SIMPLIFIED APPROACH FOR THE PREDICTION OF MAXIMUM EQUILIBRIUM SCOUR DEPTH AT SKEWED BRIDGE PIERS

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ABSTRACT

It is well established that the shape of the bridge pier, when it is aligned to the flow direction, has a strong effect on the maximum equilibrium scour depth, d_s. The smoother is the nose of the pier, the less is d_s. However, this advantage disappears once the pier is skewed to the flow direction. Melville and Sutherland (1988) suggested using two separate factors, K_s and K_α, to account for the shape and skewness effects, respectively. The objective of the present paper is to propose a new approach based on combining both factors in a simple form to predict d_s at skewed bridge piers. To achieve this goal, an extensive experimental investigation including 120 runs was conducted at both the University of Alexandria (UA) and the University of Iowa (UI) to investigate the shape and skewness effects on d_s at skewed bridge piers. Analysis of the experimental data enabled identifying a simplified approach for the prediction of d_s. The new approach which is recommended to be used for design purposes is based on introducing a new factor, $K_{\alpha s}$, based on what may be called the effective pier width, B_e, instead of both K_s and K_α. The effective width, B_e, is simply related to the projected width, B. The new approach is compared with the method of Melville and Sutherland (1988). It is shown that the latter slightly underpredicts d_s. The underproduction becomes more significant at large angles with values for the oblong piers being consistently higher than those for the rectangular piers.

Keywords: Simplified approach, Equilibrium scour depth, Skewed pier, Projected width, Effective width.

Notation

U	mean approach flow velocity
U_c	mean approach flow velocity at threshold condition
U_*	shear velocity
U_{*c}	critical shear velocity defined by Shields function
τ	shear stress of approach flow
τ_c	critical shear stress
y	distance measured from the flow surface
y_o	flow depth
g	gravitational acceleration
b	diameter of circular pier or width of noncircular pier aligned to the flow direction
B	projected width of pier skewed to the flow direction
B_e	effective projected width of pier skewed to the main flow direction
α	angle of attack or the angle between the main flow direction and the longitudinal axis of noncircular pier
θ	side slope of scour hole
L	length of pier
H	height of pier
W	flume width
r	radius of scour hole in front of the pier
d_s	maximum scour depth
d_{50}	mean diameter of sediment

d_{90}	particle size for which 90% are finer
d_{84}	particle size for which 84% are finer
d_{16}	particle size for which 16% are finer
σ_g	geometric standard deviation of particle size distribution = d_{84}/d_{50}
K_s	shape factor
K_α	angle of attack factor
K_i	flow intensity factor
K_y	flow depth adjustment factor
K_d	sediment size adjustment factor
K_σ	sediment gradation adjustment factor
K_c	contraction factor
F_r	Froude Number
Q	*flow discharge*
$K_{\alpha s}$	new factor equals B_e/B and is used instead of both K_s and K_α

INTRODUCTION

Figure (1) shows a schematic diagram showing the dimensions of the skewed pier and the flow direction.

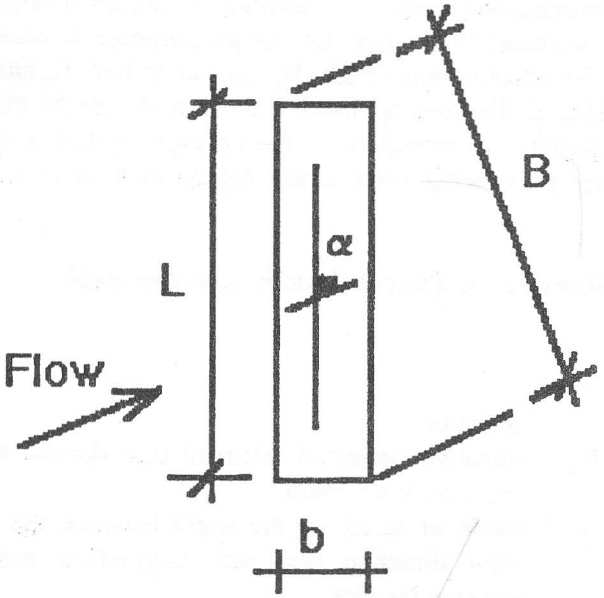

Figure 1. A schematic diagram for a skewed bridge pier.

It is shown by Mostafa et al. (1995 - II) that an accurate determination of d_s necessitates an accurate determination of both the shape factor, k_s, and the angle of attack factor, K_α. The parametric approach presented by Mostafa et al.. (1995 - II) shows that an accurate relationship of K_α may be complicated by secondary dependencies including the effects of pier shape, flow depth and sediment size.

In an attempt to use the accurate relationships of K_α and K_s simultaneously in the method of Melville and Sutherland (1988), the designer expects an accurate determination of d_s at a skewed bridge piers. However, he will be depressed by the fact that the method is still a function of b. He will also be surprised by the fact that the factors accounting for the water depth ratio, K_y, and the sediment size ratio, K_d, are both function of b (i.e. $K_y = f(y_o/b)$ and $K_d = f(b/d_{50})$). Actually, at skewed bridge piers, y_o/b and b/d_{50} do not represent the *existing conditions of water depth ratio and sediment* size ratio, respectively. Even at high values of y_o/b and b/d_{50}, d_s will be mainly affected by the product, b K_α. Thus, at very small value of b, the product will go to a very small value which means almost no scour depth. This is not true if the pier projected width, B, is respected, thereby, emphasizing the inconsistency of using the method of Melville and Sutherland (1988) to predict d_s at skewed bridge piers.

So, it is stressed in this paper that a new simplified approach to predict d_s at skewed bridge piers should be investigated. Contrary to Melville and Sutherland (1988), the proposed relationship is to be not only written in terms of dimension based on the pier projected width, B, instead of b but also the factors, K_y and K_d, should be related to the same dimension which varies from angle to angle.

PROPOSAL FOR THE SIMPLIFIED APPROACH

Melville and Sutherland (1988) proposed the following relationship to predict the maximum equilibrium scour depth, d_s:

$$d_s = K_i\, K_y\, K_d\, K_\sigma\, K_s\, K_\alpha\, b \qquad (1)$$

Mostafa et al. (1995 - I) presented the method in details. In a theoretical approach, they also proved that K_α = B/b where B is the pier projected width. Substituting K_α in the method of Melville and Sutherland (1988) leads to the following form:

$$d_s = K_i\, K_y\, K_d\, K_\sigma\, K_s\, B \qquad (2)$$

Eq. (2) is written in terms of pier projected width, B, instead of both K_α and the pier width, b. However, K_y

and K_d are still defined in terms of y_o/b and b/d_{50}, respectively, as proposed by Melville and Sutherland (1988). Furthermore, it may be assumed that K_s is already included in B which varies from shape to shape. Thus, Eq. (2) may be rewritten in the following form:

$$d_s = K_i\, K_y\, K_d\, K_\sigma\, B \qquad (3)$$

Eq. (3) is appealingly simple, sidesteps the issue of pier shape effect, and avoids the complication that may arise from using K_α and the doubt that K_α is independent of other parameters such as flow depth ratio and sediment size ratio. Eq. (3) is conservative because B is inherently conservative.

