LOCAL SCOUR DOWNSTREAM CULVERT OUTLETS

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ABSTRACT

The present study focuses on the local scouring phenomenon occurs downstream culvert outlets, particularly culvert with triangular shape cross section, constructed on nonuniform bed materials. The experimental program includes three main parts. The first part deals with the effect of the discharge and tailwater depth on the scour hole geometry, formed downstream a culvert with triangular shape cross section. The second part is concerned with the influence of the shape of culvert cross section on scour hole dimensions. Circular, square, rectangular, and triangular shapes, having the same area, were tested. The third part is intended with determination of length of protection required to safeguard the downstream bed material against local scour. Study shows that scour hole geometry sensitively affected by culvert shape, discharge, and tailwater depth. Study shows also that length of scour hole is not the only criterion to determine the required length of protection against local scour. Critical velocity may be used to estimate the minimum length of protection.

Keywords: *Culvert, Local scour, Protection against scour.*

Notations

A	flow cross sectional area,
A_c	culvert cross sectional area,
a	Height of culvert,
B	Channel bed width,
b	width of culvert,
D	Diameter of circular shape,
d	grain diameter of sand bed mixture,
d_m	Medium grain diameter (effective grain size),
d_{50}	Median grain diameter,
d_s	Scour depth at any location along channel center line,
d_{so}	Scour depth immediately at culvert outlet,
d'_{so}	Scour depth just downstream the extended apron,
d_{sm}	Maximum depth of scour hole,
d'_{sm}	Maximum depth of the reduced scour hole,
F	Froude number of downstream channel,
g	Gravitational acceleration,
H_w	Height of the end adjustable weir,
h_m	maximum height of mound,
L_c	Length of culvert,
L_s	Length of scour hole,
ℓ_s	Length of the reduced scour hole,
Q	Discharge passing through culvert,
R_H	Hydraulic radius,
V_j	Velocity of issuing jet of culvert,
V_C	Critical velocity at which scour starts to act,
W_m	Maximum width of scour hole,
X_{sm}	Location of Maximum scour depth,
X'_{sm}	Location of Maximum scour depth of reduced scour hole,
X_{wm}	Location of maximum scour width,
X_{hm}	Location of maximum height of mound,
y	Depth of flow at any section,
y_{to}	Depth of flow just downstream culvert outlet,
y_t	Tailwater depth.

1. INTRODUCTION

Culverts are generally used to convey tributary drainage discharge through highways embankments and other similar forms of water-crossing structures. When a culvert is constructed on an alluvial stream, the bed downstream culvert outlet is lowered due to erosion caused by the interaction between the high velocity of issuing jet and the loose material of stream bed. Such drop in the bed is known as local scour, Figure (1). Excessive scour can undermine the culvert foundation slab and leads to its failure. Prediction of scour hole dimensions is indispensable for designing an optimal bed protection.

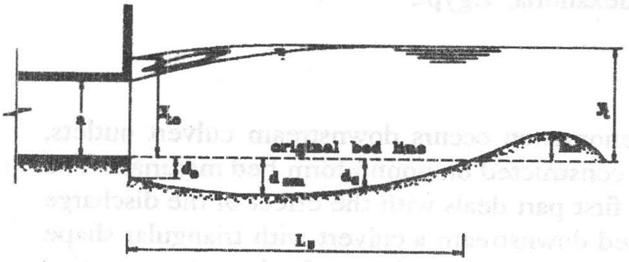

Figure 1. Definition sketch for scour D.S. a culvert.

Because of the complexity of scour process, there has been little success to develop a mathematical model to estimate scour hole dimensions. Estimation of scour dimensions is mostly based on field and laboratory studies. Scour hole geometry depends on many variables that characterize the following parameters: (1) culvert parameter; shape, size, and slope, (2) flow parameter; discharge, velocity, and tailwater depth and (3) sediment parameter; mean diameter, geometric standard deviation of bed materials, and the submerged unit weight of the grains.

The effect of hydraulic and sediment parameters on scour hole geometry, formed downstream circular, square, and rectangular culverts, has been extensively investigated in previous studies [1,3,4,7,15,17,18]. However, local scour downstream triangular shape culvert has not been previously investigated, since it is recently recommended to be used as a new shape[2].

