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EXPERIMENTAL STUDY OF SCOUR DOWNSTREAM TWO PARALLEL CULVERTS

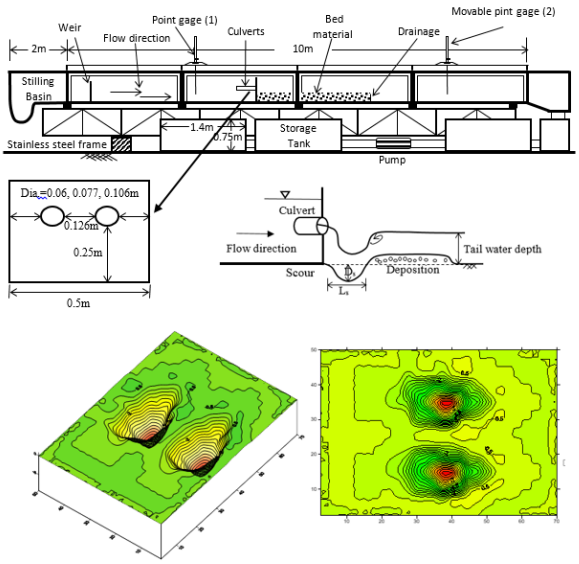
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Graphical abstract



Abstract

An experimental study was conducted to investigate scour downstream of two parallel circular culverts, where the culvert spacing was equal to the distance between the channel wall and the culvert edge. The study focused on scour hole characteristics, specifically depth and length, under varying conditions. Experiments were performed using three aggregate sizes with median diameters (D_{50}) of 3.25 mm, 4.5 mm, and 7.5 mm as the downstream bed material. Three culvert diameters (60 mm, 77 mm, and 106 mm) were tested for each aggregate size. Results indicated that increasing discharge led to greater scour depth and length, whereas larger bed material reduced the dimensions of scour. At higher discharges, overlapping scour holes formed beneath the culvert gates. Two empirical equations were derived to estimate relative scour depth and length.

Keywords: Circular culverts, Erosion, Aggregation beds

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1.0 INTRODUCTION

Water resources are one of the most important requirements for continuing human life [1]. Culverts are essential hydraulic structures that allow stream, river, or channel flows to continue beneath obstructions such as roads, railways, and industrial areas [2]. They are critical for ensuring safe waterway crossings in road construction. However, undersized culverts are often built without considering the scour caused by the high-velocity water jet exiting the culvert. This continuous scouring at the downstream outlet can lead to culvert failure and damage to adjacent infrastructure.

Predicting scour geometry—particularly the depth and length of the scour hole at the culvert outlet—is crucial for protecting downstream areas from erosion and sediment deposition. While the prediction of scour and energy dissipation in hydraulic structures remains complex [3], extensive research has been conducted on scour processes around and downstream of various hydraulic

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structures. However, studies specifically examining scour hole characteristics downstream of two parallel culverts remain scarce in the literature [4]. Moreover, Erosion is one of the most important worldwide environmental concerns [5]

Others have studied scour phenomena downstream of culverts. Ali and Lim [6] investigated scour processes, while Ali et al. [7] measured average velocity profiles along the centerline of scour holes downstream of two- and three-dimensional outlets. Siow-Yong Lim examined local scour beneath single-culvert outlets, considering the culvert as a wall jet under full-flow conditions with an unsubmerged jet. The study aimed to characterize scour hole geometry downstream of culverts [8].

Day et al. [8] analyzed the influence of tailwater depth on scour hole formation downstream of culverts, identifying it as a critical parameter. Their findings showed that tailwater depth significantly affects maximum scour depth when the ratio of downstream tailwater depth (H) to culvert diameter (D_{cuv}) ranges between 0.5 and 2, and the densimetric Froude number (F_0) varies between 2.5 and 10. Liriano et al. [9] presented turbulent flow measurements at scour holes downstream of pipe culverts at various development stages.

