PARAMETRIC APPROACH FOR THE ESTIMATION OF BRIDGE PIER NONALIGNMENT EFFECT ON MAXIMUM EQUILIBRIUM SCOUR DEPTH

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ABSTRACT

It is always emphasized the importance of an accurate determination of the nonalignment effect, the angle of attack factor, K_α , on maximum equilibrium scour depth, d_s, at skewed bridge piers. Presented herein is a comprehensive experimental investigation showing the nonalignment effect on d_s at bridge piers of rectangular and oblong shapes skewed at different angles of attack. Wide range of data was obtained from the experiments conducted at both the University of Alexandria (UA) and the University of Iowa (UI). Clear water scour was measured considering relatively shallow and deep flow depths as well as uniform and nonuniform bed sediment. A total of 100 individual experimental runs were conducted. A stepwise multiple nonlinear regression analysis was done to show that K_α is dependent not only on the aspect ratio, L/b, and the angle of attack, α, as presented by Laursen and Toch (1956) but also on other parameters including the effect of pier shape, flow depth ratio, y_o,/B and sediment size ratio, B/d_{50}. Contrary to the finding of Melville and Sutherland (1988), the flow depth ratio and the sediment size ratio were found to be related to B, the projected width of the skewed pier, instead of b, the original width. Values of K_α presented herein and those estimated from the curves of Laursen and Toch (1956) were compared with the experimental data of K_α emphasizing the inconsistency of using these curves in design purposes. Values of K_α suggested by Laursen and Toch (1956) and those proposed by the present study were used to estimate d_s by applying the method of Melville and Sutherland (1988). The accuracy of d_s estimated in both was checked against the corresponding measured values. It is shown that the method of Melville and Sutherland (1988) gives more accurate results of d_s when values of K_α proposed by the present study are used.

Keywords: Parametric approach, Nonalignment effect, Equilrium scour depth, Multiple nonlinear regression.

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_o flow depth
- g gravitational acceleration
- b diameter of circular pier or width of noncircular pier when it is aligned to the flow direction
- B projected width of pier skewed to the flow direction
- α angle of attack or the angle between the main flow direction and the longitudinal axis of noncircular pier

L	length of pier
H	height of pier
W	flume width
d_s	maximum equilibrium scour depth
d_{50}	mean diameter of bed sediment
d_{90}	particle size for which 90% are finer by weight
d_{84}	particle size for which 84% are finer by weight
d_{16}	particle size for which 16% are finer by weight
σ_g	geometric standard deviation of bed sediment = 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
Q	flow discharge
st dErr	asymptotic standard deviation of the parameter
CV%	coefficient of variation = (st dErr * 100%)/mean
Dependency	(1 - (variance of the parameter, other parameters held constant)/(variance of the parameter allowing others to change in the usual way))

INTRODUCTION

The angle of attack factor, K_α, is defined as the ratio between the maximum equilibrium scour depth, d_s, occurred at the bridge pier skewed at certain angle, α, to that occurred at the same pier when it is aligned to the flow direction. It is well known that K_α presented by the curves of Laursen and Toch (1956), as shown in Figure (1), is expressed in terms of the aspect ratio, L/b, and the angle of attack, α , where L is the length of noncircular pier and b is the pier width when it is aligned to the flow direction. For example, the curves show that the rectangular pier of aspect ratio, L/b =10, and skewed at $\alpha = 30^o$, has $K_\alpha = 3.0$. This means that the maximum equilibrium scour depth, d_s, occurred at $\alpha = 30^o$ equals three times d_s at $\alpha = 0^o$. However, at $\alpha = 90^o$, $K_\alpha = 5.0$ which means that d_s at $\alpha = 90^o$ equals five times d_s at $\alpha = 0$.

Melville and Sutherland (1988) suggested that the maximum equilibrium scour depth, d_s, at a noncircular pier aligned to the flow direction is given by $d_s = (2.4)(K_s)(b)$ where K_s is the shape factor, provided that the flow depth is deep enough so that $y_o/b \geq 2.6$ and the sediment size is fine enough so that $b/d_{50} \geq 25$. Under these conditions and at $\alpha = 90^o$, the width of the pier of which L/b =10 equals ten times its original width, b. So according to Melville and Sutherland (1988), d_s at $\alpha = 90^o$ equals ten times d_s at $\alpha = 0^o$. Considering the same pier, when the designer compares between values of d_s obtained by using the curves of Laursen and Toch (1956), d_s = 5 b, and by applying the method of Melville and Sutherland (1988), d_s = 10 b, he detects a clear contradiction. Thereby, emphasizing the inconsistency of using the curves of Laursen and Toch (1956) and the doubt they may be dependent of other influences including the effect of flow depth and sediment size. Therefore, the skewness effect needs further investigation.

