SEDIMENT SCOUR AT PIERS WITH COMPLEX GEOMETRIES

D. MAX SHEPPARD

Civil and Coastal Engineering Department, University of Florida, 365 Weil Hall
Gainesville, Florida 32611, US

TOM L. GLASSER

Ocean Engineering Associates, Inc., 2531 NW 41st St., Bldg. D.
Gainesville, Florida 32606, US

This paper presents procedures for computing local scour depths at complex piers under clear-water and live-bed flow conditions. The procedure is valid for complex piers having a column, pile cap (footer), and pile group, or any combination of these components. The procedure is based on the concept that, for the purpose of computing local scour depth, a complex pier can be replaced by a circular pile. The diameter of the circular pile (referred to as the effective diameter of the complex pier) is such that the pile will experience the same equilibrium scour depth as the complex pier under the same flow and sediment conditions. The effective diameter is computed using relationships that are functions of the shapes, locations and orientations of the pier components and the sediment properties and flow conditions. These relationships were developed using the results of laboratory tests conducted by D. Max Sheppard (University of Florida), Sterling Jones (Federal Highway Administration), and Steven Coleman (University of Auckland).

1 Introduction

Most large bridge piers are complex in shape and consist of several clearly definable components. While these shapes are sensible and cost effective from a structural standpoint, they present a challenge for those responsible for estimating design sediment scour depths at these structures. This paper presents a revised methodology for estimating scour depths at a class of structures composed of up to three components. The data used in the development of this methodology is from laboratory tests conducted by D. Max Sheppard at the University of Florida, J. Sterling Jones at FHWA, and Stephen Coleman at the University of Auckland. Additionally, the experiments listed in this paper have extended the applicability of the revised procedure to partially and fully buried complex piers, and validated the procedure for use in live bed flows.

1.1. *Methodology*

Due to space limitations the methodology presented here is brief and with little or no explanations. The reader is referred to the Florida Scour Manual (2004) (FDOT website in late 2004) for a more detailed discussion and example problems. This section presents the methodology for estimating equilibrium local scour depths at bridge piers with complex pier geometries. These methods apply to bridge piers composed of up to three components referred to here as the column, pile cap, and pile group as shown in Fig. 1. The methods presented in this chapter are based on the assumption that a complex pier can be represented (for the purposes of scour depth estimation) by a single circular pile with an "effective diameter" denoted by D^*. The magnitude of the effective diameter is such that the scour depth at a circular pile with this diameter is the same as the scour depth at the complex pier for the same sediment and flow conditions. The problem of computing equilibrium scour depth at the complex pier is therefore reduced to one of determining the value of D^* for that pier and applying the single pile equations developed by Sheppard (2004) to this pile for the sediment and flow conditions of interest. The single pile equations are listed below in Eqs.(1)-(5) for completeness.

In the clear-water scour range ($0.47 \le V/V_c \le 1$):

$$\frac{d_{se}}{D^*} = 2.5\, f_1\left(\frac{y_0}{D^*}\right) f_2\left(\frac{D^*}{D_{50}}\right) \left\{1\text{-}1.75\left[\ln\left(\frac{V}{V_c}\right)\right]^2\right\} \tag{1}$$

In the live-bed scour range up to the live-bed peak ($1 < V/V_c \le V_{lp}/V_c$)

$$\frac{d_{se}}{D^*} = f_1\left(\frac{y_0}{D^*}\right)\left[2.2\left(\frac{V/V_c - 1}{V_{lp}/V_c - 1}\right) + 2.5\, f_2\left(\frac{D^*}{D_{50}}\right)\left(\frac{V_{lp}/V_c - V/V_c}{V_{lp}/V_c - 1}\right)\right] \tag{2}$$

and in the live-bed scour range above the live-bed peak ($V/V_c > V_{lp}/V_c$)

$$\frac{d_{se}}{D^*} = 2.2\, f_1\left(\frac{y_0}{D^*}\right) \tag{3}$$

where

$$f_1\left(\frac{y_0}{D^*}\right) = \tanh\left[\left(\frac{y_0}{D^*}\right)^{0.4}\right] \tag{4}$$

$$f_2\left(\frac{D^*}{D_{50}}\right) = \frac{D^*/D_{50}}{0.4\left(D^*/D_{50}\right)^{1.2} + 10.6\left(D^*/D_{50}\right)^{-0.13}}\,. \tag{5}$$

The methodology is based on the following assumptions:

(1) The structure can be divided into up to three components.
(2) For scour computation purposes, each component can be replaced by a single, surface penetrating, circular pile with an effective diameter (D^*) that depends on the shape, size and location of the component and its orientation relative to the

flow. In situations where the pile cap is buried or partially buried D^* also depends on the sediment properties and flow conditions.

(3) The total D^* for the complex structure can be approximated by the sum of the effective diameters of the components making up the structure, that is

$$D^* = D^*_{col} + D^*_{pc} + D^*_{pg} \tag{6}$$

where D^*= effective diameter of the complex structure, D^*_{col} = effective diameter of the column, D^*_{pc} = effective diameter of the pile cap and D^*_{pg} = effective diameter of the pile group.

