LOCAL SCOUR AT BRIDGE ABUTMENTS

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ABSTRACT

Local scour at bridge abutments is experimentally studied. The effect of the contraction ratio and the inclination of the upstream face of the abutment on the formation of scour hole is studied. Experimental data are analyzed and a dimensionless equation is developed to predict the maximum equilibrium scour depth.

Keywords: Local Scour, Abutment, Scourhole, Contraction.

NOTATION

B	channel bed width
d_{50}	mean diameter of the bed sand mixture
ds_{max}	maximum equilibrium scour depth
Fr	Froude number
g	acceleration due to gravity
L	abutment length
Q	rate of flow
v	mean velocity in the channel
Y	water depth
θ	angle of abutment inclination to the flow direction
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

Many failures of water crossings were caused by undermining of abutments by scour. Therefore, the prediction of scour depth at bridge abutments has attracted the interest of several investigators. Laursen (1) studied experimentally the formation of scour hole at bridge abutments. He found that the depth of scour was much greater than scour depth caused by equivalent long contraction. He found that the maximum scour depth is depends only on the depth of flow for a given obstruction and did not significantly change with either velocity or the sediment size. He developed the following empirical equation to estimate the maximum equilibrium depth :

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

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

Where b is the width of over bank, y is the depth of flow, d_s is depth of scour hole and Q_b, Q_o are the discharge over the entire width and over bank, respectively.

Melville [4] 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.

$$d_s = 2K_sL \quad \text{for} \quad \frac{L}{y} < 1$$
$$d_s = 2K_s^* K_\theta^* (YL)^{0.5} \quad \text{for} \quad 1 \le \frac{L}{Y} \le 25 \quad (2)$$
$$d_s = 10K_\theta y \quad \text{for} \quad \frac{L}{y} > 25$$

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 the obstruction.

Melville and Ettema [6] 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 at 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

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

Where L* and y* were the width and depth of flow in flood channel. From the definition of K_G, they introduced a 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 sided in compound channel. The equivalent length was recommended to be used in equation (2) to determine the maximum local scour depth in compound channels.

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

THERETICAL APPROACH

Local scour formed around abutments is affected by the shape of abutments, hydraulic parameters and sediment bed characteristics. The abutment shape is described in this study by the angle of inclination of the upstream wing wall to flow direction "θ" and the size of obstruction "L" as described in Figure (1).

The hydraulic parameters which influence the formation of scour hole are the approach velocity "v", the depth of flow "Y", and the average boundary shear stress "τ_o". The sediment characteristics can be expressed by the mean diameter of the bed mixture and the critical shear stress of the bed mixture "τ_c". The functional relationship for the equilibrium depth of local scour, $(d_s)_{max}$ at an abutment can be written as follows:

$$ds_{max} = \phi(L, B, g, \theta, Y, v, \tau_o, d_{50}, \tau_c) \quad (4)$$

Applying the Backingham π- theory, equation (4) can be written in a dimensionless form as follows:

$$\frac{ds_{max}}{d_{50}} = \phi_1\left(\frac{L}{B}, \frac{\tau_o}{\tau_c}, Fr, \frac{\theta}{90}\right) \quad (5)$$

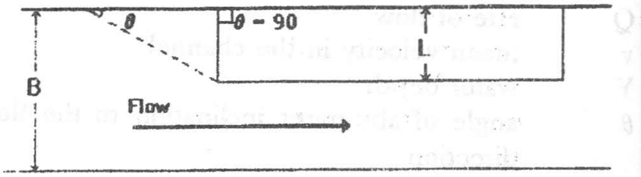

Figure 1. Definition sketch.

EXPERIMENTAL SETUP

For the purpose of observing the effect of abutment shape 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.

Table I, Scheme of experiment runs.

