Reduction of scouring depth by using inclined piers

Zafer Bozkus and Murat Çeşme

Abstract: The aim of this experimental study is to examine the effect of inclination of dual bridge piers on scour depth under clear-water conditions for various uniform flow depths. Duration of 4 h was used in the experiments for each run. Scour depths were measured at four different points around the piers. The depths of local scour around inclined piers were found to be substantially smaller than the scour depths around vertical piers. Dimensional and nondimensional curves were developed and presented to show the variation of scour depth with relevant parameters obtained in the dimensional analysis. Results of the study were compared to those obtained from a similar study performed with single inclined piers to see the effect of the second pier on scour depths. Useful equations for the design engineers were developed based on multiple regression analyses, to be used for predicting local scour depths around vertical and (or) inclined piers in uniform and (or) nonuniform sediments. Normalized scour depths measured around the vertical piers in the present study were compared with those computed by an equation suggested by Melville and Sutherland (1988), and also by an equation developed in the present study.

Key words: clear water condition, inclined dual bridge piers, scour depth, armouring.

Résumé : La présente étude expérimentale visait à évaluer l'effet de l'inclinaison de piles doubles de pont sur la profondeur d'affouillement sous des conditions d'eau limpide pour différentes profondeurs d'écoulement uniforme. Chaque passage a duré quatre heures. Les profondeurs d'affouillement ont été mesurées à quatre différents points autour des piles. Les profondeurs de l'affouillement local près des piles inclinées se sont révélées beaucoup moindres que les profondeurs d'affouillement près des piles verticales. Des courbes dimensionnelles et non dimensionnelles ont été développées et présentées pour montrer la variation de la profondeur d'affouillement par rapport à divers paramètres obtenus lors de l'analyse dimensionnelle. Les résultats de l'étude ont été comparés à ceux obtenus lors d'une étude similaire réalisée avec des piles inclinées simples afin de voir l'effet de la deuxième pile sur les profondeurs d'affouillement. Des équations utiles aux ingénieurs concepteurs ont été développées en se basant sur des analyses de régressions multiples; ces équations sont utilisées pour prédire les profondeurs d'affouillement local autour des piles verticales et (ou) inclinées dans des sédiments uniformes et (ou) non uniformes. Les profondeurs d'affouillement normalisées mesurées autour des piles verticales de la présente étude ont été comparées à celles calculées en utilisant une équation suggérée par Melville et Sutherland (1988) et une équation développée dans la présente étude.

Mots-clés : condition d'eau limpide, piles de pont inclinées doubles, profondeur d'affouillement, enrochement.

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Introduction

A few experimental studies on the effect of inclination of piers on local scour formation are available. It is already known that one of the important parameters that affects scour depth is the slope of the leading edge of the pier to the vertical, based on laboratory results of scour at piers tapered in elevation. Breusers and Raudkivi (1991) showed that scour depth increases for an upwardly widening pier and decreases for an upwardly narrowing pier. According to Bozkus and Yildiz (2004) local scour depths decrease significantly as the inclination angle of the pier towards downstream was increased. The pier configuration studied then was a single circular pier inclined in the downstream flow direction, Fig. 1. Cesme (2005) conducted a follow up of the previous study, as the inclination angle is still an important parameter. However, this time the pier configuration is more practical and feasible since it has dual bridges inclined both in the upstream and downstream directions (Fig. 2). Consequently, the present study is more meaningful as far as the engineering point of view is concerned and its partial results were presented by Bozkus and Cesme (2007).

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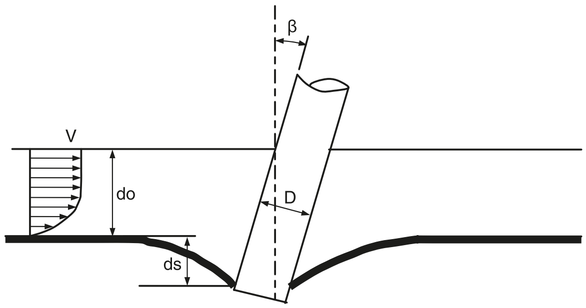
Dimensional analysis and similitude considerations

A functional relationship shown in eq. [1] describes the maximum scour depth d_s, occurring around an inclined bridge pier.

$$[1] \qquad d_s = f_1(\rho, \mu, g, V, V_c, D, D_{50}, d_o, \beta)$$

Fig. 1. Definition sketch for a single inclined pier (Bozkus and Yildiz 2004).



where ρ is density of water; μ is viscosity of water; g is the gravitational acceleration; V is the mean approach velocity; V_c is the critical mean approach velocity when sediment motion is imminent; D is the pier diameter; D_{50} is the mean sediment size, d_o is the approach flow depth; and β is the inclination angle of the pier with the vertical plane. With ρ, V, and D selected as repeating variables, the dimensional analysis gives way to the dimensionless relationship given in eq. [2]. Needless to say, different selection of repeating variables would result in somewhat different parameters, and also the third parameter within the parentheses may be rearranged to give the flow Froude number if D is replaced by d_o.

$$[2] \qquad \frac{d_s}{D} = f_2\left(\frac{d_o}{D}, \frac{V}{V_c}, \frac{V^2}{gD}, \frac{D}{D_{50}}, \frac{\rho VD}{\mu}, \beta\right)$$

Ettema et al. (1998) states that "the pier Reynolds number, $\rho VD/\mu$, usually is not a significant parameter and can be dropped from Equation 2 if flow around the pier is fully turbulent". Then, eq. [2] takes the form as

$$[3] \qquad \frac{d_s}{D} = f_3\left(\frac{d_o}{D}, \frac{V}{V_c}, \frac{V^2}{gD}, \frac{D}{D_{50}}, \beta\right)$$

Equation [3] indicates that the nondimensional scour around an inclined pier is a function of normalized approach flow depth, d_o/D; flow intensity, V/V_c; the parameter V^2/gD, is included as an indicator of degree of vorticity also used by Ettema et al. (2006) in this context; relative roughness parameter, D/D_{50}; and the inclination angle of the piers, β. Experiments were performed in light of these dimensionless parameters.

