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Local Scour at Bridge Abutments

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ABSTRACT. This paper presents the results of an experimental investigation of local scour at bridge abutment models of three common shapes placed in laboratory flume with uniform sand with d_{50} = 0.775 mm. The maximum scour depths and extent of scour were determined corresponding to clear water conditions. For design purposes, a general nondimensional equation for clear water scour prediction is proposed. The equation addresses all the important variables in terms of shape and size of abutment, sediment and flow characteristics. The equation was verified with the present experimental data as well as with the data obtained by previous investigators under comparable conditions.

1. Introduction

Knowledge about local scour at bridge abutments and piers is important. The bridge abutments and piers being in a water way offers resistance to the flow and reduces the flow area causing scours of the alluvial bed material due to the combined effect of flow and the structure. Local scour is caused by local contraction of flow due to abutment geometry resulting in the separation of the boundary layer along with horse-shoe like vortex, which is referred to as principal vortex system. The principal vortex, the reattachment of flow, the formation of eddies along with turbulence are mainly responsible for local scour at upstream corner of abutment. At downstream corner, the formation of wake vortices acts like a vacuum cleaner by sucking sediments into their low pressure cores and then deposited downstream by the eddies[1-3]. The depth and extent of such scour for which the abutment foundation must be designed, depend upon many factors such as approach flow condition, abutment geometry (shape and size), spacing between abutments or abutment and piers and bed material characteristics[3-5]. Although the interaction of all the variables is complex to develop a workable criteria for the understanding of local scour, all the concerned variables need to be identified and the important ones to be considered.

Extensive works have been done in the past and many design formulas were proposed to evaluate the local scour around bridge piers but only a few for the abutments. Many of the earlier formulas did not differentiate between the clear water and the live bed scour[6]. The clear water scour occurs when the bed material is not moved, while the live bed scour occurs with the bed load transport. Some systematic studies have focussed mainly on the live bed scour at abutments, while very few have carried out detailed studies concerning the clear water scour at abutment. Not a single workable analytical equation for predicting clear water scour at abutment is currently available. Consequently, an experimental investigation was undertaken to determine the clear water scour for three common shapes of abutment models placed in a rectangular flume with uniform sand bed. This study attempts to develop a general nondimensional equation to predict the clear water scour at abutments incorporating all the important variables in terms of sediment, size and shape of abutment and flow properties. The equation has been verified with the date obtained by other investigators as well as data developed in the current study.

2. Review of Previous Works

The earlier attempts at estimating the local scour depth at bridge crossings used the regime equation. The scour depth was computed by multiplying the regime depth with a coefficient depending on the geometry of obstruction. Examples of this approach includes the works of Inglis[7], Ahmad[1], Izzard and Bradley[8], Raudkivi and Sutherland[9]. The regime analysis method is largely based on mean flow velocity that depends very much on the choice of the investigators and is very difficult to evaluate for natural stream. Some other works on local scour and the ranges of experimental works were reported by Wong[3] and Melville[10]. To mention a few, Garde *et al.*[2], Laursen and Toch[4], Laursen[11], Liu *et al.*[5], Gill[12], Zaghloul and McCorquodale[13], Cunha[14], Simons and Senturk[15], Field and Hinchey[16], Wong[3], Zaghloul[17], Rajaratnam and Nawachukwu[18], Jones[19], Tey[20], Kandasamy[21], Kwan[22,23], Kandasamy[24], Froehlich[25] and Melville[10], presented formulas and enveloping curves on clear water as well as live bed scour around flat plate, spur dike and rectangular abutments. However, the clear water scour at abutments was considered by only a few authors using wing wall, spill through or flat plate models[3,5] and the informations related to those studies were qualitative in nature. Most of the investigators considered only two or three variables as significant factors affecting the scouring process. This study attempts a detailed analysis of the local clear scour at bridge abutments of three common shapes.

