Scour Depth at Single Cylindrical Bridge Piers with Debris Jam: An Experimental Comparative Study.

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Abstract. Rivers may carry a considerable amount of debris during floods, and the accumulation of this debris around bridge piers can change the hydraulic behaviour of flow fields and influence scour depth development. In this study, the effect of debris jam on scour depth at cylindrical bridge piers was investigated and a comparison carried out for the main existing empirical formulas. A series of 27 tests of rectangular geometry in three different groups according to width, length, submerged depth, and blocked area were studied. The results showed that the accumulation of debris increased scour depth from 10.3% to 62.1%, 22.4% to 103.4%, and 20.7% to 139.7% as the percentage blocked area of debris increased from 2.07% to 6.2%, 5.52% to 16.55%, and 8.96% to 26.89% for groups (1), (2), and (3) respectively. The comparison of the experimental results with the most commonly used empirical formulas revealed general overestimation of scour depth with debris accumulation. The Richardson and Davis (1995) and Lagasse et al. (2009) formulas were the most acceptable methods for scour prediction under debris jams, though further study is recommended for bridge pier scour depth estimation in the presence of debris.

1. Introduction

Natural events such as floods and high rainfall intensity may erode riverbanks and cause large quantities of woody vegetation to enter rivers, especially in flood plain areas. The accumulation of such debris will register as a hydraulic structure change in the flow field conditions and increase the risk of debris jam within such rivers. Debris jams around bridge piers decrease the flow area and produce large blocked areas, and in such scenarios, the possibility of bridge failure increases due to the increase of scour in front of the bridge pier. This problem has been studied by many researchers with the aim of developing a better understanding of the problem, but further focus on debris formation, accumulation, and configuration with regard to its effects on the scour process is required.

Melville and Dongol (1992), performed an experimental work to study scour development around single circular piers with cylindrical debris accumulation. The study proposed an equation to estimate the scour depth depending on the flow depth (Y) condition. The effect of debris was handled by a term based on equivalent pier diameter (Dₑ) and a design curve figure. The researchers found that the maximum scour equalled 2.4Dₑ, when Y/Dₑ ≥2.6. Lagasse et al. (2010) also carried out an experimental study to investigate...
the effects of different configurations of debris on scour depth. Their study showed insignificant effects for porosity and roughness as compared to a clear effect for geometry and location of debris on scour depth. Pagliara and Carnacina (2011) studied the temporal evolution of scour depth with different debris accumulation types. They proposed a relationship for scour depth estimation with debris effect dependent on the restriction area caused by debris up to 12%. Ebrahim Rahimi et al. (2016) investigated the effect of debris on pier groups using an experimental study; they found that rectangular debris formation produced the largest scour depth as compared with other shapes; they also clarified that debris may work as a collar when its relative depth to the flow depth equals 0.46. According to Pagliara and Carnacina (2012), there was an obvious increase in velocity and turbulence near accumulation areas around piers, with velocity patterns clearly changed in the presence of debris creating a 5% obstructed area as compared to piers without debris accumulation. The dune morphology as subjected to debris effect was also investigated by Pagliara and Carnacina (2014), who proposed an experimental study to examine dunes under clear water conditions. Their study showed a great change in dune height and configuration as well as scour depth, width and length; a significant increase in scour holes was also noticed.

Al- Khafaji et al. (2016) conducted an experimental study on the “effect of floating debris on local scour” wherein a numerical model based on HEC-RAS software was introduced. They showed that debris increased scour phenomena, though the HEC-RAS model was found to be inadequate to simulate the problem. Panici and de Almeida (2017) carried out a study to investigate the effect of log length on the debris formation; according to their results, three stages of formation debris were observed: unstable, stable, and critical. A relationship between the Froud number of log length and debris dimensions was clarified based on their design curves. Mohsen Ebrahimi et al. (2018) studied the effect of debris in different categories of jam on scour in sharp nose piers, as generally seen in old bridges. They found that the maximum effect of debris was noted at the surface of water, while there was minimum effect near the bed. Isabella et al. (2018) performed an experimental study to examine the effect of debris featuring woody logs on scour and back water rise; they confirmed the hypothesis that the decrease of water increased with the increase of scour.