An experimentally study on the effect of hydraulic variables on scour in cohesive soil caused by turbulence was conducted by Mazurek [10]. A single cohesive soil was used in this set of experiments with different jet's thickness and velocity. Maximum depth, its location, and length of scour hole were measured. Similarly, Ghodsiane et al. [11], Presented the scour downstream rectangular jet after impinging in a uniform cohesive bed. They investigated the effect sediment discharge, water discharge, and tailwater depth on the scour. The densimetric Froude number, the sediment discharge to water discharge and the drop height to tailwater depth were found is a function of scour. In addition to that, the scour depth increases with increasing the water flowrate and decreases with increasing the sediment load in the water jet. Moreover, the initial scour depth increases with increasing the depth of the tailwater and the reduction [12]. The studied of scour depth downstream outlets of culverts, an ANFIS was applied by using a sets of experimental measurement data of different literature sources. It was found that the ANFIS model was more effective compared with regression analysis and the ANN model [13].

Moreover, the study of the level of the bottom of the channel below the channels is one of the effective parameters in the terrain at different time periods. The study showed that the percentage of change in the maximum depth of erosion decreased as the time of the experiment increased [14].

Israa Jawadand Thamer Mohammad, studied an experimental work that was conducted to investigate the impact of flow atres on maximum scour depth downstream sharp crested weir. They acknowledge that the local scoure at the hydraulic structures is considered a problem which effect at the safety and stability of the structure[15].

The objectives of this study are to conduct an inquiry into the local scour downstream of the hydraulic structure of the two parallel culverts, with specific emphasis on the geometry of the scour hole in terms of depth and length. Additionally, the study aims to quantify both the maximum scoure depth and length under different flow conditions. Understanding these parameters is considered a key point that helps improve the design and stability of the parallel culvert structure by minimizing the risk of scoure and sedimentation downstream the hydrulic structures.

2.0 METHODOLOGY

The experiments were conducted at the Hydraulics Laboratory of University of Mosul – Dam and Water Resources Research Center. A hydraulic channel consisting of stainless-steel frame, 10-m-long, 0.5-m-wide, and 0.65-m-high rectangular channel, the side walls of the channel sections are made of tempered glass. a 2-m-long, 0.5-m-wide inlet basin upstream the channel was constructed to reduce turbulence, [16]. At the upstream of the channel after 3-m from the inlet 0.4-m-high sharp crest weir was installed to measure the inflow discharge that release to each experiment. Metal rail installed on the top of two side channel to hold a two-point gages, (1 and 2) which were used to measure the water depth at top of the upstream weir crest and scour hole at downstream culverts respectively.

The system operated within a closed water circuit, consisting of a series of water tanks and a pump capable of delivering a maximum discharge of 60 L/s. Figure 1(a) presents a schematic side view of the experimental channel. Before starting the experiments, discharge was measured using the volumetric method, and the following equation was developed [17].

$$Q = \frac{2}{3} C_d \sqrt{2g}\, L\, H^{3/2} \qquad [1]$$

where
Q = Flow rate (m3.s-1).
Cd = 0.86, Discharge coefficient.
L = 0.5 m, the weir length.
H = Depth of water over crest weir (m).

Two parallel culverts (pipes), with three different diameters of the culverts (0.06, 0.077, & 0.106) m, were fixed in a rectangular plate 0.5 by 0.5 m, and this build was installed at 4 m from the beginning of the channel. The distances between the channel walls to the center of the culverts for each diameter were (0.156, 0.153, & 0.149) m, and between center to center of the culverts is (0.186, 0.192, 0.202) m,

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respectively. The vertical distance between the centers of the culverts to the original bottom of the channel was 0.25 m as shown in Fig. 1(b), and 0.1 m to the upper surface of the gravel bed. A rectangular drainage 0.5 m-wide and 0.15 m-high was installed 1.5 m from the culverts. This drainage was a rectangular wood with a systematic hole with a 0.005 m diameter to help the water in the bed to drain, and the rest of water has free fall. The gravel had been laid downstream the culverts to the drainage with a 1.5-m length, 0.15 m-depth, and 0.5 m width. Three different sizes of gravel, with uniform bed material, had been used with average diameter (0.00325, 0.0045, 0.0075) m. And three different diameters of the two culverts (0.06, 0.077, 0.106)m. A bubble level was used to check the level of the upper surface of the gravel. The free distance between the bottom of the culverts and the upper level of the bed was 0.1 m.