3. Experimental Arrangements

The experiments were conducted in a 15 m long, 1.37 m wide and 0.62 m deep glass sided rectangular flume (Fig. 1). The water in the flume is recirculated by a propeller pump driven by an AC motor of 29.5 hp taking its supply from basement sump. The maximum capacity of the pump is 190 liter/sec. The tail water depth in the flume is controlled manually by an adjustable gate located at the outlet end. The test section, located 2.5 m upstream of the tail gate, consists of a sand bed of 0.275 m height. Each model abutment is attached to one side of the flume wall in the middle of the test section. The sediment size varied between 0.1 mm to 2 mm with a d_{50} equals to 0.775 mm. The degree of uniformity has been defined by the value of its geometric standard deviation, σ_g ($\sigma_g = d_{84}/d_{50}$) of 1.29 mm, which is considered to be uniform[9].

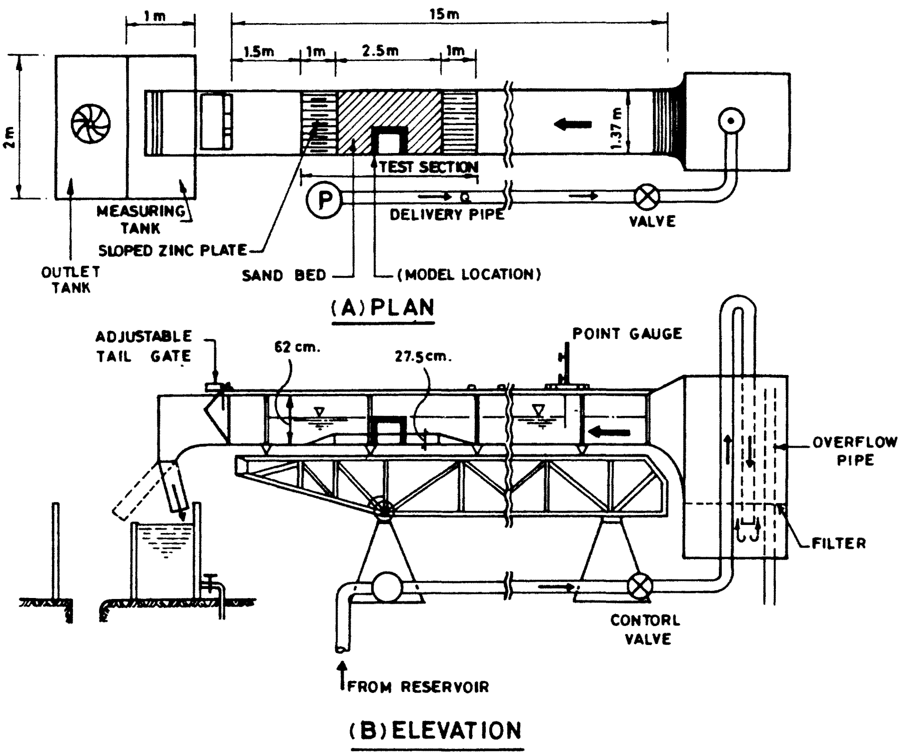

FIG. 1. Arrangement of the experimental set-up (not to scale).

The variation of scour depth with time for one typical model initially was made at certain intervals for a total duration of 12 hours in order to estimate the suitable time of each run so that maximum scour depth is achieved. Thus the duration of each experimental run was limited to about six hours, which was considered sufficient for the prototype applications[2,26]. Beyond six hours the rate of increase of scour depth was almost insignificant. Measurements of scour depths and water level were taken at about 50 points using point gauges. The critical shear velocity, u_c^* for the d_{50} size sediment was calculated using Shield's diagram. The corresponding critical mean velocity, U_{oc} was computed from the following equation[6].

$$\frac{U_{oc}}{u_c^*} = 5.75 \log \frac{y_o}{2d_{50}} + 6 \tag{1}$$

where, y_o is the mean approach flow depth, which was kept constant at 0.22 m for all the experimental runs. This depth resulted in an average flow velocity of 0.199 m/sec

(Q = 60 liter/sec.) with bed shear stress $\tau_o = 0.124$ N/m^2 (bed surface slope, $s_b = 0.0000697$), which is less than the critical shear stress, $\tau_c = 0.428$ N/m^2. This assured clear water scour. After each experimental run, sand samples were collected at the maximum scoured holes and deposition zones by pouring melted wax on the sand surface. The grain size distribution of the samples was then determined by sieve analysis.