Due to the importance of bridge safety and design considerations, and the lack of the related studies concerning the problem statement in particular, the current study was carried out to introduce new experimental data and to clarify the effect of rectangular debris jams on scour depth increases in specified ranges for different groups. A comparison was also conducted with the most widely used formulas for scour prediction with debris.

2. Materials and Methods

2.1 Flume Characteristics

Private hydraulic facilities were supplied by the research and hydraulic engineering specialist team at the University of Kerbala (Freha district). A closed recirculating system including a horizontal rectangular flume of 9.1 m, 0.70 m, and 0.5 m length, width, and height, respectively, was prepared with head and sump tanks for the experimental tests as seen in Figure (1). The whole frame of the channel was made from steel and highly transparent polyethylene wall was used for wall cladding, with a steel plate fixed for the flume bed. Two sump tanks were used to supply an electric pump of 25 l/s maximum discharge; their dimensions were 1.6 m length, 1.36 m width, and 0.7 m depth. The head tank dimensions were 1.4 m length, 0.7 m width, and 0.8 m depth. Two steel meshes were fixed inside the head tank to reduce the turbulence of the entering water, and a calibrated volumetric flow meter was used to measure the discharge, installed at the incoming pipe to the flume. A control valve was used to control the pump discharge that was installed before the flow meter. The scoured zone was simulated using a false bottom of 2.5 m length, 0.22 m depth, and 0.7 m width and a cylindrical aluminium pier of 3.1 cm in diameter was placed at the mid distance length (1.25 m) of the working section. To provide the proper transition between the water entering the
flume and the working section, an upstream ramp steel box was made of 1.3 m length, 0.7 m width, and 0.22 m depth; a thin layer of concrete (0.05 m) was used to cover the top surface of the ramp. Another steel box of 0.7 m*0.7 m was built in at the working section with a similar thin concrete layer to give the same roughness for the inlet and outlet. To adjust the required depth, a sluice gate was fixed at the end of the flume, and a digital point gauge (0.01 mm precision) was installed on a trolley steel frame to measure the maximum scour depth.

Fig (1). Experimental flume.

2.2 Bed Material Characteristics and Hydraulic Conditions

The bed material was represented using non-cohesive sediment to fill the working section and scoured zone. Table 1, shows the main characteristics of the sediment used in this study. A series of tests and a sieve analysis were performed to ensure the required characteristics in the sediment for the experimental work. According to Table 1, the median size of $d_{50}=0.716$ mm, and the geometric standard deviation sediment was uniform at $\sigma_g < 1.3$, allowing the influence of ripple formation and armouring to be ignored (Raudkivi and Ettema, 1983; Raudkivi, 1986). The clear water conditions were considered to have a velocity ratio of $v/v_c=0.92$, and initiation of motion of sediment particles ($v_c$) was calculated according to recommendations in Melville (1997) for a critical velocity of $d_{50}=0.716$mm. All tests were executed under a water depth of 10 cm, which satisfied the required hydraulic conditions for maximum scour depth. The ratio of flow depth ($Y$) to pier diameter ($D$) was selected to obtain the required hydraulic conditions for maximum scour in the presence of debris and an isolated pier ($2.6 \leq Y/D \leq 4$); the pier diameter (3.1cm) was similarly selected to allow omission of coarseness and side wall effect ($25 \leq D/d_{50} \leq 130$), with $D/B \leq 0.1$, where $B$= the channel width, $\rho$ = water density, and $\rho_s$ = sand density. Taking these hydraulic conditions into account, the flow rate was adjusted to 20.6 l/s, allowing control of turbulence during the test and ignoring the effect of the pier Reynolds number ($R_P=\frac{vD}{\nu} \geq 7000$, where $V$= average velocity in the channel and $\nu$ = kinematic viscosity) (Raudkivi and Ettema, 1983; Melville and Dongol, 1992; Tafarojrornruz et al. 2010; Lanaca et al. 2015).