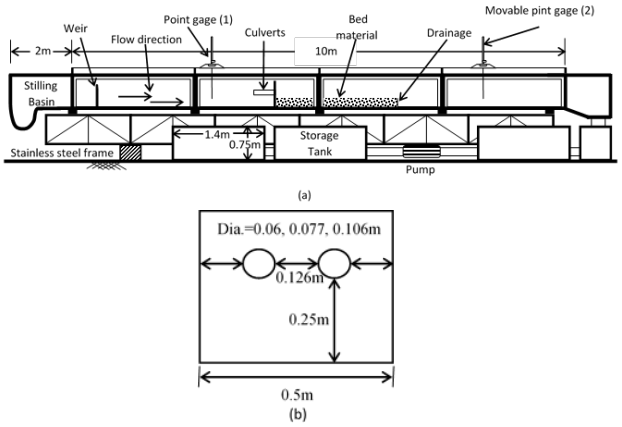


Figure 1 Experimental setup: (a) schematic side view; (b) schematic plan view of culverts, d=0.06m. (Not to scale) OSD display on the ground control station

The experimental procedure began by leveling the downstream bed surface, which was established as the zero-reference level for all subsequent measurements. This represents the initial condition with no erosion or deposition. Erosion was defined as any lowering below this level, while deposition was any accumulation above it. Before each experiment, the two-point gauges (1 and 2) were calibrated at the weir crest and the downstream bed surface, respectively.

For each bed material size, five different discharge rates, 2.2, 3.0, 3.75, 4.6, and 5.5 L/s, were tested.

The water flow condition at the downstream of the channel was clear for all experiments to be sure there is no bed material moved downstream the scour hole, Table (1)shown the flow velocity (V) to the critical velocity of bed material initiation to motion (Vc)

Table 1 The ratio of V/Vc

Q (l/s)	D_{50} (m)	V/Vc	D_{50} (m)	V/Vc	D_{50} (m)	V/Vc
2.2		0.7		0.59		0.65
3.0	3.25E-3	0.73	4.5E-3	0.61	7.5E-3	0.67
3.75		0.75		0.62		0.68
4.6		0.78		0.64		0069
5.5		0.8		0.66		0.71

The flow intensity parameter (V/Vc) for all the experiments was less than one (V/Vc<1), which demonstrated that sedimentation was stopped at specific points after the scour hole downstream the culverts. The critical shear velocity (U_{*c}) at the downstream the scour hole in the main channel were calculated by using the shield's diagram with avrage (0.052-0.075)m/s [18]. And the critical velocity of bed materials starting the motion was between (0.42-0.60), which were estimated by applying Melville and Suterland (1988) equation (2) [19],[20].

$$\frac{Vc}{U_{*c}} = 5.75 \log\left(5.53 \frac{Y}{D_{50}}\right) \quad [2]$$

The level of water at the upstream was above the culverts hole, and the flow at the beginning inside the culverts was full. The flow in the culverts was subcritical flow, and the Froude number (Fr) ranged between 0.12 and 0.86 except two cases where the values exceeded one (when D_{CUV} =0.6 and discharge 4.6 and 5.5 l/s). The downstream end of the channel was open allowed for free-fall drainage, eliminating tailwater effects, moreover it was constant for all the cases with same discharge. The experiment duration was determined by two criteria: (1) the flow reaching a steady-state condition, and (2) the cessation of sediment movement in the downstream bed. A video camera was used to monitor erosion and detect any anomalies [21].