Experimental works

Experimental facility

The present experiments were conducted in a flume at the Hydromechanics Laboratory of the Civil Engineering Department of the Middle East Technical University, Ankara, Turkey. The test facility basically consists of the main channel and the secondary channel. Figure 3 shows the side views of the test channel (upper) and the secondary channel (lower). The main channel is the channel where scouring takes place. The effective dimensions of the main channel are 14.00 m × 0.72 m, with a wall height of 1 m. The bottom of the channel is made of varnished concrete, the back side is of sheet iron, and the front side is made of glass. Steel meshes of 160 cm high have been placed at the entrance of the channel to avoid coherent turbulence, where the water is driven from the pump. Including the length of the meshes, the total length of the main channel is 15.60 m. The centre of pier models is placed at 6.50 m downstream of the end point of the meshes. The area between 6 m and 7 m from the end of the mesh is designated as the "test section", which has a length of 1.00 m and width of 0.72 m. The piers were installed in this zone tightly to prevent them from moving by the effect of flow. The water depth and bed level measurements in the test section were made with a mobile point gauge, which is connected to a wheeled tray, permitting the measurements at different locations with a sensitivity of 0.1 mm. Flow was measured in a subsequent channel by means of sharp-crested weir.

Material used in the experiments

The experiments were conducted in the main channel, consisting of a 30 cm thick sand layer at its bottom. The bed material was placed with a slope of 0.001 for the total length of the channel. There is approximately a 15 mm difference between the bed level, at the beginning and end of the channel, since the channel length is about 15 m. The characteristic properties of the bed material are: D_{50} = 1.44 mm, γ_s = 26.5 kN/m^3, σ_g = 3.0, where D_{50} is the mean particle size, γ_s is the specific weight of the sediment used, and σ_g is the geometric standard deviation of the particle size distribution. It is known that when $\sigma_g > 1.3$ the sediment is considered non-uniform and armoring occurs on the channel bed and in the scour hole (Melville (1997). This aspect will be investigated later in detail.

The experiments were conducted with cylindrical piers of three different diameters; D = 25 mm, 50 mm, and 70 mm. Measurements with various flow depths and corresponding discharges were taken. However, since it was almost impossible to obtain noticeable scour values with piers of 25 mm diameter in the preliminary studies, these experiments were not considered in the analyses.

Experimental procedure

Steady clear-water conditions were studied only. This means that no sediment inflow from upstream was allowed into the channel. During the experiments, changes in the bed elevation were measured at four different locations at specified time intervals. The scour measurements were taken at the upstream and downstream faces of the first pier, and upstream face of the second pier; d_{s1}, d_{s2}, and d_{s3}, respectively, and finally aggradation was measured on the downstream side of the second pier; h (Fig. 2). Scour immediately downstream of the second pier was not measured as it was relatively small. The analysis of the scours was made solely using the data at the upstream face of the first pier, d_{s1}; since the largest value of the scour occurred there. Figure 2 shows the four different recording locations. At the downstream side of the downstream pier, a sediment deposition of height h occurs. The termination time, t_{max}, of the experiments was taken as 240 min, which is considered sufficiently long enough since the rate of change of the scour depth was negligibly small beyond 4 h (Fig. 4). It should be noted that the aim of the study is not to find the ultimate equilibrium scour depths. Rather, the main motiva-

Fig. 2. Definition sketch for the scour measurements around the two inclined piers.

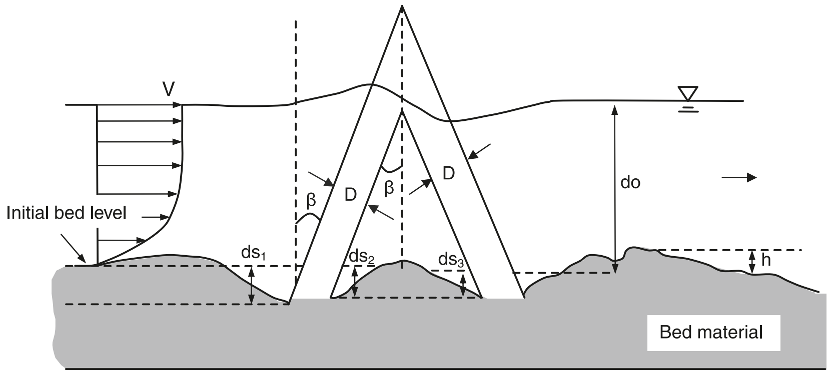


Fig. 3. Side views of the test channel (upper) and secondary channel (lower).

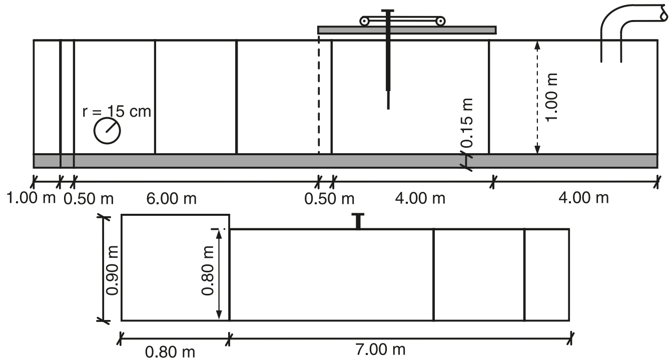
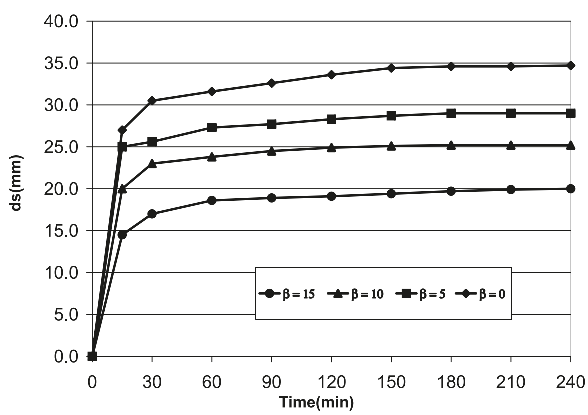


Fig. 4. Variation of scour depth with time for D = 5 cm and d_o/D = 2.5.



tion for the study is to show the effect of the inclination of the piers on the reduction of scour depths.