| Material | $d_{50}$ (mm) | $d_{84}$ (mm) | $d_{16}$ (mm) | $\sigma_g = \left(\frac{d_{84}}{d_{16}}\right)^{0.5}$ | $\frac{\rho_s-\rho}{\rho}$ |
|----------|---------------|---------------|---------------|-----------------------------------|------------------|
| Sand     | 0.716         | 0.85          | 0.516         | 1.283                             | 1.596            |
2.3 Woody debris configuration
The test programme of experimental work considered the effects of debris configurations for rectangular debris. The work was divided into three groups to cover and introduce a range of variations in terms of width of debris ($W_d$), stream wise length ($L_d$), and submerged depth ($T_d$). The percentage area obstructed 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 ($E_d$) was kept constant (1 cm from the end of pier) as seen in Figure (2). Each surface of the simulated debris was roughed by using thin pins of 1.5 mm diameter and average length of 3 cm, with an average density of one pin for every 6.25 cm, to give variation in surface roughness and to examine the effects on bed erosion and morphology near the pier. The ratio range of debris configuration geometry for this study is shown in Table 2, (NCHRP, 2010; Pagliara and Carnacina, 2011; Ebrahim Rahimi, et al. 2016).

Table 2. Geometry of rectangular debris.

| $W_d/D$ | $L_d/D$ | $T_d/D$ | $E_d/L_d$ | $A_{pd}/%$ |
|---------|---------|---------|-----------|------------|
| 4-14    | 2-7     | 0.5-1.5 | 0.12-0.42 | 2.1-26.89  |

2.4 Test methodology
The preparation for experimental work included many steps to allow correct execution of the tests. The scoured zone of the working section was levelled carefully to the required reference level for each test, then the debris models was tied properly to the pier and adjusted to the desired height. A guarded release of water to the flume was then begun, up to the required discharge, while the sluice gate was adjusted to the target water depth in the flume (10 cm), and the starting time recorded once this target depth was attained. Slow drainage was performed after each test while the scour depth was measured. Based on preliminary tests, each test was concluded at 4hrs duration. The evolution of scour with time with respect to a single pier without debris and with is shown in Figure (3), which clearly indicates a significant increase of scour depth with time during the first 3hrs, after which the development of scour tends to be constant.

3. Results analysis and discussion
3.1 Analysis approach
It is obvious from the scour-time evolution curve that after 3.5 hrs of testing, the rate of change was less...
than 0.03D, similar to that at 6hrs; 4hrs duration was thus considered suitable to investigate the objective of study (Zhao et al. 2010). In spite of many definitions for the equilibrium time of scour that require long hours of test execution, with a rate of change of less than 10% t time of equilibrium, the scour depth at four hours is likely to be about 50 to 80% of max scour, and economic factors must considered when selecting the optimal time test for a study (Melville and Chiew, 1999; (Zafer and Yildis, 2004).

The scour around a single cylinder pier depends on many parameters, including fluid parameters, sediment parameters, and time effects with respect to the equilibrium time, flow geometry parameters and pier geometry. The accumulation of debris adds a new parameter to the analysis and the configurations of debris shapes must thus be taken in consideration. Buckingham π-theorem was used to analyse the scour problem with respect to debris jams, and the results of such analysis produced the following equation, which can be used to represent the effect of these parameters on scour with debris:

\[
d_{DS/D} = f\left(A_{PD}, W_d/D, L_d/D, T_d/D\right) \quad (1)
\]

where \(d_{DS}\) is the scour depth with debris jam, with the other parameters as defined in section 2-3. In all tests, a comparison was made with respect to the original test for a single pier without debris, as clearly seen in Table (3), where \(F_r, F_p,\) and \(F_d\) are the Froude numbers for the flume, pier and sediments respectively; \(g\) is the gravity acceleration; and \(d_s\) is the scour at the face of the pier without debris.