To obtain accurate results for the estimation of d_s, a new factor, $K_{\alpha s}$, which is always less than one, is introduced. This factor is defined as

$$K_{\alpha s} = \frac{\text{effective pier width}}{\text{projection pier width}} = B_e/B \qquad (4)$$

where B_e is called the effective pier width and B is defined as the projected pier width. Moreover, the factors K_y and K_d which were originally expressed in terms of pier width, b, are assumed to be related to B_e (i.e. $K_y = f_1(y_o/B_e)$ and $K_d = f_2(B_e/d_{50})$) Therefore, Eq. (3) may take the following form:

$$d_s = K_i\, K_y\, K_d\, K_\sigma\, K_{\alpha s}\, B \qquad (5)$$

In order to verify the use of Eq. (5) in design purposes, a comprehensive experimental investigation was conducted.

EXPERIMENTAL PROGRAM

The experiments were conducted in two sets using two laboratory flumes; one at the University of Alexandria (UA), and the other at the University of Iowa (UI). Described herein are the experimental set up program and the procedures adopted for both sets of experiments which were conducted under clear water scour with the bed surface of sediment near the condition of incipient particle motion.

UA Experiments

The experiments at UA were conducted in a flume 12 m long, 0.86 m wide and 0.6 m deep, as shown in Figure (2a). The flume was equipped with a sand recess 6.0 m long, 0.86 m wide and 0.25 m deep. A nonuniform sand (medium size, d_{50} = 0.6 mm, sediment gradation, σ_g = 2.4) was used. Two pier shapes, oblong and rectangular, with aspect ratios, L/b = 4, 6, 8, 10 and 12 for each, were investigated, as given in Table (1). For all experiments, the pier width was set constant at b = 3.5 cm. However, the flow depth was held constant y_o =10.5 cm. For each pier, the skewness was varied in 15° steps from 0° to 90°. A total of 55 individual experimental runs were conducted. In case of nonuniform sediment, armor layer forms in the bottom of the scour hole so that each run took several hours until equilibrium scour was attained.

UI Experiments

The experiments at UI were conducted in a flume 25 m long, 1.5 m wide and 0.6 m deep, as shown in Figure (2b). The flume was equipped with a sand recess 2.0 m long, 1.0 m wide and 0.4 m deep. A uniform sand (d_{50} = 0.9 mm, σ_g = 1.1) was used for the UI experiments. The same UA pier shapes were investigated and oriented at the same skewness angles. The flow depth was held constant at y_o = 35 cm, however, for the purpose of comparing UA and UI data, a water depth of 10.5 cm was used. A total of 65 individual experimental runs were conducted. In case of uniform sediment, no armor layer forms so that each run took several days until equilibrium scour depth was attained. Additional experiments to investigate further features of pier orientation and shape on scour were conducted using square, circular and thin plate piers of the same projected width, as given in Table (1)

Experimental Procedure

The following procedure was adopted for the UA and UI experiments which were carried out under the mentioned conditions of approach-flow, bed-sediment, and bed- slope; 1- fixing a mounting seat to the flume bottom, 2- fixing a pier of certain shape and aspect ratio to the seat, 3- filling the sand recess with sand, 4- leveling bed sediment surface, 5- closing the tail gate and adjusting the pump valve to produce a very small discharge to fill the flume with a depth of about 5.0 cm, 6- closing the valve, 7- keeping still water in the flume for a period to allow filling sediment voids and to ensure a full saturated sand, 8- opening the pump valve and the tail gate gradually until filling the flume with a predetermined steady uniform flow depth of 105 mm at UA and 300 mm at UI, 9- keeping the valve and the tail gate opened, 10- allowing water to recirculate until reaching the equilibrium stage for the scour hole. At this stage, 11- the pump control valve was gradually closed and the water in the flume was slowly drained. When the scour hole was drained, 12- the scour depths and deposition heights were measured, 13- the sand around the pier was then removed, and either pier orientation was adjusted, or a pier of different aspect ratio was mounted. Steps were repeated for both shapes, rectangular and oblong, at different angles (α=0, 15, 30, 45, 60, 75, 90°) and for aspect ratios, L/b=4, 6, 8, 10, 12.

Table 1. Details of test pier shapes and dimensions (UA and UI).

L/b	pier shape						remarks
	oblong			rectangular			
	b (width)	L (length)	H (height)	b	L	H	
1	0.035	0.035	0.82	0.035		0.82	dimensions used at both UA , UI
4		0.14			0.14		
6		0.21			0.21		
8		0.28			0.28		
10		0.35			0.35		dimensions used at UA only
12		0.42			0.42		
1	0.14	0.14		0.1	0.1		dimensions used at UI only
5	0.14	0.7		0.14	0.7		
10	0.07	0.7		0.07	0.7		
200	----	----		0.001	0.2		

all dimensions in meter

SIMPLIFIED RECOMMENDED APPROACH

Presented herein is an alternate, simplified approach which is independent of pier shape effects, and avoids the complications arising from the secondary dependencies on K_α of other parameters including flow depth and sediment size.

The new approach utilizes the equation of Melville and Sutherland (1988) in a new suggested form, Eq. (5), as presented in the proposal for the simplified approach. It is important to point out that in Eq. (5) and at α= 0°, $K_{\alpha s} = K_s$ (i.e., the classical shape factor). In this case, B = b and both K_y and K_d are defined in terms of y_o/b and b/d_{50}, respectively. In the most simplified forms of Eq. (5) and to be somewhat conservative, knowledge of $K_{\alpha s}$ is unnecessary and Eq. (5) can be rewritten in the following form:

$$d_s = K_i \, K_d \, K_y \, B \tag{6}$$

Eq. (6) is conservative because B exceeds B_e. Now, K_y and K_d are defined in terms of an effective pier width, B_e, rather than b (i.e. $K_y = f_1 (y_o/B_e)$ and $K_d = f_2 (B_e/d_{50})$). Actually, one could use B_e, but since $K_{\alpha s} \approx 1.0$, it is simpler to use B. Thus, when $y_o/B < 2.5$, as suggested by Melville and Sutherland (1988), the water depth factor, K_y, can be estimated as following:

$$K_y = 0.78 \, (y_o/B)^{0.255} \tag{7}$$

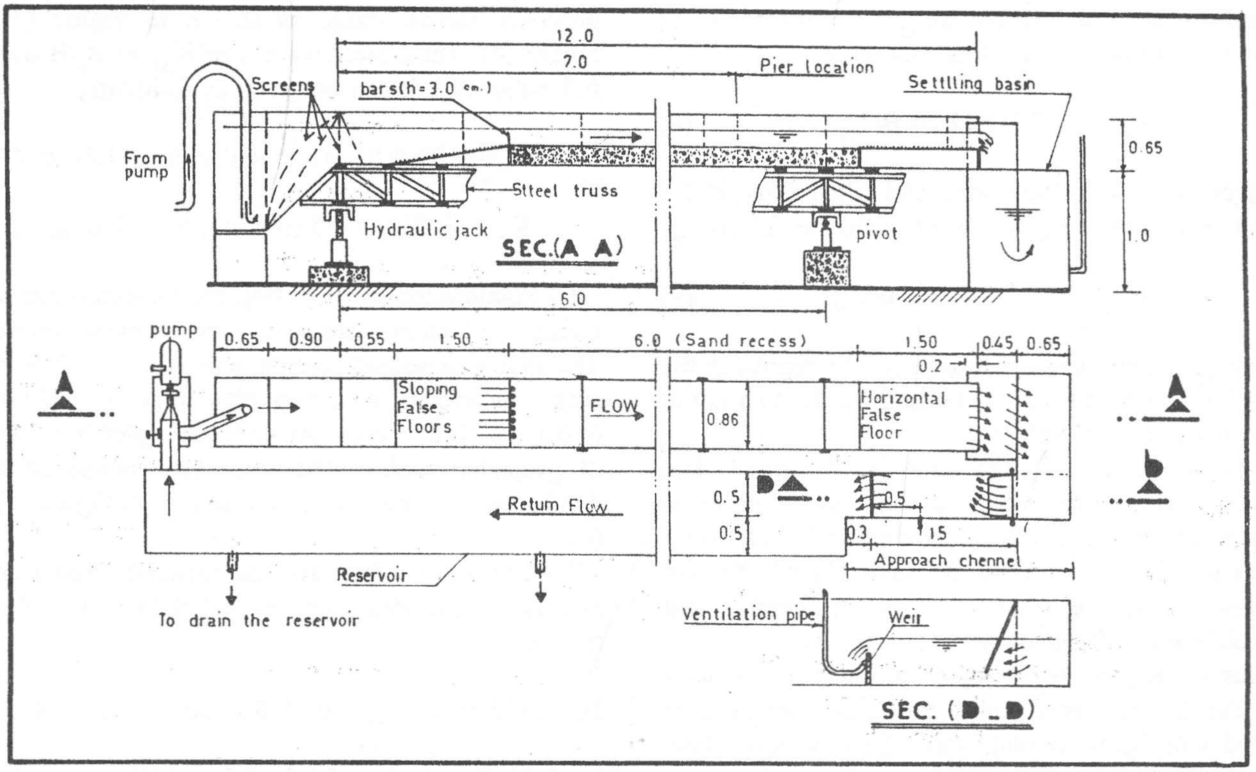

Figure 2a. a Plan and longitudinal cross section of UA flume.

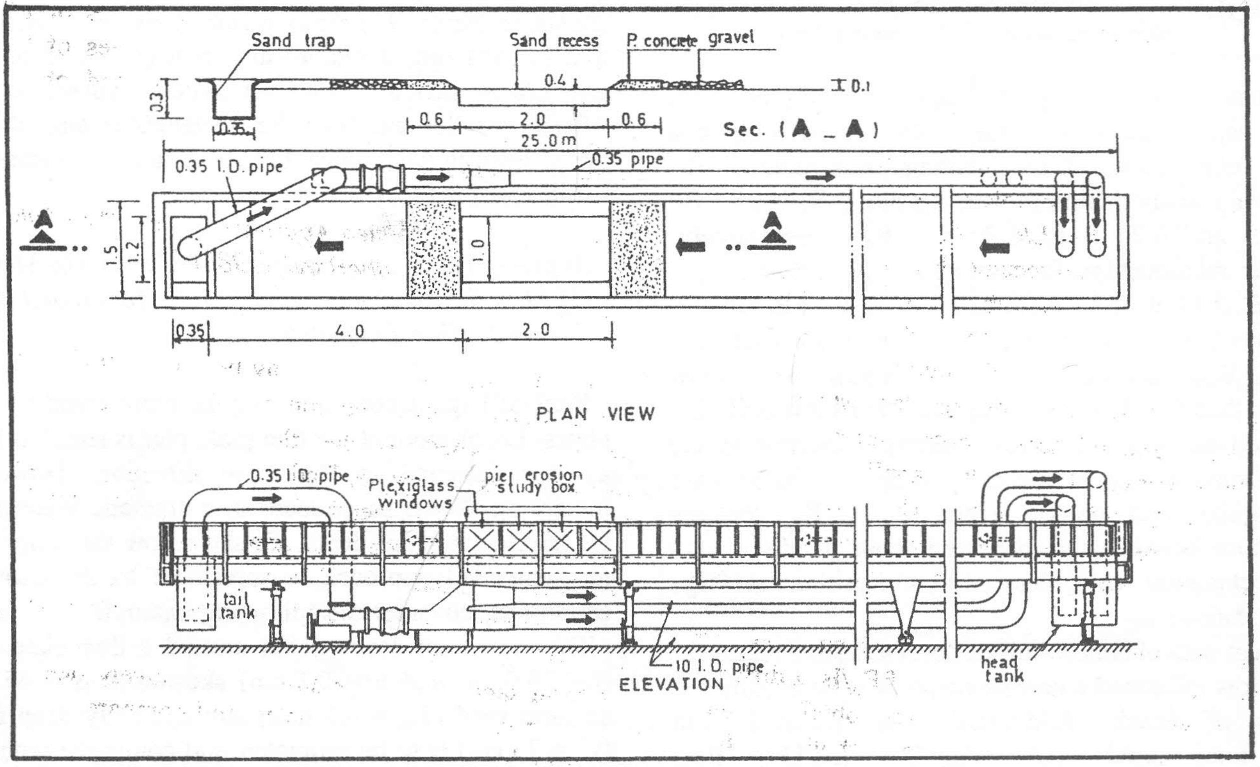

Figure 2b. a Plan and elevation of UI main flume.

for uniform sand and when $B/d_{50} < 26$, the sediment factor, K_d, can be estimated as following:

$$K_d = 0.57 \log (2.24 \cdot B/d_{50}) \qquad (8)$$

However, for nonuniform sand and when $B/d_{90} < 26$, the sediment factor, K_d, can be estimated as following:

$$K_d = 0.57 \log(2.24\ B/d_{90}) \qquad (9)$$

where d_{90} is experimentally assumed to represent the nonuniform sand or keep Eq. (8) and use K_σ to account for the nonuniformity effect.