Three common shapes of abutment model, *e.g.*, rectangular, trapezoidal and circular edge with inclined (1:1) wing wall were tested (Fig. 2). The width of the flume in this study was wide enough to neglect the boundary effect of the flume wall on the flow. As shown in Table 1, the projected lengths of each type of abutment were varied systematically for comparison and the results were also compared with the data of other investigators as applicable.

Table 2 shows the results of all experiments of this study as well as the works of other investigators for comparison.

TABLE 1. Details of abutment models.

Model shape (1)	Encroachment width of model b (cm) (2)	Channel width B (cm) (3)	Contraction ratio, $\alpha = (B-b)/B$ (4)
R_1, T_1, CE_1	40	137	0.708
R_2, T_2, CE_2	60	137	0.562
R_3, T_3, CE_3	80	137	0.416

TABLE 2. Scope of experiments.

Test series (1)	S. no. (2)	Expt. no. (3)	Model shape (4)	t_e^* (min) (5)	b (cm) (6)	B (cm) (7)	Q (m^3/s) (8)	y_o (cm) (9)	d_{50} (mm) (10)	α (11)	D_s (cm) (12)	Non-dim. scour depth D_s/y_o (13)
1[a]	1	1	R_1	360	40	137	0.06	22	0.775	0.708	9.9	0.45
	2	2	R_2	360	60	137	0.06	22	0.775	0.562	17.5	0.795
	3	3	R_3	360	80	137	0.06	22	0.775	0.416	27.5	1.25
	4	1	T_1	360	40	137	0.06	22	0.775	0.708	7.9	0.359
	5	2	T_2	360	60	137	0.06	22	0.775	0.562	14.5	0.659
	6	3	T_3	360	80	137	0.06	22	0.775	0.416	22.2	1.0
	7	1	CE_1	360	40	137	0.06	22	0.775	0.708	4.5	0.205
	8	2	CE_2	360	60	137	0.06	22	0.775	0.562	8.2	0.372
	9	3	CE_3	360	80	137	0.06	22	0.775	0.416	12.5	0.568
		Run										
2[b]	10	64	T_1	300	38.1	121.9	0.034	12.19	0.65	0.687	11.27	0.92
	11	65	T_2	300	30.48	121.9	0.034	12.19	0.65	0.75	8.53	0.70
	12	66	T_3	300	57.0	121.9	0.034	12.19	0.65	0.533	16.7	1.36
	13	67	CE	300	41.75	121.9	0.034	12.19	0.65	0.656	6.7	0.55
	14	68	CE	300	41.75	121.9	0.034	12.19	0.65	0.656	6.4	0.525

TABLE 2. Contd.

Test series (1)	S. no. (2)	Expt. no. (3)	Model shape (4)	t_e* (min) (5)	b (cm) (6)	B (cm) (7)	Q (m^3/s) (8)	y_o (cm) (9)	d_{50} (mm) (10)	α (11)	D_s (cm) (12)	Non-dim. scour depth D_s/y_o (13)
	15	69	CE	300	57.0	121.9	0.034	12.19	0.65	0.533	11.88	0.975
	16	70	CE	300	57.0	121.9	0.034	12.19	0.65	0.533	12.80	1.0
3[c]	17	1	T	>360	58.96	152.0	<0.29	12.5	0.62	0.612	17.1	1.36
	18	2	CE	>360	45.00	152.0	<0.29	12.5	0.62	0.643	10.8	0.86
	19	3	T	>360	60.60	152.0	<0.29	12.5	0.62	0.60	20.0	1.60
	20	4	T	>360	60.20	152.0	<0.29	12.5	0.62	0.603	22.3	1.27
				(about)								
4[d]	21	1	R_1	480	20	50	>0.02	10	4.5	0.60	9.5	0.95
	22	2	R_1	480	20	50	>0.02	10	4.5	0.60	14.5	1.45
	23	3	R_1	480	20	50	>0.02	10	4.5	0.60	19.0	1.90
	24	4	R_1	480	20	50	>0.02	10	4.5	0.60	23.0	2.30
	25	5	R_1	480	20	50	>0.02	10	4.5	0.60	27.0	2.70
5[e]	26	1	R_1	380	30.4	76.2	>0.02	4.5	0.92	0.60	11.5	2.55
6[f]	27	1	R_1	300	10.24	60.96	<0.01	5.0	0.3	0.667	4.0	0.80
	28	2	R_1	300	10.24	60.96	<0.01	5.0	0.3	0.667	5.2	1.04
	29	3	R_1	300	10.24	60.96	<0.01	5.0	0.3	0.667	6.5	1.30

