LOCAL SCOUR AT SLOPED FACE ABUTMENTS

Mohamed Abdel Razek and Khaled H. Baghdadi
Irrigation and Hydraulics Department, Faculty of Engineering,
Alexandria University, Alexandria, Egypt

ABSTRACT

The effect of the slope of the upstream abutment face on the formation of local scour is experimentally studied. Experimental data are analyzed and dimensionless equations are developed to predict both the maximum equilibrium scour depth and the length of scour hole upstream the abutment.

Keywords: Local scour - Abutment- Sloping face.

NOTATION

B	channel bed width.
d_{50}	mean diameter of the bed sand mixture.
d_s	maximum equilibrium scour depth.
Fr	Froude number.
g	acceleration due to gravity.
L	abutment length.
L_s	maximum equilibrium scour length upstream the abutment.
Q	rate of flow.
v	mean velocity in the channel.
Y	water depth.
α	vertical angle of inclination of the upstream face of abutment.
γ_s	specific weight of bed sand mixture.
τ_o	average boundary shear stress.
τ_c	critical shear stress of the bed sand mixture.

INTRODUCTION

Bridge abutments constructed in an alluvial stream will change the flow pattern in the vicinity of that abutment. This modification of flow pattern will increase the sediment transport capacity near the construction causing local scour which endanger the foundation of the abutments. Therefore, the formation of local scour at bridge abutments has attracted many investigators.

The mechanics of local scour at wing walls and abutments has been discussed by Liu et al [4]. They considered the approach flow to consist of an upper and lower layer which separate into upflow and downflow on a hitting face of the abutment. The upflow forms a surface roller, while the downflow roles up to form the bottom vortex, called principal vortex. The principal vortex formed at the upstream face and side develops large shear on the boundary and causes scour.

Laursen [1] studied experimentally effect of the abutment size on the formation of scour hole. He found that the depth of scour was much greater than scour depth caused by equivalent long contraction. He concluded that the maximum scour depth depends only on the depth of flow for a given obstruction and does not significantly change with either velocity or the sediment size. He developed the following empirical equation to estimate the maximum equilibrium depth :

$$\frac{Q_o b}{Q_b Y} = 2.75\frac{d_s}{Y}\left[\frac{\left(\frac{1}{t}\frac{d_s}{Y}+1\right)^{7/6}}{\left(1+\frac{1}{t}\right)^{\frac{1}{3-a}}}-1\right] \qquad (1)$$

$$\text{Where} \quad t = \frac{(Q_o+Q_b)^2}{120 b^2 Y^{7/3} d^{2/3}}$$

Where b is the width of over bank, Y is the depth of flow, d_s is depth of scour hole, d is the mean diameter of bed mixture, "a" is an exponent which depends on the ratio of shear velocity to fall velocity and Q_b , Q_o are the discharge over the entire width and over bank, respectively.

Melville [5] found that equilibrium scour depth in case of clear water scour is greater than in case of live bed condition. Time needed to attain the equilibrium condition in live bed condition is shorter than in case of clear water condition. Melville classified abutments to long and short abutments according to the abutment length to depth of flow ratio (L/Y). Based on the analysis of experimental data, Melville developed empirical equations for the equilibrium scour depth at long and short abutment in terms of abutment shape and alignment.

$$d_s = 2K_sL \qquad \text{for} \qquad \frac{L}{y} < 1$$

$$d_s = 2K_s^* K_\theta^* (YL)^{0.5} \qquad \text{for} \qquad 1 \leq = \frac{L}{Y} \leq 25 \qquad (2)$$

$$d_s = 10K_\theta y \qquad \text{for} \qquad \frac{L}{y} > 25$$

Where K_s is the abutment shape factor, k_θ is the abutment alignment factor and L is the length of abutment. Most of the experiments were conducted using a thin plate as an obstruction.