A clear as well as a close view of this effect should be confidently presented to the designer who is currently using the curves of Laursen and Toch (1956). It is well known that b, the pier original width, is the main factor affecting d_s at $\alpha = 0^o$. However, once the pier is skewed to the flow direction, the projected width, B, as shown in Figure (2), should be considered instead. In this case, the effect of B/d_{50} and y_o/B on K_α should be examined. As the angle of attack, α, increases, B increases and so does B/d_{50}. On the other hand, as B increases y_o/B decreases. So, at certain angle, it is easy to have $B/d_{50} \geq 25$ so that B/d_{50} does not affect d_s. Contrarily, similar condition, $y_o/B \geq 2.6$, is not so easy to be obtained. This implies that the effect of y_o/B is more significant than B/d_{50}.

Generally, the relationship of the angle of attack factor, K_α, may take the following functional relationship form:

$$K_\alpha = f(L/b, \alpha, \text{shape}, y_o/B, B/d_{50}, \sigma_g) \quad (1)$$

A comprehensive experimental investigation is needed in order to formulate Eq. (1) for design purposes.

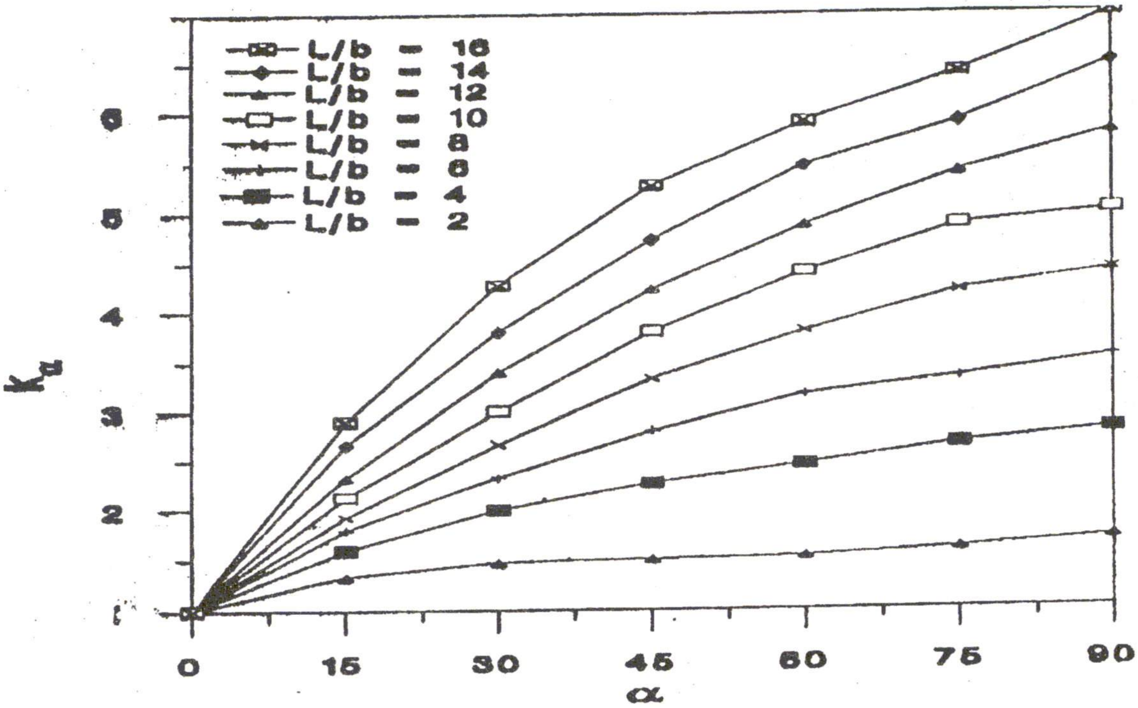

Figure 1. Curves of Laursen and Toch (1956).

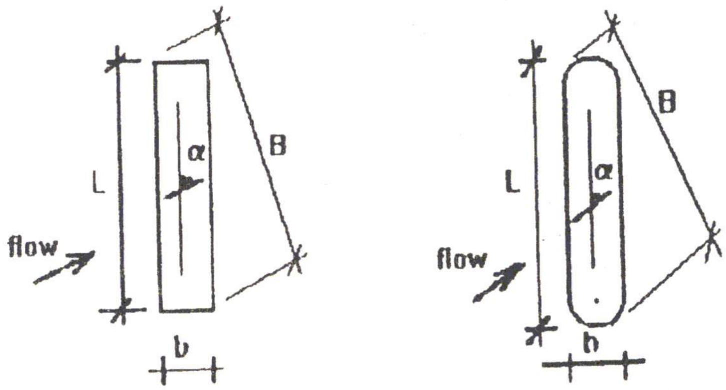

Figure 2. Skewed rectangular and ablong pier shapes in plan.