*t_e = time of each experimental run.
a . Test series on abutment for present study.
b Test series on abutment by Liu et al.[5].
c Test series on abutment by Wong[3]
d Test series on spur-dike by Zaghloul and McCorquodale[13].
e . Test series on spur-dike by Gill[12].
f . Test series on spur-dike by Garde et al.[2].

where,

R_1, R_2, R_3 = Rectangular model abutments
T_1, T_2, T_3 = Trapezoidal model abutments
CE_1, CE_2, CE_3 = Circular-edge model abutments.

The functional relationship for the local clear water scour at abutment can be written in the form

$$\frac{D_s}{y_o} = f_1\left[\frac{b}{y_o}, \frac{B-b}{B}, \frac{d_{50}}{y_o}, S_f, Fr_1\right] \tag{2}$$

in which D_s is the scour depth, y_o = Flow depth in the channel, b is encroachment width, B is the channel width, $\alpha = (B\text{-}b)/B$ is the contraction ratio, d_{50} is the mean sediment size, Fr_1 = Approach Froude number = $U_1/\sqrt{gy_0}, U_1$ = Approach velocity and g is the acceleration due to gravity and S_f is the shape of abutment. The shape factor, S_f is defined as the ratio of D_s/y_o for the circular-edge model at comparable condition. Figure 3 is a plot of D_s/y_o (any shape) v., D_s/y_o for circular edge model with Froude number, contraction ratio, α and d_{50}/y_o constant. The shape factors S_f were evaluated