Melville and Ettema [7] conducted experimental study on bridge abutment scour in compound channels. The effect of the approach channel geometry was taken into consideration for the estimation of local scour around bridge abutments. The channel geometry factor K_G was defined as the scour depth for an abutment in compound channel, divided by scour depth at the abutment in the rectangular channel of the same overall width. They developed the following equation to determine the channel shape factor

$$K_G = \sqrt{1 - \frac{L^*}{L}\left[1 - \left(\frac{y*}{y}\right)^{5/3}\right]} \qquad (3)$$

Where L* and y* were the width and depth of flow in flood channel. From the definition of K_G, they introduced the so called equivalent abutment length "L_e" which was defined as the length of abutment which would induce the same scour depth in a rectangular channel as the actual abutment when sated in compound channel. The equivalent length was recommended to be used in equation (2) to determine the maximum local scour depth in compound channels.

Yassin, Rezk and Baghdadi [9] studied experimentally the effect of contraction ratio and the inclination of the upstream face of the abutment on the formation of scour hole. Local scour formed around abutments is affected by the size of abutment, abutment geometry, hydraulic parameter and sediment bed characteristics. They developed the following empirical equation to estimate the maximum equilibrium scour depth:

$$\frac{d_s}{d_{50}} = 0.04653\left(\frac{\tau_o}{\tau_c}\right)^{4.168}\left(\frac{L}{B}\right)^{1.1043}\left(\frac{\theta}{90}\right)^{1.54} Fr^{0.512} \qquad (4)$$

Where τ_o & τ_c were average bed shear stress and the critical shear stress of the bed mixture, respectively, θ is the angle of inclination of the wing-wall and B is the channel width.

According to the investigations made by Shen [8] and Lui [4], local scour is formed due to the principal vortex formed at the bottom of the upstream face and side of abutment. The principal vortex is created because of the downward velocity acquired at the hitting face of abutment. Consequently, the amount of scour depth can be reduced by decreasing the downward velocity. Since the downward velocity is a function of the angle of attack "α", the local scour can be reduced by decreasing the vertical angle of inclination of the upstream face of the abutments, as shown in Figure (1).

The aim of this study is to investigate the effect of the vertical inclination of the abutment face on the formation of equilibrium scour hole and to develop an empirical equation to determine the maximum equilibrium scour depth.

EXPERIMENTAL SETUP

For the purpose of observing the effect of the inclination angle of the upstream face of the abutment "α" on the maximum equilibrium scour depth, a set of experiments were conducted in the hydraulic laboratory, Alexandria University. The experiments were performed in a recirculating tilting flume 12.0 m long and 86 cm wide. A sediment mixture having mean diameter of 0.65 mm and geometric standard deviation 1.65 was used to cover the bed flume. The thickness of the sediment mixture was 25 cm. Figure (2) shows the grain size distribution of the bed material.

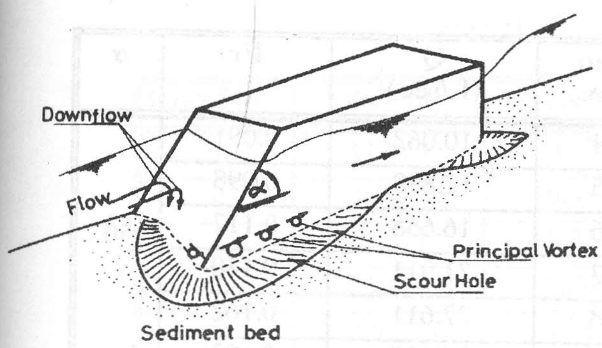

Figure 1. Flow pattern at sloped abutment.