![Fig 3. Scour evolution curves](image.png)

Table 3. Hydraulic conditions and results for single pier without debris

| \(d_s\) in mm | \(v/v_c\) | Duration of test in hrs. | \(F_r = \sqrt{V \over g y}\) | \(F_p = \sqrt{V \over g D}\) | \(F_d = \sqrt{V \over g d_{50}}\) | Q in l/s | Max water rise in cm |
|---|---|---|---|---|---|---|---|
| 58 | 0.92 | 4 | 0.298 | 0.535 | 3.52 | 20.6 | 10.8 |
Generally, the mechanism of scour for a single pier without debris is a function of the main components related to “down flow, horseshoe vortex, wake vortex and bow wave” (Raudkivi, 1986). An increase in pressure appears due to the difference in the approach section and stagnation point at the pier face. The downward flow thus produces a horseshoe vortex that will erode the bed around the pier accordingly. In addition, the separation of flow produces a wake vortex that can be seen beyond the pier that is weaker than the horseshoe vortex. Finally, the bow wave increases the water level in the opposite direction to the horseshoe vortex. In this study, the water level increased by 8% at a distance of 14D from upstream face of the pier.

3.2 Scour depth characteristics with debris accumulation

The results of tests for all groups are elaborated in Tables 4, 5 and 6. The results of the experimental work show increases in scour depth percentage as compared to the original test. Generally, there were significant increases in scour depth as the $A_{Pd}\%$ increased. From Table 4, the maximum increase in scour depth percentage was 62.1%, while the minimum was 10.3%, while from Table 5, the maximum increase in scour depth percentage was 103.4%, while the minimum was 22.4%. It can also be clearly observed that the highest increase in the scour percentage from Table 6, group3, which was 139%, while the minimum in that group was 20.7%. The variations in debris dimensions for different groups can be used to explain the effects of width, depth and length. The effects of width and depth can be summarized by the $A_{Pd}\%$ which represents width and depth as clarified in Figure (4). The effect of stream wise length of debris is shown in Figure (5). For all groups, the maximum effect of debris length was found at fully submerged depth $T_d/D = 1.5$ and $L_d/D=4.5$, which can thus be considered the critical ratios for scour estimation with debris. For $L_d/D> 4.5$ there was a clear decrease in scour percentage due to decrease in flow area and increase in velocity. Observation of tests at conditions where $L_d/D> 4.5$ suggest that sediment particles move to the scour holes and reduce the scour percentage increase, which may create an increase in velocity beyond initiation of motion for sediment particles. Figure (6) shows the scour evolution for fully submerged depths of debris and dune formation as in the beds formed behind the pier.

Table 4. Scour depth characteristics with debris for group 1.

