the water density, $\rho_s$ is the sand density. Also, the pier Reynolds number ($R_p$) satisfied the turbulence limits ($R_p = \frac{vD}{\nu} \geq 7000$), where $\nu$ is the average velocity in the channel and $\nu$ is the kinematic viscosity (Raudkivi and Ettema, 1983; Tafarojnoruz et al. 2010; Lanaca et al. 2015). By taking into account the limitations mentioned above the flow rate in the flume was regulated within 20.6 l/s.

![Grain size distribution](image)

Figure 2. Grain size distribution.

2.3 Debris Configuration

The tests program of experimental work contains the effect of debris configuration for rectangular debris. The work was divided into three groups to cover and introduce new ranges of variations in width of debris ($W_d$), stream wise length ($L_d$) and submerged depth ($T_d$). The percentage obstructed area by debris ($A_{Pd}$) was estimated according to, (Pagliara and Carnacina, 2011) as $A_{Pd} = \frac{(W_d-D) \times T_d}{B \times Y}$. The rectangular debris geometry was represented by woody material and the downstream extension of debris ($E_d$) remained constant (1 cm from the end of pier), Figure 3. Each surface of simulated debris was roughed by thin pins of 1.5 mm diameter and average length of 3 cm with average density of one pin for every 6.25 cm² to give the variation in surface roughness and its reflections on bed erosion and morphology near pier. For this study, the ratios range of debris configuration geometry was elaborated in Table 1 (NCHRP, 2010; (Pagliara and Carnacina, 2011; Ebrahim Rahimi, et al. 2016).

| $W_d/D$ | $L_d/D$ | $T_d/D$ | $E_d/L_d$ | $A_{Pd}$% |
|--------|--------|--------|----------|----------|
| 4-14   | 2-7    | 0.5-1.5| 0.12-0.42| 2.1-26.89|
2.4 Tests Methodology
To perform the tests successfully, preparations were made to cover the program of the experimental work. The working section of sediment zone was levelled precisely to the desired reference level. Each debris model mentioned previously was fixed to the pier specifically with different elevations from the bed to give the required change in the thickness of debris as shown in Figure 4. The flume was guardedly filled with water, while the tail gate was regulated to get the required depth (10 cm) and the starting time recorded. All tests were carried out with the same discharge ($v/v_c=0.92$) and depth. After each test, the flume was carefully drained and measurements have been observed. Preliminary tests were executed to investigate the time required for test, two tests were done with and without debris. The measured scour with respect to time increments increase was investigated. The significant increase of scour depth with time reach to the considerable amount during three hours, after that the rate of change decreases rapidly. However, the rate of increase was less than 0.03D during the 4th hour. Hence, the 4 hours duration test is suitable to satisfy the objective of the study, according to Zhao et al. (2010). Although the equilibrium time may take long hours of test execution, but near 50-80% of max scour may occur with 10% of time of equilibrium (Melville and Chiew, 1999). Also, the economic conditions and the goals of study should be considered to investigate the appropriate time for experimental work (Zafer and Yildis, 2004).

![Figure 3. Debris descriptions. (a), transverse section and (b) top view plan.](image)

![Figure 4. Rectangular debris during the test for group1](image)

3. Results Analysis and Discussion

3.1 Analysis Approach
According to Melville and Chiew (1999), the scour around bridge piers is a function of major parameters which contain Fluid flow parameters, sediment parameters, time effect with respect to the
equilibrium time and Pier geometry. The accumulation of debris add new parameters to the analysis and the configurations of debris shapes should be taken into consideration. By using above parameters and dimensional analysis of Buckingham π-theorem, the scour hole characteristic and modification debris coefficient with respect to isolated pier to depth, width and length of scour hole can be estimated as following:

\[ \frac{d_{Ds}}{D}, \frac{w_{Ds}}{D}, \frac{l_{Ds}}{D} = f\left(\frac{A_{pd}}{D}, \frac{W_{d}}{D}, \frac{L_{d}}{D}, \frac{T_{d}}{D}\right) \]  

\[ K_{Ds} = \frac{d_{Ds}}{d_{s}} = f\left(\frac{A_{pd}}{D}, \frac{W_{d}}{D}, \frac{L_{d}}{D}, \frac{T_{d}}{D}\right) \]  

\[ K_{Ws} = \frac{w_{Ds}}{w_{s}} = g\left(\frac{A_{pd}}{D}, \frac{W_{d}}{D}, \frac{L_{d}}{D}, \frac{T_{d}}{D}\right) \]  

\[ K_{Is} = \frac{l_{Ds}}{l_{s}} = h\left(\frac{A_{pd}}{D}, \frac{W_{d}}{D}, \frac{L_{d}}{D}, \frac{T_{d}}{D}\right) \]

Where: \( d_{s}, w_{s}, l_{s}, d_{Ds}, w_{Ds}, \) and \( l_{Ds} \) are scour depth, width and length for test without debris and with debris, respectively, while \( K_{Ds}, K_{Ws} \) and \( K_{Is} \) are debris modification coefficients for scour hole depth, width and length. The measured characteristic of scour hole can be represented in Figure 5.