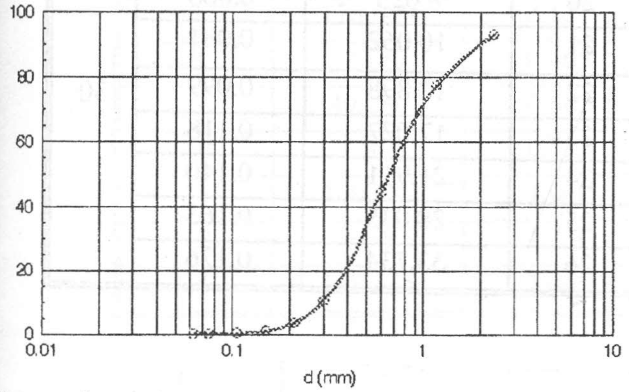

Figure 2. Grain size distribution of bed material.

Four different abutment models were constructed having angle of inclination α equals 30°, 50°, 70° and 90°. The contraction ratio L/B for all abutment models was taken equals 0.5. The length of abutment models was taken constant and equals 60.0 cm.

For each type of abutment model, various discharges were allowed to recirculate, to study the effect of flow parameters on the formation of scour hole, the details of which are shown in Table (I). For each run the rate of flow was gradually increased to the required discharge in a way that no local scour take place during this process. Water was then allowed to circulate for a sufficient period of time till equilibrium stage is practically attained. At this stage the flow was gradually reduced, the flume was slowly drained and the levels of the created scour hole were measured. The water levels upstream and through the channel contraction were also measured.

ANALYSIS OF THE RESULTS

All the experimental runs show that the equilibrium scour patterns have almost the same shape. Scour hole is formed nearly at the upstream corner of the abutment, where a shallow depression is excavated due to the principal vortex created at this point. The depression rapidly proliferate around the upstream corner of the abutment and a small mound develops downstream of it. The scour hole reaches its equilibrium condition when the rate of erosion equal to the rate sediment transport capacity. The equilibrium scour hole started to take place upstream the abutment, the scour depth is increased till it reaches its maximum scour depth at the bottom of the upstream corner for abutments having vertical upstream face. The amount of the eroded sediments was deposited just downstream the scour hole forming a mound. Figure (3) shows a typical contour line of the local scour formed due to channel contraction.

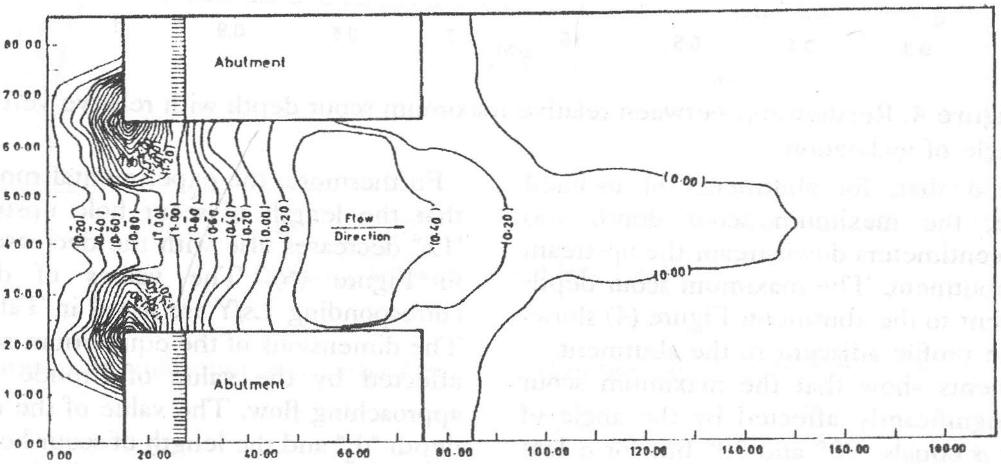

Figure 3. Contour lines of channel bed for run No. 10, all dimensions are in cm.

Table (I).