The effect of culvert shape on scour geometry has been dealt with in different approaches. In these approaches, length and maximum depth of scour were correlated to the parameter $Q/D^{2.5}$ [6,10], the discharge intensity $Q/g^{0.5} R_H^{2.5}$ [7,14,16], and the modified discharge intensity $Q/A\ g^{0.5}\ R_H^{0.5}$ [3,5,8]. However, these parameters thoroughly can not represent the culvert shape factor. The parameter $Q/D^{2.5}$ can not be generalized for culvert shapes other than circular one. The denominators $g^{0.5} R_H^{2.5}$, and $Ag^{0.5} R_H^{0.5}$, which were considered as the culvert shape factor, unequally reflect the different culvert shapes. From one hand, the less volume of scour produced by a square shape with height equals to the diameter of a circular shape [7,14,16] is not referred to culvert shape, but to the less velocity of square shape. On the other hand, the excess scour volume resulted by square shape compared to circular one, [3,5,8], is caused by the higher velocity of square shape for the same discharge intensities.

The current mainly experimental investigation aims at studying the three following aspects:

(i) local scour downstream triangular shape culvert.

(ii) effect of culvert shape one scour geometry, considering the same condition for all shapes; culvert's area and length, discharge, tailwater depth, width of downstream, channel, and bed material. Culverts with circular, square, rectangular, and triangular shapes were used for this purpose.

(iii) length of required protection to safeguard downstream bed against scour.

2. TEST FACILITY AND EXPERIMENTAL PROCEDURE

2.1 *Experimental Set-Up*

Experiments were carried out in the Irrigation and Hydraulic Research Laboratory, Faculty of Engineering, Alexandria University. Figure (2) shows the arrangement of the experimental set- up which consists of the following:

(i) *Testing flume*: Experiments were conducted in 9,0 m long flume that has a rectangular cross section 0.5 m high by 0.4 m wide. The flume was fabricated from 10 mm perespex sheets supported by a steel frame. The middle reach of channel was equipped by culvert models and bed mixture.

(ii) *Culvert models*: Culvert models of square, rectangular, and triangular shapes were prepared from perespex sheet 4 mm thick. Culvert of circular shape was taken PVC pipe. Table (1) summarizes the dimensions of each shape. Culverts models were projected horizontally in the centerline of the testing flume.

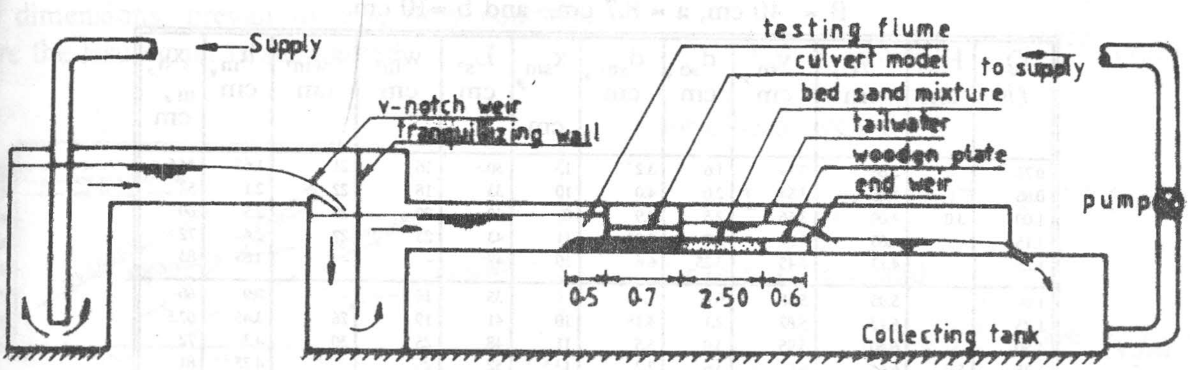

Figure 2. Experimental set-up (Not to scale; dimensions in meters).

Table 1. Summary of culvert shapes dimensions.

Shape	dimensions, Cm			R_H, Cm	A_c, Cm^2	L_c, Cm
	a	b	D			
circular	-	-	7.5	1.87	44.2	70
square	6.6	6.6	-	1.65	43.56	70
Rectangular	8.7	5.0	-	1.59	43.50	70
Rectangular	5.0	8.7	-	1.59	43.5	70
Triangular	8.7	10	-	1.45	43.5	70

(iii) *Sand bed mixture*:The sand bed, which covered the full width extending 2.5 m long and 0.2 m thick. The san bed was followed by a horizontal wooden plate of 0.6 m length at the same level of sand surface. The soil properties were: median grain diameter d_{50} of 0.86 mm; medium grain diameter d_m of 0.97 mm; geometric standard deviation $\delta = (d_{84}/d_{16})^{0.5}$ of 2.2; specific weight of 2.65 t/m^3; and angle of repose $\phi = 33.7°$.The grain size distribution curve for the sand mixtures is plotted in Figure (3).