| MODEL  | $W_d/D$ | $L_d/D$ | $T_d/D$ | $A_{Pd}\%$ | $V/V_c$ | Duration | $d_{Vs}$ | $d_{Vs}/D$ | Increase % in scour depth |
|--------|---------|---------|---------|-------------|---------|----------|----------|-------------|---------------------------|
| G1R1C1 | 4       | 2       | 0.5     | 2.07%       | 0.92    | 4        | 64       | 2.065       | 10.3                      |
| G1R2C1 | 4       | 4.5     | 0.5     | 2.07%       | 0.92    | 4        | 65       | 2.097       | 12.1                      |
| G1R3C1 | 4       | 7       | 0.5     | 2.07%       | 0.92    | 4        | 64       | 2.065       | 10.3                      |
| G1R1C2 | 4       | 2       | 1       | 4.14%       | 0.92    | 4        | 78       | 2.516       | 34.5                      |
| G1R2C2 | 4       | 4.5     | 1       | 4.14%       | 0.92    | 4        | 73       | 2.355       | 25.9                      |
| G1R3C2 | 4       | 7       | 1       | 4.14%       | 0.92    | 4        | 72       | 2.323       | 24.1                      |
| G1R1C3 | 4       | 2       | 1.5     | 6.2%        | 0.92    | 4        | 90       | 2.903       | 55.2                      |
| G1R2C3 | 4       | 4.5     | 1.5     | 6.2%        | 0.92    | 4        | 94       | 3.032       | 62.1                      |
| G1R3C3 | 4       | 7       | 1.5     | 6.2%        | 0.92    | 4        | 86       | 2.774       | 48.3                      |
Table 5. Scour depth characteristics with debris for group 2.

| MODEL  | \( W_d/D \) | \( L_d/D \) | \( T_d/D \) | \( A_{Pd} \% \) | \( V/Vc \) | Duration hrs | \( d_{Ds} \) in mm | \( d_{Ds}/D \) | Increase \% in scour depth |
|--------|-------------|-------------|-------------|----------------|------------|-------------|----------------|--------------|--------------------------|
| G2R1C1 | 9           | 2           | 0.5         | 5.52%          | 0.92       | 4           | 72             | 2.323        | 24.1                     |
| G2R2C1 | 2           | 4.5         | 0.5         | 5.52%          | 0.92       | 4           | 71             | 2.290        | 22.4                     |
| G2R3C1 | 9           | 7           | 0.5         | 5.52%          | 0.92       | 4           | 80             | 2.581        | 37.9                     |
| G2R1C2 | 9           | 2           | 1           | 11.03%         | 0.92       | 4           | 89             | 2.871        | 53.4                     |
| G2R2C2 | 9           | 4.5         | 1           | 11.03%         | 0.92       | 4           | 102            | 3.290        | 75.9                     |
| G2R3C2 | 9           | 7           | 1           | 11.03%         | 0.92       | 4           | 93             | 3.000        | 60.3                     |
| G2R1C3 | 2           | 2           | 1.5         | 16.55%         | 0.92       | 4           | 109            | 3.584        | 89.7                     |
| G2R2C3 | 4.5         | 4.5         | 1.5         | 16.55%         | 0.92       | 4           | 118            | 3.806        | 103.4                    |
| G2R3C3 | 9           | 7           | 1.5         | 16.55%         | 0.92       | 4           | 117            | 3.774        | 101.7                    |

Table 6. Scour depth characteristics with debris for group 3.

| MODEL  | \( W_d/D \) | \( L_d/D \) | \( T_d/D \) | \( A_{Pd} \% \) | \( V/Vc \) | Duration hrs | \( d_{Ds} \) in mm | \( d_{Ds}/D \) | Increase \% in scour depth |
|--------|-------------|-------------|-------------|----------------|------------|-------------|----------------|--------------|--------------------------|
| G3R1C1 | 14          | 2           | 0.5         | 8.96%          | 0.92       | 4           | 73             | 2.355        | 25.9                     |
| G3R2C1 | 14          | 4.5         | 0.5         | 8.96%          | 0.92       | 4           | 72             | 2.323        | 24.1                     |
| G3R3C1 | 14          | 7           | 0.5         | 8.96%          | 0.92       | 4           | 70             | 2.258        | 20.7                     |
| G3R1C2 | 14          | 2           | 1           | 17.92%         | 0.92       | 4           | 95             | 3.065        | 63.8                     |
| G3R2C2 | 14          | 4.5         | 1           | 17.92%         | 0.92       | 4           | 104            | 3.355        | 79.3                     |
| G3R3C2 | 14          | 7           | 1           | 17.92%         | 0.92       | 4           | 106            | 3.419        | 82.8                     |
| G3R1C3 | 14          | 2           | 1.5         | 26.89%         | 0.92       | 4           | 122            | 3.935        | 110.3                    |
| G3R2C3 | 14          | 4.5         | 1.5         | 26.89%         | 0.92       | 4           | 139            | 4.484        | 139.7                    |
| G3R3C3 | 14          | 7           | 1.5         | 26.89%         | 0.92       | 4           | 137            | 4.419        | 136.2                    |