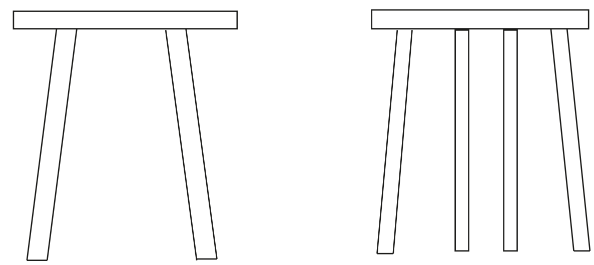
The experiments were performed for the angles $\beta = 0°$ (vertical), 5°, 10°, and 15°. During the experiments, steady – uniform flow conditions were maintained. The pier configuration shown in Fig. 2 was built for practical reasons for carrying out the experiments in the scope of this study. Actual configurations in practice are shown in Fig. 5.

Experimental results

Experiments with vertical piers (β = 0°)

The experimental data obtained from the two vertically mounted piers are shown in Table 1. Six discharge values

Fig. 5. Recommended configurations for practice.



were used for the pier diameter of 50 mm, and three discharge values for the pier diameter of 70 mm as shown in Table 1. The maximum scour depth always occurred upstream of the first pier, d_{s1}. The values given for the parameter h in Table 1 indicate that aggradation takes place at the downstream side of the second pier.

Experiments with (β = 5°)

The experimental results involving, β = 5° are shown in Table 2. There are six sets of experiments conducted with piers of 50 mm diameter. During the experiments, it was observed that the scour depths obtained with this pier inclination angle are smaller than the scour depths obtained for vertical piers. From the experimental results, it was observed that the d_{s2} and d_{s3} values are relatively close to each other. It is also apparent that aggradation takes place at the downstream side of the second pier, despite the pier inclination angle.

Experiments with (β = 10°)

The list of the experiments conducted with β = 10° are shown in Table 3. In this set of experiments, again it was observed that maximum scour depths continue to decrease as the pier angle, β, is increased further. The d_{s1} values of this pier inclination are smaller than the scour depths of both β = 0° and β = 5°. As observed from Table 3, as the scour depths decrease, the aggradation at the downstream side of the downstream pier also decreases. Aggradation occurs as the dislocated grains from upstream are transported downstream. Therefore, as the erosion from upstream decreases, the transportation of the grains downstream also decreases.

Experiments with (β = 15°)

Table 4 shows the results of the experiments conducted

Table 1. Experiments conducted with α = 90° or β = 0°.

No	Pier size (cm)	Q (L/s)	d_o (cm)	d_{s1} (mm)	d_{s2} (mm)	d_{s3} (mm)	h (mm)
1	5	5.67	5.8	30.0	18.0	21	7.0
2	5	8.46	7.5	32.6	20.0	20	6.5
3	5	14.0	10.5	34.7	17.0	18	6.5
4	5	18.5	12.5	35.7	22.0	24	8.0
5	5	23.7	14.6	37.8	22.5	26	11.0
6	5	31.2	17.5	41.3	22.5	24	8.5
7	7	8.46	7.5	44.0	31.0	25	13.5
8	7	18.5	12.5	49.2	34.5	34	14.5
9	7	31.2	17.5	51.3	33.0	34	13.5

Note: α and β are pier inclination angles; Q is the flow rate; d_o is the approach flow depth; d_{s1} and d_{s2} are the scour depths at the upstream and downstream face of the upstream pier, respectively; d_{s3} is the scour depth at the upstream face of the downstream pier; h is the sediment deposition height downstream of the downstream pier.

Table 2. Experiments conducted with α = 85° or β = 5°.

No	Pier size (cm)	Q (L/s)	d_o (cm)	d_{s1} (mm)	d_{s2} (mm)	d_{s3} (mm)	h (mm)
1	5	5.67	5.8	25.8	15	17.0	8
2	5	8.46	7.5	27.9	20	18.0	10
3	5	14.0	10.5	29.0	23	16.5	7
4	5	18.5	12.5	30.6	17	14.5	11
5	5	23.7	14.6	34.0	24	19.0	13
6	5	31.2	17.5	40.5	25	23.0	12

Note: α and β are pier inclination angles; Q is the flow rate; d_o is the approach flow depth; d_{s1} and d_{s2} are the scour depths at the upstream and downstream face of the upstream pier, respectively; d_{s3} is the scour depth at the upstream face of the downstream pier; h is the sediment deposition height downstream of the downstream pier.

Table 3. Experiments conducted with α = 80° or β = 10°.