(iv) *End weir*: An adjustable-height weir was located just at the end of the horizontal wooden plate to control tailwater depth in the sand bed reach.

2.2 *Testing procedure*

Prior to each test the sand bed mixture was carefully prepared and leveled so that the top of sand surface was even with the culvert invert. The end weir was adjusted to the required height to control the type of flow through culvert. To avoid any initial scour, a very small rate of flow was slowly allowed to fill the test section. Then, the flow rate was gradually increased to the required discharge. A flow of clean water was then allowed to circulates for a period of 6 hours, which was found to be practically sufficient to establish equilibrium scour hole [9]. The flow was then gradually decreased and the flume was slowly drained. At the end of each test, the scour hole levels was measured by point gauge. Discharge were measured using V-notch weir. Velocities of flow at the downstream channel were measured by a digital current meter having propeller diameter of 0.01 m.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. *Characteristics of local scour downstream a triangular culvert*

The effect of both discharge and tailwater depth, on scour hole geometry, was accounted for by adjusting the tailwater depth to satisfy three cases of flow through culvert; (1) weir flow, for values of y_t/a up to 0.95, (2) Orifice flow, when $0.95 < y_t/a \leq 1.05$, and (3) pipe flow, for $y_t/a > 1.05$. The culvert entrance was kept free in the first case, while it was submerged in the last two cases. Table (2), summarizes the geometric of local scour downstream triangular culvert.

Table 2. Geometric Characteristics of Local Scour Downstream Triangular Culvert; B = 40 cm, a = 8.7 cm, and b =10 cm.

Q, ℓ/s	H_w, cm	y_t, cm	y_{to}, cm	d_{so}, cm	d_{sm}, cm	x_{sm}, cm	L_s, cm	w_m, cm	x_{wm}, cm	h_m, cm	x_{h_m}, cm
0.75	3.0	3.68	3.44	1.6	3.2	13	30.5	16	21	1.65	44.5
0.85		3.85	3.54	2.0	4.0	10	33	18	22	2.1	52
1.00		4.00	3.56	2.5	4.9	8	38	20	25	2.5	60
1.15		4.05	3.57	3.0	5.95	11	43	23	27	2.6	72
1.25		4.13	3.45	3.25	6.6	10	49	-	-	2.85	83
1.00	5.0	5.95	5.68	0.2	1.4	-	35	16	-	0.9	60
1.25		6.12	5.87	2.1	4.15	10	41	19	26	3.45	67.5
1.50		6.40	5.95	3.0	5.5	11	48	25	30	4.3	72
1.75		6.66	6.07	3.6	7.2	13.5	52	26	-	4.75	81
2.00		6.80	6.03	4.2	8.0	13.5	57	28	36	5.05	92
2.25		6.91	5.98	5.4	10.15	15	63.5	29	-	5.2	105
1.25	6.5	7.60	7.3	0.2	2.9	10	39	19	23	2.45	63
1.50		7.90	7.6	2.6	5.1	13	44	22	26	4.5	66
1.75		8.13	7.66	3.0	6.45	13.5	47.7	25	27	5.2	68
2.00		8.30	7.45	4.4	8.2	13	54	28	30	5.42	77
1.75	7.0	8.50	8.02	2.9	6.3	15	49	24	26	5.2	68
1.88		8.54	8.04	3.0	6.55	19	50.5	25	27	5.4	69
2.00		8.60	8.06	3.1	6.7	18	52.5	27	28	5.55	75
2.13		8.64	8.10	3.2	7.0	18	54.5	28	30	5.8	77
2.25		8.71	8.11	3.25	7.15	16.5	55.5	29	33	6.1	79.5
1.50	7.5	8.80	8.4	2.2	5.0	15.5	43	21	25	4.45	60.5
1.75		8.95	8.53	2.4	5.95	19	47.5	24	28	4.95	66
2.00		9.05	8.55	2.7	6.75	20	51	25	30	5.4	75
2.25		9.20	8.50	3.0	7.2	19	53.5	27	31	6.3	81
1.25	10	11.14	10.76	0.10	0.8	11	34.0	15	-	1.9	50
1.50		11.30	10.8	1.8	4.50	16	40	19	24	4.9	57.5
1.75		11.43	10.9	2.65	5.80	19	46	23	28	5.55	63.5
2.00		11.54	11.0	2.80	6.8	19.5	52	26	32	6.5	70.5
2.25		11.64	11.14	3.3	7.4	20	55.5	28	34	8.05	75
2.50		11.73	11.17	3.5	7.75	21	57.5	25	33	8.6	82

