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Empirical Formulas to Predict the Maximum Scour Depth With Debris Accumulation Around A Single Cylindrical Bridge Pier: An Experimental Study

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KEYWORDS

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ABSTRACT

The probability of debris accumulation near bridge piers during the heavy storm and river flood convert the hydraulic action of flow and increase the scour depth due to the reduction of flow area and the increase in velocity of flow. In this paper, the effects of debris accumulation length, width and submerged depth on scour depth near bridge pier were investigated. An experimental study for three groups of woody debris accumulation was conducted under clear water condition to investigate the effects on maximum scour depth. The results showed that the increase of blocked area of debris to 27% increases the scour depth by approximately 140%. Furthermore, two empirical exponential formulas was proposed to predict the effect of debris on the maximum scour depth and the modification factor required for single pier. Well agreement was obtained for both derived formulas with coefficient of determination (R^2) of 0.96.

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1. Introduction

A considerable amount of woody logs may get into the river due to the banks erosion during flood and high intensity of rainfall with flood plain areas and the possibility of debris accumulation that will increase near bridge piers which produce different hydraulic flow conditions. The reduction of flow area and the increase in flow velocity as a result of debris jam raises the degree of hazard of bridge failure due to the development of scour depth in front of bridge pier. Many studies, however, have investigated this problem and the researchers tried to give a clear understanding of the flow behavior and scour development with debris accumulation, but there are many objectives that should be considered to give a simple and clear visions regarding this problem. Melville and Dongol [1] studied the effect of debris accumulation around a single bridge pier considering the cylindrical shapes. Proposed equations were conducted to predict the maximum scour depth depending on the depth of flow (Y). Also, the equivalent pier diameter (De) principle and design curve were introduced. This study showed that the maximum scour depth with debris accumulation can be estimated as 2.4De when Y/De ≥2.6. Lagasseet al. [2] conducted an experimental study to investigate the scour depth with different debris characteristics. Their study explained that the porosity and roughness of debris had insignificant effect on scour depth as compared with locations and geometry of debris. Pagliara and Carnacina [3] carried out a study to observe the temporal evolution of debris modification factors according to different shapes of debris and proposed a relationships with respect to contraction area by debris up to 13%. The maximum scour depth with debris was observed when the rectangular formation considered at single and pier groups as compared with other geometries of debris, Further, debris can reduce the scour depth when and act just as collar at relative submerged depth of 0.46 [4]. Pagliara and Carnacina [5] performed an experimental study to evaluate the change in the velocity and turbulence patterns when debris accumulated around a pier. They found a significant increase in the velocity pattern with 5% obstruction area of debris. The dune morphology was studied in the presence of debris jam near bridge pier by Pagliara and Carnacina [6]. They concluded that different types of dunes under clear water conditions. Their study showed that the difference of dune heights with flow intensity change. Also their study introduced formulas to assess the scour hole morphology with rectangular debris accumulation. According to Al- Khafaji, et al. [7] there was an obvious effect of floating debris on scour depth increase. Also, they found that the numerical modeling by using HEC-RAS model was over estimated to simulate the problem. Panici and de Almeida [8] investigated the debris formation based on the woody log length. According to their study, three types of formation were concluded called unstable, stable and critical. The researchers also proposed design figures to show the relationship between debris dimensions and Froud number of log length. Ebrahimi et al. [9] conducted an experimental study to show the effect of debris categories jam on maximum scour with the face of sharp nose piers which can be seen in historical and old bridges. They concluded that the maximum scour depth can be observed when the debris at the surface, while the minimum scour depth obtained when the debris is located with the bed level. The effect of debris of woody logs formation on the scour depth and back water rise were studied with extensive experimental work by Schalko et al. [10]. The results of the study agreed with the hypothesis of scour development decrease the water surface level. The importance of safety design, however, in such cases and hazard analysis and lack of studies related to the problem clarified in this section. This study was carried out to introduce a new empirical equations that show the effect of rectangular debris configurations on the scour depth with respect to debris geometry based on new experimental data and to clarify the risk of the increase in scour depth as compared with isolated pier.