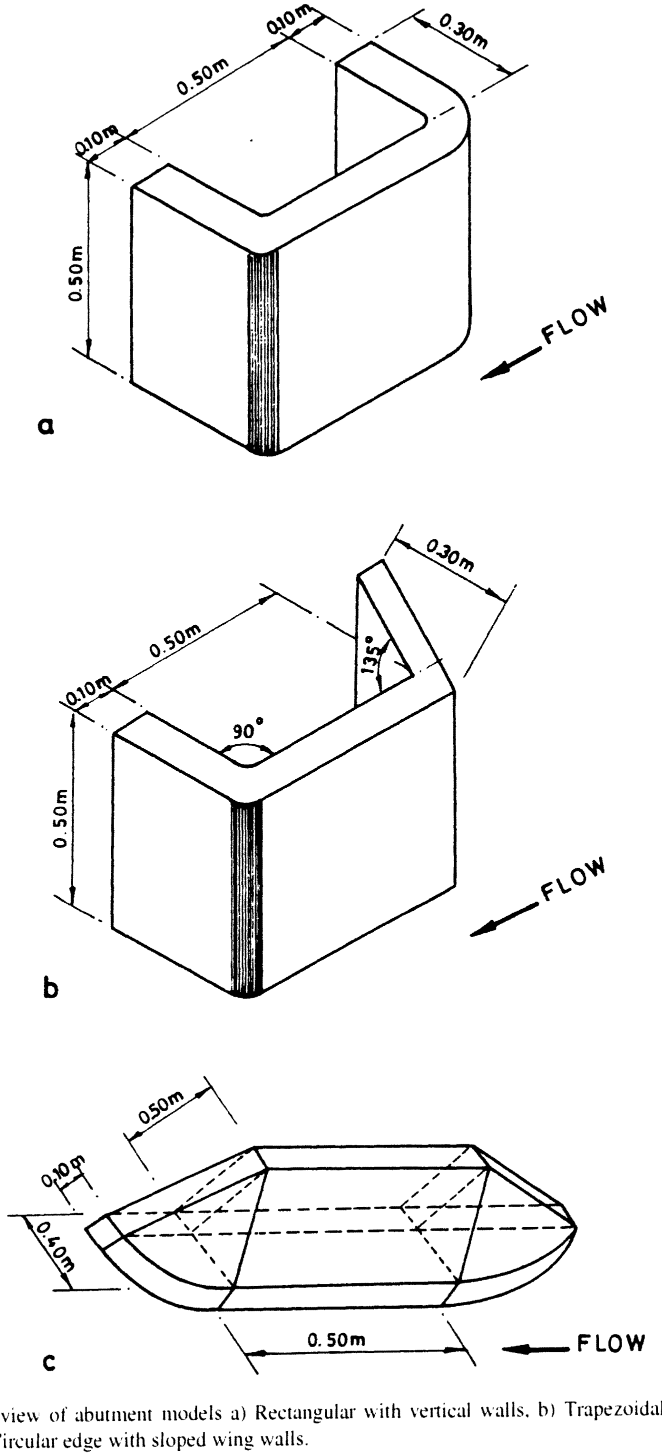

FIG. 2. Isometric view of abutment models a) Rectangular with vertical walls, b) Trapezoidal with vertical walls, c) Circular edge with sloped wing walls.

from the slope of the graphs as 2.2, 1.77 and 1.0 for rectangular, trapezoidal and circular-edge abutments, respectively.

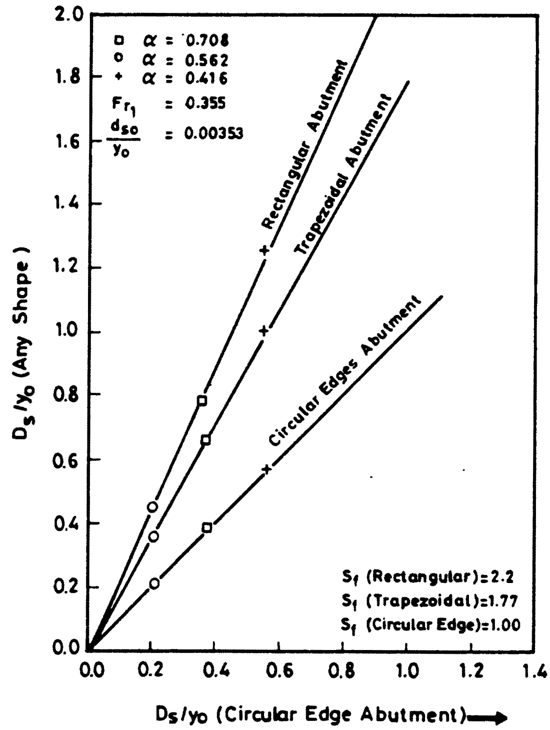

FIG. 3. Evaluation of shape factor, S_f.

4. Results

The scour depth was found to be affected by a number of variables. A discussion of the effects of the model geometry, contraction ratio and encroachment width on the variation of scour depth is presented below.

4.1 Model Geometry

It is well known fact that scouring at any obstruction in alluvial channel is primarily due to the combined effect of the flow pattern and the geometry of the structure. The variation of scour caused by different shapes and sizes of the model abutments was studied. Figures 4(a), (b) and (c) present a typical scour depth contours for the rectangular, trapezoidal and circular-edge models, respectively. It can be seen from Fig. 4(a) that scouring begins at upstream corner *u* of the rectangular model, abutment forming a depression caused by the separation of flow. The extent of this depression is affected by the zone of separation. Further downstream, there is a deposition due to the reattachment of the separated flow. Similar trend was also observed in the case of the trapezoidal models. However, the scour depth of the trapezoidal model is slightly less. The scour pattern at circular-edge model indicates that scour initiates at the upstream corner with a smaller size hole and extends parallel to the longitudinal wall due to a streamlined shape of the model abutment.