During each experiment, a scour hole formed immediately downstream of the culverts, followed by sediment deposition beyond the hole. The experiment was stopped once visual inspection confirmed no further erosion or deposition. After shutting down the pump, the setup was left to drain, ensuring all water exited the channel and scour hole. Scour and deposition depths were measured using point gauge 2. A grid of measurement points, spaced 0.025 m × 0.025 m longitudinally and transversely, was established downstream of the culverts. At each intersection, scour and deposition depths were recorded. The scour hole length was measured using a measuring tape for each experiment. These measurements provided a detailed representation of the scour hole geometry, identifying maximum scour depth and its location.

Two scour holes formed downstream due to the two culverts. In most experiments, their maximum depths were nearly identical, and an average depth was used for measurements and analysis. The same

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approach was applied to determine scour hole length.

Specialized software was used to visualize and illustrate the scour hole geometry, as shown in Figure 3 [22].

Model for Scour Depth and Length

The reduction in the depth and length of scour hole at downstream culverts, Ds and Ls, is considered to be a function of the flow discharge, characteristics of bed material, and flow characteristics. The Buckingham II Theorem [23], can be used to propose a non-dimensional relationship between the depth and length of the scour hole as dependent variables and the independent variables. The functional relationship between the dependent and the independent variables can be expressed as shown:

$$Ds = f\ (Q, D_m, D_{cuv}, \rho s, \rho w, \mu, g) \quad [3]$$

$$Ls = f\ (Q, D_m, D_{cuv}, \rho s, \rho w, \mu, g) \quad [4]$$

where, Ds and Ls are the depth and length of scour hole, the dependent variable, and independent variable, Q is the flow discharge, D_m is the mean diameter of bed material, D_{cuv} is the culverts diameter, ρs is the density of substance (bed material), ρw is density of water, μ is the dynamic viscosity, g is the gravitational acceleration. The non-dimensional form of equations (3) is found to be

$$\frac{D_s}{D_{cuv}} = f\left(\frac{D_m}{D_{cuv}}, Fr, \frac{\rho_s}{\rho_w}, Re\right) \quad [5]$$

And for equation (4) the length of scour hole is found to be

$$\frac{L_s}{D_{cuv}} = f\left(\frac{D_m}{D_{cuv}}, Fr, \frac{\rho_s}{\rho_w}, Re\right) \quad [6]$$

Where:

D_s/D_{CUV} : The ratio of the depth of scour to culverts diameter.

L_s/D_{CUV} : The ratio of the length of scour to culverts diameter.

Fr: Froude number, which equals $\left(\frac{g D^5_{cuv}}{Q^2}\right)$.

Re: Reynolds number, which equals $(Q\ \rho/\mu\ D_{cuv})$.

ρ_s/ρ_w : The ratio of the density of bed material to the density of water. However, the ratio was neglected because it has the same density and constant value. The equations 5 and 6 be written as

$$\frac{D_s}{D_{cuv}} = f\left(\frac{D_m}{D_{cuv}}, Fr, Re\right) \quad [7]$$

And

$$\frac{L_s}{D_{cuv}} = f\left(\frac{D_m}{D_{cuv}}, Fr, Re\right) \quad [8]$$

Although there were three different diameters of culverts used, the distance between the centers of the culverts was equal and constant. This makes the effect of water falling on the gravel bed fall into one point, which is the location of the maximum point of scour. Therefore, this parameter doesn't affect the max depth of scour and is not included in the equations.

Furthermore, the values of geometric standard deviation (σ_g) for the samples is about 1.2 which is considered very uniform and the flow condition remain quasi-steady. Add to that the flow velocity are almost low to provide local acceleration effects negligible compeered to drag and viscous resistance with pours media. In addition to that, the porosity of the bed material is assumed to be constant almost and the variation in void ratio du to extension are expected to be very small. As a results the equations were generated whatnot considered the sedimentary media.