2. Materials and Methods

I. Flume Characteristics

The experimental work was carried out in private hydraulic lab at The University of Kerbala, Iraq. All hydraulic requirements and lab facilities had been provided by the research team based on hydraulic engineering specialists Figure 1. A closed recirculating system of horizontal rectangular flume of (9.1, 0.70 and 0.5 m) in length, width and height respectively with head and sump tanks for the program tests of experimental work. The whole frame of channel was made from steel and highly transparence polyethylene wall was used for wall cladding, while a steel plate was fixed for the flume bed. Two sump tanks were used to supply the electric pump of 25 l/s maximum discharge, their dimensions are 1.6m length, 1.36m width and 0.7m depth. The head tank dimensions are 1.4m length 0.7m width and 0.8m depth. Two steel mesh were fixed inside the head tank to reduce the turbulence of entering water.

Figure 1: Experimental flume.

A calibrated volumetric flow meter was used to measure the discharge which was installed at the incoming pipe of the flume. A control valve was used to control the pump discharge and installed before the flow meter. The scoured zone was simulated by false bottom with 2.5 m length, 0.22m depth and 0.7m width with a cylindrical aluminum pier of 3.1 cm at mid distance length, 1.25 m of working section. To provide the proper transition between the entering water of flume and working section, an up stream ramp of steel box was made of (1.3m length, 0 .7m width and 0.22 m depth) and a thin layer of concrete (0.05m) was covered the top surface of the ramp. Also a steel box of 0.7m×0.7m was built in at the working section with upper concrete thin layer similar to that covered of upstream to give the same roughness for inlet and out let of the section. To adjust the required depth, a sluice gate was fixed at the end of the flume, and a digital point gauge (0.01mm precision) was installed on a trolley steel frame to measure the maximum scour depth.

II. Bed Material Characteristics and Hydraulic Conditions

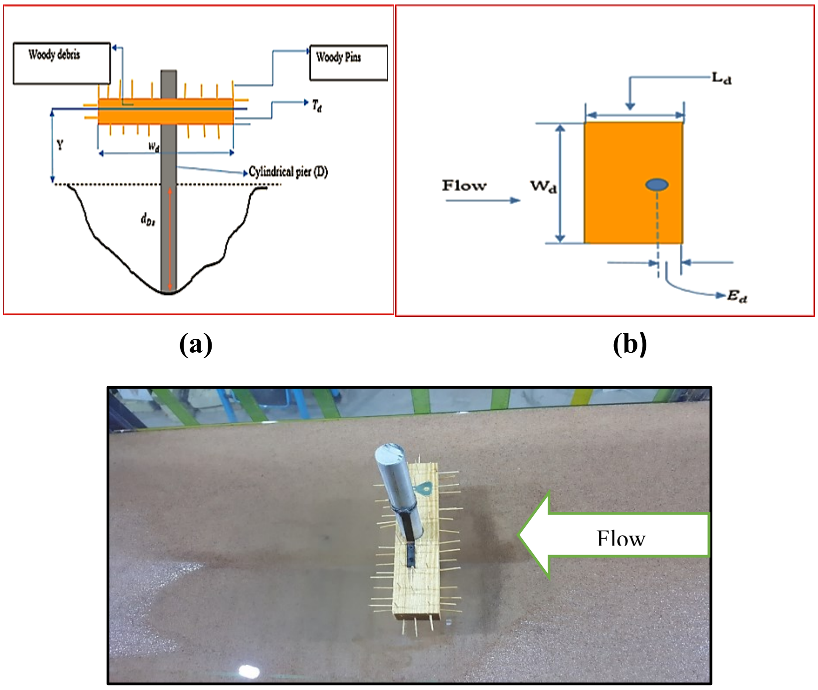
The bed material has been modeled by a non-cohesive sediment which fills the working section or scour zone. Table I shows the main characteristics of sediment used in this study. A series of tests and sieve analyses were carried out to ensure the required sediment for the experimental work. Accordingly, the median size (d_50) of the sand particle was 0.716 mm and the geometric standard deviation was uniform 〖σ〗_g<1.3, so the influence of ripples formation and armoring can be ignored. The clear water conditions was considered with flow intensity v/v_c=0.92 [11, 12]. In addition, the initiation of motion of bed material particle (v_c) was calculated according to Melville [13] recommendations of critical velocity for d_50= 0.716mm. All tests were performed under the same water depth of 10 cm, which satisfies the required hydraulic condition for maximum scour depth. 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≤ Y/D≤4). In addition, a pier diameter of 3.1cm was selected to omit the coarseness and side wall effect (25≤D/d_(50)≤130) and (D/B≤0.1), where B is the channel width. By considering these hydraulic conditions, however ,the flow rate was adjusted as 20.6 l/s, which means the control of turbulence during the test and ignoring the effect of pier Reynolds number (R_P=(V D)/ν ≥ 7000), where V is the average velocity in the channel and ν is the kinematic viscosity, [1,11, 14, 15].