Run No	Q	L/B	θ	Run No	Q	L/B	θ
1	6.41			19	7.747		
2	7.742			20	13.228	0.2	90
3	12.48	0.5	90	21	22.305		
4	17.389			22	34.189		
5	21.912			23	7.200		
6	28.037			24	12.899	0.5	60
7	7.201			25	24.302		
8	12.899			26	34.189		
9	17.752	0.4	90	27	7.201		
10	22.305			28	12.899	0.5	45
11	28.037			29	21.913		
12	34.189			30	34.189		
13	7.21			31	7.201		
14	12.889			32	12.899	0.5	30
15	17.752	0.3	90	34	21.913		
16	22.305			35	34.189		
17	28.037						
18	37.189						

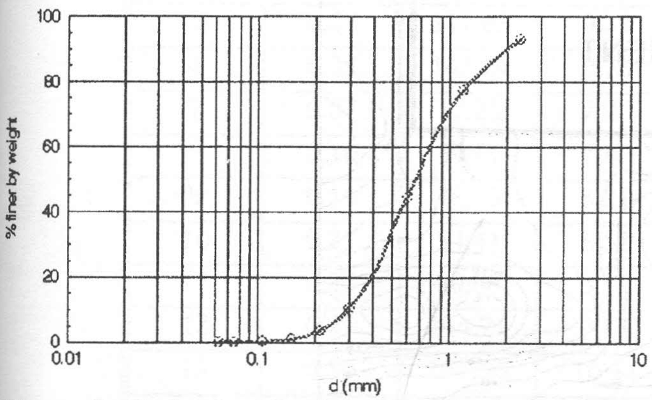

Figure 2. Grain size distribution of bed material.

To study the effect of wing wall angle θ, three different abutment models were constructed having angle 30°, 45° and 60°. For θ=90°, four different abutment models were constructed so that the contraction ratios were 0.2, 0.3, 0.4, and 0.5.

To study the effect of channel Froude number on the formation of scour hole, for each type of abutment model, various discharges were allowed to recirculate, 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 in which the scour hole no further sediments are removed from it. At this stage the flow was gradually reduced, the flume is slowly drained and the created scour hole levels was measured. The water level upstream and through the channel contraction was measured.

ANALYSIS OF THE RESULTS

As the flow approach the upstream face of the abutment, the upper layer tends to deviate into two parts, one part of the flow accelerate around the upstream corner of the abutment while the remaining part flow slowly circulating in near a stagnant pool adjacent to the head of the abutment (Figure 3).

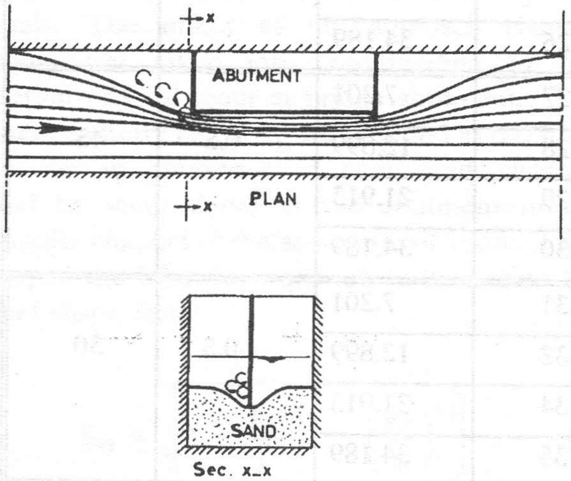

Figure 3. Flow pattern adjacent to an abutment.

A horse shoe vortex is formed around the upstream edge of the abutment causing erosion of bed material adjacent to the abutment and is swept out of the vortex field. The volume of scour hole increases with time till it reaches its final equilibrium form.

All experiment runs show that the equilibrium scour have almost the same shape. Scour hole is formed at the upstream corner of the abutment, where a shallow depression is excavated due to the flow acceleration at this point. The scour hole reaches its equilibrium condition when the rate of erosion equal to the rate sediment transport capacity. Figure (4) shows a typical contour line of an equilibrium scour hole at abutment. The maximum scour depth is located adjacent to the upstream corner of the abutment as shown in figure (4).It is observed from experiments that the shape of the scour hole profile is nearly the same, in which the bed is eroded at a distance upstream the abutment till it reaches its maximum scour depth at the upstream corner of the abutment. Thereafter, the scour depth will decrease till it equals zero within contraction zone. Farther downstream, the eroded amount of eroded material will be deposited forming a mound as shown in figure (5).