![Figure 5. Measured scour hole characteristics, (a) longitudinal and (b) transverse sections.](image)

3.2 Scour Hole Characteristics in Reference Test

The results of experimental work tests were compared with the reference test for the same hydraulic conditions. The reference test represents the results for scour hole characteristic without debris accumulation and the hydraulic conditions as shown in Table 2, where \( F_r, F_p, \) and \( F_d \) are Froude numbers for flume, pier and sediments while the other terms defined as earlier.

| \( d_s \) (mm) | \( w_s \) (cm) | \( l_s \) (cm) | \( v/v_c \) | Test duration (hrs) | \( F_r \) | \( F_p \) | \( F_d \) | \( Q \) (l/s) | Max water rise (cm) |
|---------------|---------------|---------------|--------------|----------------------|----------|----------|----------|------------|-------------------|
| 58            | 26            | 34.5          | 0.92         | 4                    | 0.298    | 0.535    | 3.52      | 20.6       | 10.8              |

The development of scour hole and its dimensions related to the scour process and mechanism. The flow characteristics around single pier or the reference test can be subdivided into 4 main parts which are, “down flow, horse shoe vortex, wake vortex and bow wave”. Due to the stagnation point at the pier face, there is a difference between the dynamic pressure at stagnation point and the approach
section lead to increase the pressure by \(\frac{\rho u^2}{2}\) (Raudkivi, 1986). The horse shoe vortex is developed due to the down flow and scour hole formation and take the sediment away from scour hole, while the wake vortex is developed due to the flow separation and located at the downstream of pier with lower effects as compared with horse shoe vortex. On the other hand, the bow wave is rotated with opposite direction of horse shoe vortex and increase the water level, so the water rise due to piers obstruction was measured at different sections from the upstream and downstream face of pier at uniform intervals of 15 cm. The maximum water rise was observed at the beginning of test execution with 10.8 cm at 14D from the upstream face of pier, then the effect of water rise gradually decrease after the distance of 16D from the upstream and downstream face of pier.

### 3.3 Scour Hole Characteristics with Debris Accumulations

The results of all the 27 tests of debris configurations and their effects on scour hole morphology according to debris modification coefficient illustrate and showed the increase in scour hole dimensions with respect to depth, width and length compared with the reference test. Also, the modification of debris coefficient for scour hole depth, width and length increase accordingly.