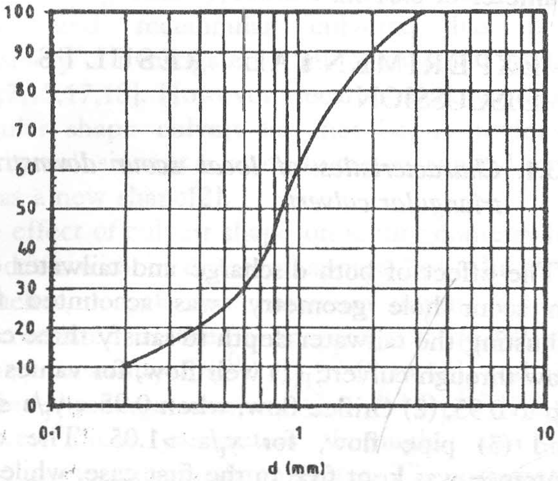

Figure 3. Grain size distribution of sand bed mixture used in the experiments.

As shown in Figure (1), scour starts just at the culvert outlet, resulting an initial scour depth, d_{so}. Moving further towards downstream, the scour depth, d_s, gradually increases, reaching its maximum value, d_{sm}, at distance X_{sm} from the outlet. Afterwards, the scour depth gradually decreases reaching its lower value (zero) at the scour hole end. Immediately downstream of scour hole end, a mound is developed. Such a mound is initiated by a rapid settling out of the coarser grains contained in the flow exiting the scour hole. The length and the maximum depth of scour were generally found to increase with increasing culvert discharge as well as tailwater depth. For a same value of Froude number in the downstream channel, the relative values of maximum scour depth d_{sm}/d_m, and scour length L_s/d_m increase as the tailwater depth increases, as indicated in

Figures (4) and (5). The large increase, in scour hole dimensions, prevail in pipe flow condition where the issuing jet is submerged.

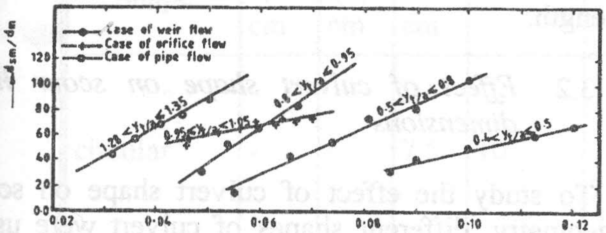

Figure 2. Maximum relative scour depth, resulted by triangular shape, versus Froude number.

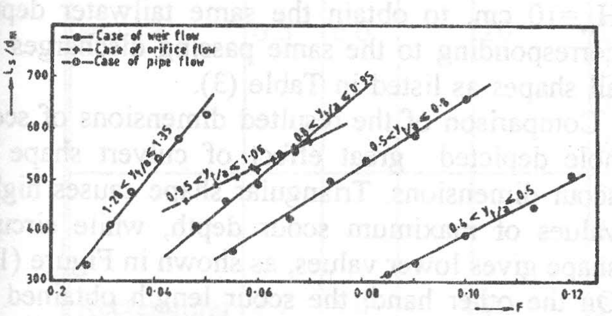

Figure 3. Maximum relative scour length, resulted by triangular shape, versus Froude number.

Using the experimental data, a regression analysis was performed to obtain general equations governing the relation between scour hole dimensions and both Froude number and tailwater depth as follows :

(i) Maximum scour depth;

$$d_{sm}/d_m = 26924 \quad F^{2.16} \quad (y_t/a)^{1.77} \qquad (1)$$

for case of weir flow,

$$d_{sm}/d_m = 741.72 \quad F^{0.855} \; (y_t/a)^{1.27} \qquad (2)$$

for orifice flow, and

$$d_{sm}/d_m = 95 \quad F^{0.75} \quad (y_t/a)^{7.25} \qquad (3)$$

for pipe flow.

(ii) Scour length,

$$L_s/d_m = 5446.77 \quad F^{0.822} \quad (y_t/a)^{0.93} \qquad (4)$$

for case of weir flow,

$$L_s/d_m = 3038.47 \quad F^{0.624} \quad (y_t/a)^{0.927} \qquad (5)$$

for orifice flow, and

$$L_s/d_m = 12058.9 \quad F^{0.896} \quad (y_t/a)^{-0.979} \qquad (6)$$

for pipe flow.