TABLE I: Main characteristics of tested bed material.

Material	d_{50} (mm)	d_{84} (mm)	d_{16} (mm)	σ_g
Sand	0.716	0.85	0.516	1.283

III. Simulated Debris Characteristics

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 a 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 (2010) as 〖A〗_Pd=((W_d-D)× T_d)/(B×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 2. Each surface of simulated debris was roughed by a thinly pins of 1.5 mm diameter and average length of 3 cm with average density of one pin for every 6.25 cm^2 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 were elaborated in Table II, [2, 3, 4]. The width of debris was the main parameter for dividing groups, the ratio of debris width to the pier diameter was W_d/D = 4, 9 and 14 for group 1, 2 and 3 respectively. For each group the ratio of stream wise length was varied accordingly L_d/D from 2 to 7 with different submerged ratio depth T_d/D from 0.5 to 1.5.



(a) **(b)**

(c)

Figure 2: Debris configurations and dimensions. (a), transverse section, (b) top view, and (c) at experiments.

TABLE II: Characteristics of debris dimensions.

W_d	L_d	T_d	A_{pd} %
4-14	2-7	0.5-1.5	2.1-26.89

IV. Dimensional Analysis

According to Melville and Chiew [16], the scour around bridge piers is a function of major parameters which contains fluid flow parameters, sediment parameters, time effect with respect to the equilibrium time and pier geometry. The accumulation of debris add a new parameters to the analysis and the configurations of debris shapes and dimensions should be taken in the consideration. By using these parameters, the maximum scour depth function for a single pier will be f (d_Ds,ρ, V,μ, Y,g,, d_50, ρ_s, V_C, t_e, D, W_d, L_d, T_d)=0, where d_(Ds,) μ and t_e are the maximum scour depth with debris, dynamic viscosity and time of equilibrium, while the other parameters were elaborated previously. Buckingham π-theorem [17] was used in the analysis and the max depth of scour that reflects the effect of debris configuration at v/v_c=0.92 will be as follows:

$$d_{Ds/D} = \mathrm{f}\,(W_d/\mathrm{D}, L_d/\mathrm{D}, T_d/\mathrm{D}) \quad (1)$$

The modification factor required for scour depth of isolated pier (ds) to consider debris accumulation is

$$KD_{ds}=\frac{d_{Ds}}{d_s}=\text{f}\,(W_d/\text{D}, L_d/\text{D}, T_d/\text{D}) \quad (2)$$

V. Methodology of Tests

The preparations for experimental work include many steps to achieve the tests correctly. Firstly, the scoured zone of the working section was levelled carefully to the required reference elevation, then the debris models have been tied properly to the pier and adjusted to the desired height of test. A guardedly filling of water to flume was considered up to the required discharge. Also, the sluice gate was adjusted to target water depth in the flume of (10cm), and the starting time was recorded when the target depth verified. Finally, a slow drain was performed after each test and the measurements of scour depth will be observed.