A comparison of Eq. (6) with the measured data obtained in the present study is summarized in Table (2) as a sample. The whole experimental data were documented by the Ph.D of Mostafa (1994). Eq. (6) consistently predicts values of scour depths that moderately exceeds measured scour depths.

Values of $K_{\alpha s}$ or B_e/B for rectangular and oblong piers can be estimated from the experimental data obtained with uniform sand and relatively deep flow. The method assumes that:

$$K_{\alpha s} = B_e/B = \frac{\text{measured scour depth}}{\text{estimated scour depth using Eq.(6)}} \qquad (10)$$

Values of B_e were plotted against values of B for each aspect ratio and for both the oblong and rectangular piers. Curve fitting summarized the following relationships for oblong piers; $B_e = 0.82$ B, 0.75 B and 0.70 B for L/b = 4, 6,8 , respectively. Similar relationships for rectangular piers were; $B_e =$ 0.89 B, 0.77 B, 0.71 B for L/b = 4, 6, 8, respectively. The mentioned relationships, show that, for each pier shape, B_e/B decreases as L/b increases. This result means that the divergence between the estimated, Eq. (6), and the measured scour depths, increases as the aspect ratio increases. The result is applied for both the rectangular and oblong piers. Also, $K_{\alpha s}$ or the difference between the measured scour depths around the rectangular and oblong piers vanishes at large aspect ratios.,

Present data obtained with uniform sand and relatively deep flow exhibited a narrow range of B_e/B at different angles of attack. Additional data obtained with nonuniform sand and relatively shallow flow consistently show that values of B_e/B were within the previous narrow range as shown in Figure (3) and Figure (4). Thus, mean values of $K_{\alpha s}$ or B_e/B over the full range of L/b can be given as following:

$$K_{\alpha s} = Be/B = 0.85 \ (\text{rectangular}, 8 \geq L/b \geq 4) \qquad (11)$$

$$K_{\alpha s} = Be/B = 0.75 \ (\text{oblong}, 8 \geq L/b \geq 4) \qquad (12)$$

To examine the idea of using the projected pier width within the extreme cases, two more piers were used. The first is a square section pier (L/b = 1.0, b =10.0 cm). The second is a thin plate pier (L = 20.0 cm, b=0.1 cm, L/b = 200). At 45°, each pier has 14.0 cm of projected width. The maximum measured scour depths around both shapes are shown in Figure (5) and (6).

The comparison between the measured scour depths and those estimated using Eq.(6) shows the following results:

$$B_e = 0.75 \text{ B or } K_{\alpha s} = 0.75 \text{ for } L/b = 1 \text{ at } \alpha = 45° \qquad (13)$$

$$B_e = 0.75 \text{ B or } K_{\alpha s} = 0.75 \text{ for } L/b = 200 \text{ at } \alpha = 45° \qquad (14)$$

The relationship between B_e/B or $K_{\alpha s}$ versus L/b is shown in Figure (7) from which it can be concluded that generalizing a relationship between B_e/B or $K_{\alpha s}$ and L/b is difficult. However average values of $K_{\alpha s}$ =Be/B = 0.85 and 0.75 for rectangular and oblong piers, respectively, when L/b ≥ 1, are recommended for design purposes.

Applying The Simplified Approach Versus The Method Of Melville And Sutherland (1988) To Predict d_s At A Skewed Thin Plate Pier

Piers of large aspect ratio may be represented by thin plates. Local scour at the thin plate pier is small as long as it is aligned to the flow direction. However, increasing skewness, α, leads to a dramatic increase in the maximum scour depth. To show how the simplified recommended approach is applicable to the extreme conditions, consider the following example:

The maximum scour depth around a thin plate pier (L= 20.0 cm and b = 0.1 cm) skewed at $\alpha = 45°$ in uniform sand ($d_{50} = 0.9$ mm) and relatively deep flow ($y_o = 35$ cm) is to be estimated and compared with the measured one.

Table (2) Sample of d_s data measured around skewed rectangular piers in uniform sand (UI data) and those estimated using Eq. (6).

α	L/b	B	U/U_c	y_o/B	B/d_{50}	σ_g	K_i	K_v	K_d	K_σ	K_s	d_s estim-ated	d_s meas-ured	B_e/B
0	4	3.5	0.9	3	39	1.1	2.2	1	1	1	1.3	9.5	9.3	1
15	4	7	0.9	1.5	78	1.1	2.2	0.9	1	1	1	13	11	0.8
30	4	10	0.9	1	111	1.1	2.2	0.8	1	1	1	17	15.4	0.9
45	4	12	0.9	0.8	137	1.1	2.2	0.7	1	1	1	20	18.7	0.9
60	4	14	0.9	0.8	154	1.1	2.2	0.7	1	1	1	22	21.5	1
75	4	14	0.9	0.7	160	1.1	2.2	0.7	1	1	1	22	21.2	0.9
90	4	14	0.9	0.8	156	1.1	2.2	0.7	1	1	1	22	21.2	1
0	4	3.5	0.9	10	39	1.1	2.2	1	1	1	1.3	9.5	9.5	1
15	4	7	0.9	5	78	1.1	2.2	1	1	1	1	15	13.8	0.9
30	4	10	0.9	3.5	111	1.1	2.2	1	1	1	1	22	17	0.8
45	4	12	0.9	2.8	137	1.1	2.2	1	1	1	1	27	22.3	0.8
60	4	14	0.9	2.5	154	1.1	2.2	1	1	1	1	30	25	0.8
75	4	14	0.9	2.4	160	1.1	2.2	1	1	1	1	30	27	0.9
90	4	14	0.9	2.5	156	1.1	2.2	1	1	1	1	30	26.8	0.9
0	6	3.5	0.9	10	39	1.1	2.2	1	1	1	1.3	9.5	9.5	1
15	6	8.8	0.9	4	98	1.1	2.2	1	1	1	1	19	15.4	0.8
30	6	14	0.9	2.6	150	1.1	2.2	1	1	1	1	29	21.2	0.7
45	6	17	0.9	2	192	1.1	2.2	0.9	1	1	1	35	25.4	0.7
60	6	20	0.9	1.8	222	1.1	2.2	0.9	1	1	1	39	30.4	0.8
75	6	21	0.9	1.7	235	1.1	2.2	0.9	1	1	1	41	34.2	0.8
90	6	21	0.9	1.7	233	1.1	2.2	0.9	1	1	1	40	30.2	0.7
0	8	3.5	0.9	10	39	1.1	2.2	1	1	1	1.3	9.5	9.3	1
15	8	11	0.9	3.3	118	1.1	2.2	1	1	1	1	23	17	0.7
30	8	17	0.9	2.1	189	1.1	2.2	0.9	1	1	1	34	24	0.7
45	8	22	0.9	1.6	247	1.1	2.2	0.9	1	1	1	42	30	0.7
60	8	26	0.9	1.3	289	1.1	2.2	0.8	1	1	1	47	34.8	0.7
75	8	28	0.9	1.3	311	1.1	2.2	0.8	1	1	1	50	36	0.7
90	8	28	0.9	1.3	311	1.1	2.2	0.8	1	1	1	50	33.2	0.7

