Scour Around Wide Piers in Shallow Water

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The assessment of pier scour at many bridges is a difficult task because of the numerous complexities of the scour process. One of these complexities occurs when the flow depth is shallow relative to the pier width. A preliminary examination of the effect of wide piers in shallow water is provided and a modification or correction factor for currently used scour equations to account for this effect is developed. An experiment was conducted to test the effect of shallow flow depths and wide piers while keeping all other variables constant. Existing laboratory data along with data from the study were analyzed to incorporate the effects of wide piers on the scour at bridge piers. During the study regions of relative flow depth (flow depth–to–pier width ratio) at which the scour process differs were determined. The definitions of wide piers and shallow flow in terms of the relative depth to pier width were established.

Engineers across the United States assess scour conditions at existing bridges and determine the need for scour mitigation. The assessment of scour at many bridges is a difficult task because of the numerous complexities of the scour process, one of which occurs when the flow depth is shallow relative to the pier width. In addition, the Froude number upstream of the bridge may be quite low, a condition for which current scour equations do not account. These conditions exist at many bridges in coastal areas. Two examples in Maryland are the Severn River and Woodrow Wilson bridges. At the Severn River Bridge, for example, 8 of the 12 piers have widths that exceed the flow depth. The ratios of flow depth to pier width range from 0.18 to 0.86. The Froude numbers at these piers, even for a large storm event, are quite low (about 0.2 or less). At inland bridges the flow depth may be very shallow relative to an exposed pier foundation. At these coastal and inland bridges it is often noted by engineers that the scour equations recommended by FHWA (*1*) yield excessively large scour depths.

In studies conducted at the University of Auckland (*2*), the effect of flow depth on scour for shallow water conditions was recognized. To account for this condition, Melville and Sutherland (*2*) recommended a multiplicative factor when the ratio of flow depth to pier width is less than 2.6. Although this factor yields lower scour depths compared with those from HEC-18 estimates, the estimates are still quite high relative to observed scour depths in the field.

The objective of the present study was to provide a preliminary examination of the effect of wide piers in shallow water and to develop a modification or correction factor for currently used scour equations to account for this effect.

LOCAL SCOUR AT WIDE PIERS IN SHALLOW WATER

Local scour can be caused by an obstruction, such as a bridge pier or abutment, in the stream flow. Although many parameters affect local scour (*3,4*), the present study concentrated on three parameters: pier size, flow depth, and velocity.

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It is generally accepted by researchers [e.g., Laursen and Toch (*5*), Laursen (*6*), and Neill (*7*)] that relative scour depth (y_s/b, where y_s is scour depth and b is pier width) increases as the relative flow depth (y/b, where y is flow depth) increases until a certain limiting value of y/b is reached, after which the relative scour depth is independent of y/b. The limit expressed by most researchers is in the range of $1 < y/b < 3$. Flow depth affects both clear-water and live-bed scour depths. When considering the effect of flow depth on local scour depth, it is essential that all other variables affecting pier scour, especially pier size and sediment size, be held constant. To keep the effect of velocity on scour depth constant, the velocity ratio (V/V_c, where V is the stream flow velocity and V_c is the critical velocity) needs to be kept constant (e.g., at incipient motion).

For clear-water scour, Bonasoundas (*8*) concluded that the effects of flow depth became insignificant for $y/b > 1$ to 3. Ettema (*9*) stated that the influence of flow depth is affected by the relative size of the pier and sediment. He concluded that for high values of b/d_{50} (typical of a prototype setting), the development of local scour is almost independent of flow depths for $y/b > 1$, whereas for low values of b/d_{50} (typical of a laboratory setting), scour depth is still dependent on flow depths even when the value of y/b is as high as 6. Ettema (*9*) stated three reasons that account for the reduction in equilibrium scour depths for shallow flows. First, the portion of the approach flow available to be diverted into the scour hole diminishes for low values of y/b. Second, the development of the scour hole is influenced by the formation of a sediment bar behind the pier for low values of y/b. Third, the formation of a surface roller, on a bow wave that has a sense of rotation opposite that of the horseshoe vortex at the free surface around the pier, interferes with the horseshoe vortex and the down flow into the scour hole. Ettema (*9*) further added that a y/b value equal to 3 was especially significant for coarse sediment.