EXPERIMENTAL INVESTIGATION

Experiments were conducted at the University of Alexandria (UA) in Egypt and the University of Iowa (UI) in USA. They were conducted under clear water scour with the bed surface of sediment near the condition of incipient particle motion (i.e. the condition at which maximum equilibrium scour depth occurs). Data and results are documented by the Ph.D thesis of Mostafa (1994). The experiments at UI were conducted in a 25 m long, 1.5 m wide and 0.6 m deep flume, as shown in Figure (3). The flume used at UA was 12 m long, 0.86 m wide and 0.6 m deep. Each flume was equipped with a sand recess. A uniform sand (medium size, d_{50} = 0.9 mm and geometric standard deviation of bed sediment,

$\sigma_g = d_{84}/d_{50} = 1.1$) was used for the UI experiments, however, a nonuniform sand ($d_{50} = 0.6$ mm, $\sigma_g = 2.4$) was used for the UA data. Two pier shapes, oblong and rectangular, with aspect ratios, L/b = 4, 6, 8, 10 and 12, were investigated. For all experiments the pier width was set constant at b = 3.5 cm while the flow depth was held constant at either 10.5 cm (UA) or 35 cm (UI). For each pier, the skewness was varied in 15° steps from 0° to 90°. A total of 100 individual experimental runs were conducted, each one running for several hours in case of nonuniform sand at UA and for several days in case of uniform sand at UI until equilibrium scour was practically attained.

Experimental Procedure

The procedure adopted for the experiments which were carried out under the same conditions of approach-flow, bed-sediment, and bed slope are summarized as following: 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 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 10.5 cm at UA and 35.0 cm 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 UA, it was observed that after few hours, an armour layer formed in the bottom of the scour hole. Thereafter no more scour occurred. At this stage, the pump control valve was gradually closed and the water in the flume was slowly drained. It was observed that 6 hours was a sufficient time for equilibrium scour around piers which were aligned to the flow direction. On the other hand, in case of skewed piers which presented a wider face to the flow, it was found that 8 to 10 hours (depending on the angle of attack) was enough time. When the scour hole was drained, the scour depths were measured. 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. For piers of aspect ratios L/b = 8, 10, 12 only three angles (α=0, 15, 30°) were studied.

Essentially the same procedure adopted at UA were done at UI. However, because the sand used at UI was uniform and armoring did not occur and, consequently, did not reduce maximum equilibrium scour depth, d_s, each run took several days to reach the equilibrium condition. Piers of aspect ratios, L/b = 4, 6, 8 were used and skewed at angles, α = 0, 15, 30, 45, 60, 75, 90°. A total of hundred experimental runs were conducted at both UA and UI.

PARAMETRIC APPROACH FOR THE ESTIMATION OF K_α

The aim of this approach is to relate the dependent parameter, K_α, to the independent parameters on the right hand side of Eq. (1).

Comprehensive Angle Of Attack Factor, K_α

An accounting of all the parameters affecting K_α, leads to the following relationship for rectangular or oblong piers:

$$K_\alpha = a(\text{Log}(B/b))^b \, (y_o/b)^c \, (b/d_{50})^d \, (\sigma_g)^e + 1 \qquad (2)$$

The form of Eq.(2) was chosen to satisfy the boundary condition; at α = 0°, B/b = 1 and K_α = 1.0, where B is the projected width of the skewed pier, as shown in Figure (2). Mostafa et al (1995-I) gave a geometrical definition to B/b. For rectangular piers they proposed

$$B/b = (L/b) \sin \alpha + \cos \alpha \qquad (3)$$

and for oblong piers, they suggested

$$B/b = (L/b - 1) \sin \alpha + 1 \qquad (4)$$

Values of the five coefficients, a, b, c, d and e, can be estimated separately for rectangular or oblong piers by conducting a regression analysis.