Run No.	Q (L/sec)	Fr	α	Run No.	Q (L/sec)	Fr	α
1	3.558	0.034	90	14	10.062	0.081	50
2	9.762	0.079		15	12.898	0.098	
3	12.898	0.099		16	16.668	0.117	
4	17.027	0.118		17	21.911	0.140	
5	21.911	0.143		18	27.611	0.162	
6	28.035	0.166		19	34.187	0.183	
7	34.642	0.192		20	8.025	0.068	30
8	10.062	0.081	70	21	10.062	0.081	
9	12.898	0.099		22	12.898	0.099	
10	17.027	0.118		23	17.027	0.118	
11	21.521	0.138		24	21.911	0.140	
12	28.035	0.163		25	28.035	0.163	
13	34.642	0.183		26	33.734	0.176	

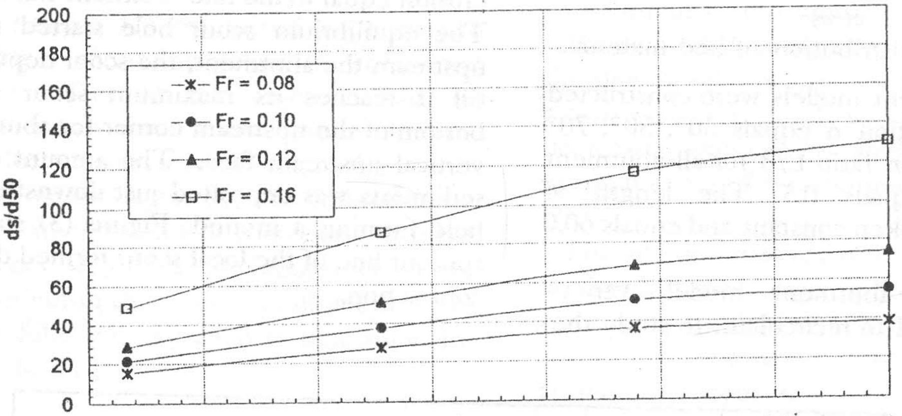

Figure 4. Relationship between relative maximum scour depth with relative vertical angle of inclination.

It was noticed that, for abutments of inclined upstream face, the maximum scour depth was displaced few centimeters downstream the upstream corner of the abutment. The maximum scour depth is always adjacent to the abutment. Figure (4) shows the bed surface profile adjacent to the abutment.

The experiments show that the maximum scour depth is not significantly affected by the angle of inclination for α equals 90° and 70° but for α less than 70° d_s decreases with the decrease of α as shown in Figure (5).

Furthermore, the experimental runs have revealed that the length of scour hole upstream abutment "Ls" decreases also with the decrease of α as shown in Figure (6). The values of d_s/d_{50} and the corresponding Ls/Y are listed in Table (II).

The dimensions of the equilibrium scour hole is also affected by the value of Froude number of the approaching flow. The value of the maximum scour depth "d_s" and the length of scour hole upstream the abutment "Ls" increase with the increase of Froude number as shown in Figure (7) and (8).

Table II. Experimental flow parameters.

Run No	ds/d50	Ls/Y	Run No	ds/d50	Ls/Y
1	11.475	0.174	14	26.230	0.271
2	36.066	0.391	15	34.426	0.373
3	57.377	0.526	16	50.820	0.709
4	75.410	0.845	17	72.131	0.800
5	109.836	1.014	18	108.197	1.132
6	157.377	1.962	19	149.180	1.657
7	178.689	2.121	20	18.033	0.081
8	32.787	0.465	21	18.033	0.156
9	49.180	0.602	22	26.230	0.226
10	70.492	0.775	23	26.230	0.282
11	100.000	1.000	24	34.426	0.333
12	136.066	1.250	25	37.705	0.438
13	188.525	1.469	26	67.213	0.640