No	Pier size (cm)	Q (L/s)	d_o (cm)	d_{s1} (mm)	d_{s2} (mm)	d_{s3} (mm)	h (mm)
1	5	5.67	5.8	22.3	13.0	14	6.5
2	5	8.46	7.5	23.8	14.0	11	7.0
3	5	14.0	10.5	25.2	16.0	15	9.0
4	5	18.5	12.5	26.5	16.5	17	8.5
5	5	23.7	14.6	30.5	20.0	24	11.5
6	5	31.2	17.5	32.8	24.0	22	9.5
7	7	8.46	7.5	32.7	23.0	18	13.0
8	7	18.5	12.5	36.5	26.0	26	14.5
9	7	31.2	17.5	37.4	32.0	25	16.5

Note: α and β are pier inclination angles; Q is the flow rate; d_o is the approach flow depth; d_{s1} and d_{s2} are the scour depths at the upstream and downstream face of the upstream pier, respectively; d_{s3} is the scour depth at the upstream face of the downstream pier; h is the sediment deposition height downstream of the downstream pier.

with the maximum pier inclination angle used in the study, β = 15°. During the experiments it was again observed that the scour depths decrease substantially as the pier inclination angle is increased even further. The scour values of this pier inclination are smaller than the scour depths obtained previously for β = 0°, 5°, 10° as expected. In this case, again the decrease in scour depths is seen not only for the maximum scour depth, d_{s1}, but also for the values of d_{s2} and d_{s3}. As seen from the table, it can be observed that d_{s2} and d_{s3} values are very close, i.e., the scour depth at the downstream side of the first pier is very close to the scour depth at the upstream face of the second pier.

Observations in the experimental results

The important observations of the present study relating to the pier–scour phenomenon are

- All the scour depth values significantly decrease with increasing inclination angles when compared to scours developed around vertical piers. For instance, scour depth reduction of more than 60% was measured when piers were placed at an inclination angle of 15° as opposed to vertically placed piers. That can be clearly seen if one compares the scour depths of Table 1 and Table 4. Figure 4 also shows the variation of scour depth with time for a

Table 4. Experiments conducted with α = 75° or β = 15°.

No	Pier size (cm)	Q (L/s)	d_o (cm)	d_{s1} (mm)	d_{s2} (mm)	d_{s3} (mm)	h (mm)
1	5	5.67	5.8	15.6	6.0	6.5	4.0
2	5	8.46	7.5	18.8	11.0	12.0	5.0
3	5	14.0	10.5	20.0	11.0	12.5	5.0
4	5	18.5	12.5	21.5	15.0	14.0	6.5
5	5	23.7	14.6	23.2	16.0	17.0	4.5
6	5	31.2	17.5	25.4	16.0	18.0	6.0
7	7	8.46	7.5	26.0	19.0	12.0	8.0
8	7	18.5	12.5	29.5	22.5	15.0	10.5
9	7	31.2	17.5	30.7	24.0	17.0	12.0

Note: α and β are pier inclination angles; Q is the flow rate; d_o is the approach flow depth; d_{s1} and d_{s2} are the scour depths at the upstream and downstream face of the upstream pier, respectively; d_{s3} is the scour depth at the upstream face of the downstream pier; h is the sediment deposition height downstream of the downstream pier.

constant value of 2.5 of the normalized approach flow depth, that is, for d_o/D = 2.5. The scour depths decrease substantially as the inclination angle increases as it is evident in that figure. Such reductions in scour depths would lead to significant savings in the construction of the bridge piers. It is speculated that the vertical component of the downflow occurring in front of the piers loses its strength gradually as the pier inclination angle, β, increases. Consequently, the weakened downflow may have less power to excavate the channel bed around the piers, resulting in reduced scours.

- As the pier inclination angle, β, increases, the scour depths decrease. However, as the inclination angle increases, the distance between the piers gets larger; since the lengths of the pier models have been kept constant throughout the experiments. When there is a considerable gap between the upstream and downstream piers, some amount of transported particles gather in between the piers. This sediment accumulation may cause problems at a later time.
- The aggradation that occurs at the downstream side of the second pier considerably decreases for β = 15° and for β = 0. This may be because of the relatively large spacing of the piers, as the pier spacing gets larger and larger only a small portion of the eroded material can reach the downstream side of the second pier.
- As the pier diameters increase, the scour depths at all three locations and the amount of aggradation downstream of the second pier increase considerably. But as the pier size increases, not only the depth of scour, but also the volume of scour zone increases. The scoured area expands in all directions, and the radius of the scour hole increases.
- An aggradation takes place at the downstream side of the second pier. The height of this transported material, h, appears to be proportional to the scour that occurs at the upstream face of the first pier. As the pier inclination angle increases, the erosion of particles from upstream vanishes. Consequently, since the strength of the vortices that transport the particles downstream decreases, the amount of aggradation also decreases.
- The rate of scour hole development is higher in the earlier stages of each run, and then decreases as time passes and approaches asymptotically to an equilibrium value.

Armoring effect

The geometric standard deviation of the particle size distribution in the present study was computed to be $\sigma_g > 1.3$. This indicates that scour depths measured in the experiments were subject to the armoring effect in addition to the inclination of the piers. Armor layer formation is known to reduce the scour depths. Melville and Sutherland (1988) stated that the limiting armor condition occurs at the mean approach flow velocity V_{ca}, beyond which armoring of a nonuniform channel bed is impossible. In other words, the coarsest or most stable armored bed for a given bed material occurs at this velocity. Consequently, V_{ca} should be determined for each sediment size and grading. Chin (1985) showed that the value of V_{ca} for a given sediment is related to the maximum size of the nonuniform sediment and suggested a method to determine V_{ca} using D_{max}. In addition, Chin (1985) and Chin et al. (1994) showed that mean sediment size for the coarsest possible armor, D_{50a}, may be computed by the following equation:

$$[4] \qquad D_{50a} = \frac{D_{max}}{1.8}$$

In which D_{max} is the maximum particle size for the nonuniform sediment. The value for D_{50a} is needed to determine the critical shear velocity, u_{*ca}, of the armored bed from either the Shields diagram as provided by Henderson (1966) or eq. [5], which is stated by Melville (1997) as a useful approximation to the Shields diagram for quartz sediments in water at 20 °C.

$$[5] \qquad u_{*ca} = 0.0305\sqrt{D_{50a}} - \frac{0.0065}{D_{50a}}$$

In which u_{*ca} is in m/s and D_{50a} is in mm, and valid for the range of 1 mm < D_{50a} < 100 mm. Next, V_{ca} can be computed by eq. [6].

$$[6] \qquad \frac{V_{ca}}{u_{*ca}} = 5.75\log\left(5.53\frac{d_o}{D_{50a}}\right)$$