3. Results Analysis and Discussion

I. Duration of Test

The measured scour with time with respect to single pier without and with debris was illustrated in Figure 3. Looking into this figure, significant increase of scour depth with time can be clearly noticed during the first 3hrs. Subsequently, development of scour tends to be constant. It is obvious from the curve of scour–time evolution, and after 3.5 hrs of test, the rate of change was less than 0.03D as compared with 6hrs, so the 4hrs duration was suitable to investigate the objective of study [18] . In spite of many definitions for the equilibrium time of scour that may take long hours of test execution, but at 10% of time of equilibrium, the scour depth may increase to approximately 50 - 80% of the max scour, also the economic factors should be considered to select the optimal test time [16, 19].

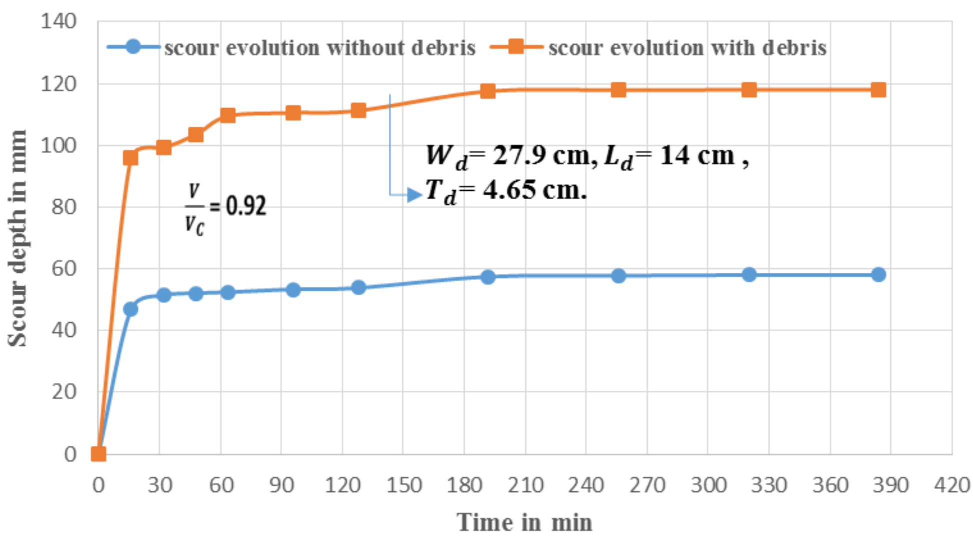


Figure 3: Maximum scour evolution curves.

II. Scour Depth for Single Pier without Debris

Table III shows the maximum scour depth according to related hydraulic conditions for single pier without debris which can be considered as a comparative case with debris accumulation where Fr, Fp and Fd are Froude numbers for flume, pier and sediments respectively, while d_s is the scour at the face of pier without debris. In this study, the water level increased by Δh 8% at the distance of at 14D from the upstream face of pier and the maximum scour depth was 58 mm. Gradually decrease in water profile was noted after the distance 14D from the upstream face of pier until the target depth of 10 cm. From these results, the unobstructed section for negligible effect of pier on water rise level can be considered beyond 14D which can be considered for water profile analysis in bridge construction and for comparisons with the unobstructed section of 10D which introduced by Pagliara and Carnacina [3] . The increase in water rise level reveal the effect of the bow waves which are in the opposite direction of horse shoe vortex. The variation in water surface profile became in significant as the scour hole increase and the maximum scour obtained due to increase in flow area and decrease in velocity head.