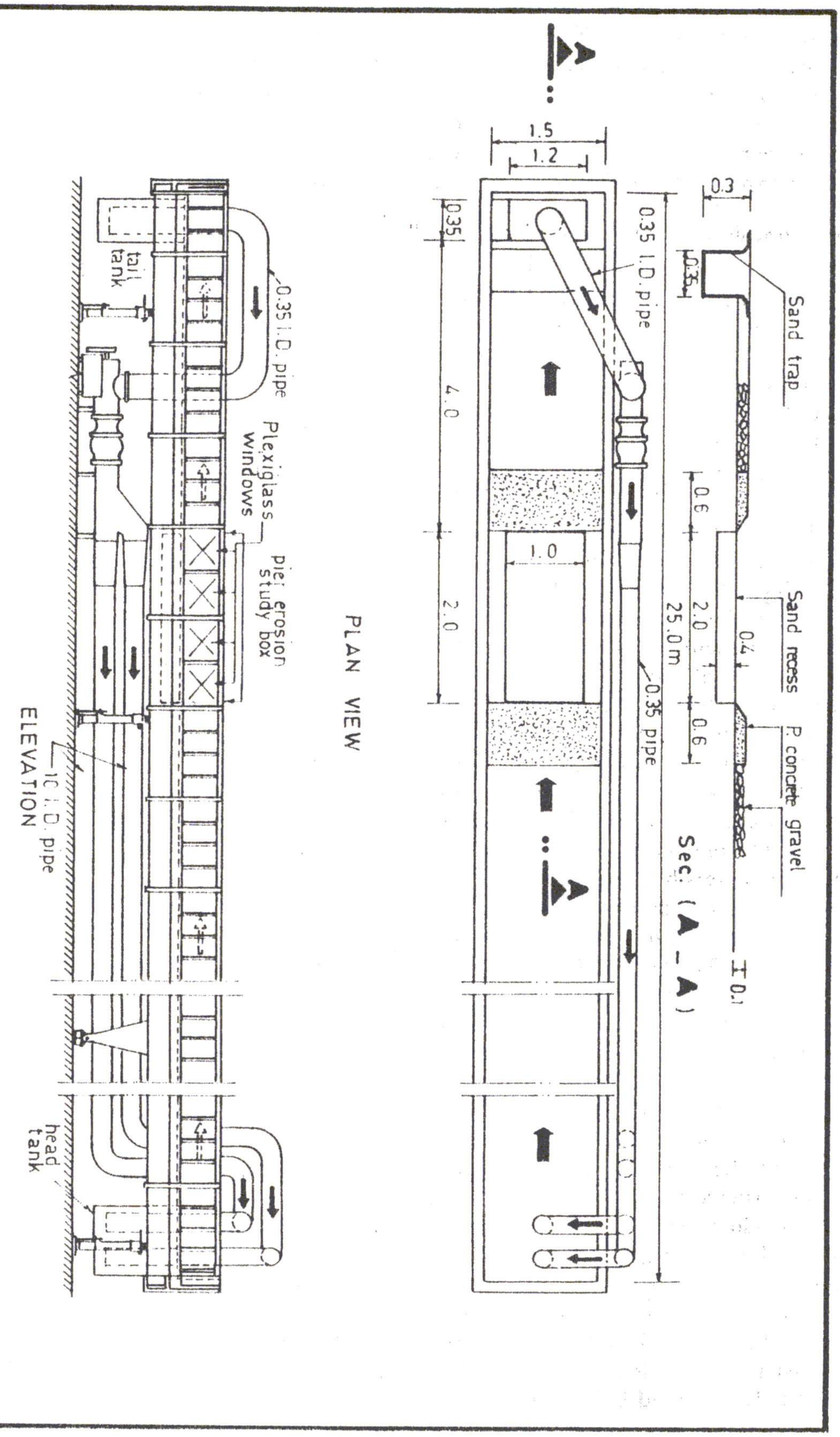

Figure 3. University of Iowa Flume.

Because y_o/b does not change as α changes, it may be advantageous to use y_o/B instead of y_o/b. Similarly, it might be better to use B/d_{50} instead of b/d_{50}. Actually, using B instead of b is logical once the pier is skewed to the flow direction. In this case, Eq. (2) may be changed to the following form:

$$K_\alpha = a(Log(B/b))^b \ (y_o/B)^c (B/d_{50})^d \ (\sigma_g)^e + 1 \quad (5)$$

Multiple nonlinear regression analysis was done to estimate the five coefficients. The data used in the analysis are presented in Table (1) as a sample for rectangular piers. Similar data for oblong piers are documented by the Ph.D thesis of Mostafa (1994). In Table (1), $(K_\alpha-1)$ is defined as the dummy term Y, while, the parameters, Log(B/b), (y_o/B)' (B/d_{50}) and (σ_g) are defined as X_1, X_2, X_3 and X_4, respectively. The degree of correlation of a dependent variable, Y, with many independent variables, X_1, X_2, X_3 and X_4, in a multiple regression analysis is measured by the asymptotic standard deviation of the parameter, st dErr, and (CV%) which is defined as a coefficient of variation = ((st dErr)*100%)/mean. When the number of dimensionless independent variables are many, the effective variables of them should be selected in a step-wise procedure by applying a criterion for the addition or deletion of a variable. In the regression, a coefficient called Dependency (1- (variance of the parameter, other parameters held constant)/(variance of the parameter allowing others to change in the usual way)) is used to select the effective independent variables. The strong dependency (i.e., its value is close to 1.0) suggests that the present model is overparameterized or too complex for the data and that a model with fewer parameters would be better.

During the regression, when the number of parameters exceeds the first one, Log(B/b), on the right hand of Eq. (5), the system of equations used, was in some cases unstable for determining the five coefficients and random errors occur leading to different solutions. The result given in Table (2) as a sample for rectangular piers shows that when the parameters are two or more, the dependency value is very close to one, however, it is between 0.7 to 0.8 when only the first parameter is used. Similar data for oblong piers are documented by the Ph.D thesis of Mostafa (1994). This implies that B/b or in other words L/b and a, mainly affect K_α.

It was found that y_o/B affects d_s around a skewed pier. For example, the scour depths around a skewed rectangular pier in uniform sand as shown in row (2) in Table (2), can be affected by y_o/B where values of Dependency were 0.738, 0.769 and 0.711. When the data of scour depths in nonuniform sand were analyzed, the ratio (y_o/B) did not affect the scour depths as shown in row (8) in the same table where the corresponding values of Dependency are 0.997, 0.995 and 0.985. This is likely because the range, $3 \geq y_o/B \geq 0.4$, used for the UA experiments was relatively shallow (i.e., limited range). However, when the data for both uniform and nonuniform sand were together analyzed, the ratio of y_o/B remains affecting the scour depths as shown in row (12) in Table (2). The results at both UA and UI show that y_o/B affects not only d_s but also the flow field and consequently affects the location of maximum equilibrium scour depth.