3.0 RESULTS AND DISCUSSION

A steady-state flow condition was monitored using the first point gage. The measurements focused on a scour hole at two locations downstream of each culvert. The maximum depth and length of the scour hole were recorded after erosion and deposition had stabilized. Figure 2 shows a schematic side view of the scour hole.

The depth of scour (Ds) and the length of the scour hole (Ls) were analyzed by comparing results from experimental runs conducted with varying average bed material diameters (D_m) and discharge rates (Q). Table 2 presents the experimental conditions and results.

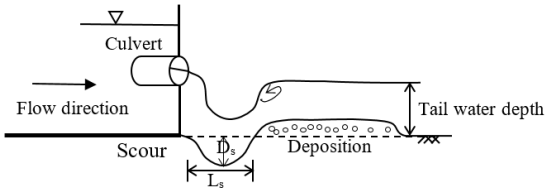


Figure 2 The schematic side view of the scour hole

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Table 2 Summary of experiments

Experiment number	Average diameter of the bed material (m) *E-3	Culverts diameter (m) *E-2	Depth of scour hole, Ds (m) *E-2	Length of scour hole, Ls (m) *E-2	Discharge (l/s)
1	0.325	6.0	3.9	18	2.2
2			5.5	21	3.0
3			8.1	32	3.75
4			8.7	35	4.6
5			9.3	38	5.5
6		7.7	2.7	15	2.2
7			4.9	17	3.0
8			7.0	25	3.75
9			8.6	30	4.6
10			9.0	37	5.5
11		10.6	2.6	14	2.2
12			4.4	16	3.0
13			6.5	22	3.75
14			7.7	28	4.6
15			8.5	33	5.5
16	0.45	6.0	3.0	14.4	2.2
17			4.1	16.8	3.0
18			6.2	25.6	3.75
19			7.1	28.2	4.6
20			7.7	30.8	5.5
21		7.7	2.2	12.4	2.2
22			4.0	13.6	3.0
23			6.1	20.3	3.75
24			7.1	23.8	4.6
25			7.9	30.0	5.5
26		10.6	1.9	11.4	2.2
27			3.7	12.8	3.0
28			5.2	17.6	3.75
29			6.4	22.4	4.6
30			7.1	26.6	5.5
31	0.75	6.0	2.5	12.6	2.2
32			3.1	14.9	3.0
33			5.1	22.6	3.75
34			5.7	24.2	4.6
35			6.2	26.9	5.5
36		7.7	1.9	10.7	2.2
37			3.3	12.2	3.0
38			4.6	17.1	3.75
39			5.9	21.3	4.6
40			6.1	26.2	5.5
41		10.6	1.8	10.1	2.2
42			2.9	11.4	3.0
43			4.4	15.7	3.75
44			5.0	20.0	4.6
45			5.7	23.4	5.5

Effect of Dimensional Variables on Scour Hole:

The dimensional variables have a significant effect on the characteristics of the scour hole. The primary factors influencing the scour hole are flow rate (Q) and the mean diameter of the downstream bed material (D_m) [24]. The discharge has direct proportion and clear effect on increasing the depth and length of scour hole, table 3 and 4 shown the change of percentage flowrate increase with increasing in the depth and length of scour, these findings were agreed with [25].

In contrast, the size of the downstream bed material exhibits an inverse relationship with scour hole characteristics. Tables 5 and 6 shown the percentage increase in mean bed material diameter and the corresponding reduction in scour depth and length. These observations align with findings reported by Ruff et al. [26] and Alrahhawi and Hayawi [27]. Figure (3, a&b) shown that a two and three dimensional of scour hole respectively of arbitrary experiment by Surfer software. And, Figure (4, a,b, and c) show the relationship between the length of scour and discharge with average (R^2=0.96), Figure (5, a,b, and c) Variation depth of

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scour hole with discharge with (R^2=0.95). Direct proportion between the length and depth of scour hole and discharge.