The initial scour depth, d_{so}, being higher when the outlet is free (weir and orifice flow conditions). As shown in Figure (6), the values of d_{so} slightly increase as Froude number increases. However, the average value of d_{so} equals 0.475 of the maximum scour depth, which is very close to those obtained for square culvert [18].

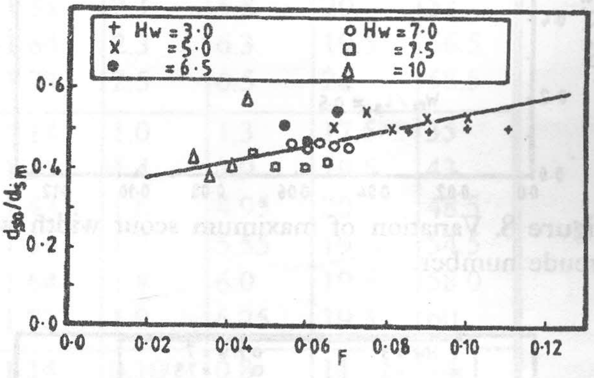

Figure 4. Variation of initial scour depth with Froude number.

As shown in Figure (7) the distance of maximum scour depth X_{sm}, slightly decreases as Froude number increases, giving an average value equals 0.30 of the scour length. Noting that, the location of maximum scour depth equals 0.40 and 0.34 of the scour length for rectangular, and square culverts, respectively, [1,18]. It is observed, from Table (2), that the average maximum scour depth, d_{sm} equals 0.13 of the scour length.

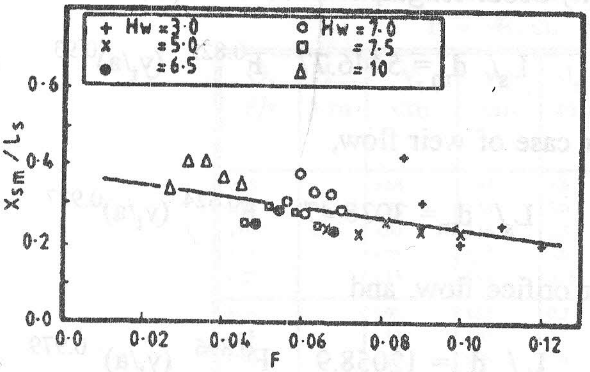

Figure 7. Variation of the distance maximum scour with Froude number.

Referring to Figures (8) and (9), the relative values of maximum scour width W_m/L_s and its location X_{wm}/L_s are 0.5 and 0.6, respectively.

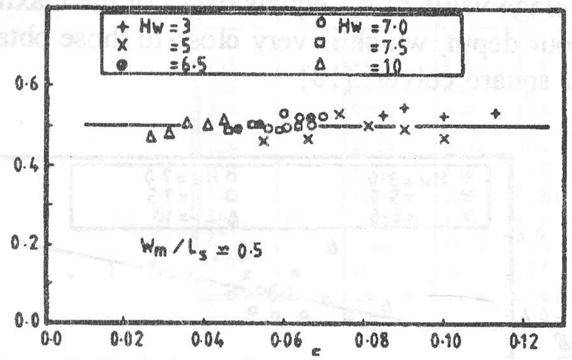

Figure 8. Variation of maximum scour width with Froude number.

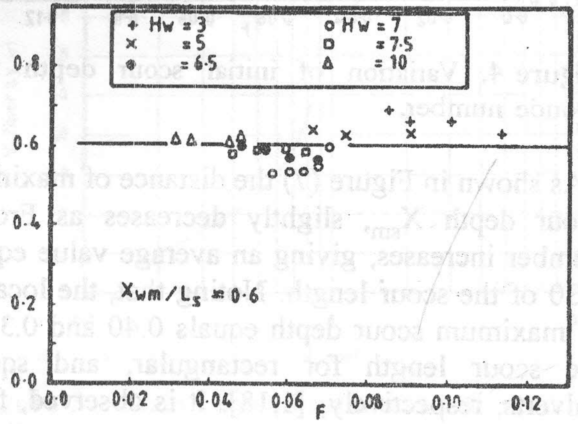

Figure 9. Variation of distance of maximum width of scour with Froude number.

As listed in Table (2), the values of maximum relative height of mound h_m/d_{sm} ranges between 0.5 and 1.0 for values of y_t/a from 0.4 to 1.35. It was found also that the distance of maximum height of mound is about 1.5 times the scour hole length.