Fig (4). Scour percentage increases for debris groups
Fig (5). Stream wise length effects of debris on scour percentage increases

Fig (6). Rectangular debris during the test for group 1
3.3 Comparisons with existing empirical formulas

The measured scour depth with debris accumulation with the highest scour increases for all groups are listed in Table 7, which can be used to determine the critical shapes of debris for design purposes. From the table, the maximum increase in scour depth can be compared with respect to pier diameters, which ranged from 2D to 4.5 D. The increase in velocity due to restriction of the flow area and the variation of velocity according to the scour hole explain the variations seen in scour percentage increases. Different empirical formulas were used to evaluate related existing equations against these results. These equations were based on the results of experimental work under clear water conditions for debris accumulation around a single circular pier. Several different approaches to calculations to predict the scour at pier with debris are available: Melville and Dongol (1992) introduced the idea of equivalent pier width to reflect the effect of debris and, using the same methodology, Lagasse et al. (2009) proposed their equations and applied the resultant equivalent width in a common equation with Richardson and Davis (1995). Pagliara and Carnacina (2011) developed their formula based on the area obstructed by debris. Table 8 shows the equations used compared against the results for highest percentage scour in this study, where De is the effective pier diameter; Td is the debris thickness; Dd is the debris dimension with respect to the normal of flow; Y is the depth of flow; D is the pier diameter; Ld is the debris length; kd1 and kd2 are dimensionless factors for rectangular debris, 0.79 and -0.79, respectively; k1, k2,k3, and k4 are the shape factors, =1 for a circular pier, alignment factor =1 for no angle of attack, bed condition factor =1 for clear water scour, and armouring factor=1 for no armouring; and kd is the modification factor for scour depth in the presence of debris, which represents the ratio of scour depth with debris to scour depth for single pier. The Root Mean Square Error (RMSE) was used to evaluate the performance of the equations versus the measured data for the critical shapes’ max percentage increase in scour. According to RMSE, the lowest value is noted when the Richardson and Davis (1995) model is used with Lagasse et al. (2009), where RMSE =1.71, while the Melville and Dongol (1992) and Pagliara and Carnacina (2011) formulas introduce higher RMSE. Figure (7) shows the comparison between the predicted and measured data for the existing equations. In general, there was an over estimation in scour predicted with debris for all models. The variations of hydraulic conditions in the experimental work, the effect of debris length, which was ignored in Melville and Dongol (1992) and Pagliara and Carnacina (2011), and the limitations of the area obstructed by debris may explain these overestimations.

Table 7. Highest scour percentage increase for worst case in each group

| MODEL   | Wd/D | Ld/D | Td/D | Apd% | dDs in mm | dB/D | Increase % in scour depth |
|---------|------|------|------|------|-----------|------|--------------------------|
| G1R2C1  | 4    | 4.5  | 0.5  | 2.07 | 65        | 2.097| 12.1                     |
| G1R1C2  | 4    | 2    | 1    | 4.14 | 78        | 2.516| 34.5                     |
| G1R2C3  | 4    | 4.5  | 1.5  | 6.2  | 94        | 3.032| 62.1                     |
| G2R3C1  | 9    | 7    | 0.5  | 5.52 | 80        | 2.581| 37.9                     |
| G2R2C2  | 9    | 4.5  | 1    | 11.03| 102       | 3.290| 75.9                     |
| G2R2C3  | 9    | 4.5  | 1.5  | 16.55| 118       | 3.806| 103.4                    |
| G3R1C1  | 14   | 2    | 0.5  | 8.96 | 73        | 2.355| 25.9                     |
| G3R3C2  | 14   | 7    | 1    | 17.92| 106       | 3.419| 82.8                     |
| G3R2C3  | 14   | 4.5  | 1.5  | 26.89| 139       | 4.484| 139.7                    |
Fig (7). Comparison of observed and predicted scour depth based on existing formulas