TABLE III: Maximum scour depth for single pier without debris.

d_s (mm)	v/v_c	Duration (hrs)	$F_r = \sqrt{\frac{V}{gy}}$	$F_p = \sqrt{\frac{V}{D}}$	$F_d = \sqrt{\frac{V}{g\,d_{50}}}$	Q (l/s)	Max water rise (cm)
5	0	4	0.298	0.535	3.52	2	10.8

III. Scour Depth Characteristics with Debris Accumulations

The results of tests according to the dimensional analysis for all groups can be elaborated in Table IV. The significant increase in scour depth with debris jam can be clearly noticed as compared with the reference test. The maximum increase in scour depth percentage was 62.1%, 103.4%, and 139.7%, while the minimum was 10.3%, 22.4% and 20.7% for group 1, 2 and 3 as A_Pd% increased from 2% to 27% respectively. The variations in debris dimensions at different groups can be used to explain the effect of width, depth and length. The effect of width and depth can be summarized by the A_Pd% which is width and depth representations, Figure 4. It is obvious from Figure (4), the ranges of increase in scour depth for each group which can be used for design criteria purposes. The effect of stream wise length of debris was shown in Figure 5. For all groups, the maximum effect of debris length can be found at fully submerged depth T_d "/D =1.5" and L_d/ D=4.5 which can be considered as a critical ratio 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. From the observation of test at these conditions for L_d/ D>4.5, sediment particle move to scour hole and reduce the scour percentage increase which may refer to the increase in velocity beyond initiation of motion for sediment particle. Figure 6 shows the scour hole obtained due to debris accumulation of group 1 at L_d/D=2 and T_d "/D =0.5." By looking at Table IV, worst cases design can be concluded, by considering the stream wise length ratio for the same submerged depth ratio. For group 1, the maximum effect of debris can be noted in the models G1R2C1, G1R1C2 and G1R1C2, while for group 2 in models G2R3C1, G2R2C2 and G2R2C3 and for group 3 in models G3R1C1, G3R3C2 and G3R2C3. These results explained the effect of geometry of the debris with width, depth and stream wise length on scour depth, which may give new methodology for risk analysis in scour problem and bridge hydraulic according to the importance of the case study under clear water condition. Also, the results confirming the highly effect of width and depth of debris cluster around bridge piers obtained by [1, 3] .

IV. Developing of the New Formulas

Through the results obtained in Table IV, statistical analysis by multiple nonlinear regression was applied to derive the new formulas. The computer program package IBM SPSS 24 (Statistical Package for the Social Science) was utilized for both training and testing parts by using two sets of data. The training part included about 67% of experimental results, while other 23% was used for testing. The best form model was obtained after many trials depending on the goodness of the relation for scour prediction with debris accumulation which can be reached as the following:

$$d_{Ds/D} = b_1 \times exp\{(b_2 \times (W_d/D)^{c_1}) \times (b_3 \times (L_d/D)^{c_2}) \times (b_4 \times (T_d/D)^{c_3})\} \quad (3)$$

By the same approach, the modification factor required for scour depth of isolated pier to consider debris jam can be written as following:

$$KD_{ds} = g_1 \times exp\{(g_2 \times (W_d/D)^{e_1}) \times (g_3 \times (L_d/D)^{e_2}) \times (g_4 \times (T_d/D)^{e_3})\} - g_5 \quad (4)$$

TABLE IV: Characteristics of maximum scour depth with accumulation of debris for a duration of 4 hrs.