Basak (*10*), Jain and Fischer (*11*), and Chee (*12*) showed that flow depth has an effect on live-bed scour similar to that on clear-water scour in which scour depth is lower for decreasing values of y/b.

EXISTING MODELS FOR PREDICTING SCOUR DEPTH

The Hydraulic Engineering Circular 18 (HEC-18) equation is recommended by FHWA (*1*) to estimate both live-bed and clear-water pier scour depths. The equation predicts maximum pier scour depths as follows:

$$\frac{y_s}{y} = 2.0K_1K_2K_3\left(\frac{b}{y}\right)^{0.65}F^{0.43} \qquad (1)$$

where

y_s = scour depth,
y = flow depth,

K_1 = correction factor for pier nose shape,
K_2 = correction factor for angle of attack of flow,
K_3 = correction factor for bed condition,
b = pier size,
y = flow depth, and
F = Froude number.

Equation 1 applies only to subcritical flow. For circular piers, Equation 1 reduces to

$$\frac{y_s}{y} = 2.0\left(\frac{b}{y}\right)^{0.65} F^{0.43} \tag{2}$$

The University of Auckland pier scour equation (*1*) is based on a set of corrective factors based on laboratory data:

$$\frac{y_s}{b} = K_I K_y K_d K_\sigma K_s K_\alpha \tag{3}$$

where

K_I = correction factor for the flow intensity,
K_y = correction factor for the flow depth,
K_d = correction factor for the sediment size,
K_σ = correction factor for sediment gradation, and
K_s, K_α = correction factors for pier shape and alignment, respectively.

For circular piers and uniform sediment sizes of b/d_{50} of more than 50, Equation 3 reduces to

$$\frac{y_s}{b} = K_I K_y \tag{4}$$

K_y accounts for wide piers and shallow flow depths. Melville and Sutherland (*2*) determined the following equation for K_y on the basis of laboratory experimentation:

$$K_y = 0.78\left(\frac{y}{b}\right)^{0.255} \quad \text{for } y/b < 2.6 \tag{5}$$

$$K_y = 1 \quad \text{for } y/b \geq 2.6$$

EXPERIMENTAL PROGRAM

A set of experiments was conducted to further determine the effect of wide piers in shallow water on scour depth. The effects of various values of flow depth to pier width ratios (y/b) on scour depth were studied by systematically varying the pier size and the flow depth. During the experiment a uniform sediment (d_{50} = 0.93 mm) was used with a b/d_{50} of >50 to avoid the influence of sediment size on scour depth. All runs were conducted at approximately incipient motion velocity to represent maximum scour conditions. Only subcritical flow and circular piers were used. In this manner only the effects of the pier size and the flow depth on scour were studied.

The ranges of y/b studied were selected on the basis of the corrective factors of y/b between 0 and 2.6 suggested by Melville and Sutherland (*2*). Within this range the effects of pier size and flow depth are most noticeable. A few experimental runs of y/b between 2.6 and 5 were conducted to observe the limiting value of y/b at which the flow depth no longer influences the scour depth. The experiments were conducted at the FHWA Hydraulics Laboratory at the Turner-Fairbank Research Center in McLean, Virginia. All of the experiments were conducted in a 1.8-m-wide, 21.3-m-long, glass-walled tilting flume. The flume had a fixed bed except for a 1.8-m-wide, 1.2-m-long, 0.46-m-deep observation area located approximately in the center of the flume. The bed upstream of the observation area was covered with a 5-cm layer of sand to stabilize the approach velocity and shear stress of the bed at the observation area. Five models with various pier diameters were used to ensure an adequate range of y/b values. Model bridge piers constructed from 6-, 9-, 11-, 16-, and 25-cm (outside diameter) polyvinylchloride pipes were used. Each pipe was bolted to a square wooden plate by an o-ring plastic joint and was placed on the floor in the center of the flume observation area.

To avoid side-wall effects on scour, the circular pier sizes used in the experiment were close to the recommended values for the pier width-to-flume width ratio by Chiew (*13*) of 1/10 and Shen et al. (*14*) of 1/8. The 1/10 and 1/8 ratios were established to ensure that no contraction scour was present as a consequence of decreasing the flow area by the pier width; thus, all scour was local only. However, during the experiment it was observed that the limiting value for pier width-to-flume width ratio is highly dependent on the flow depth. Thus, the pier width-to-flume width ratios can be reduced even further for shallow flow experiments.