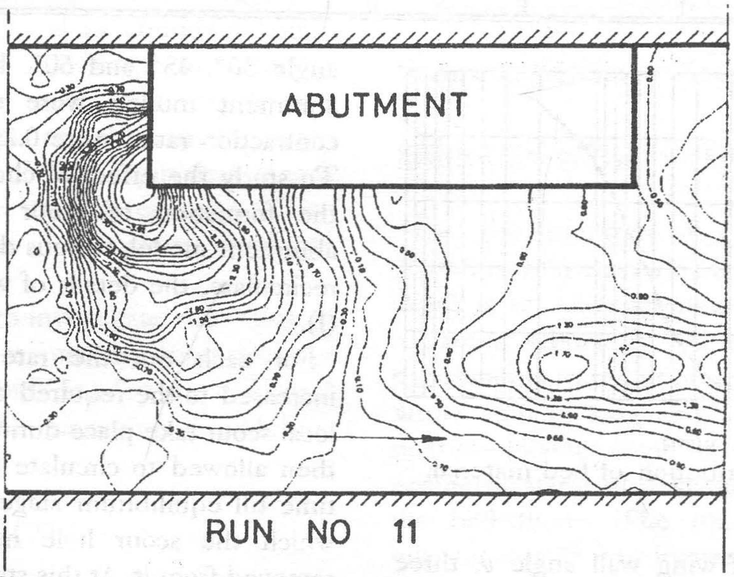

Figure 4. Contour lines of channel bed box abutment.

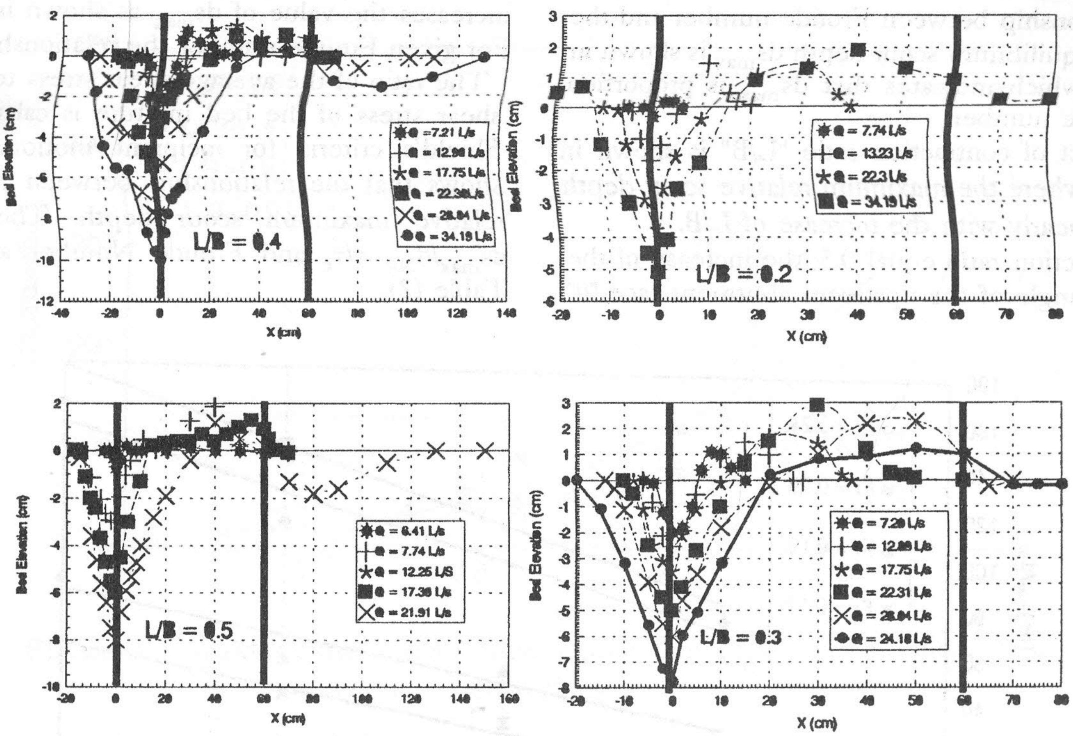

Figure 5. Variation of scour depth adjacent to the abutment.

Table 2. Experimental flow parameters.