3.2 *Effect of culvert shape on scour hole dimensions*

To study the effect of culvert shape on scour geometry, different shapes of culvert were used. These shapes are: circular, square, rectangular, and triangular, as shown in Table (1). In experiments, the end control weir was adjusted to a height H_w=10 cm, to obtain the same tailwater depths corresponding to the same passing discharges for all shapes as listed in Table (3).

Comparison of the resulted dimensions of scour hole depicted great effect of culvert shape on scour dimensions. Triangular shape causes higher values of maximum scour depth, while circular shape gives lower values, as shown in Figure (10). On the other hand, the scour length obtained by the triangular shape has a lower values while the circular shape causes higher values, as shown in Figure (11). This may be referred to that the hydraulic radius of circular shape has higher value while it has lower value for triangular, as shown in Table (1). Results indicated that the scour dimensions, obtained by the two different positions of rectangular shape, are very close to each others for small discharges. In case of large discharges, the downstream channel width is being small enough to interfere with scour hole development which leads to deviations of both length and depth of scour caused by the two different positions of rectangular shape.

With regard to distance of maximum scour, X_{sm}/L_s, it has higher values for both circular and square shapes; 0.53, and 0.46, respectively. For both rectangular and triangular, X_{sm}/L_s has closed values, nearly 0.4.

The initial scour depth, d_{so}, caused by circular shape, has a negligible value. However, other shapes, have closed values of d_{so}/d_{sm} of about 0.35 in average.

Table 3. Comparison Between effect of different shapes of culvert on scour hole dimensions

culvert Shape	dimensions a, cm	b cm	D cm	H_w cm	Q, ℓ/s	y_t, cm	d_{so}, cm	d_{sm}, cm	X_{sm}, cm	L_s, cm
circular	-	-	7.5	10	1.25	11.14	0.0	1.15	28	39
					1.50	11.30	0.0	3.35	28.5	51
					1.75	11.43	0.0	4.4	29.0	55.5
					2.00	11.54	0.10	5.2	28.5	59
					2.25	11.64	0.15	5.7	29.0	62.5
					2.50	11.73	0.20	6.05	27.5	64
square	6.6	6.6	-	10	1.25	11.14	1.05	1.5	16.0	38
					1.50	11.30	1.4	4.25	22.5	47
					1.75	11.43	1.8	5.35	27.0	53
					2.00	11.54	2.0	6.05	26.5	58.5
					2.25	11.64	2.1	6.4	30	62
					2.50	11.73	2.2	6.8	28	63.5
Rectangular	8.7	5.0	-	10	1.25	11.14	1.0	1.45	16	35
					1.50	11.30	1.6	4.1	20	42
					1.75	11.43	1.7	5.15	19.5	48
					2.00	11.54	2.1	5.8	20	53
					2.25	11.64	2.3	6.3	19.5	56.5
					2.50	11.73	2.5	6.5	20	58.5
Rectangular	5.0	8.7	-	10	1.25	11.14	1.0	1.3	17.5	35
					1.50	11.30	1.4	3.9	19.5	43
					1.75	11.43	1.6	4.95	20	48.5
					2.00	11.54	1.7	5.55	19	54.5
					2.25	11.64	1.8	6.0	19.5	58.0
					2.50	11.73	1.9	6.25	19.5	60
Triangular	8.7	10	-	10	1.25	11.14	0.10	0.8	11	34
					1.50	11.30	1.8	4.5	16	40
					1.75	11.43	2.65	5.8	19.5	46
					2.00	11.54	2.80	6.8	19.5	52
					2.25	11.64	3.3	7.4	20	55.5
					2.50	11.73	3.5	7.75	21	57.5

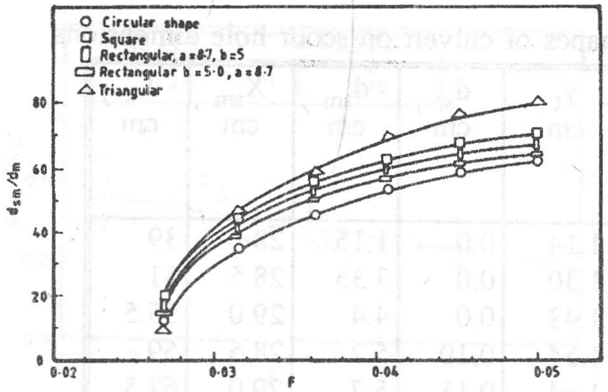

Figure 8. Effect of culvert shape on maximum scour depth.