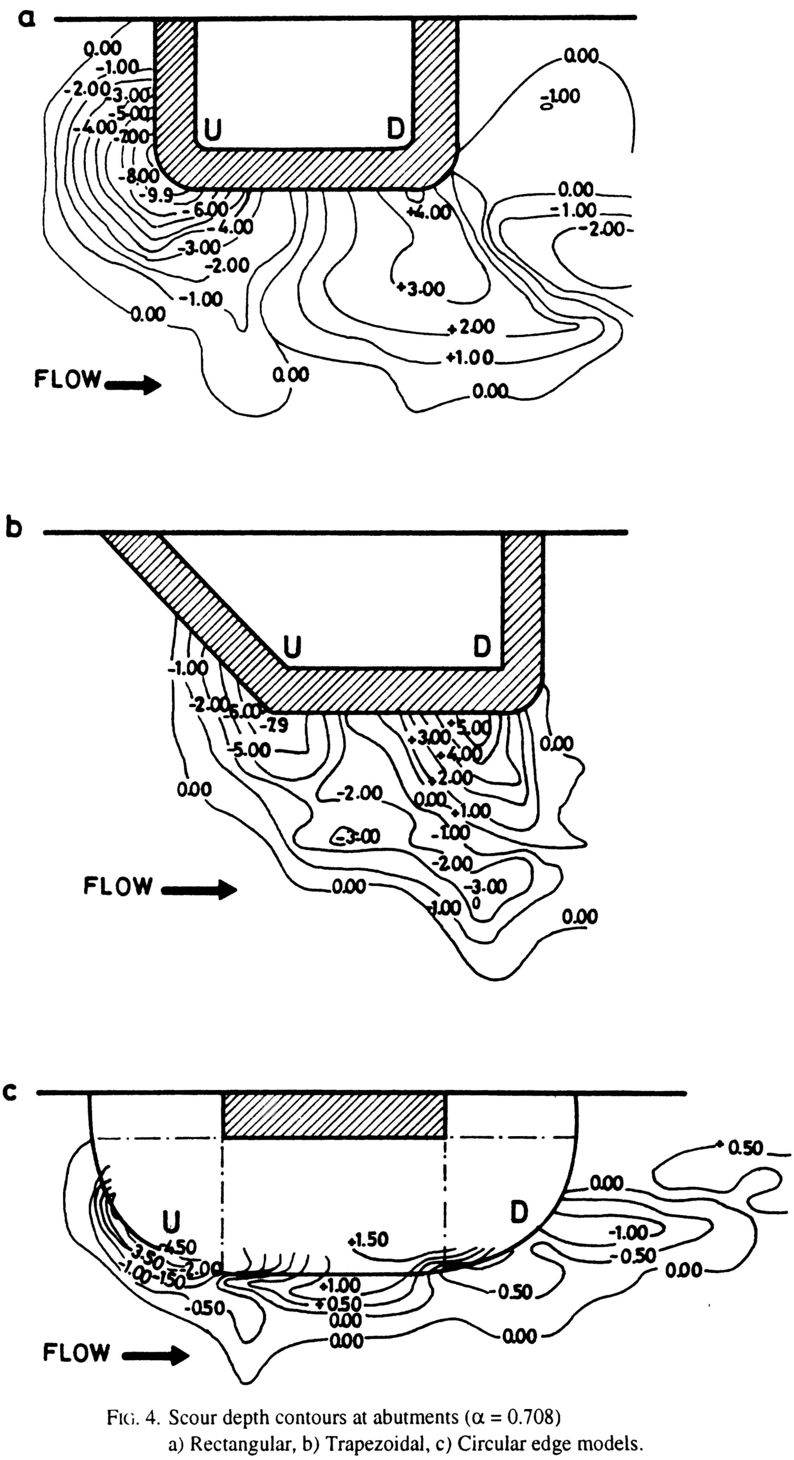

FIG. 4. Scour depth contours at abutments (α = 0.708)
a) Rectangular, b) Trapezoidal, c) Circular edge models.