MODEL	W_d/D	L_d/D	T_d/D	A_{Pd}%	V/Vc	d_{Ds} (mm)	$d_{Ds/D}$	KD_{ds}
G1R1C1	4.0	2.0	0.5	2.07	0.92	64	2.065	1.103
G1R2C1	4.0	4.5	0.5	2.07	0.92	65	2.097	1.121
G1R3C1	4.0	7.0	0.5	2.07	0.92	64	2.065	1.103
G1R1C2	4.0	2.0	1.0	4.14	0.92	78	2.516	1.345
G1R2C2	4.0	4.5	1.0	4.14	0.92	73	2.355	1.259
G1R3C2	4.0	7.0	1.0	4.14	0.92	72	2.323	1.241
G1R1C3	4.0	2.0	1.5	6.20	0.92	90	2.903	1.552
G1R2C3	4.0	4.5	1.5	6.20	0.92	94	3.032	1.621
G1R3C3	4.0	7.0	1.5	6.20	0.92	86	2.774	1.483
G2R1C1	9.0	2.0	0.5	5.52	0.92	72	2.323	1.241
G2R2C1	9.0	4.5	0.5	5.52	0.92	71	2.290	1.224
G2R3C1	9.0	7.0	0.5	5.52	0.92	80	2.581	1.379
G2R1C2	9.0	2.0	1.0	11.03	0.92	89	2.871	1.534
G2R2C2	9.0	4.5	1.0	11.03	0.92	102	3.290	1.759
G2R3C2	9.0	7.0	1.0	11.03	0.92	93	3.000	1.603
G2R1C3	9.0	2.0	1.5	16.55	0.92	110	3.548	1.897
G2R2C3	9.0	4.5	1.5	16.55	0.92	118	3.806	2.034
G2R3C3	9.0	7.0	1.5	16.55	0.92	117	3.774	2.017
G3R1C1	14.0	2.0	0.5	8.96	0.92	71	2.29	1.224
G3R2C1	14.0	4.5	0.5	8.96	0.92	70	2.258	1.207
G3R3C1	14.0	7.0	0.5	8.96	0.92	68	2.194	1.172
G3R1C2	14.0	2.0	1.0	17.92	0.92	95	3.065	1.638
G3R2C2	14.0	4.5	1.0	17.92	0.92	104	3.355	1.793
G3R3C2	14.0	7.0	1.0	17.92	0.92	106	3.419	1.828
G3R1C3	14.0	2.0	1.5	26.89	0.92	122	3.935	2.103
G3R2C3	14.0	4.5	1.5	26.89	0.92	139	4.484	2.397
G3R3C3	14.0	7.0	1.5	26.89	0.92	137	4.419	2.362

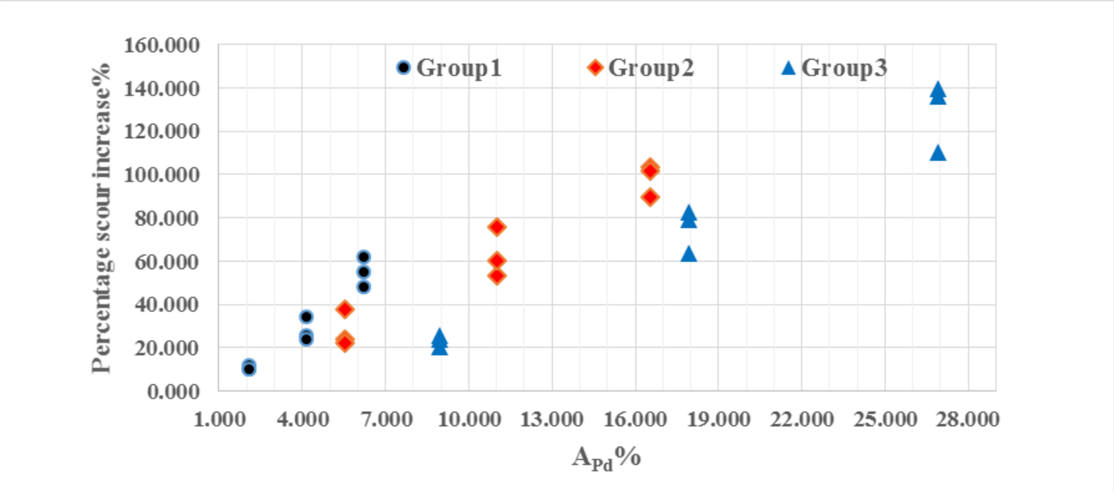


Figure 4: Scour percentage increase.