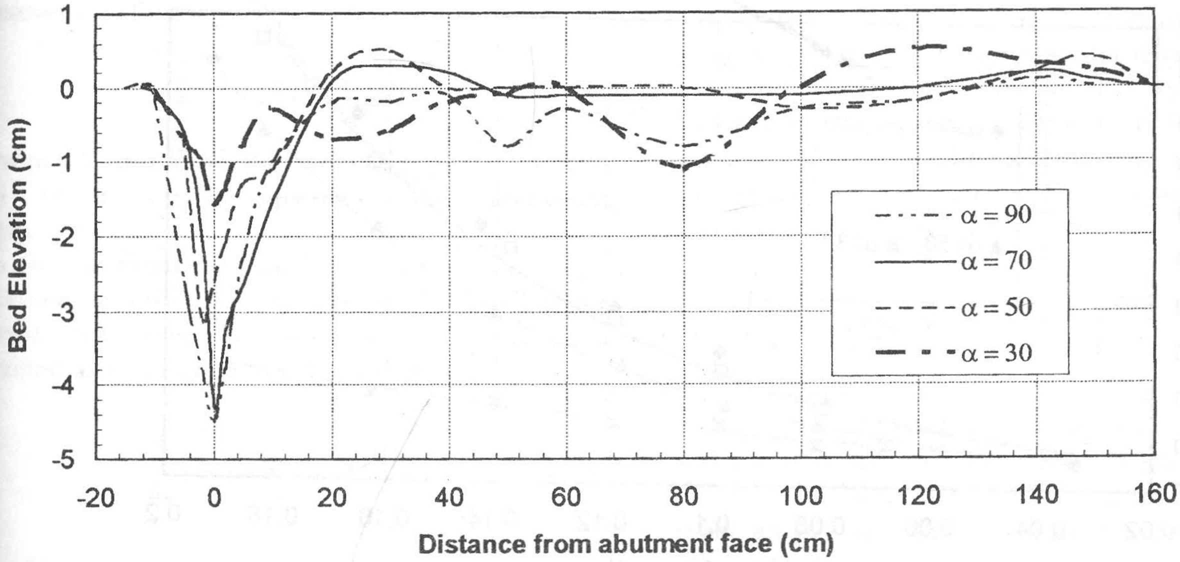

Figure 5. Variation of equilibrium scour adjacent to the abutment for froude No. 0.118

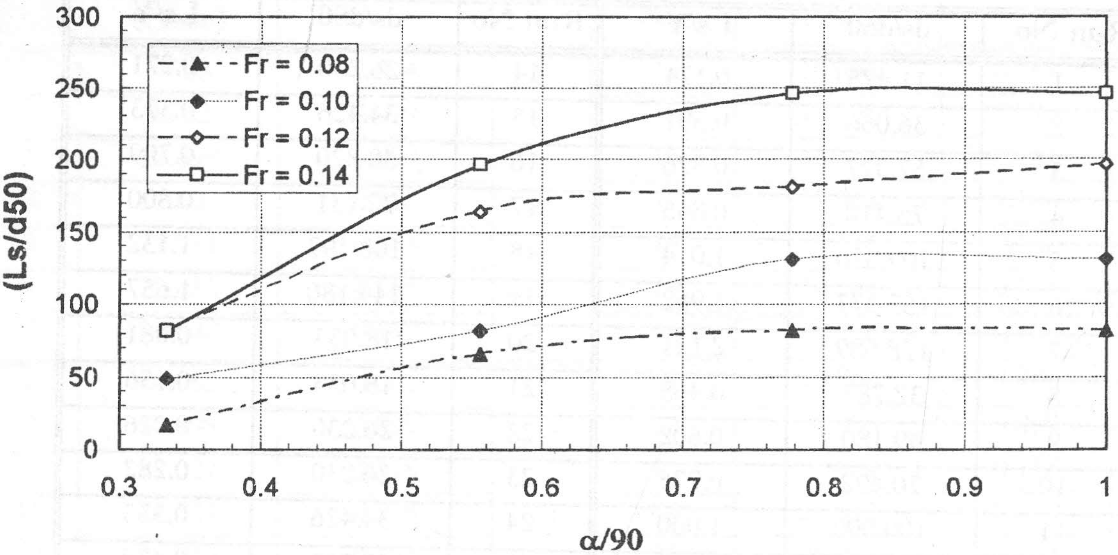

Figure 6, Variation of relative upstream length of scour hole with relative vertical angle of inclination