The general trend of the test results agrees reasonably well with the results of previous investigators[3,5].

4.2 Contraction Ratio α

Wong[3] reported that at any bridge site where abutments constrict the flow, both contraction scour and local scour will occur. The contraction due to abutments can be considered in terms of the contraction ratio parameter, $\alpha = (B - b)/B$. In the present study the contraction ratio,α varied from 0.416 to 0.708. It was observed that the scour depth increased with the decrease in the value of α, keeping other variables constant. Garde *et al.*[2] and Liu *et al.*[5] also varied α from 0.53 to 0.9 and obtain similar results.

4.3 Encroachment Width b

Using a bridge crossing model, Laursen[11] developed an enveloping curve to show the effect of abutment encroachment on local scour. The scour depth ratio, D_s/y_o increased with the increase of the nondimensional encroachment width-depth ratio, (b/y_o). For the present study it was observed that D_s/y_o value increased with the increase of b/y_o, keeping the other variables same, which agrees with the results of other investigators[3].

The above discussion shows that scour depth is significantly affected by shape and size of abutment as well as by contraction ratio, encroachment width. A general nondimensional equation for predicting clear water scour at abutment can, therefore, be written as

$$\frac{D_s}{y_o} = K(S_f)^{A_1}(Fr_1)^{A_2}\left(\frac{d_{50}}{y_o}\right)^{A_3}\left(\frac{b}{y_o}\right)^{A_4}\left[1-\left(\frac{B-b}{B}\right)^{A_5}\right] \quad (3)$$

where K is a constant.

The value of K and exponents A_1 through A_5 were determined using the data from the analysis serial no. 1-9 as well as the data of Liu *et al.*[5] (serial no. 10-16) and Wong[3] (serial no. 17-20). (Table 2). The data sets of other investigators were chosen at comparable conditions with present study like local scour at clear water condition, time of experimental runs (about 6 hours), flow condition (Froude number), uniformity of sediment sizes, similarity in shapes of abutments and spur-dikes ... etc.

Using a 95% confidence, limit the values are

$K = 4.5$, $A_1 = 1.0$, $A_2 = 0.653$, $A_3 = 0.225$,
$A_4 = 0.598$ and $A_5 = 1.80$.

The mean absolute errors resulted by the proposed scour prediction equation is about 7.9 percent with present data and 8.62 percent, when it is combined with other investigators' data. Figure 5 presents the verification of Eq. 3, by comparing the scour-depth ratio predicted by the equation to those observed. Therefore, the proposed general nondimensional equation would be useful to predict the local clear water scour at abutments. The nondimensional Eq. 3 for abutment was also verified against the data of spur-dike reported by other investigators like Grade *et al.*[2], Gill[12], and Zaghloul and

McCorquodale[13] (Fig. (6)). The mean absolute error was found to be 7% for spur-dike data, although for the spur-dikes the flow separation and location of reattachment occurred on the bank downstream, rather on the dike itself.