RESULTS AND DISCUSSION OF RESULTS

The results of the experiments collected during the 23 runs are given in Table 1. There was very little variation in velocity since d_{50} was constant and V/V_c was kept at approximately 1. Relative flow depths varied from $0.25 \leq y/b \leq 5.0$. Resulting scour depths ranged from 8 to 21 cm.

Effect of Pier Size

Scour depth versus pier size is plotted in Figure 1 using the experimental data. Melville and Sutherland (*2*) found that the ratio of scour depth and pier size, y_s/b, reaches a maximum of 2.3 at y/b of about 2.6. The line of 2.3 times the pier size was plotted in Figure 1 to show that the 2.3 limiting value applies mostly to small piers, where the ratio of y/b is usually >2.6. The line of 2.3 grossly overestimates the scour depth for larger pier sizes. The influence of flow depth on scour depth is shown as the variation between the upper and the lower values of scour obtained for the different pier sizes used in the experiment (Figure 1). The upper values represent deep flows. The closeness of the points at deep flows indicates that the influence of the flow depth is diminished. The lower values of scour represent shallow flows. At shallow flows the points are more separated, indicating that the flow depth has a greater influence on scour depth.

In summary, pier size has a direct relationship with scour depth: the larger the pier size, the deeper the scour depth. However, the data show that for small piers the influence of pier size is greater than that for large piers (Figure 1). Also, the value of y_s/b equal to 2.3 as established by previous researchers is only applicable to small piers, where the influence of the flow depth is diminished considerably.

TABLE 1 Experimental Data

Run #	Velocity (m/s)	Pier Width (cm)	Flow Depth (cm)	Vc (m/s)	V/Vc	F	y/b	Scour Depth (cm)
1	0.482	16.8	5.2	0.38	1.27	0.68	0.31	14.6
2	0.457	16.8	6.6	0.40	1.16	0.57	0.39	15.3
3	0.456	16.8	8.5	0.41	1.11	0.50	0.50	17.1
4	0.512	16.8	11.9	0.44	1.17	0.47	0.71	17.5
5	0.468	16.8	15.2	0.45	1.03	0.38	0.90	19.8
6	0.464	16.8	16.7	0.46	1.01	0.36	0.99	20.4
7	0.482	16.8	21.8	0.48	1.00	0.33	1.30	20.8
8	0.482	16.8	25.2	0.49	0.98	0.31	1.50	20.9
9	0.477	16.8	28.5	0.50	0.95	0.29	1.70	21.0
10	0.455	16.8	33.6	0.52	0.88	0.25	2.00	21.0
11	0.468	6.0	6.0	0.39	1.20	0.61	1.00	8.0
11-A	0.480	6.0	9.2	0.42	1.15	0.51	1.53	9.3
12	0.455	6.0	12.1	0.44	1.04	0.42	2.00	9.0
13	0.475	6.0	18.1	0.47	1.02	0.36	3.00	10.3
14	0.488	6.0	24.1	0.49	0.99	0.32	4.00	9.8
15	0.482	6.0	30.2	0.51	0.95	0.28	5.00	10.8
16	0.458	11.4	5.7	0.39	1.19	0.61	0.50	11.7
17	0.455	11.4	11.4	0.43	1.05	0.43	1.00	14.5
18	0.492	11.4	22.9	0.49	1.01	0.33	2.00	16.1
18-A	0.484	11.4	34.3	0.52	0.93	0.26	3.00	16.3
19	0.484	11.4	28.5	0.50	0.96	0.29	2.50	16.2
20	0.476	8.9	28.5	0.50	0.94	0.28	3.21	13.3
21	0.485	8.9	8.9	0.42	1.17	0.52	1.00	11.0
22	0.487	25.4	26.4	0.50	0.98	0.30	1.04	27.7
23	0.467	25.4	6.5	0.39	1.19	0.59	0.25	18.5

Effect of Flow Depth

The laboratory results of scour depth and flow depth are plotted in Figure 2. Scour depth has a direct relationship with flow depth. The influence of flow depth on scour depth diminishes as the flow depth increases (Figure 2). At higher flow depths there is a maximum at which flow depth no longer influences scour depth; instead, it is influenced primarily by pier size. Thus, for each pier size there is a maximum flow depth at which scour depth is influenced by pier size alone (in the absence of other factors). At lower flow depths the importance of pier size decreases and the flow depth becomes more influential on scour depth. The results agree with the analysis whose results are shown in Figure 1.