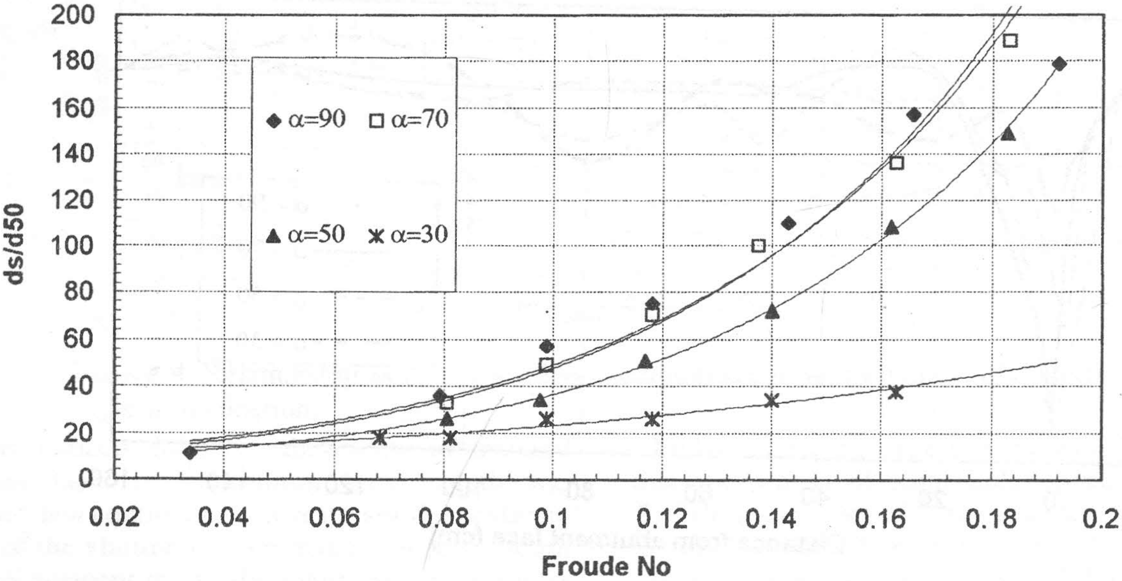

Figure 7, Relationship between relative maximum equilibrium scour depth with Froude Number