Summarizing the parametric approach, as given in Table (2), the following equations can be used to estimate the angle of attack factor, K_α, for skewed rectangular piers:

$$K_\alpha = 1 + 3.374 \ (\log \ (B/b))^{1.736} \quad (6)$$

or for better accuracy (less Dependency):

$$K_\alpha = 1 + 3.393 \ (\log(B/b))^{1.76} \ (y_o/B)^{0.05} \quad (7)$$

For skewed oblong piers, the following equations can be used

$$K_\alpha = 1 + 4.54 \ (\log \ (B/b))^{1.56} \quad (8)$$

or for better accuracy (less Dependency):

$$K_\alpha = 1 + 4.51 \ (\log(B/b))^{1.523} \ (y_o/B)^{-0.054} \quad (9)$$

The negative value of c in Eq. (9) may be due to the narrow range of y_o/B which used for oblong piers if compared with that range used for rectangular piers. It is shown that σ_g did not affect K_α. The reason is that the effect of σ_g on d_s at $\alpha = 0$ and at certain angle is almost the same.

Table (1) Values of the independent parameters, x1, x2, x3 and x4 as well as the dependent one , Y , for the rectangular piers (UI and UA data)

α	sin α	b (cm)	L/b	B (cm)	B/b	log(B/b)	y_o (cm)	y_o/B	d_{50} (cm)	B/d_{50}	σ_g	d_s (cm)	d_s/B	K_α	K_α -1
						X1		X2		X3	X4				Y
0	0	3.5	4	3.5	1	0	10.5	3	0.09	38.89	1.1	9.3	2.657	1	0
15	0.259	3.5	4	7.004	2.001	0.301	10.5	1.499	0.09	77.82	1.1	11	1.57	1.183	0.183
30	0.5	3.5	4	10.03	2.866	0.457	10.5	1.047	0.09	111.5	1.1	15.4	1.535	1.656	0.656
45	0.707	3.5	4	12.37	3.536	0.548	10.5	0.849	0.09	137.5	1.1	18.7	1.511	2.011	1.011
60	0.866	3.5	4	13.87	3.964	0.598	10.5	0.757	0.09	154.2	1.1	21.5	1.55	2.312	1.312
75	0.966	3.5	4	14.43	4.123	0.615	10.5	0.728	0.09	160.3	1.1	21.2	1.469	2.28	1.28
90	1	3.5	4	14	4	0.602	10.5	0.75	0.09	155.6	1.1	21.2	1.514	2.28	1.28
0	0	3.5	4	3.5	1	0	35	10	0.09	38.89	1.1	9.5	2.714	1	0
15	0.259	3.5	4	7.004	2.001	0.301	35	4.997	0.09	77.82	1.1	13.8	1.963	1.447	0.447
30	0.5	3.5	4	10.03	2.866	0.457	35	3.489	0.09	111.5	1.1	17	1.695	1.789	0.789
45	0.707	3.5	4	12.37	3.536	0.548	35	2.828	0.09	137.5	1.1	22.3	1.798	2.342	1.342
60	0.866	3.5	4	13.87	3.964	0.598	35	2.523	0.09	154.2	1.1	25	1.802	2.632	1.632
75	0.966	3.5	4	14.43	4.123	0.615	35	2.426	0.09	160.3	1.1	27	1.871	2.842	1.842
90	1	3.5	4	14	4	0.602	35	2.5	0.09	155.6	1.1	26.8	1.911	2.816	1.816
0	0	3.5	6	3.5	1	0	35	10	0.09	38.89	1.1	9.5	2.714	1	0
15	0.259	3.5	6	8.816	2.519	0.401	35	3.97	0.09	97.95	1.1	15.4	1.747	1.621	0.621
30	0.5	3.5	6	13.53	3.866	0.587	35	2.587	0.09	150.3	1.1	21.2	1.567	2.232	1.232
45	0.707	3.5	6	17.32	4.95	0.695	35	2.02	0.09	192.5	1.1	25.4	1.466	2.674	1.674
60	0.866	3.5	6	19.94	5.696	0.756	35	1.756	0.09	221.5	1.1	30.4	1.525	3.2	2.2
75	0.966	3.5	6	21.19	6.054	0.782	35	1.652	0.09	235.4	1.1	34.2	1.614	3.6	2.6
90	1	3.5	6	21	6	0.778	35	1.667	0.09	233.3	1.1	30.2	1.438	3.179	2.179
0	0	3.5	8	3.5	1	0	35	10	0.09	38.89	1.1	9.3	2.657	1	0
15	0.259	3.5	8	10.63	3.036	0.482	35	3.293	0.09	118.1	1.1	17	1.6	1.828	0.828

Table (2) Values of the coefficients and their dependencies according to the form of Eq. (5) (UA and UI data of rectangular piers)