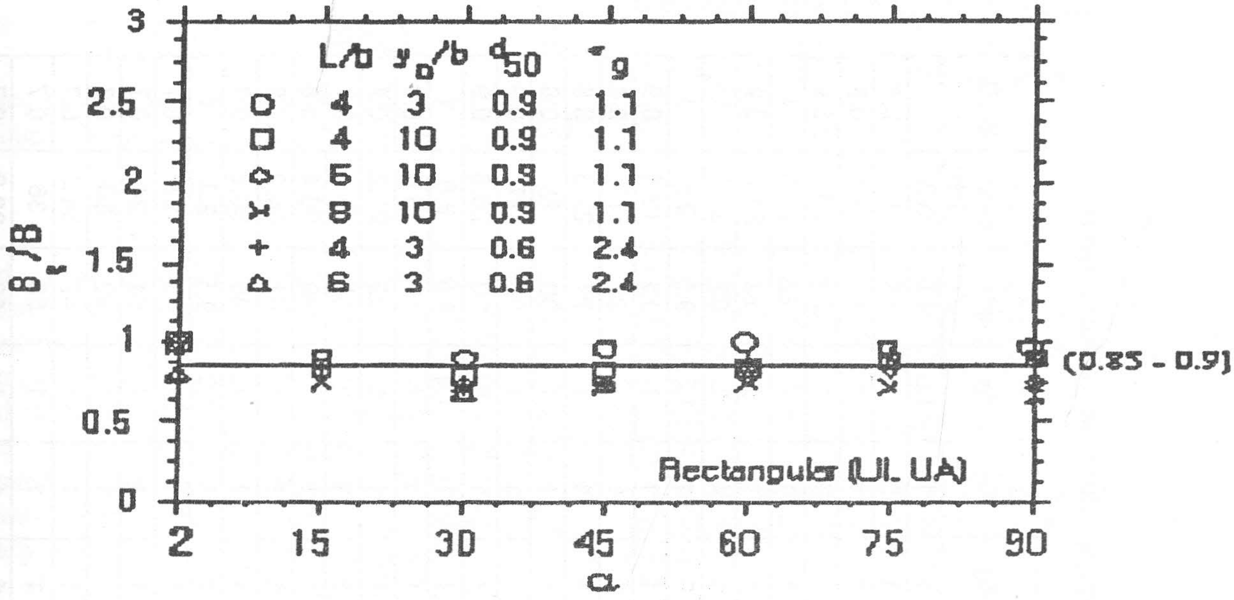

Figure 3. Values of B_e/B or $k_{\alpha s}$ versus α for rectangular piers.

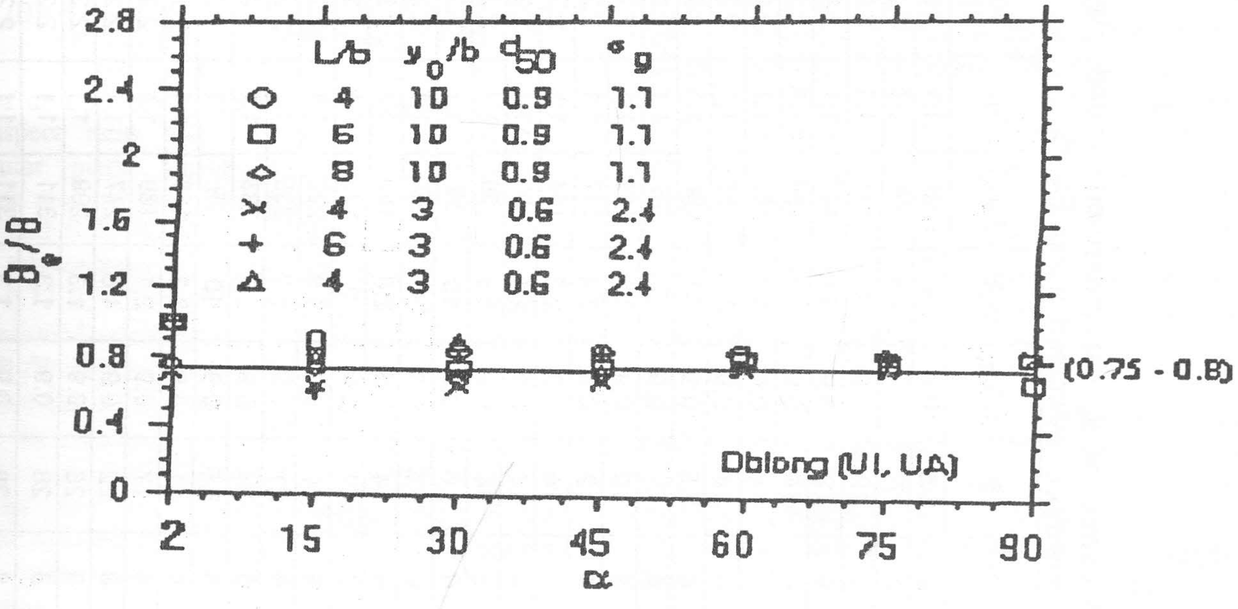

Figure 4. Values of B_e/B or K_{as} versus α for oblong piers.