Figure 6 shows the variation of scour hole characteristic with increase in the obstructed area of debris percentage \(A_{pd}\) from 2.07% to 26.89% which lead to the increase in \(KD_{ds}\), \(KD_{ws}\) and \(KD_{ls}\) from 1.103 to 2.397, 1.154 to 2.308 and 1.043 to 2.145, respectively, showing an increase in debris width and thickness. The influence of variation in \((L_d/D)\) on \(KD_{ds}\), \(KD_{ws}\) and \(KD_{ls}\) was illustrated in Figure 7 with respect to different \((W_d/D)\). The significant effect of \((L_d/D)\) on the \(KD_{ds}\) can be clearly seen at \((L_d/D) = 4.5\), and \(T_d/D = 1.5\) for all groups which give the maximum \(KD_{ds}\) because the increase in velocity due to reduction in flow area, while there is a slight decrease after this limit, marked at \((L_d/D) = 7\). The combination effect of increase in length of debris and fully submerged conditions of thickness may explain this decrease because large increase in velocity which may be higher than critical velocity. This means there is a local scour area below \((L_d/D) = 4.5\) may be subjected to bed erosion and move sediment into the scour hole which produce slight decrease in scour depth at the pier face when \((L_d/D) = 7\), and \(T_d/D = 1.5\). Also, the effect of \((L_d/D)\) variations on \(KD_{ws}\) can be seen at \(T_d/D = 1.5\) for all groups. A significant increase in scour hole width as \((L_d/D)\) increase from 2 to 7. There was different effect for \((L_d/D)\) on scour hole length according to different \(W_d/D\) of each group, for group 1 there was a clear decrease in \(KD_{ls}\), as \((L_d/D)\) increase from 2 to 7 and \(T_d/D = 1.5\), while there was an increase in \(KD_{ls}\) in group 2 for the same limits. For group 3, there was a slight decrease in \(KD_{ls}\) beyond \(L_d/D = 4\) for \(T_d/D = 1.5\). The changes in scour hole dimensions reflect the variations of flow field with debris accumulation geometries. The water rise effect was obviously seen at 14D from the upstream face of pier with percentage increase from 0.09 to 0.13 compared with the uniform depth 10cm, then there was a slight decrease after distance 16D toward uniform condition. The increase in water rise was clearly appeared up to 0.013 at group 3 with fully submerged condition at the beginning of the test, while the minimum seen at group 1 with \(T_d/D = 0.5\). According to the above results, the most critical tests according to maximum scour was specified in Table 3. It can be noted from the summarized data for worst model that the maximum scour hole depth for group 1 was equal to 3.032 D, while the maximum scour width and length was 12.903 D and 15.806 D respectively. By the same way of comparison for group 2 the maximum scour hole depth, width and length was 3.806 D, 17.419 D and 19.355 D and for group 3 was 4.484 D, 18.71 D and 23.871 D. These values can be used as worst design value for rectangular debris according to the hydraulic conditions mentioned previously and the debris geometry listed. Using these value may give a better understanding for scour hole characteristic with debris effect according to pier diameter.
Figure 6. Debris modification coefficient for scour hole; a-depth, b-width, c-length.

Figure 7. Effect of $L_d/D$ variations on the scour hole; a-depth, b-width, c-length.
Table 3. The worst effect of debris model with respect to maximum scour depth.

| Model    | \( W_d/D \) | \( L_d/D \) | \( T_d/D \) | \( A_{pd} \) | \( d_{ds}/D \) | \( W_{ds}/D \) | \( L_{ds}/D \) | \( K_D_{ds} \) | \( K_D_{ws} \) | \( K_D_{ls} \) | Water rise percentage |
|----------|-------------|-------------|-------------|-------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------------|
| G1R2C1  | 4           | 4.5         | 0.5         | 2.07        | 2.097         | 9.677         | 11.935        | 1.121         | 1.154         | 1.072         | 0.1                  |
| G1R1C2  | 4           | 2           | 1           | 4.14        | 2.516         | 11.290        | 14.839        | 1.345         | 1.346         | 1.333         | 0.09                 |
| G1R2C3  | 4           | 4.5         | 1.5         | 6.2         | 3.032         | 12.903        | 15.806        | 1.621         | 1.538         | 1.420         | 0.1                  |
| G2R3C1  | 9           | 7           | 0.5         | 5.52        | 2.581         | 13.226        | 17.097        | 1.379         | 1.577         | 1.536         | 0.1                  |
| G2R2C2  | 9           | 4.5         | 1           | 11.03       | 3.290         | 16.258        | 19.355        | 1.759         | 1.938         | 1.739         | 0.1                  |
| G2R2C3  | 9           | 4.5         | 1.5         | 16.55       | 3.806         | 17.419        | 18.387        | 2.034         | 2.077         | 1.652         | 0.11                 |
| G3R1C1  | 14          | 2           | 0.5         | 8.96        | 2.355         | 10.000        | 13.226        | 1.259         | 1.192         | 1.188         | 0.1                  |
| G3R3C2  | 14          | 7           | 1           | 17.92       | 3.419         | 17.419        | 19.355        | 1.828         | 2.077         | 1.739         | 0.12                 |
| G3R2C3  | 14          | 4.5         | 1.5         | 26.89       | 4.484         | 18.710        | 23.871        | 2.397         | 2.231         | 2.145         | 0.13                 |

3.4 Comparison with the most common Empirical Formula

The results of the worst case models of debris have been compared with Melville and Dongol (1992) equation which is considered one of the most important empirical formula to predict the maximum scour depth with debris. The formula was derived from several experimental data and it depended on the width and thickness of debris as shown in Eq. (5). According to this equation the effective pier diameter for debris effect should be estimated, then the maximum scour depth can be proposed as shown in Eq. (6) and Eq. (7). Where \( D_e \) is the effective pier diameter, \( T_d \) is the debris thickness, \( D_d \) is the debris dimension with respect to the normal flow, \( Y \) and \( D \) are the depth of flow and pier diameter, respectively. The observed results and results predicted from the formula can be seen in Figure 8. The comparison showed that the predicted values of scour depth with debris accumulation were overestimated and that was noted by Pagliara and Carnacina (2011) and Mohsen Ebrahimi et al. (2018). This overestimation reflects the effect of length and shapes of debris which was illustrated in previous section and the hydraulic conditions difference.