No.	Conditions	Equation	Coeffi-cients	Values	St dErr	CV %	Dependency
1	rectangular & uniform sediment	$Y = aX_1^b$	a	3.436	0.0143	4.17	0.703358
			b	1.777	0.015	6.47	0.703358
2		$Y = aX_1^bX_2^c$	a	3.31	0.133	4.02	0.738
			b	1.89	0.117	6.23	0.769
			c	0.1618	0.065	40.34	0.711
3		$Y = aX_1^bX_3^d$	a	10.8	33	306	0.999
			b	2.08	0.922	44.3	0.995
			d	-0.197	0.586	298	0.999
4		$Y = aX_1^bX_2^cX_3^d$	a	42.3	120	280	0.999
			b	2.56	32	32	0.995
			c	0.158	40	40	0.707
			d	-0.43	120	120	0.999
5		$Y = aX_1^bX_2^cX_3^d$ **(repeat)**	a	30.11	89	290	0.999
			b	2.47	0.83	33	0.995
			c	0.158	0.063	40	0.708
			d	-0.377	0.53	140	0.999
6		$Y = aX_1^bX_2^cX_3^d$ **(repeat)**	a	0.03	89.89	298.6	0.999
			b	2.467	0.8335	0.033	0.995
			c	1.582	0.0638	0.04	0.7082
			d	-3.767	0.536	0.014	0.999
7	rectangular & nonuniform sediment	$Y = aX_1^b$	a	3.22	0.354	10.9	0.824
			b	1.633	0.268	16.4	0.824
8		$Y = aX_1^bX_2^c$	a	0.4356	0.02	0.001	0.997
			b	-1.139	0.008	0.003	0.995
			c	-5.5256	0.01	0.002	0.985
9		$Y = aX_1^bX_3^d$	a	0.264	2.15	815	0.999
			b	1.05	2.14	204	0.999
			d	0.401	1.48	370	0.999
10		$Y = aX_1^bX_2^cX_3^d$	a	0.196	91.7	4660	1.0
			b	4.125	2.82	68.3	0.998
			c	2.57	90.7	3500	0.999
			d	0.887	90.8	10200	1.0
11	rectangular & uniform & nonuniform sediment	$Y = aX_1^b$	a	3.374	0.1563	4.63	0.753
			b	1.736	0.1214	6.99	0.753
12		$Y = aX_1^bX_2^C$	a	3.393	0.156	4.6	0.752
			b	1.76	0.122	6.92	0.758
			c	0.05	0.041	81.5	0.052
13		$Y = aX_1^bX_3^d$	a	5.075	3.55	72.0	0.998
			b	1.83	0.207	11.3	0.914
			d	-0.0685	0.12	177.0	0.9988
14		$Y = aX_1^bX_2^cX_3^d$	a	0.03	14.7	47500	1.0
			b	4.22	2.88	68.4	0.998
			c	3.0	90.7	3019	0.999
			d	1.26	90.8	7200	1.0
15		$Y = aX_1^bX_2^cX_3^dX_4^e$	a	0.52	1.57	303	0.999
			b	1.42	0.9	64	0.995
			c	0.173	0.094	54	0.817
			d	0.313	0.59	190	0.999
			e	0.54	0.32	590	0.983

COMPARATIVE ANALYSIS

A comparative analysis is carried out to compare the accuracy of estimating K_α by using either the parametric approach or the curves of Laursen and Toch (1956). Statistically, the more accurate method must have a smaller standard error of estimate, S_e, which is given by the following equation:

$$S_e = \sum \left[\frac{\{d_s(\text{measured}) - d_s(\text{estimated})\}^2}{n-2} \right]^{0.5} \quad (10)$$

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

$$A_e = \sum \left[\left| \left\{ \frac{d_s(\text{measured}) - d_s(\text{estimated})}{d_s(\text{measured})} \right\} \right| * 100\% \right] / n \quad (11)$$

Table (3) shows values of S_e and A_e for the angle of attack factor, K_α. These results also show that the curves of Laursen and Toch (1956) give greater values of S_e and A_e than those given by Eq. (6) or Eq. (7) of the parametric approach for rectangular piers. The difference increases for the oblong piers. So, estimating K_α by using Eq. (7) for rectangular and Eq. (8) for oblong piers is more accurate than using the curves of Laursen and Toch (1956).

Table (4) shows values of S_e and A_e for the maximum equilibrium scour depth, d_s, estimated by applying the method of Melville and Sutherland (1988). The method was presented in details by Mostafa et al. (1995-I). They proposed $K_s = 1.25$ for rectangular and $K_s = 0.9$ for oblong piers. It can be seen from these results that the method of Melville and Sutherland (1988) is more accurate when K_α is estimated by using Eq. (7) and Eq. (8) of the parametric approach than it is when K_α is estimated from the curves of Laursen and Toch (1956).

Data of K_α, collected from the previous studies and obtained around oblong piers, were compared with those estimated by using Eq. (8). As shown in Figure (4), it is shown that the limited data of Schnieble (1951), Maza (1964), Chabert and Engeldenger (1956), Zarzeliot (1960) and Hanna (1978) all are under the line of perfect agreement (i.e., underpredict K_α) except only one point. Some of the collected data are in details so that d_s can be estimated. Data of Chabert and Engeldenger (1956) are given in Table (5) and those of Varzeliotis (1960) are given in Table (6). The regression analysis yields a high dependencies as shown in row 5 and 6 of Table (7) which means a bad correlation. The resulted coefficients, a and b, are not compatible with those obtained when the present experimental data were used. When the method of Melville and Sutherland (1988) was used to estimate d_s, the data of Chabert and Engeldenger (1956) and Varzeliotis (1960) underpredict d_s as shown in Figure (5). This disagreement might be due to the following:

1. use of coarse sand in most of the previous studies which is responsible for decreasing the maximum scour depth.
2. use of shallow water depth which is also responsible for decreasing d_s at large angles more than at small angles of attack.