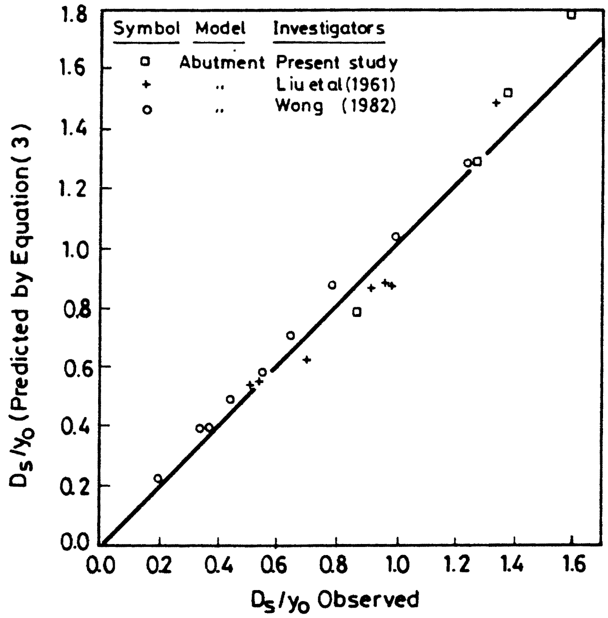

FIG. 5. Verification of predicted Eq. (3) for local scour at abutment.

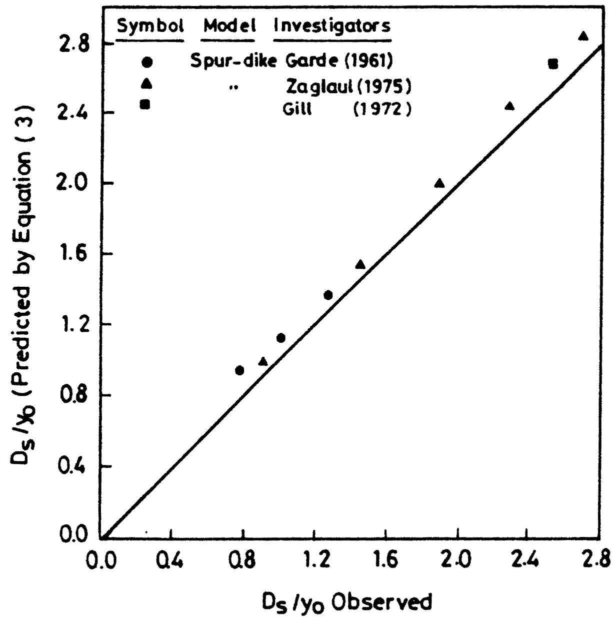

FIG. 6. Comparison of Eq. (3) predicted for scour at abutment with spur-dike data.

5. Summary and Conclusion

1. Based on experimental results from this study, the interaction between the flow pattern and geometry of abutment is found to be very important. The stream-lined flow around circular-edge with sloped wing wall model causes minimum scour, while the separated flow with the vorticity and turbulence at rectangular or trapezoidal abutment results in relatively larger scour depth and larger hole size.

2. The influence of abutment geometry and contraction ratio α have significant effect on the scour depth. Rectangular model resulted in the largest scour while the circular-edge stream-lined models resulted in the minimum scour.

3. A generalized, nonlinear, nondimensional equation for predicting the local scour at bridge abutment is proposed, which can be used for various types of abutment (rectangular, trapezoidal or Wing wall, circular-edge or spill-through). The prediction equation is based on the experimental results obtained from the clear water scour at abutment. The equation has been verified with the results of other investigators at comparable condition.

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الجـــرف المـــوضعي عنـــد الحـــوائط السانـــدة للجســـور

دلوار حسين ، وعلي قريشي ، وعبد اللّه البراهيم
قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود
الريـــــاض - المملكة العربية السعودية

المستخلص . يعرض هذا البحث نتائج دراسة معملية للجرف الموضعي عند نماذج للحوائط الساندة للجسور . عُملت هذه النماذج على ثلاثة أشكال متعارف عليها ، ووضعت في قناة معملية فرشت أرضيتها برمل منتظم الحبيبات (d_{50} = 0.775 mm) . تم إيجاد أعلى قيمة لأعماق الجرف ، ومدى امتدادها تحت ظروف المياه الرائقة ، واقترحت معادلة عامة لابعدية لتقدير الجرف في المياه الرائقة . تأخذ المعادلة كل المتغيرات الهامة بدلالة شكل ومقاس الحائط الساند ، وخصائص الرواسب والجريان ، وتم التحقق من المعادلة باستخدام البيانات المعملية الحالية بالإضافة إلى بيانات أوجدها باحثون سابقون تحت ظروف مشابهة .