In which d_o is the uniform flow depth in mm. The values for V_{ca} now can be computed for each uniform flow depth. Once V_{ca} values are computed, next V_a, which is the mean approach flow velocity at the armor peak, may be computed by eq. [7] (Baker 1986).

$$[7] \qquad V_a = 0.8V_{ca}$$

It should also be noted that for nonuniform sediment distribution, V_a should be greater than V_c, which is the case in the present study. Because of the armoring effect, the V_c term in eqs. [2] and [3] may be replaced by V_a. Equation [8] shows the final dimensionless functional relationship of the scouring depth for the inclined piers in the present study.

$$[8] \qquad \frac{d_s}{D} = f_4\left(\frac{d_o}{D}, \frac{V}{V_a}, \frac{V^2}{gD}, \frac{D}{D_{50}}, \beta\right)$$

Table 5 shows some of the important measured and computed quantities. First five columns present measured quantities and they are, respectively, the inclination angle of the piers with the vertical in degrees, β; the pier diameters used, D; approach flow depths, d_o; scour depths measured in front of the upstream piers, d_s; approach flow velocities, V. Next seven terms are computed quantities and the first of which is the mean approach flow velocity at the armor peak, V_a computed by eq. [7]. The remaining six terms are the dimensionless parameters appearing in eq. [2], namely, d_s/D, V/V_a; d_o/D; D/D_{50}; Reynolds number, and V^2/gD. As clearly seen in the V/V_a column in the table, all of the V/V_a values are less than unity indicating that all of the experiments (i.e., 33 runs) have been conducted under clear water conditions. The magnitude of the Reynolds numbers in the table verifies the fact that the flow is fully turbulent and dropping them from eq. [2] is rightly justified.

Figures 6 and 7 are constructed based on some of the dimensionless parameters obtained in the dimensional analysis. They show, respectively, the variation of normalized scour depths with the ratio of the approach flow velocity to the mean approach flow velocity at the armor peak, and with the normalized approach flow depth, respectively, for all of the inclination angles. Figure 8 shows the variation of the normalized scour depth with all of the pier inclinations for different approach flow depths for piers of D = 50 mm diameter. Figure 8 clearly indicates the effect of the inclination angle on the scour depths regardless of the approach flow depth magnitudes. Figure 9 shows that d_s/D decreased while V^2/gD decreased as Ettema et al. (2006) also observed in their experiments.

Comparison of the results of the present study with those of Bozkus and Yildiz (2004)

The results of the present study were compared to the results of Bozkus and Yildiz (2004), in which local scour around a single pier was studied (Fig. 1). In that study, single piers of varying diameters were placed in a uniform sediment bed with various inclination angles including the vertical configuration. Two D/D_{50} values, namely, 100 and 200 were used. It was found that as the pier inclination angle increased the local scour depth around the pier reduced substantially and that maximum scour depths were always observed at the upstream face of the piers. Now that scour measurements of dual bridge piers of Fig. 2 are available, it was thought that it would be interesting to see the effect of downstream pier on the scours occurring in front of the first pier. To compare the results from both studies, separate multiple regression analyses of the experimental data were performed first, using the dimensionless parameters in eq. [8]. However, prior to performing multiple regression analyses, two parameters considered having negligible effects, were not included in the analyses. Those removed parameters are D/D_{50a} and V^2/gD. Since only two diameters were used in the present study it did not make sense to use D/D_{50a} as a variable in multiple regression analysis. Furthermore, it has been shown in the previous studies that the maximum value of scour is unaffected by particle size as the value of $D/D_{50a} > 25$ (Breusers and Raudkivi 1991). The values of D/D_{50a} in the present study were ($50/1.44 \approx 35$) and ($70/1.44 \approx 49$), thus removing it from the multiple regression analysis was justified. Moreover, the main observation in both studies is the fact that the scour depths decrease significantly as the inclination angle of the piers increases regardless of the grain size distribution of the bed material used.

Similarly, V^2/gD term was assumed to have a relatively less important role in reducing the scour depth in the present study as compared to the effect of the remaining parameters such as d_o/D, V/V_a, and pier inclination angle. As a result of multiple regression analyses with the parameters kept, a single equation was developed for each study, namely, eq. [9] for Bozkus and Yildiz (2004), and eq. [10] for the present study.

$$[9] \qquad \frac{d_s}{D} = 0.455\left(\frac{d_o}{D}\right)^{0.202}\left(\frac{V}{V_c}\right)^{0.591}\alpha^{1.725} \text{ with } R^2 = 0.98$$

$$[10] \qquad \frac{d_s}{D} = 0.249\left(\frac{d_o}{D}\right)^{0.172}\left(\frac{V}{V_a}\right)^{0.373}\alpha^{2.888} \text{ with } R^2 = 95$$

In the study of Bozkus and Yildiz (2004), uniform sediment had been used, hence there was no armoring in that study. That is the reason why V/V_c term was used in eq. [9], instead of V/V_a. In addition, it should be noted that for the pier inclination angle, α was used in the equations instead of β, to avoid using zero degree angle in multiple regression analyses and it is defined as, $\alpha = 90^\circ - \beta$. This is simply a coordinate change for measuring the pier inclination angle and does not have any influence in the physical problem as it is done only for practical purposes. If one compares eqs. [9] and [10], one can see that the pier inclination angle, which is to be inserted in radians in the equations, has a significant impact in determination of the scour depth as evident with the magnitude of its exponents.

In Fig. 10, normalized measured scour data from Bozkus and Yildiz (2004) and the present study are plotted against the normalized estimated (computed) scour data by eqs. [9] and [10], respectively. This figure indicates that there is not much scatter in the regression relations represented by eqs. [9] and [10] for which R^2 values (i.e., coefficient of determination) were computed, respectively, to be 0.980 and 0.946 in the regression analyses. It may be concluded that most of the experimental and estimated scour depths converge very closely on the perfect correlation line (i.e., R^2 = 1) indicating that eqs. [9] and [10] based on the dimensionless parameters used in their development represent the measured data statistically very well.