Table 3. Values of standard error of estimate, S_e, and average percentage error, A_e, for K_α.

Pier shape	statistical parameters	K_α by Laursen & Toch (1956)	K_α by Parametric Approach	
rectangular			Eq. (6)	Eq. (7)
	S_e	0.25	0.246	0.242
	A_e	7.72	7.07	6.9
oblong			Eq. (8)	Eq. (9)
	Se	0.5	0.20	0.19
	A_e	11.3	4.73	4.72

Table 4. Values of standard error of estimate, S_e, and average percentage error, A_e, for d_s.

		Applying the method of Melville & Sutherland (1988)		
Pier shape	statistical parameters	K_α by Laursen and Toch (1956)	K_α by Parameric Approach	
rectangular			Eq. (6)	Eq. (7)
	S_e	2.37	1.78	1.69
	A_e	17.9	15.0	14.4
oblong			Eq. (8)	Eq. (9)
	S_e	2.25	1.68	1.73
	A_e	15.17	19.33	20.4

Table 5. Values of the independent parameters, X1, X2, X3 and X4 as well as the dependent one, Y, for the oblong pier (data of Chabert and Engeldinger (1956)).

α	sin α	b (cm)	L/b	B (cm)	B/b	log (B/b)	y_o (cm)	y_o/B	d_{50} (cm)	B/d_{50}	σ_g	d_s (cm)	d_s/B	K_α	K_α-1
						X1		X2		X3	X4				Y
0	0	15	4	15	1	0	15	1	0.3	50	1.12	24.7	1.647	1	0
15	0.259	15	4	26.65	1.776	0.25	15	0.563	0.3	88.82	1.12	27.9	1.047	1.13	0.13
30	0.5	15	4	37.5	2.5	0.398	15	0.4	0.3	125	1.12	36.8	0.981	1.49	0.49

Table 6. Values of the independent parameters, X1, X2, X3 and X4 as well as the dependent one, Y, for the oblong pier (data of Varzeliotis (1960)).

α	sin α	b (cm)	L/b	B (cm)	B/b	log (B/b)	y_o (cm)	y_o/B	d_{50} (cm)	B/d_{50}	σ_g	d_s (cm)	d_s/B	K_α	K_α-1
						X1		X2		X3	X4				Y
0	0	2.5	6	2.5	1	0	10.7	4.28	0.17	14.71	1.15	3.5	1.4	1	0
15	0.259	2.5	6	5.735	2.294	0.361	10.7	1.866	0.17	33.74	1.15	4.8	0.837	1.371	0.371
30	0.5	2.5	6	8.75	3.5	0.544	10.7	1.223	0.17	51.47	1.15	8.3	0.949	2.371	1.371
45	0.707	2.5	6	11.34	4.536	0.657	10.7	0.944	0.17	66.7	1.15	13.2	1.164	3.771	2.771

Table 7. Values of the coefficients a, b, c and d and their dependencies (UA and UI data of skewed rectangular and oblong piers and those of Chabert and Engeldinger (1956) and Varzeliotis (1960) for oblong piers are included).

No	Conditions	Source	Equation	Coeffi-cients	Values	St dErr	CV %	Dependency
1	rectang.& uniform and nonuniform sediment $\alpha \leq 60$	present study	$Y = aX_1^b$	a b	3.22 1.785	0.162 0.119	5.03 6.64	0.784 0.784
2			$Y = aX_1^bX_2^c$	a b c	3.32 1.879 0.1	0.155 0.113 0.037	4.68 6.04 3.66	0.788 0.8 0.113
3	oblong & uniform and nonuniform sediment $\alpha \leq 60$		$Y = aX_1^b$	a b	4.716 1.662	0.143 0.0.67	3.03 4.017	0.79 0.79
4			$Y = aX_1^bX_2^c$	a b c	4.693 1.646 -0.016	0.148 0.072 0.024	3.157 4.37 1.45	0.803 0.816 0.143
5	oblong & uniform sediment $\alpha \leq 60$	Chabert & Engelding-er (1956) & Varzeliotis (1960)	$Y = aX_1^b$	a b	12.0 3.5	0.51 0.087	4.29 2.48	0.94 0.94
6			$Y = aX_1^bX_2^c$	a b c	12.0 3.5 -0.054	0.514 0.087 0.056	4.3 2.5 104.1	0.94 0.94 0.013