Effect of Velocity

The depth of the local scour hole is closely related to the approach flow velocity for clear-water conditions. It was shown by Chabert and Engeldinger (*15*), Ettema (*9*), and Chiew (*13*) that under clear-water conditions *y/b* increases almost linearly as V/V_c increases from 0 to 1, reaching a maximum when V/V_c is nearly equal to 1.

The variation of the velocity during the experiment was minimal, as seen in Table 1. This is because the incipient motion velocities for the size of sediment used in the experiment do not vary significantly with flow depth. For this reason no conclusions can be drawn about the velocity by using the laboratory data. Data from other studies along with the data from the present experiment (all sub-

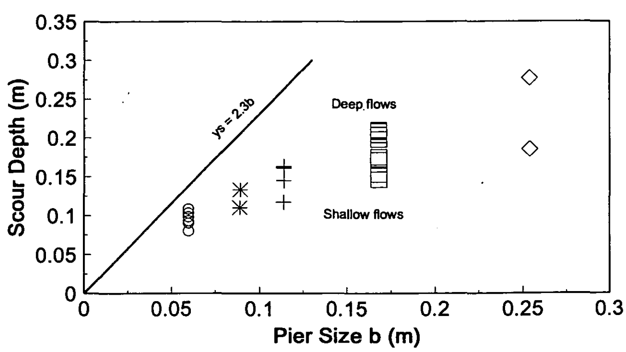

FIGURE 1 Experimental results of scour depth as function of pier width.

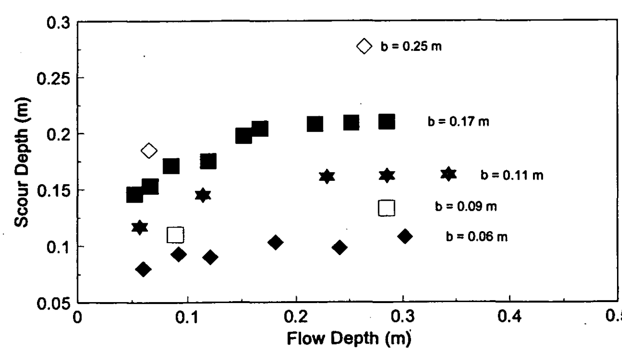

FIGURE 2 Experimental results of scour depth as function of flow depth.

critical flow) for an approximate 15-cm pier size were analyzed to account for the effect of velocity on scour depth. The results are shown in Figure 3. The plot shows that the scour depth increases as the velocity increases until a maximum is reached, after which the scour depth is independent of velocity. It is important to mention that there is a slight decrease in scour depth after incipient motion is reached. The decrease of scour depth at high velocities has been attributed to bed forms (*13*). The Froude number can be used to describe the velocity effect on scour depth, although it should be recognized that the Froude number is also a function of flow depth. Therefore, variation in scour depth with changes in Froude number may be caused by either velocity or flow depth.

Effect of Flow Depth–to–Pier Width Ratio

Pier size and flow depth have been shown to affect pier scour. This effect can be analyzed further through the use of ratios. Dimensionless laboratory ratios are frequently used in pier scour engineering as a way to scale from laboratory results to prototype sizes.

Data from Chiew (*13*), Colorado State University (CSU) (*16*), Chabert and Engeldinger (*15*), Hancu (*17*), Jain and Fischer (*11*), Shen et al. (*14*), Yanmaz and Altinbilek (*18*), and the present study are plotted in Figure 4 as y_s/b versus y/b for b/d_{50} of >50 and for Froude numbers of <0.7. These data represent both clear-water and live-bed conditions. It was shown by Chiew (*13*) that for a b/d_{50} of >50 the influence of y/b on scour depth for live-bed conditions is about the same as that for clear-water conditions. From Figure 4 it is apparent that the relative scour depth increases with relative flow depth at a decreasing rate and that there is a limiting relative flow depth beyond which the relative scour depth is unaffected by flow depth. It is also apparent that the scour depth is mostly independent of relative flow depth at the limiting y/b value of 2.6 (*2*), at which the scour depth is largely influenced by the pier size. The limiting value of y_s/b of 2.3 indicates the maximum relative scour depth to pier width (Figure 4).