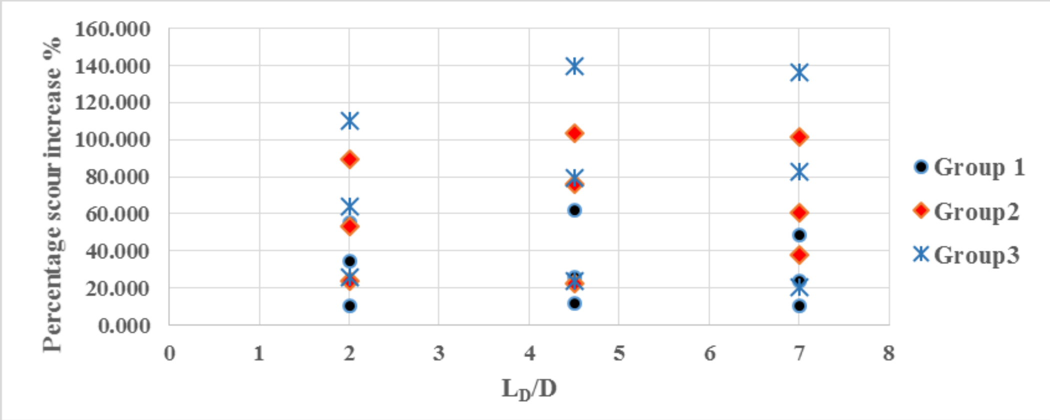


Figure 5: Stream wise length effect of debris.

Figure 6: Scour hole of debris accumulation of group 1, L_d/D=2 and T_d "/D =0.5" .

Where b_n,c_n,g_n and e_n are the calibrated constant parameters and n is the sequences indicator. The SPSS multiple nonlinear regression adjusted and optimized the constants mentioned previously after the initial suggested values to get best coefficient of determination R^2, so the new derived formulas can be written as following:

$$d_{Ds/D}=1.463 \times exp\{(2.189 \times (W_d/D)^{0.309}) \times (0.055 \times (L_d/D)^{0.073}) \times (2.718 \times (T_d/D)^{0.647})\} \quad (5)$$

$$KD_{ds} = 1.523 \times exp\{(1.123 \times (W_d/D)^{0.375}) \times (0.09 \times (L_d/D)^{0.089}) \times (1.574 * (T_d/D)^{0.785})\}-0.7 \quad (6)$$

The coefficient of determination R^2 for both Eq (5) and Eq (6) was 0.96. To analyze and compare the obtained formulas mentioned above, three statistical indicators were used for testing phase which contained the correlation coefficient (R), root mean square error (RMSE) and mean absolute error (MAE), [20] that can be written as following:

$$R=\frac{\sum_{i=1}^{N}(M_i-M^-)*(P_i-P^-)}{\sqrt{\sum_{i=1}^{N}(M_i-M^-)^2*\sum_{i=1}^{N}(P_i-P^-)^2}} \quad (7)$$

$$RMSE=\sqrt{\frac{\sum_{i=1}^{N}(P_i-M_i)^2}{N}} \quad (8)$$

$$\text{MAE}=\frac{\sum_{i=1}^{N}|P_i-M_i|}{N} \tag{9}$$

Where M_i and M^-the measured and the mean value are for the results of experimental work, while P_i and P^-are the predicted and the mean value for the results of the new proposed formulas respectively and N is the number of the input data. It can be seen that predicting results by the new formulas conducted, show well agreement with the measured results, Figures (7) and (8). The values of R, RMSE and MAE can be listed as 0.982, 0.189 and 0.144 for Eq (5), while they were 0.982, 0.101 and 0.077 for Eq (6). The proposed formulas contain new parameters for scour depth analysis which clarify the effect of debris accumulation around single pier near threshold velocity for initiation of motion under clear water conditions. These formulas take into account the effect stream wise length of debris accumulation with in the new ranges of validity which can be used for comparisons with other formulas to ensure optimal design without over or under predicting.