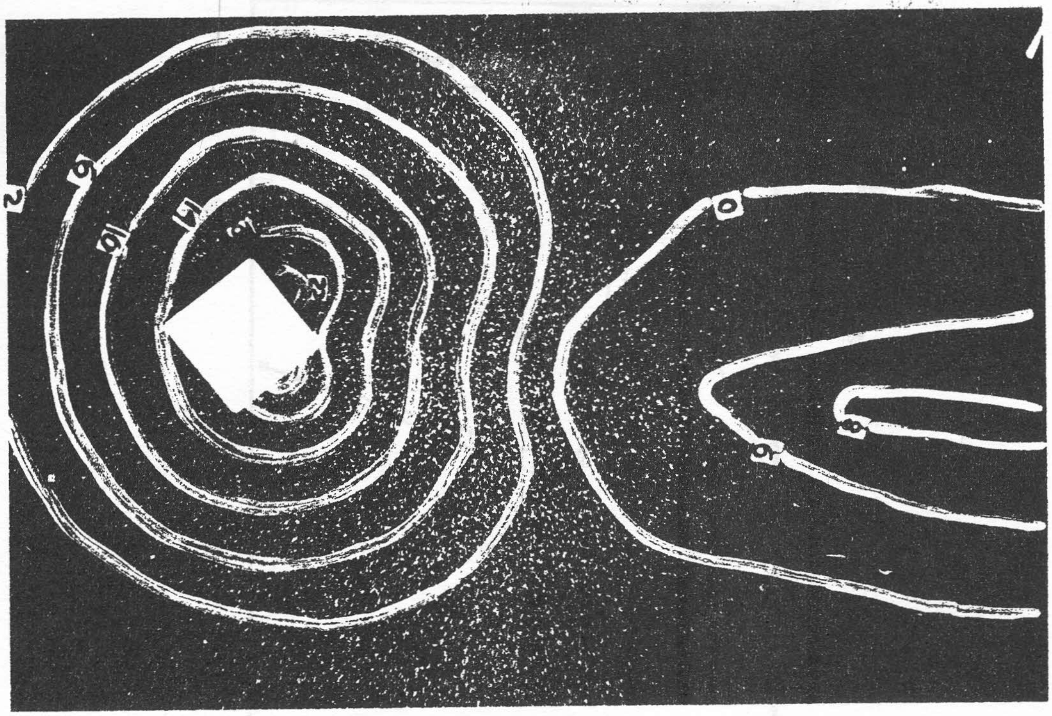

Figure 5. Scour hole around 45° skewed square pier in uniform sand (B=14.0 cm, L/b=1.0, $y_o/B=2.5$, $d_s=22.8$ cm).

Figure 6. Scour hole around 45° skewed thin plate pier in uniform sand (B=14.0 cm, L/b=200, $y_o/B=2.5$, $d_s=22.8$ cm).

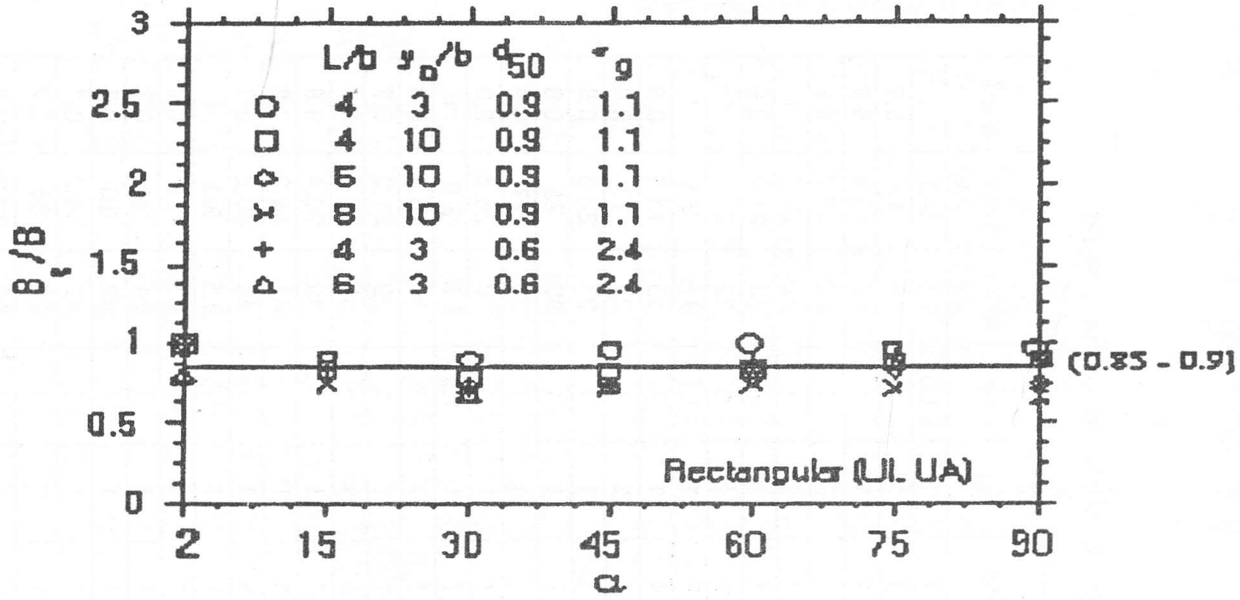

Figure 3. Values of B_e/B or $k_{\alpha s}$ versus α for rectangular piers.

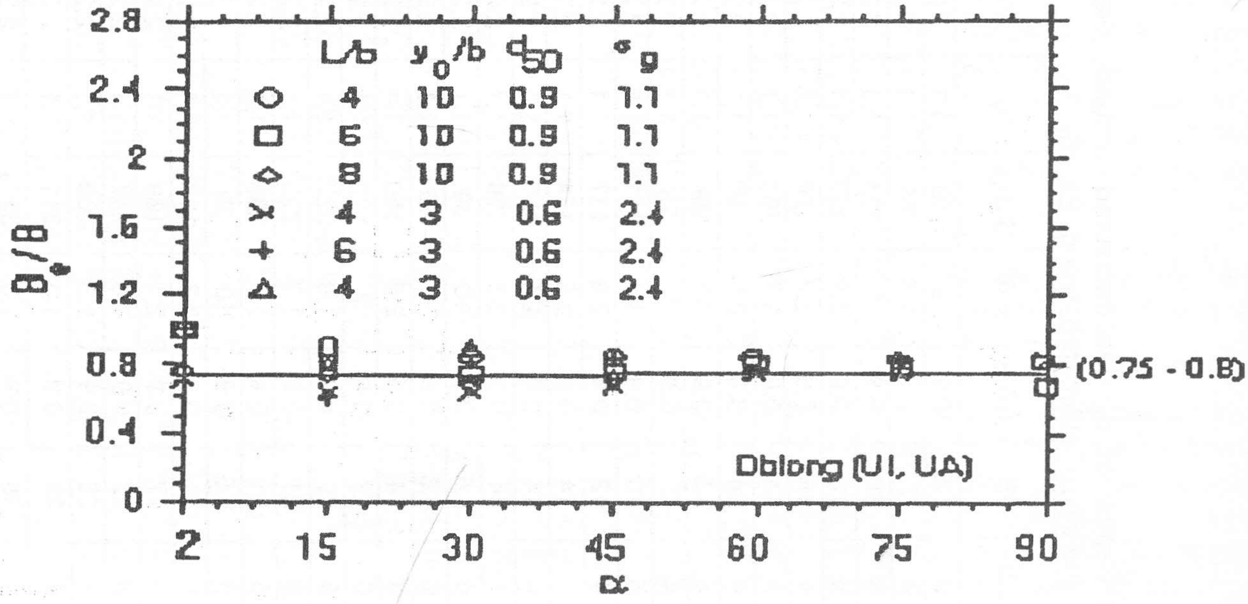

Figure 4. Values of B_e/B or K_{as} versus α for oblong piers.