Moreover, one can see the influence of the second pier on scour magnitudes on Fig. 11, which shows all of the experimental data from both studies. Scour depths are normalized

Table 5. Experimental measurements and computed quantities.

β (deg)	D (cm)	d_o (cm)	d_s (mm)	V (m/s)	V_a (m/s)	d_s/D	V/V_a	d_o/D	D/D_{50}	Re	V^2/gD
0	5	5.8	30.0	0.1358	0.4601	0.60	0.2951	1.16	34.72	6 788 793	0.0376
0	5	7.5	32.6	0.1567	0.4850	0.65	0.3230	1.50	34.72	7 833 333	0.0500
0	5	10.5	34.7	0.1852	0.5176	0.69	0.3578	2.10	34.72	9 259 259	0.0699
0	5	12.5	35.7	0.2056	0.5345	0.71	0.3846	2.50	34.72	10 277 778	0.0861
0	5	14.6	37.8	0.2255	0.5495	0.76	0.4103	2.92	34.72	11 272 831	0.1036
0	5	17.5	41.3	0.2476	0.5671	0.83	0.4367	3.50	34.72	12 380 952	0.1250
0	7	7.5	44.0	0.1567	0.4850	0.63	0.3230	1.07	48.61	10 966 667	0.0357
0	7	12.5	49.2	0.2056	0.5345	0.70	0.3846	1.79	48.61	14 388 889	0.0615
0	7	17.5	51.3	0.2476	0.5671	0.73	0.4367	2.50	48.61	17 333 333	0.0893
5	5	5.8	25.8	0.1358	0.4601	0.52	0.2951	1.16	34.72	6 788 793	0.0376
5	5	7.5	27.9	0.1567	0.4850	0.56	0.3230	1.50	34.72	7 833 333	0.0500
5	5	10.5	29.0	0.1852	0.5176	0.58	0.3578	2.10	34.72	9 259 259	0.0699
5	5	12.5	30.6	0.2056	0.5345	0.61	0.3846	2.50	34.72	10 277 778	0.0861
5	5	14.6	34.0	0.2255	0.5495	0.68	0.4103	2.92	34.72	11 272 831	0.1036
5	5	17.5	40.5	0.2476	0.5671	0.81	0.4367	3.50	34.72	12 380 952	0.1250
10	5	5.8	22.3	0.1358	0.4601	0.45	0.2951	1.16	34.72	6 788 793	0.0376
10	5	7.5	23.8	0.1567	0.4850	0.48	0.3230	1.50	34.72	7 833 333	0.0500
10	5	10.5	25.2	0.1852	0.5176	0.50	0.3578	2.10	34.72	9 259 259	0.0699
10	5	12.5	26.5	0.2056	0.5345	0.53	0.3846	2.50	34.72	10 277 778	0.0861
10	5	14.6	30.5	0.2255	0.5495	0.61	0.4103	2.92	34.72	11 272 831	0.1036
10	5	17.5	32.8	0.2476	0.5671	0.66	0.4367	3.50	34.72	12 380 952	0.1250
10	7	7.5	32.7	0.1567	0.4850	0.47	0.3230	1.07	48.61	10 966 667	0.0357
10	7	12.5	36.5	0.2056	0.5345	0.52	0.3846	1.79	48.61	14 388 889	0.0615
10	7	17.5	37.4	0.2476	0.5671	0.53	0.4367	2.50	48.61	17 333 333	0.0893
15	5	5.8	15.6	0.1358	0.4601	0.31	0.2951	1.16	34.72	6 788 793	0.0376
15	5	7.5	18.8	0.1567	0.4850	0.38	0.3230	1.50	34.72	7 833 333	0.0500
15	5	10.5	20.0	0.1852	0.5176	0.40	0.3578	2.10	34.72	9 259 259	0.0699
15	5	12.5	21.5	0.2056	0.5345	0.43	0.3846	2.50	34.72	10 277 778	0.0861
15	5	14.6	23.2	0.2255	0.5495	0.46	0.4103	2.92	34.72	11 272 831	0.1036
15	5	17.5	25.4	0.2476	0.5671	0.51	0.4367	3.50	34.72	12 380 952	0.1250
15	7	7.5	26.0	0.1567	0.4850	0.37	0.3230	1.07	48.61	10 966 667	0.0357
15	7	12.5	29.5	0.2056	0.5345	0.42	0.3846	1.79	48.61	14 388 889	0.0615
15	7	17.5	30.7	0.2476	0.5671	0.44	0.4367	2.50	48.61	17 333 333	0.0893

Note: β is the inclination angle of the pier with the vertical; D is the pier diameter; d_o is the approach flow depth; d_s is the scour depth measured in front of the upstream piers; V is the approach flow velocity; V_a is the mean approach flow velocity at the armor peak; d_s/D, V/V_a, d_o/D, and D/D_{50} are the dimensionless parameters appearing in eq. [2]; Re is the Reynolds number.

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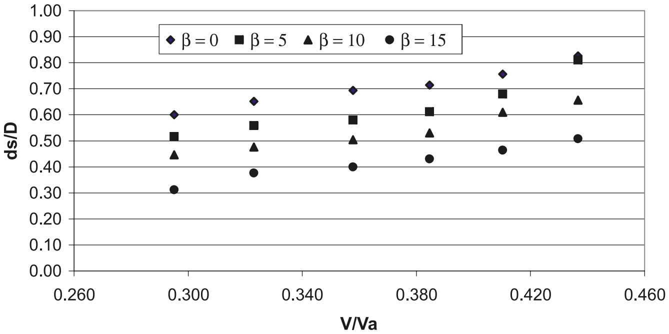


Fig. 6. Variation of d_s/D with V/V_a for all inclination angles.