\[
D_e = \frac{0.52 \times T_d \times D_d + (Y - 0.52 \times T_d) \times D}{Y} \quad \text{ Equation (5)}
\]

\[
d_s = 2.4D_e \quad \text{ for } Y/D_e > 2.6 \quad \text{ Equation (6)}
\]

\[
d_s = 1.872 \times (Y/D_e)^{2.55} \times D_e \quad \text{ for } Y/D_e < 2.6 \quad \text{ Equation (7)}
\]

Figure 8. Comparison between the Melville’s formula and the measured scour depth.

The general form of Melville and Dongol (1992) equations can be written as:

\[
d_s = K_D \times D_e \quad \text{ Equation (8)}
\]
By using the same form of Eq. (8) and modifying the K values with respect to the experimental data of this study, the values listed in Table 4 can be used to predict the scour depth with the presence of debris as worst case and according to width of debris, fully submerged depth and with \( L_d/D = 4.5 \), which give a combination between the maximum scour, debris geometries, and the modification for K values required according to equivalent pier width of Melville and Dongol (1992).

Table 4. Modification K values required for the present study using equivalent pier width of Melville and Dongol (1992).

| \( W_d/D \) | \( L_d/D \) | \( T_d/D \) | \( Y/D_e \) | K |
|------------|------------|------------|------------|---|
| 4          | 4.5        | 1.5        | \( \leq 2.6 \) | 1.76 |
| 9          | 4.5        | 1.5        | \( \leq 2.6 \) | 1.3  |
| 14         | 4.5        | 1.5        | \( \leq 2.6 \) | 1.08 |

4. Conclusions

In this study, new experimental measurements for the effect of debris configuration on the scour hole morphology was investigated and analyzed according to 3 groups of rectangular geometries. The study compared the results of experimental work of single cylinder pier without accumulation as a reference test and with that of debris jam as stationary case. From the results of this investigation, the following points can be concluded:

- The presence of debris and accumulation around bridge pier increases the scour hole dimension with depth, width and length. Generally, as the width of debris and submerged thickness increase, the scour hole dimension increases. In addition, there is a special influence of debris length which can be noted at models of fully submerged condition because of the large effect on scour depth at \( L_d/D = 4.5 \), while there was a significant increase in scour hole width with increase of \( L_d/D \) form 2 to 7. Furthermore, the debris length affect differently on scour length according to group width. For group 1 there was a clear decrease in scour hole length as \( (L_g/D) \) increased from 2 to 7 and \( T_g/D = 1.5 \), while there was an increase in the same limits. For group 3, there was a slight decrease in beyond \( L_g/D = 4 \) for \( T_g/D = 1.5 \).
- For group 1, the maximum scour depth was equal to 3.032D, while the maximum scour width and length was 12.903D and 15.806D, respectively, while for group 2 the maximum scour hole depth, width and length was 3.806 D, 17.419 D and 19.355 D and for group 3 was 4.484 D, 18.71 D and 23.871D.
- Debris modification coefficient for scour depth, width and length were derived with the increase in obstructed area of debris percentage \( A_{pd} \) from 2.07% to 26.89%, there was increase in \( K_{Dds}, K_{Dws} \) and \( K_{Dls} \) from 1.103 to 2.397, 1.154 to 2.308 and 1.043 to 2.145.
- From the results that have been obtained and analyzed, worst case models were concluded, which may be used for future study in different hydraulic conditions for rectangular debris.
- The results of study were compared with Melville and Dongol (1992) formula. It is found that that this formula gives over estimated results as compared with the worst models. Accordingly, the study proposed a new modification for the formula.
- According to the study, the effect of debris length should be considered in scour hole morphology. Further researches may focus on the effect of this parameter with width and depth to obtain new empirical formula.
- The maximum water rise was observed at 14D and increase from 0.09 to 0.13 as increase the obstructed area by debris from 2.06% to 26.89% at the beginning of each test and this may give a better understanding for flood risk analysis.
- More attention should be given for bridge piers contour measure in the debris jam state to have a safe and economical design protection.
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