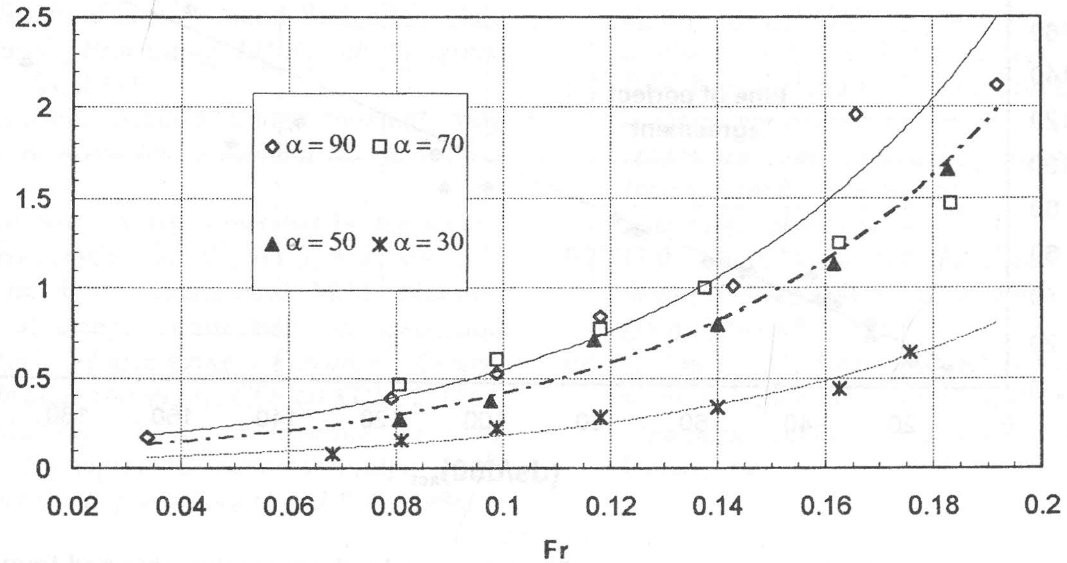

Figure 8. Relationship between the ratio of maximum length of scour upstream abutment to the depth of flow and froude number.

For box type abutments and for contraction ratio equals 0.5, the maximum scour depth can be expressed as follows:

$$d_s = f(Y, V, d_{50}, \alpha) \tag{5}$$

In which V and Y are the average approach velocity and water depth upstream the abutment, respectively.

In order to determine the best function of equation (5) a comprehensive multiple regression analysis was carried out using the experimental data. The obtained best fit equation, for $90° \geq \alpha \geq 70°$, is:-

$$\frac{d_s}{d_{50}} = 2867.247\, Fr^{1.6913} \tag{6}$$

The correlation coefficient for equation (6) equals 0.98 and the standard error of estimate is 15.07 For $\alpha < 70°$, the best fit equation is :-

$$\frac{d_s}{d_{50}} = 3861.725\, Fr^{1.7207} \left(\frac{\alpha}{90}\right)^{1.029} \tag{7}$$

The correlation coefficient for equation (7) is 0.88 and the standard error of estimate for d_s/d_{50} is 12.45. Figure (9) shows a plot of the estimated relative scour depth with the experimental data.

An empirical equation is also developed to determine the length of scour hole upstream the abutment using the obtained experimental data and the method of least square. The obtained empirical equation is expressed as follows:

$$\frac{Ls}{Y} = 2.152 \times 10^{-6}\, Fr^{0.958} \left(\frac{\alpha}{90}\right)^{1.098} \left(\frac{Y}{d_{50}}\right)^{2.759} \tag{8}$$

The correlation coefficient of equation (8) is 0.9753 and the standard error of estimate Ls/Y is 0.1569. Figure (10) shows a plot of the estimated relative scour length with the experimental data. Equation (7) and (8) are valid only for the range of experimental data.

In order to prevent formation of local scour, it is recommended to start protecting the canal bed for a length upstream the abutment equals at least Ls obtained from equation (8). The protection material should be of plain concrete blocks or riprap.