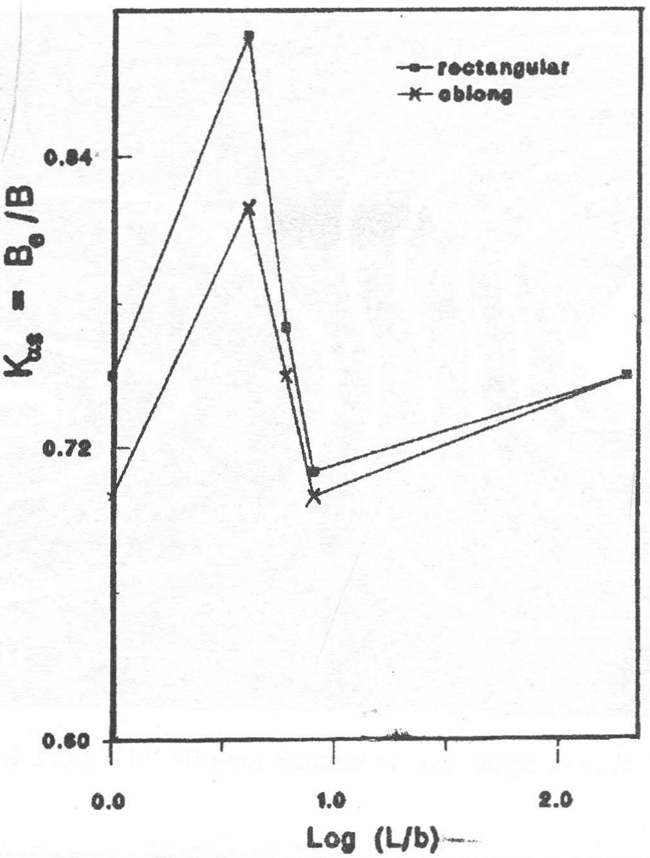

Figure 7. $K_{\alpha s}$ or B_e/B versus L/b.

When the method of Melville and Sutherland (1988), Eq. (1), is applied, the first step is to estimate K_α for L/b = 20/0.1 = 200. The curves of Laursen and Toch (1956), as shown in Figure (8), are limited to L/b = 16 only. By using Eq. (17) proposed by Mostafa et al. (1995 - I), $K_\alpha = ((L/b) \sin \alpha + \cos a)^{0.8} = ((200) \sin 45 + \cos 45)^{0.8} = 52.74$. Also, as suggested by Melville and Sutherland, for $U/U_c = 0.9$, $K_i = (0.9)(2.4)$. For rectangular piers, assume $K_s = 1.25$. For $y_o/b = 35/0.1 = 350 > 2.6$, $K_y = 1.0$. Also for $b/d_{50} = 1/0.9 = 1.11 < 25$, $K_d = 0.57 \log(2.24\ b/d_{50}) = 0.57 \log((2.24)(1.11)) = 0.23$. Thus, the maximum scour depth by using Eq. (1) can be estimated as following:

$d_s = (0.1)(0.9)(2.4)(0.23)(1.0)(1.25)(52.74) = 3.28$ cm

The actual maximum scour depth measured as shown in Figure (6), though, was $d_s = 22.8$ cm. Therefore, Eq. (1) underpredicts the maximum scour depth at skewed piers of small thickness (i.e., small b). The only way for predicting a reasonable maximum scour depth around a thin plate pier skewed at certain angle, is to use the simplified recommended approach. The procedure of using this approach is as following: $K_i = (0.9)(2.4)$ which is the same as before. The projected width of a thin plate is B = 14.0 cm. For $y_o/B = 35/14 = 2.5$, $K_y = 1.0$. Also for $B/d_{50} = 140/0.9 = 155.5 > 25$, $K_d = 1.0$. Thus, d_s can be estimated according to Eq. (6) as following:

$d_s = (0.9)(2.4)((1.0)(1.0)(14) = 30.24$ cm

The method is conservative. However, utilizing a reasonable value of $K_{\alpha s}$ or B_e/B can decrease the difference between the measured and estimated scour depths. For more accurate results, Eq. (5) can be used as following:

For rectangular piers, $K_{\alpha s} = B_e/B = 0.85$. For $y_o/B_e = 35/((0.85)(14)) = 2.94 > 2.6$, $K_y = 1.0$. Also, For $B_e/d_{50} = (0.85)(140)/0.9 = 132.22 > 25$, $K_d = 1.0$. Thus the maximum scour depth can be:

$$d_s = (0.9)(2.4)(1.0)(1.0)(0.85)(14) = 25.7 \text{ cm}$$

which is still conservative compared with 22.8 cm of the measured scour depth.

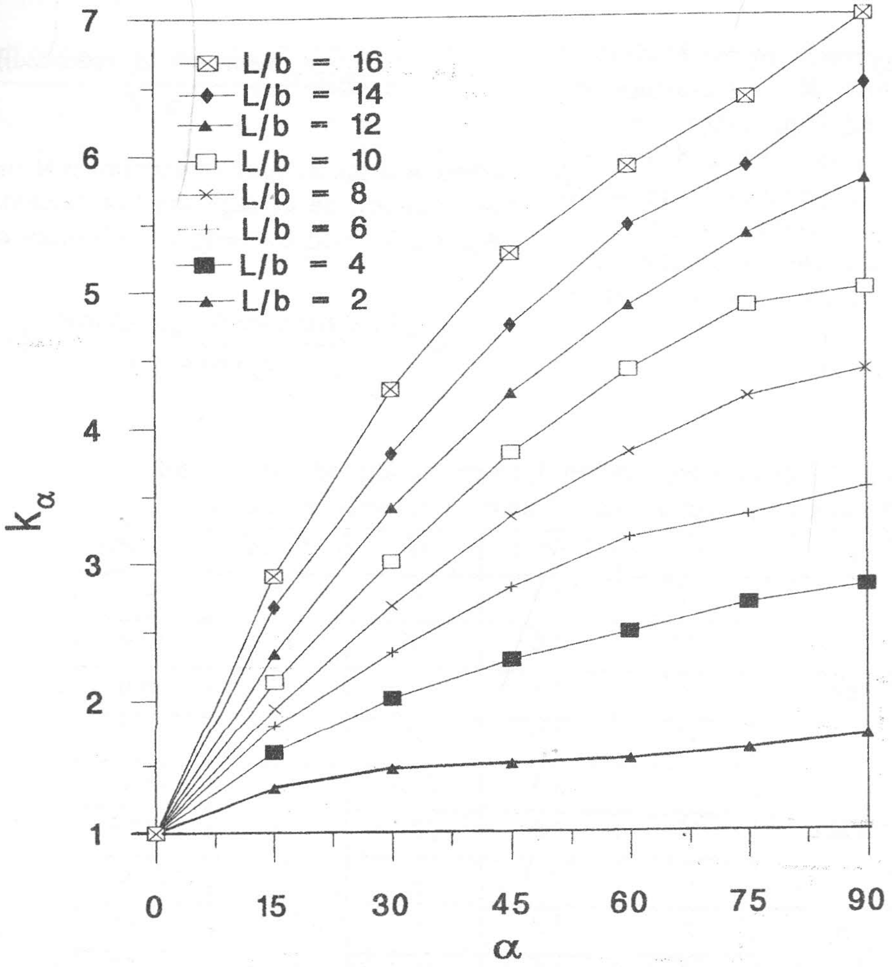

Figure 8. Curves of laursen and Toch 1956.