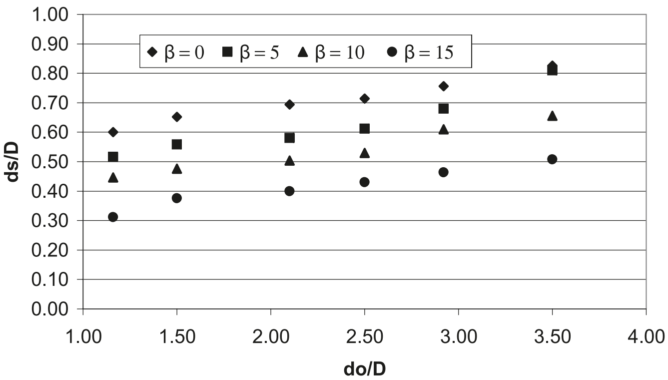


Fig. 7. Variation of d_s/D with d_o/D for all inclination angles.

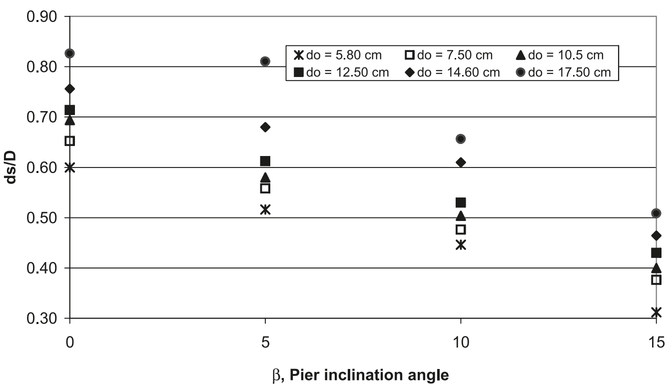


Fig. 8. Variation of d_s/D with β for all approach flow depths.

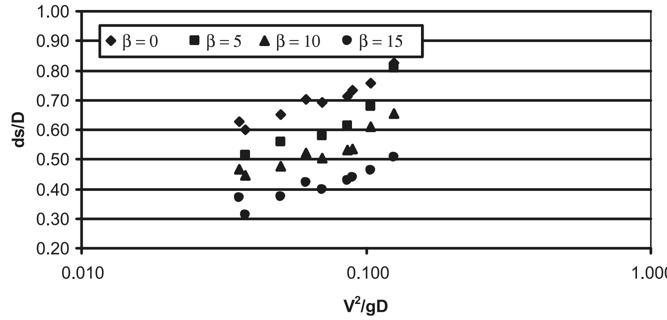


Fig. 9. Variation of d_s/D with V^2/gD for all pier inclinations.

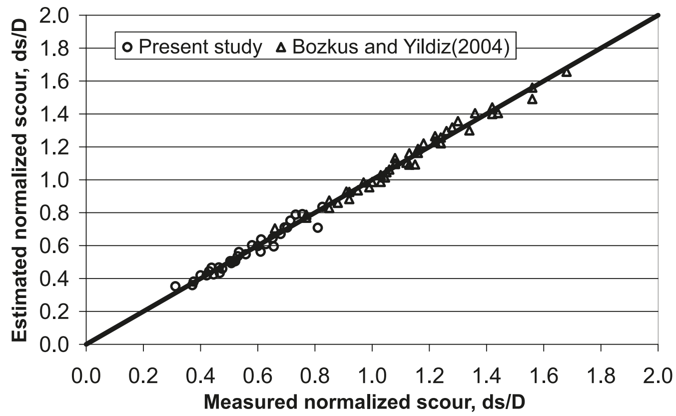


Fig. 10. Comparison of all normalized measured scours with those computed by proposed eqs. [9] and [10].

with the corresponding pier diameters and plotted against normalized uniform approach flow depths. A trend line for the data group of $\beta = 10$ is shown in the figure for comparison purposes only. Clearly, the second pier, along with armoring effect, has a significant influence in reducing the scours by as much as 60% as opposed to scours obtained around a single inclined pier. For instance, for $d_o/D = 1.5$, the normalized scour value on the trend line of Bozkus and Yildiz (2004) data is about $d_s/D = 1.15$, while it is about $d_s/D = 0.46$ in the present study, indicating about 60% drop in the scour. Similar observations can be deduced from Fig. 11, for $d_o/D = 2$ and $d_o/D = 2.5$.

Comparison of the measured scour depths with the design equation of Melville and Sutherland (1988)

It was thought that it would be interesting to compare the scour depths measured around vertically placed piers in the present study (i.e., $\beta = 0$ or $\alpha = 90°$) with those to be obtained from eq. [11] proposed by Melville and Sutherland (1988) to check how closely the design equation predicts the scour depths.

$$[11] \qquad \frac{d_s}{D} = K_I K_y K_d K_\sigma K_s K_\alpha$$

where K_I is the flow intensity factor; K_y is the flow depth factor; K_d is the sediment size factor; K_σ is the sediment gradation factor; K_s is the pier shape factor; and K_α is the pier alignment factor. The flow intensity factor K_I is given by eq. [12] if the term within the absolute signs is less than unity, which is the case in the present study.