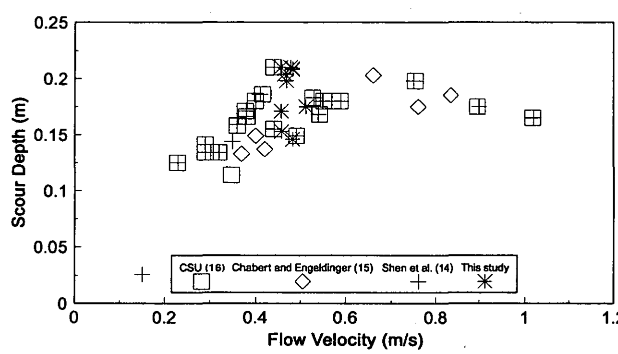

FIGURE 3 Laboratory data showing scour depth as function of velocity.

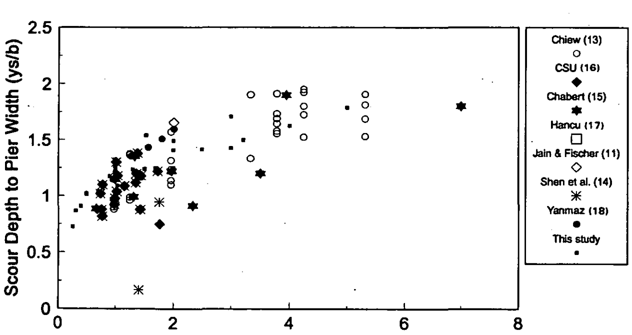

FIGURE 4 Relative scour depth as function of relative flow depth.

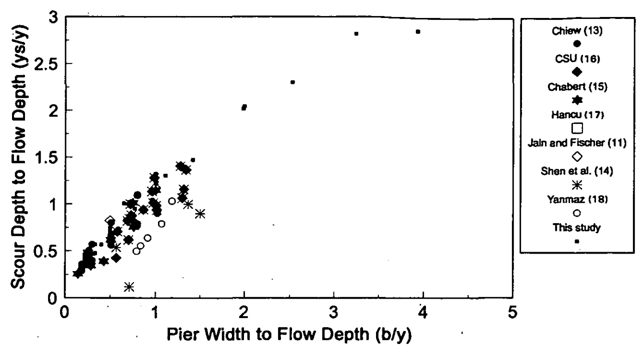

FIGURE 5 Relative scour depth as function of relative pier width.

Using the same data, y_s/y versus b/y is plotted in Figure 5. It shows that the relative scour depth increases with pier size at a decreasing rate and that there is a limiting pier size beyond which the scour depth is mostly unaffected by the relative pier size.

DEVELOPMENT OF CORRECTION FACTOR FOR WIDE PIERS

FHWA recommends the use of Equation 1 for estimating maximum scour at a pier. This equation was developed for a y/b value of ≥ 0.8. As shown in the previous sections the process for wide piers in shallow flows differs from that in deeper flows; therefore, extrapolation of Equation 1 to values of y/b of ≤ 0.8 may result in overprediction. The process also differs depending on whether V/V_c is greater than or less than 1.

Two correction factors were developed for Equation 1 for wide piers in shallow flow (i.e., $y/b < 0.8$), depending on the value of V/V_c, using data from the present study and the other studies mentioned in the previous section. To develop the correction factors, two equations were calibrated in a manner similar to that for the format of Equation 1. For y/b of < 0.8 and V/V_c of < 1, only nine sample points were available. This is a very small sample set from which to calibrate three coefficients, and the results should be regarded as preliminary. A sample set of 21 datum points was used for V/V_c of ≥ 1. The calibration yielded the following equation:

$$\frac{y_s}{y} = 5.16\left(\frac{b}{y}\right)^{0.31}F^{1.08} \qquad \text{for } V/V_c > 1 \tag{6a}$$

$$\frac{y_s}{y} = 2.00\left(\frac{b}{y}\right)^{0.52}F^{0.68} \qquad \text{for } V/V_c \geq 1 \tag{6b}$$

Equations 6a and 6b were calibrated by a nonlinear, least-squares optimization. Problems in creating bias and spurious correlations were avoided by calibrating the equations for y_s and holding the coefficient of y at 1. For Equation 6a R^2 was 0.97, and for Equation 6b R^2 was 0.99.