Run No.	Fr	ds/d50	τo/τc	Run No.	Fr	ds/d50	τo/τc
1	0.10	55.88	7.90	19	0.30	114.71	10.34
2	0.12	10.29	7.90	20	0.11	4.41	7.60
3	0.19	44.12	7.90	21	0.16	25.00	8.21
4	0.26	88.24	8.21	22	0.20	55.88	10.34
5	0.28	117.65	9.12	23	0.30	75.00	10.34
6	0.33	163.24	9.73	24	0.10	14.71	7.86
7	0.07	17.65	7.30	25	0.15	16.18	8.45
8	0.10	39.71	7.60	26	0.24	19.12	9.44
9	0.16	48.53	8.21	27	0.30	77.94	10.43
10	0.21	54.41	8.51	28	0.30	70.59	10.43
11	0.24	80.88	9.12	29	0.09	22.06	7.87
12	0.27	114.71	9.73	30	0.17	30.88	7.87
13	0.30	147.06	10.34	31	0.22	48.53	9.42
14	0.10	29.41	7.60	32	0.30	100.00	10.43
15	0.16	39.71	8.21	33	0.10	26.47	7.86
16	0.20	51.47	8.82	34	0.15	42.65	8.54
17	0.24	73.53	9.12	35	0.22	66.18	9.46
18	0.27	88.24	9.73				

The relationship between Froude number and the maximum equilibrium scour depth ds_{max} is shown in figure (6), which indicates that ds_{max} is proportion with Froude number.

The effect of contraction ratio "L/B" is shown in figure (6), where the maximum relative scour depth increases linearly with the increase of L/B.

For contraction ratio equal 0.5, the increase of the inclination angle of the upstream abutment face "θ" increases the value of ds_{max} as shown in figure (7). For given Froude number the relationship is linear.

The ratio of the average shear stress to the critical shear stress of the bed mixture is calculated using Shield's criteria for incipient motion. Figure (8) shows that the relationship between τ/τ_c with the relative maximum scour depth. The values of ds_{max}/d_{50}, τ/τ_c and Froude Number are listed in Table (2).

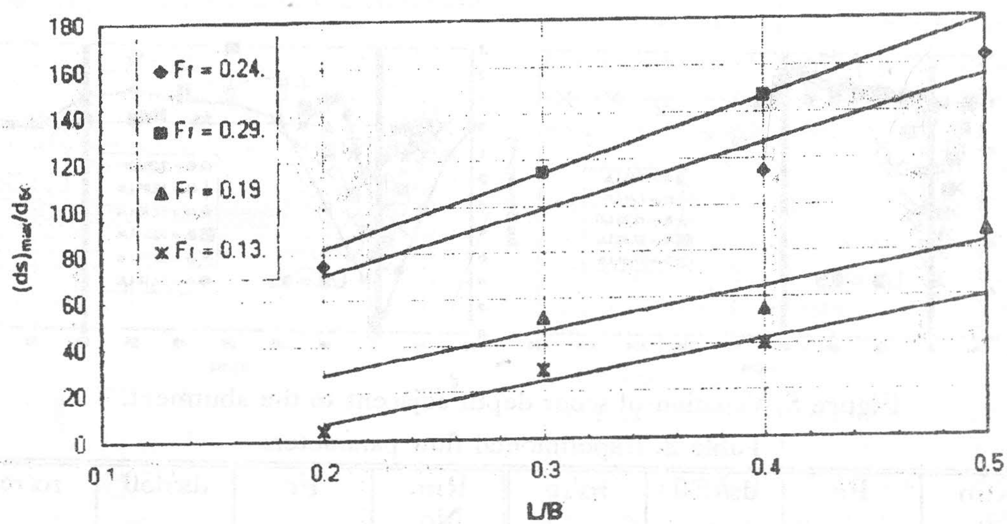

Figure 6. Effect of channel contraction on the formation of maximum equilibrium scour depth for θ=90.