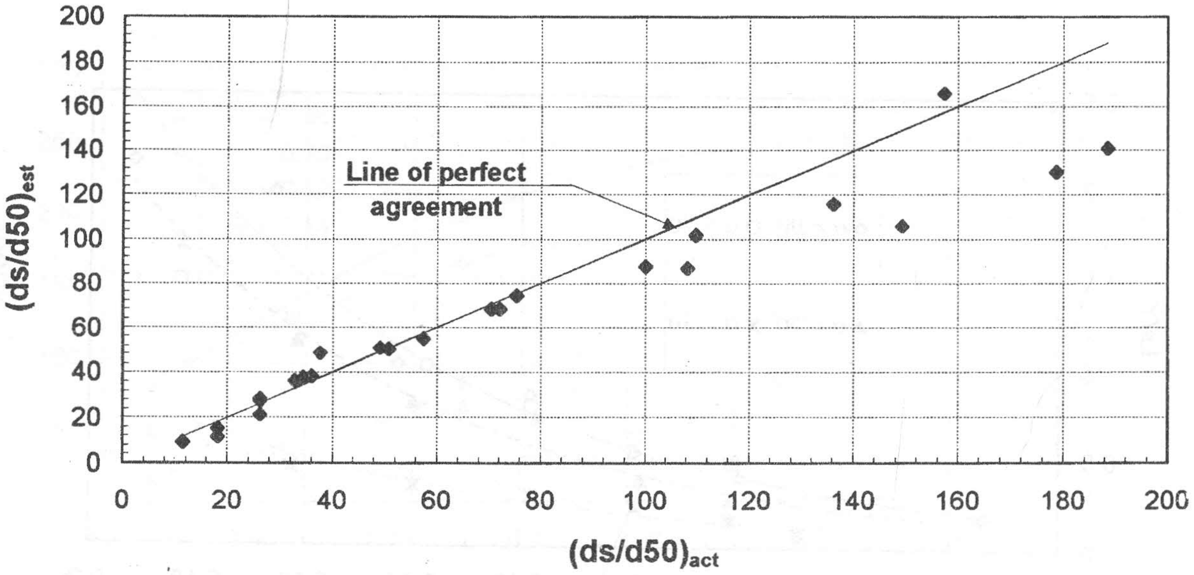

Figure 9. Plot of estimated relative maximum equilibrium scour depth versus that obtained from experiments.

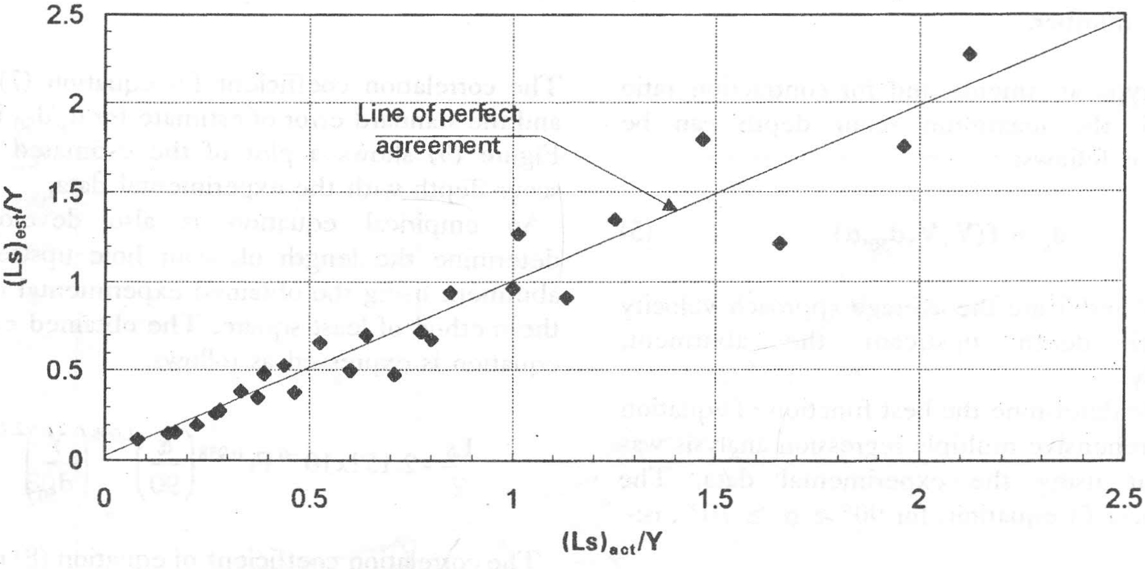

Figure 10. Plot of estimated relative maximum upstream scour length versus that obtained from experiments.

CONCLUSIONS

The effect of the vertical slope of the upstream abutment face on the formation of equilibrium local scour is presented in this study. Based on the analysis of the obtained experimental data, it is found that for angle of inclination α less than 70° the maximum scour depth decreases with the decrease of the vertical abutment face slope, while for angles equal or greater than 70° the size of scour hole is not affected by the upstream abutment slope. Dimensionless equations are presented for the prediction of maximum equilibrium scour hole.

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