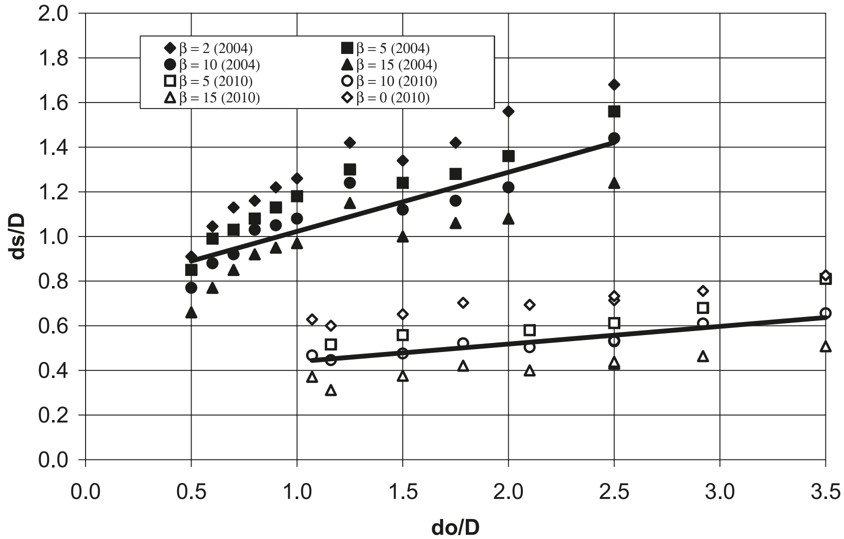
$$[12] \qquad K_I = 2.4\left|\frac{V-(V_a-V_c)}{V_c}\right|$$

On the other hand, the flow depth factor K_y is equal to unity if $d_o/D > 2.6$. If the opposite is true, that is, $d_o/D < 2.6$ then K_y is computed by eq. [13].

$$[13] \qquad K_y = 0.78\left(\frac{d_o}{D}\right)^{0.255}$$

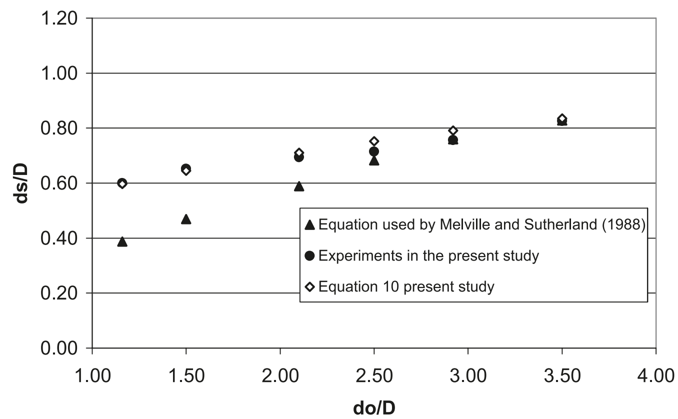
All other remaining factors in eq. [11] may be taken to be unity for the present study based on the design methodology described in Melville and Sutherland (1988). Figure 12 shows the variation of the normalized scour depths with the normalized approach flow depths. It is clearly evident in the figure that as the normalized approach flow depths increase

Fig. 11. Influence of the second pier on scour magnitudes as opposed to single piers.



(i.e., $d_o/D > 2$) the equation proposed by Melville and Sutherland (1988) predicts the scour depths very closely. It should be noted that this comparison was made for the vertically placed piers since the Melville and Sutherland equation is valid only for vertically placed piers. In addition, computed scours by eq. [10] are also shown in the same figure. It is very clear that eq. [10], developed through multiple regression analysis based on all of the experimental data including vertical and inclined piers, converge to the normalized measured scours very closely, as expected.

Fig. 12. Comparison of measured d_s/D values with those computed by eqs. [10] and [11].



Conclusions

The present study is basically an extension of a previous study in which local scour had been measured around single inclined piers in uniform bed material (Bozkus and Yildiz 2004). The primary novelty in the present paper is the fact that a second downstream pier was included in the physical modeling and also armoring was considered since the sediment used now was nonuniform. In addition, a single equation was developed for each study based on separate multiple regression analyses considering their experimental data, respectively.

- For the double pier configuration of the present study shown in Fig. 2 scour depths decreased significantly compared to the scours measured in the single pier configuration of Fig. 1, studied by Bozkus and Yildiz (2004). Reduction in scour depths up to 60% was noted.
- Two equations expected to be very useful in local scour predictions around bridge piers for prototype design were developed based on multiple regression analyses of the data from both studies. The exponents of the inclination angles in the equations indicate that inclination has a substantial effect on reducing scour depths.
- The design equation used by Melville and Sutherland (1988) was employed to simulate the experiments of the vertical piers. The correlation between the scour depths predicted by that equation and those measured in the present study was found to be very good, especially for the larger values of the normalized approach flow depths.
- The armoring effect exists for all piers including the vertical piers in the present study. Consequently, it does not affect the trend that the scour depth decreases as the inclination angle of the piers is increased.
- It is concluded that inclined pier configurations such as those suggested in Fig. 5 may be considered reliably by engineers for the design of future bridge piers. Needless to say, the degree of inclination for the piers should be decided after taking structural aspects into consideration as well.

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List of Symbols

d_o approach flow depth
d_s maximum value of the scour depth
d_{s1} scour depth at the upstream face of the upstream pier
d_{s2} scour depth at the downstream face of the upstream pier
d_{s3} scour depth at the upstream face of the downstream pier
D pier diameter
D_{max} maximum particle size for the nonuniform sediment size
D_{50} mean sediment size
D_{50a} mean sediment size for the coarsest possible armor
g gravitational acceleration
h sediment deposition height downstream of the downstream pier
K_d sediment size factor
K_I flow intensity factor
K_s factor indicating the shape of pier
K_y flow depth factor
K_α pier alignment factor
K_σ sediment gradation factor
Q flow rate
R^2 squared correlation coefficient or coefficient of determination
Re Reynolds number
S_0 flume bed slope
t_{max} maximum time of the experiment
u_{*ca} critical shear velocity of the armored bed
V mean approach flow velocity
V_a mean approach flow velocity at the armor peak
V_c critical mean approach flow velocity
V_{ca} mean approach flow velocity beyond which armoring of channel bed is impossible
β inclination angle of piers
α another coordinate used to describe inclination angle of piers, $\alpha = 90 - \beta$
γ specific weight of the water
γ_s specific weight of the sediment
ρ density of water
ρ_s density of the sediment
σ_g geometric standard deviation of sediment grading
μ dynamic viscosity of the fluid