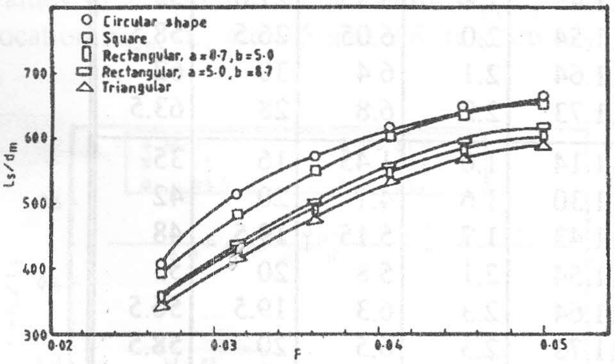

Figure 9. Effect of culvert shape on scour length.

3.3. *Protection of downstream bed against local scour*

Bed material, downstream of culvert, should be safeguarded against scour, to ensure both safety and durability of functioning of culvert. In general, the length of the bed protection depends on the permissible amount of scour (length and maximum scour depth) and the geotechnical structure of the soil involved (densely or loosely packed sand) [13]. To protect the bed downstream culvert, it was recommended to extend the culvert apron to distance equals length of scour hole [9,12,18]. However, extension of culvert apron will eliminate the effect of equilibrium scour hole since it acts as an energy dissipator (water cushion). Consequently, the excess energy which should be lost in scour hole will requires more length of protection.

To ensure this fact,length of protection based on scour hole length, was checked using two ways. In the first check, a set of experiments were conducted using a solid floor, roughened with the same bed mixture, acting as an extension of culvert apron. The solid floor has different lengths, taken equal to the same lengths of scour hole formed downstream triangular culvert. For the same discharge and the corresponding tailwater depth a scour hole, with less dimensions, was formed downstream the solid floor, as shown in Figure (12). Table (4), summarizes the dimensions of the reduced scour hole.

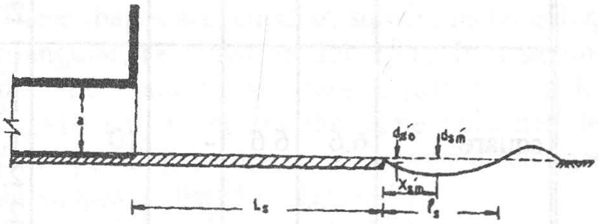

Figure 10. Formation of reduced scour hole downstream extended apron of culvert.

In the second check, the entire length of bed material was covered by the roughened solid floor. Sections defining the end of scour hole lengths were fixed. The jet velocity on the bed, V_j, due to the same discharges and tailwater depths, was measured at these sections. These measured velocities were compared to critical velocities V_c, calculated by Garde's equation [11]. Results are tabulated in Table (5). It is clear that for all lengths of scour hole, the jet velocities are always higher than critical velocities. The above to checks ensure that length of protection, based on scour hole geometry, is not sufficient.

According to Garde's critical velocity, the safe length of protection is that length which has a jet velocity, at its end, less or equal to critical velocity, or $V_c/V_j \leq 1.0$. Accordingly, the critical velocity may be used as a design criterion to estimate the safe length of protection. For this purpose, the velocities of flow jet V_j were measured, on the roughened surface of solid floor, for different discharges. For every discharge, the section which has $V_c/V_i = 1.0$ is considered as the end section of scour length which should be protected. Results are listed in Table (6).

Table 4. Dimensions of scour hole formed downstream the extended apron of triangular culvert.

Q, ℓ/s	y_t, cm	d_{so}, cm	d_{sm}, cm	x_{sm}, cm	L_s, cm	d'_{so}, cm	d'_{sm}, cm	X'_{sm}, cm	ℓ_s, cm
1.50	11.30	1.8	4.50	16	40	0.95	2.45	7.0	14.5
1.75	11.43	2.65	5.8	19	46	1.3	2.70	8.0	16
2.00	11.54	2.8	6.8	19.5	52	1.4	2.80	8.5	17
2.25	11.64	3.3	7.4	20	55.5	1.6	2.90	9.0	18
2.50	11.74	3.50	7.75	21	57.5	1.8	3.0	10.0	18.5

Table 5. Jet velocity at sections located at scour hole end.