From Equations 6a and 6b correction factors for Equation 1 were developed by dividing Equations 6a and 6b by Equation 1 to yield the following:

$$K = 2.58\left(\frac{y}{b}\right)^{0.34}F^{0.65} \qquad \text{for } V/V_c < 1 \tag{7a}$$

$$K = 1.0\left(\frac{y}{b}\right)^{0.13}F^{0.20} \qquad \text{for } V/V_c \geq 1 \tag{7b}$$

It is worth repeating that the correction factors of Equations 7a and 7b are for y/b of <0.8 only and are developed to correct Equation 1.

To illustrate the use of the correction factors developed in Equations 7a and 7b, the Severn River Bridge in Maryland is used as an example. This bridge has 12 piers with y/b values ranging from 0.17 to 1.88. For Pier 1, y/b is 0.18, F is 0.19, and y is 1.1. By using Equation 1, y_s is equal to 3.57 m. From Equation 7a, K is equal to 0.49. The adjusted scour depth is 3.57(0.49) = 1.75 m. This is a square-nosed footing, so multiplying by 1.1 yields a final scour depth of 1.93 m. At another pier at this same bridge, y/b is 0.68, F is 0.1, and y is 5.24 m. Equation 1 yields a scour depth of 4.27 m. The correction factor K, from Equation 7a, yields 0.51, producing an adjusted scour depth of 0.51(4.27) = 2.16 m.

The Woodrow Wilson Bridge across the Potomac River in Maryland also has several wide piers. As an example, at one of the piers y/b is 0.73 and F is 0.26. Equation 1 for this pier provides an estimated scour depth of 1.68 m. Use of Equation 7b yields a correction factor of 0.73, producing an adjusted scour depth of 1.22 m.

LIMITATIONS OF CORRECTION FACTORS

Several limitations of the correction factors developed here should be noted. The correction factors apply only for subcritical flows and uniform noncohesive sediments with b/d_{50} of >50. The correction factors were developed only for y/b values of <0.8 and for both live-bed and clear-water conditions; the factors should be limited to use under these conditions. Extrapolation to values outside the range of data used in the calibration could result in inappropriate values of scour.

The correction factors developed in the present study are only preliminary results. Equation 6a was based on a limited number of datum points and should be recalibrated when more data become available. In addition, the Froude numbers associated with wide piers in shallow water are often quite small. The Froude numbers used in the calibration of Equations 6a and 6b were not less than about 0.2; therefore, care should be taken in using the correction factors for extremely low Froude numbers.

CONCLUSIONS

This preliminary study on scour at wide piers has demonstrated the differences in scour processes at wide piers in shallow water. Correction factors were developed for use with the HEC-18 equation (Equation 1). These factors reduce the amount of scour for wide piers in shallow water. Although previous studies have also demonstrated the reduction of scour at wide piers, this information was not readily usable with the HEC-18 equation. Use of the correction factors can assist in estimating scour at bridges, particularly in coastal areas where pier widths tend to be shallow relative to flow depths.

The preliminary results provided here could be improved by conducting additional experiments to produce larger sample sizes from which to calibrate the equations. Experiments should also be conducted to examine the process of scour at very low Froude numbers (less than about 0.25). These data could then be used with the wide pier data to develop a method or correction factors to estimate the scour in tidal areas. In addition, field verification of the correction factors would be of value.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the valuable comments and discussions of Sterling Jones and Stanley Davis as well as the technical assistance provided by David Bertoldi and Edward Umbrell during the laboratory experiment at the FHWA laboratory in McLean, Virginia.

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Publication of this paper sponsored by Committee on Hydrology, Hydraulics, and Water Quality.