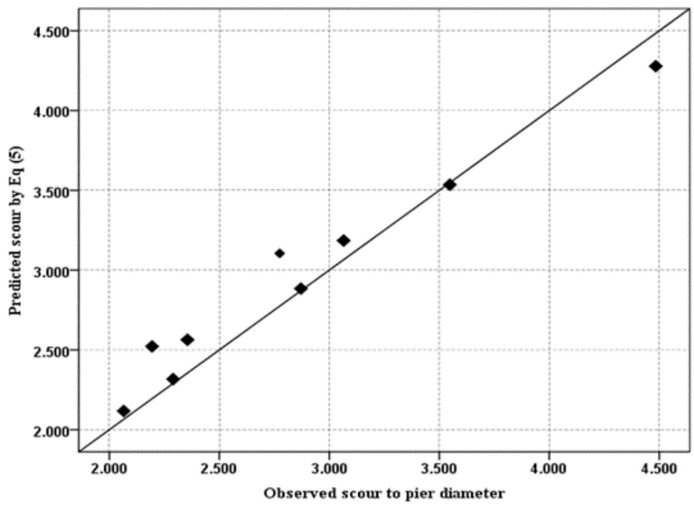


Figure 7: Comparison between observed and predicted scour depth with debris by Eq (5).

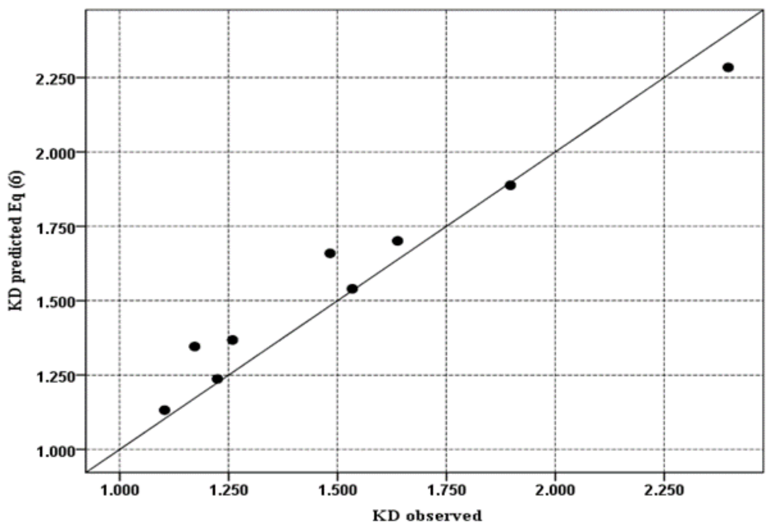


Figure 8: Comparison between observed 〖KD〗_ds and predicted by Eq (6).

4. CONCLUSIONS

In this study, the effect of debris jam around a single cylindrical pier on maximum scour depth was investigated experimentally and the main parameters of debris length, width, and submerged depth were studied according to the dimensional analysis. According to the results of experiments, and the proposed regression models, the main conclusions can be summarized as follows:

The blocked area by debris may consider a good way of comparison for scour depth increase due to the contraction of flow area and that clearly noticed when the scour depth increased up to 140% as A_Pd% increased up to 27%.

The maximum effect of stream wise length of debris accumulation can be found at L_d/D=4.5 and fully submerged depth 〖T〗_d "/D =1.5", an obvious decrease in scour depth for all groups of experimental work when L_d/D≥4.5 was observed.

The new derived empirical formulas for scour depth prediction with debris effect and the modification factor required, introduce new approach for debris jam analysis around single pier under clear water condition, which allows to use the main dimension of debris (W_d/ D, L_d/ D, T_d/"D"). The including of all dimensions of debris with new experimental ranges and simplicity in use may lead to accurate prediction as compared with the available equations that depends mainly on effective pier diameter which was performed by Melville and Dongol [1] or obstructed area of debris which was conducted by Pagliara and Carnacina [3].

More consideration should be taken for scour prediction with debris jam in order to have safe design of scour depth and to avoid bridges failure.

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