Q, l/s	H_w, cm	L_s, cm	y, cm	V_j, m/s	V_c, m/s	V_j/V_c
1.25	10	34	10.9	0.3593	0.3327	1.08
1.50	10	40	11.03	0.3818	0.333	1.15
1.75	10	46	11.15	0.4155	0.3333	1.25
2.0	10	52	11.23	0.4437	0.3335	1.33
2.25	10	55.5	11.33	0.4610	0.3337	1.38
2.50	10	57.5	11.45	0.4755	0.3341	1.43

Table 6. Measured lengths of scour based on critical velocity criterion (V_j=V_c).

Q, l/s	y_t, cm	F	L_s, cm	L_s/y_t
1.25	11.14	0.0268	43	3.85
1.50	11.30	0.0315	55	4.9
1.75	11.43	0.0361	64	5.6
2.0	11.54	0.0407	71	6.15
2.25	11.64	0.0452	77	6.62
2.5	11.73	0.0500	84	7.15
2.75	11.85	0.0538	89	7.5
3.0	12.15	0.0565	95	7.82

A plot of the relative scour length L_s/y_t versus Froude number is shown in Figure (13), from which a simple relation may be expressed as;

$$L_s/y_t = -1968\,F^2 + 291.2\,F - 2.435, \quad 0.01 < F < 0.1 \qquad (7)$$

Using the above relationship, the scour length can be determined and in turn the minimum length of protection can be estimated.

It is clear that values of scour lengths based on critical velocity are always higher than those obtained from scour hole geometry which requires more lengths of protection and in turn more costs. Therefore, in the case of a dry execution of the bed protection, it is recommended to make an artificial scour hole beforehand and to protect it with gravel. This will be make use of the equilibrium scour hole to act as an energy dissipator.

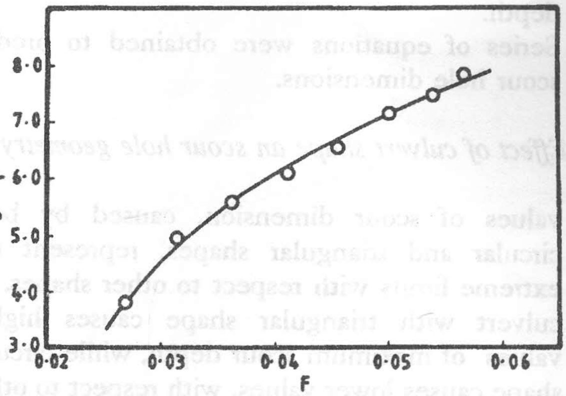

Figure 13. Relative scour length based on critical velocity, (V_j=V_c).

Using a solid apron for protection, the magnitude of maximum scour depth is not of importance as long as the hole length of scour is protected. In such a case, the triangular shape is more economic since it causes lower values of scour length compared to other shapes.

4. CONCLUSIONS

A total of 73 individual experimental tests, combining different culvert flows and tailwater depths with different culvert sizes and shapes, were performed in the course of the present study. Based on the analysis of the experimental results, the main conclusions can be summarized as follows:

1. *Local scour downstream a triangular culvert*

(i) The dimensions of an equilibrium scour hole increase with increasing Froude number of the downstream channel.
(ii) The dimensions of scour hole formed downstream submerged culvert are larger than that caused by unsubmerged culvert for the same value of Froude number.
(iii) The values of maximum scour depth and its location are; 0.13 and 0.30 of the scour hole length, respectively.
(iv) the values of maximum scour width and its location are; 0.5 and 0.6 of the scour hole length respectively.
(v) The value of scour depth immediately at culvert outlet, d_{so}, is about 0.475 of the maximum scour depth.
(vi) Series of equations were obtained to predict scour hole dimensions.

2. *Effect of culvert shape an scour hole geometry*

(i) values of scour dimension, caused by both circular and triangular shapes, represent the extreme limits with respect to other shapes.
(ii) culvert with triangular shape causes higher values of maximum scour depth, while circular shape causes lower values, with respect to other shapes.
(ii) triangular shape culvert produces lower values of scour length, while circular shape gives higher values.
(iv) square shape causes higher values of both length and maximum scour depth than rectangular shape.
(v) scour depth immediately at culvert outlet, d_{so}, has a negligible value for circular shape compared with other shapes.

3. *Length of required Protection for bed material against scour*

(i) Extension of culvert apron to distance equals to length of scour hole will not prevent scour, but reduces its dimensions.
(ii) Scouring length based on critical velocity is higher than that based on scour hole geometry.
(iii) It is recommended to create an artificial scour hole having the predicted dimensions (equilibrium length and scour depth) and to protect it with proper material. This lead to a shorter and more reliable design of the bed protection.

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