Table 3 The percentage of discharge rising and average increasing scour depth at downstream hole

Parentage of discharge Increasing (%)	Percentage of scour hole increasing (Ds%) (Min-Max) Increase ratio (%)	Average increase (%)
36	(24 – 94.7)	62.63
70	(104 – 177.27)	140.56
110	(120 – 222.7)	183.36
150	(273.6 – 138.4)	208.21

Table 4 The percentage of discharge rising and average increasing length of scour hole

Parentage of discharge Increasing (%)	Percentage of increasing length scour hole (Ds%) (Min-Max) Increase ratio (%)	Average increase (%)
36	(9.6 – 18.25)	13.222
70	(54.38 – 79.36)	63.22
110	(91.93 – 100)	89.89
150	(111.11 – 146.66)	128.25

Table 5 The percentage of increasing mean bed diameter verses percentage of decrease scour depth

Percentage of mean bed diameter increasing (%)	Percentage of scour hole reduction (Ds%) (Min-Max) reduction ratio (%)	Average reduction (%)
38.5	(12.22 – 26.9)	18.87
130.8	(29.6 – 43.63)	33.98

Table 6 The percentage of increasing mean bed diameter verses percentage of decrease length of scour hole

Percentage of mean bed diameter increasing (%)	Percentage of reduction length scour hole (Ds%) (Min-Max) reduction ratio (%)	Average reduction (%)
38.5	(18.57 – 20)	19.47
130.8	(28.23 – 31.6)	29.20

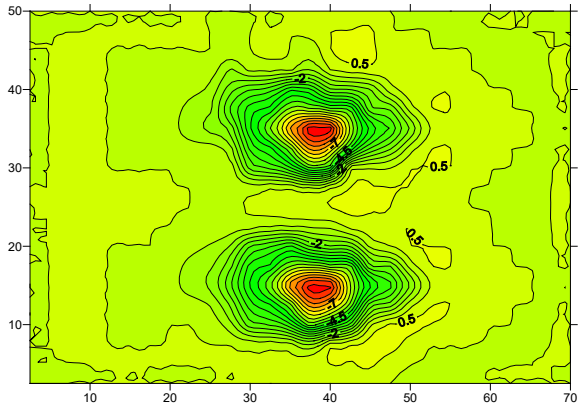


Figure 3. a. Two-directional scour contour lines (unite in cm)

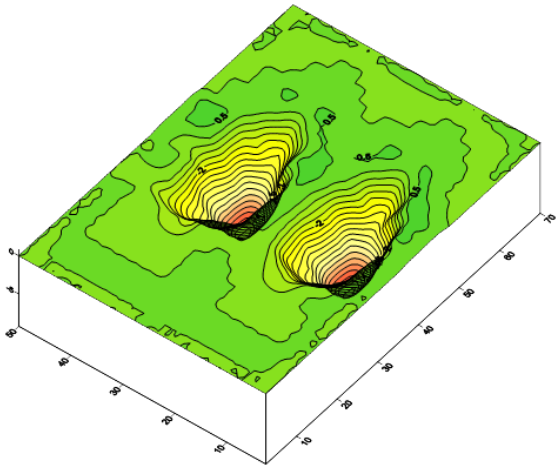


Figure 3.b. Three directional scour contour lines

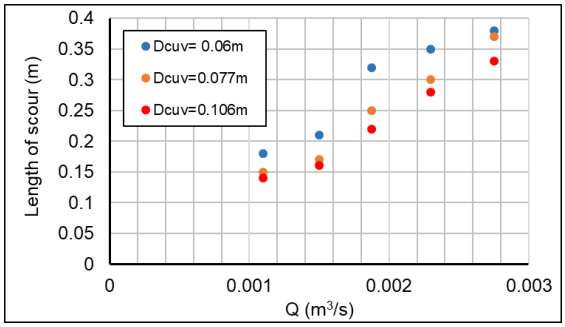


Figure 4.a. Relationship between the length of scour and Discharge (Dm=3.25E-04 m)