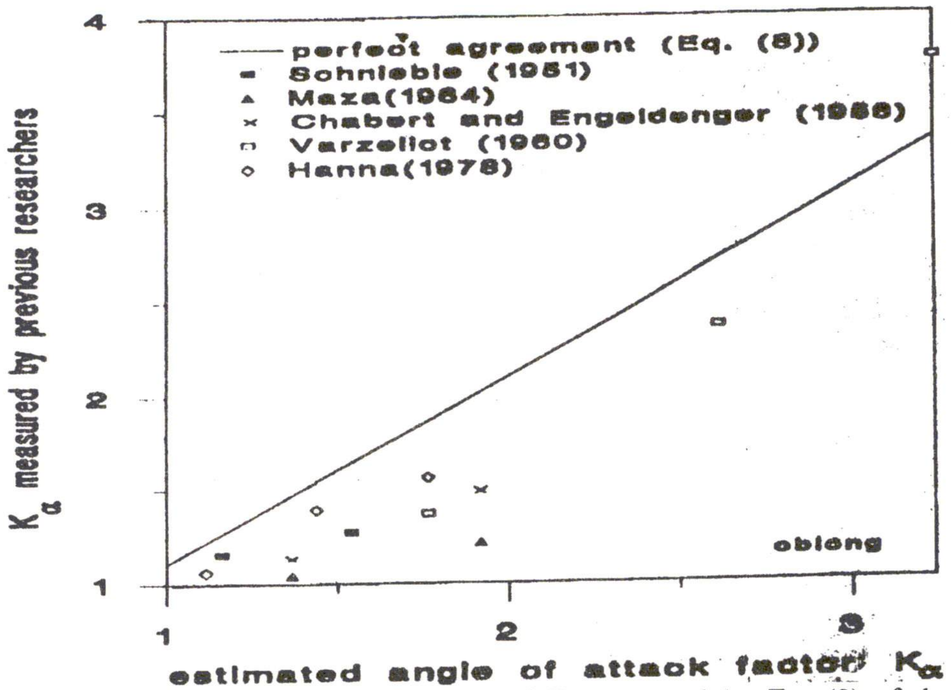

Figure 4. Comparison between values of K_α proposed by Eq. (8) of the parametric approach and those measured by other previous researchers.

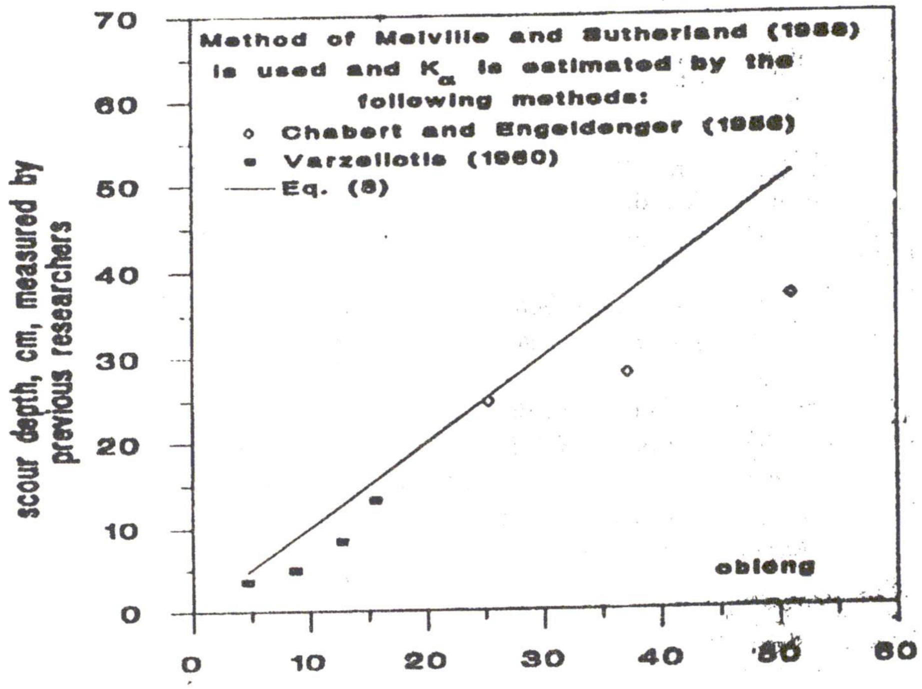

Figure 5. Comparison between values of d_s measured by previous researchers and predicted by the method of Melville and Sutheriand (1988) where k_α is estimated by Eq. (8) of the parametric approach.

CONCLUSIONS

Based on the analysis of 100 individual experimental runs which were conducted at the University of Alexandria, UA, and the University of Iowa, UI, the following conclusions were derived for the mentioned range of experiments:

1-The angle of attack factor, k_α, is affected primarily by the aspect ratio, L/b, the angle of attack, a, and the shape of the pier. Whereas, the ratio of water depth to pier projected width, y_o/B, is shown to have a lesser effect on the magnitude of k_α around a skewed pier, it has an effect on the flow field around the pier and consequently on the location of d_s. On the other hand, regression analysis shows that both B/d_{50} and σ_g have neglected effect on K_α for the range specified in the experiments.

2-Values of k_α given by Eq. (7) and Eq. (8) of the parametric approach for rectangular and oblong piers, respectively, are more accurate than those given by the curves of Laursen and Toch (1956).

3-It is shown that the method of Melville and Sutherland (1988) gives more accurate results of d_s when values of K_α proposed by the present tudy, Eq. (7) and Eq. (8), are used.

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