Table 8. Existing formulas for scour prediction with debris

| Authors                  | Formulas                                                                 |
|--------------------------|--------------------------------------------------------------------------|
| Melville and Dongol (1992). | $D_e = \frac{0.52 \times T_d + D_d + (y - 0.52 \times T_d) \times D}{Y}$  \(\text{(2-a)}\) |
|                          | $d_e = 2.4D_e$ \(\text{for } Y/D_e > 2.6\) \(\text{(2-b)}\) \(\text{for } Y/D_e < 2.6\) \(\text{(2-c)}\) |
| Lagasse et al. (2009).   | $D_e = \frac{kd_1 \times T_d \times w_d \times (1)^{kd_2}}{y} + (y - kd_1 \times T_d) \times D$ \(\text{(3-a)}\) |
|                          | $D_e = \frac{kd_1 \times T_d \times w_d + (y - kd_1 \times T_d) \times D}{y}$ \(\text{for } L_d \leq 1\) \(\text{(3-b)}\) |
| Richardson and Davis (1995) | $d_{DS}/D_e = 2k_1 k_2 k_3 k_4 \left(\frac{Y}{D_e}\right)^{35} \times F_{r}^{43}$ \(\text{(4)}\) |
| Pagliara and Carnacina (2011). | $k_d = 1 + 0.036 \times A_{pd}^{1.5}$ \(\text{(5)}\) |
4. Conclusions

This study introduced new experimental work to help estimate the effect of debris around a circular pier and compared the results with the most commonly used existing formulas. Three groups of rectangular debris were investigated and the scour percentage increase as compared to the isolated pier without debris was used to evaluate the effect of debris. The main conclusions were noted as follows:

- The results showed an increase in scour depth percentage as the $A_{pD}\%$ increased (obstructed area of debris) for all groups. For group 1, as $A_{pD}\%$ increased from 2.07% to 6.2%, the scour depth increased from 10.3% to 62.1%, while for group 2, the scour depth increased from 22.4% to 103.4% as $A_{pD}\%$ increased from 5.52% to 16.55%; for group 3, the scour depth increased from 20.7% to 139.7% as $A_{pD}\%$ increased from 8.96% to 26.89%. These results explain the effect of increases in width and submerged depth of debris.

- The maximum effect of debris length was found at $T_{d}/D = 1.5$ and $L_{d}/D = 4.5$ for all groups, which may thus reflect the maximum scour increase percentage. According to the test observations, there was a clear decrease in scour depth beyond $L_{d}/D>4.5$, which may point to an increase in the velocity of flow over the critical velocity of bed material particle and sediment transport to the scour hole.

- The study examined nine debris shapes of rectangular cross section with maximum percentage scour depths increase, which can be used for design purposes.

- According to the pier diameter comparisons, the maximum scour depths with debris jam were 3.032D, 3.806 D, and 4.484 D for groups 1, 2, and 3, respectively.

- The comparison of measurements from the experimental work with the most common existing formulas for scour depth estimation with debris accumulation showed over prediction for Melville and Dongol (1992) and Pagliara and Carnacina (2011). The combination of Richardson and Davis (1995) and Lagasse et al. (2009) may be considered the most suitable formula for scour depth estimation with debris based on Root Mean Square Error (RMSE) evaluation (1.71) for the worst debris geometry.

- The countermeasures emplaced for bridge piers in worst cases should be investigated in order to develop a safe and optimal design for such foundations.

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