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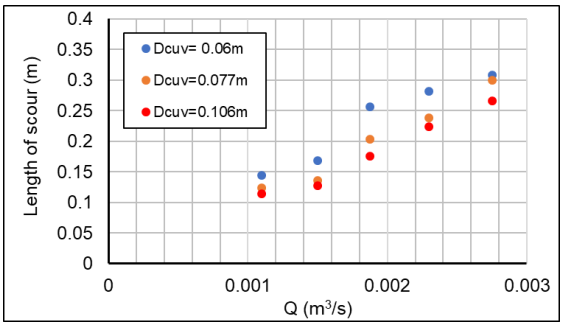


Figure 4.b. Relationship between the length of scour and Discharge (Dm=4.5E-04 m)

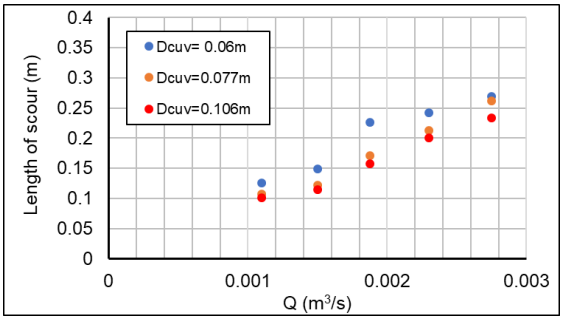


Figure 4.c. Relationship between the length of scour and Discharge (Dm=7.5E-04 m)

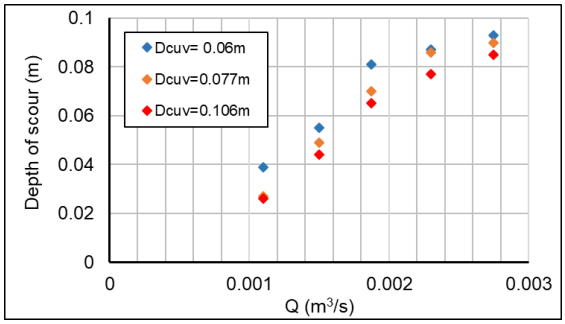


Figure 5.a. Relationship between the depth of scour and Discharge (Dm=3.25E-04 m)

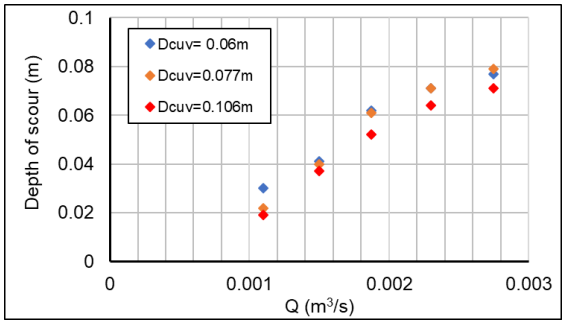


Figure 5.b. Relationship between the depth of scour and Discharge (Dm=4.5E-04 m)

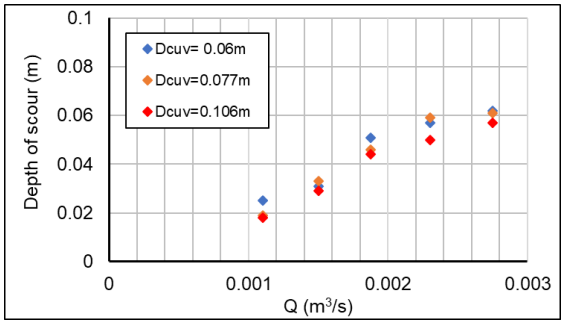


Figure 5.c. Relationship between the depth of scour and Discharge (Dm=7.5E-04 m)

Two non-dimensional relationships were developed by using linear regression analysis in the Excel program. The depth and length of scour hole, respectively were found as in equations (9,10).