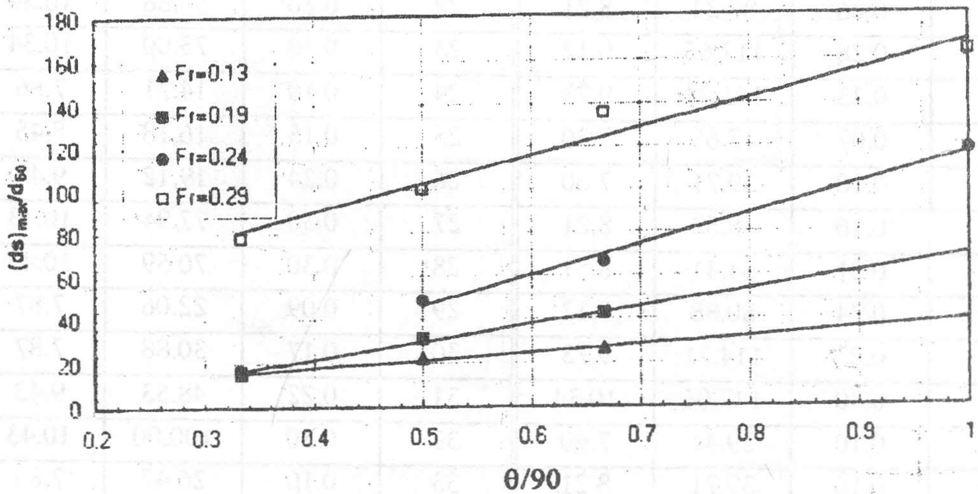

Figure 7. Relationship between relative upstream angle face of abutment and relative maximum scour depth for L/B=0.5.

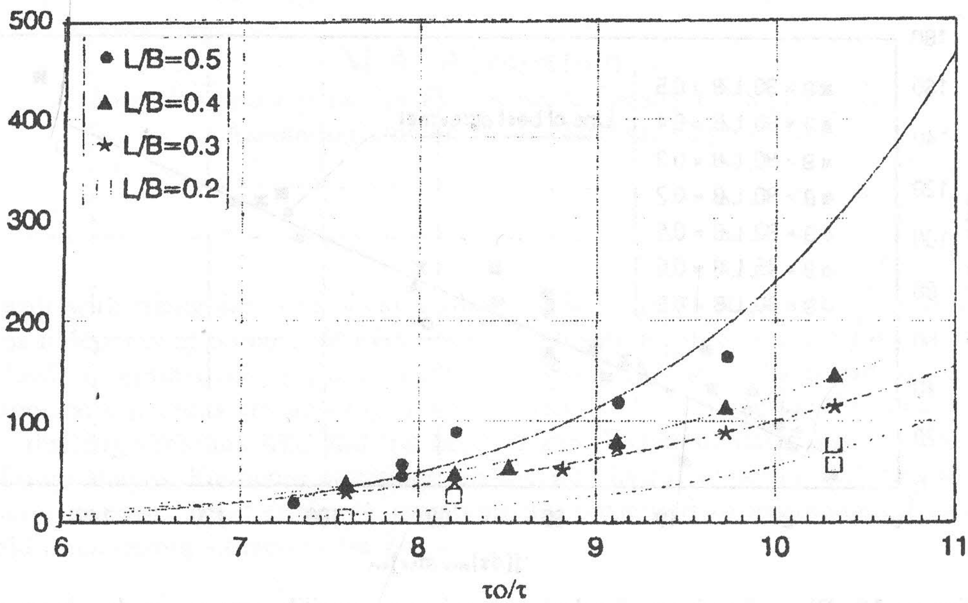

Figure 8. Variation of maximum relative equilibrium depth versus critical shear stress ratio.