Comparison Between Values Of d_s Measured At Bridge Piers Of The Same Projected Width And Of different skewness Angle

To further investigate the simplified approach, values of d_s measured at piers aligned and skewed and of the same projected width were compared. For rectangular piers, values of d_s are almost the same, while for oblong shapes, d_s measured around the pier skewed at 19.5° seems to be deeper than that around the pier of the same projected width and aligned to the flow direction. Data are given in Table (3). This means that the advantage of streamlined pier shape (oblong) seems to strongly affect d_s at zero angle more than at any other angle.

To examine the trend at larger angles, as listed in Table (3), the comparison shows that, for rectangular piers, d_s at $\alpha = 0°$ is deeper than that around the piers skewed 31.5° or 22.6° of the same projected widths. Also, it is seen that the maximum scour depth at rectangular pier of aspect ratio 6 skewed 31.5° is deeper than that at pier skewed 22.6°, and of aspect ratio 8, even though B is about the same for both cases. However, the difference is small. A reverse trend was obtained for the oblong piers. The maximum scour depth around zero angle is less than that around piers skewed 25.4° or 37°. Also the maximum scour depths around pier skewed at 25.4° and of aspect ratio 6 is less than that around pier skewed 37° of aspect ratio 8 and of the same projected width. Despite the fact that the differences are small, this result means that the round corners do not strongly affect the maximum scour depth at any angle as they do at zero angle.

COMPARATIVE ANALYSIS

A comparative analysis was carried out to compare the accuracy between d_s estimating by applying the method of Melville and Sutherland (1988) and the recommended simplified approach. In the Method of Melville and Sutherland (1988), K_α was estimated by using the curves of Laursen and Toch (1956). Values of K_s used in the method were 1.25 and 0.9 for rectangular and oblong piers, respectively, as proposed by Mostafa et al. (1995- I). Statistically, the more accurate method must have a smaller standard error of estimate, S_e, which is given by the following equation:

$$S_e=\Sigma\left[\frac{[d_s(\text{measured})-d_s(\text{estimated})]^2}{n-2}\right]^{0.5} \qquad (15)$$

where n is the number of experimental runs. Additionally, an average absolute percentage error, A_e, is calculated by using the following equation:

$$A_e=\Sigma\left[\left|\{\frac{d_s(\text{measured})-d_s(\text{estimated})}{d_s(\text{measured})}\}\right|*100\%\right]/n \qquad (16)$$

Table 3. Comparison between d_s measured around piers of zero angles and those around skewed piers of the same projected width.

shape	L/b	b (cm)	α^o	B(cm)	d_s (cm)
rectangular	4	3.5	15	7.0	13.75
	10	7.0	0		14.0
oblong	4	3.5	19.5		13.0
	10	7.0	0		10.7
rectangular	6	3.5	31.5	14.0	21.6
	8	3.5	22.6		20.54
	5	14.0	0		23.0
oblong	6	3.5	37		21.98
	8	3.5	25.4		20.57
rectangular (rounded corners)	5	14.0	0		19.0

Table (4) shows values of S_e and A_e for the maximum equilibrium scour depth. For rectangular piers, values of S_e and A_e of the simplified approach are 3.43 and 11.8, respectively. On the other hand, similar values of the method of Melville and Sutherland (1988) are 2.37 and 17.9, respectively. It is obvious that Se for the simplified is greater than that for the method of Melville and Sutherland (1988). For the oblong piers similar values are 2.2 and 9.2 for the simplified approach and 2.25 and 15.17 for the method of Melville and Sutherland (1988). The difference in S_e is so small, while the difference in Ae means that the simplified approach is more accurate.

Thus, generally, the simplified method always has the smallest values of A_e for both the rectangular and oblong piers. On the other hand, the difference between similar values of S_e is small. However, the simplified approach is appealingly simple, sidesteps the issue of pier shape effects, and avoids the complications arising from the secondary dependencies on K_α of other parameters such as flow depth and sediment type. In addition, the simplified approach enabled the refinement of the factors, K_y and K_d suggested by Melville and Sutherland (1988) to be defined in terms of an effective pier width, B_e, rather than b which has a physical meaning only when the pier is aligned to the flow direction. So , it is stressed that the simplified approach is recommended for design purposes of predicting the maximum scour depth, d_s at skewed bridge piers.

Table 4. Values of standard error of estimate, S_e, and average percentage error, A_e, for d_s measured at rectangular and oblong pier shapes skewed at different angles of attack.

Pier shape	Statistical measures	The method of Melville and Sutherland (1988) Eq. (1)	Simplified Approach (present study) Eq. (5)
rectangular	S_e	2.37	3.43
	A_e	17.9	11.8
oblong	S_e	2.25	2.2
	A_e	15.17	9.2

CONCLUSIONS

Based on the analysis of the 120 experimental runs obtained at UA and UI with the theoretical approach to the angle of attack problem, the following conclusions are derived:

1- The method of Melville and Sutherland (1988) uderpredicts values of maximum equilibrium scour depth at skewed bridge piers of small width, b. The fact is that the product b K_α gives values of d_s less than it should be if a dimension based on B is used.

2- Contrary to the method of Melville and Sutherland (1988), the factors K_y and K_d accounting for the water depth ratio and sediment size ratio should be defined in terms of B instead of b which is respected only when the pier is aligned to the flow. direction.

3- The simplified approach, Eq. (5), based on a new factor, $K_{\alpha s}$, and B, is recommended for design purposes to predict d_s at skewed bridge piers. The factors, K_y and K_d, are defined in terms of B_e instead of pier width, b. The experimental data of the present study exhibit a narrow range for $K_{\alpha s}$ or B_e/B. For design purposes, $K_{\alpha s} = B_e/B = 0.85$ for rectangular and 0.75 for oblong piers are proposed to be used to estimate the effective projected width, B_e. The simplified approach avoids the complications arising from the secondary dependencies on K_α of other parameters such as flow depth and sediment type. Contrary to the method of Melville and Sutherland (1988), the recommended simplified approach is applicable to extreme conditions (i. g., thin plate pier or more generally piers of L/b > 20). It is important to point out that at $\alpha = 0°$ $K_{\alpha s} = K_s$, the classic shape factor, and B = b. Thus, Eq. (5) as well as the factors, K_y and K_d, become function of b.

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