$$\frac{D_s}{D_{cuv}} = 0.02141 - 4.008 * \frac{D_m}{D_{cuv}} - 0.008\,Fr + 1.81\,Re \quad [9]$$

$$\frac{L_s}{D_{cuv}} = 0.4201 - 10.018 * \frac{D_m}{D_{cuv}} - 0.018866\,Fr + 7.167E-5\,Re \quad [10]$$

The linear regression analysis yielded R^2 values of 0.908 and 0.87; standard error 0.11 and 0.51; and Significance F of 2.63E-21 and 3.88E-18. The F-values for both depth and length of scour are 135.4 and 90.68, respectively, more than the critical value, which is 2.86, indicating that the regression models are statistically significant, where the P-Value is the probability of observing a f-statistic as extreme as the one observed under the assumption that the null hypothesis is true. The F-statistic determines the model's significance overall. A higher F-value indicates that the model is a better fit for the data, [28]. Consistent with the findings of Ahmed et al. (2023). An examination of the P-values of the terms indicates that D_m/D_{cuv} Fr, Re, are significant in the first relationship, equation (9). However, in the second relationship, equation (10), the Fr is insignificant compared to D_m/D_{cuv}, and Re which exhibits a significant effect. Figures 6a and 6b compare the measured data with the predictions from Equations 9 and 10, respectively, along with the line of agreement and 25% deviation bounds.

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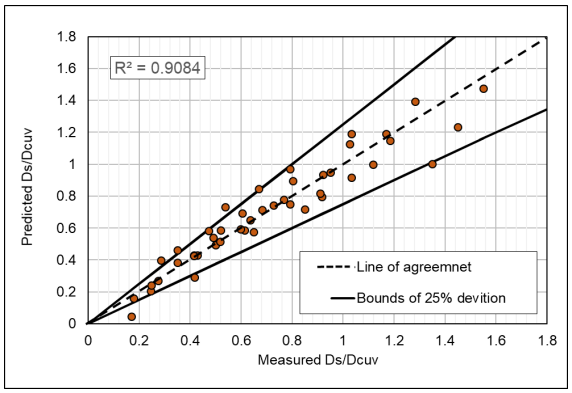


Figure 6.a. Predicted and measured for the ratio of scour depth to culverts diameter, predicted using equation (8)

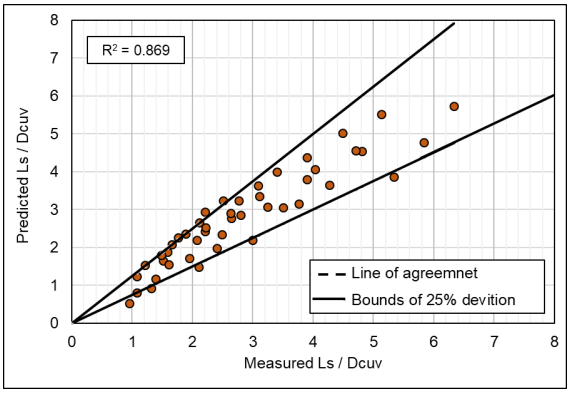


Figure 6.b. Predicted and measured for the ratio of scour length to culvert diameter, predicted using equation (9)

4.0 CONCLUSION

An experimental investigation was conducted to study the scour hole downstream of culverts. The following conclusions can be drawn from the study:
i) An increase in discharge leads to an increase in both the length and depth of the scour hole. Tables 2 and 3 present the percentage increase in flow rate and its corresponding effect on scour depth and length.
ii) The experimental results demonstrate a significant effect of the mean diameter of the bed material. Tables 4 and 5 show that as the mean bed material diameter increases, the scour hole depth and length decrease.
iii) For future work, it is recommended to do the same set of experiments for a single pipe and compare the result for depth and length of scour with this result and come up with which case is better.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics declaration

Formal ethical approval was not obtained for this study. However, the authors confirm that the research was conducted in accordance with established ethical principles and good research practices, with due consideration given to participant rights, informed consent, confidentiality, and responsible data handling.

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