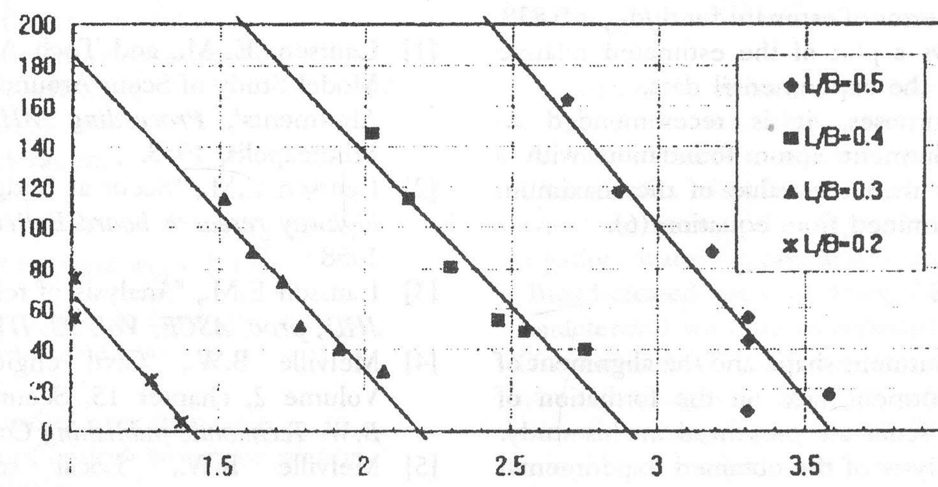

Figure 9. Relationship between relative abutment length with relative maximum equilibrium scour depth $\theta = 90$.

Furthermore, the experimental runs has revealed that for given L/B the relative scour depth increases linearly with the decrease of the relative abutment length "L/Y" as shown in figure (9).

In order to determine the best function of equation (5) a comprehensive multiple regression analysis is carried out using the experimental data. The obtained best fit equation is:

$$\frac{ds_{max}}{d_{50}} = 0.04653\left(\frac{\tau_o}{\tau_c}\right)^{4.168}\left(\frac{L}{B}\right)^{1.1043}\left(\frac{\theta}{90}\right)^{1.54} Fr^{0.512} \quad (6)$$

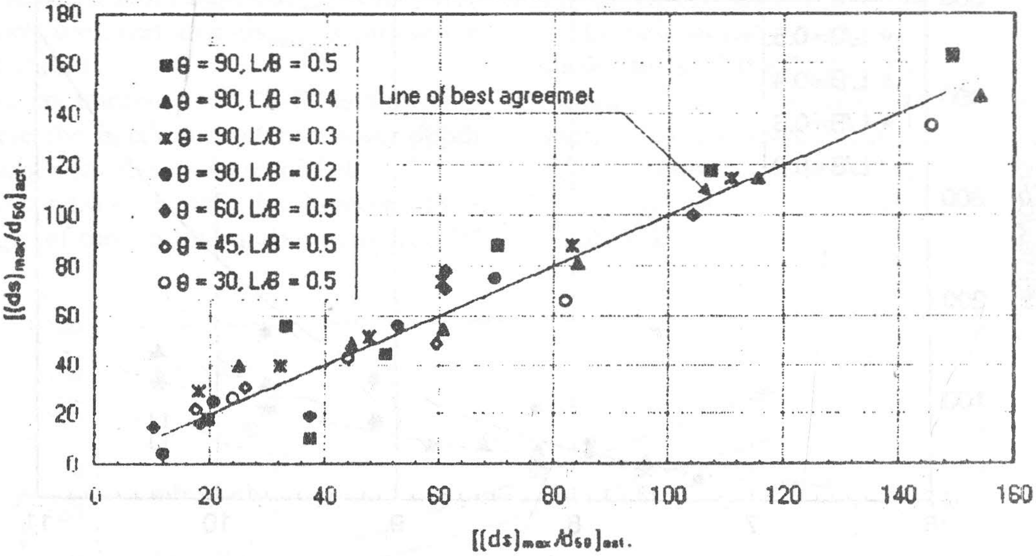

Figure 10. Plot of estimated relative maximum equilibrium scour depth versus that obtained from experiments.

The correlation coefficient for equation (6) is 0.988 and the standard error of estimate for d_s/d_{50} is 9.838. Figure (10) shows a plot of the estimated relative scour depth with the experimental data.

For design purposes, it is recommended to construct the abutment apron foundation with a thickness greater than the value of the maximum scour depth determined from equation (6).

CONCLUSIONS

The effect of abutment shape and the alignment of the upstream abutment face on the formation of equilibrium local scour are presented in this study. Based on the analysis of the obtained experimental data, it is found that the factors affecting the value of the maximum equilibrium scour hole are the critical shear stress of the bed mixture, the average boundary shear stress, the length of abutment, the inclination of the upstream face of the abutment to the direction of flow and the contraction ratio , depth of flow and the velocity of the approach channel.

A dimensionless equation is presented for prediction of maximum equilibrium scour hole.

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