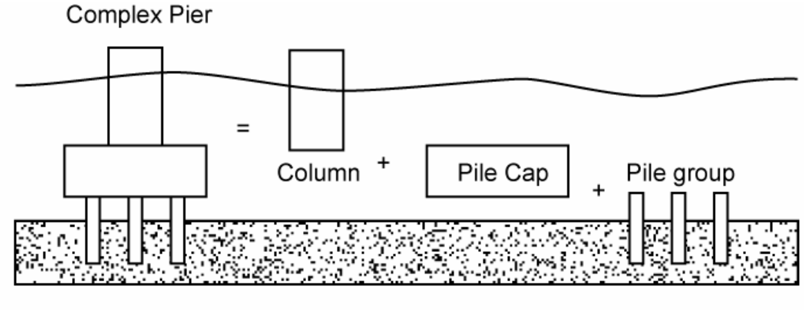

Figure 1. Complex pier composed of column, pile cap and pile group.

The procedure for computing the local scour depth for complex piers is further divided into three categories as illustrated in Fig. 2:

(1) Case 1 complex pier
(2) Case 2 complex pier
(3) Case 3 complex pier

The case 1 complex pier is fully exposed to the flow prior to calculating the scour. The case 2 complex pier has a partially buried pile cap, and the case 3 complex pier is completely buried. The procedure for computing the local scour depth at the three different categories of complex piers is listed below in Sections *1.1.1-1.1.3*.

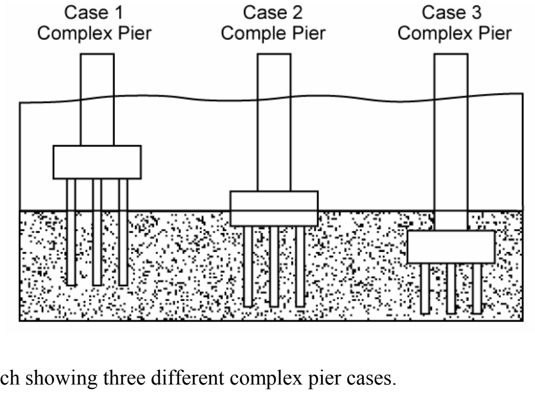

Figure 2. Definition sketch showing three different complex pier cases.

1.1.1. Case 1 complex pier local scour prediction procedure

The procedure for computing local scour depth for Case 1 complex piers is outlined in steps (1) through (22). The procedure starts by analyzing the upper most component and proceeding to the lowest component. Fig. 3 illustrates a complex pier and the naming conventions used throughout the procedure for computing the local scour at complex piers for the three different cases.

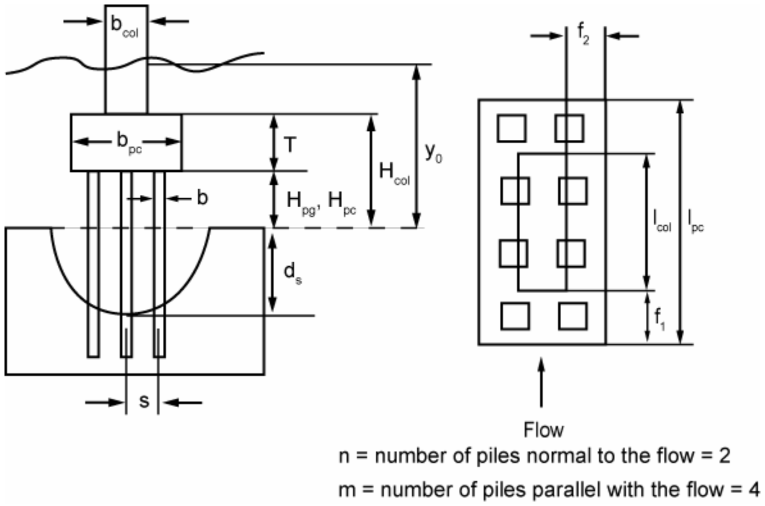

Figure 3. Complex pier definition sketch showing symbols used in the analysis.

The procedure for computing effective diameter of the column, D^*_{col}, is given in steps 1-7.

(1) Calculate $y_{0(max)}$ for the column using Eq. (7).

$$y_{0(max)} = \begin{Bmatrix} 5\,b_{col} & \text{for } y_o \geq 5\,b_{col} \\ y_o & \text{for } y_o < 5\,b_{col} \end{Bmatrix} \tag{7}$$

(2) Determine if the column contributes to the complex structure effective diameter. If $H_{col} \geq y_{o(max)}$, the column will not contribute to the effective diameter (set $D^*_{col} = 0$ and proceed to step (8), otherwise go to step (3).

(3) Compute the column shape factor, K_s, with Eq. (8).

$$K_s = \begin{Bmatrix} 1 & \text{for circular columns} \\ 0.86+0.97\left|\dfrac{\pi}{\alpha}\right|^4 & \text{for square columns} \end{Bmatrix}, \tag{8}$$

where α is the flow skew angle.

(4) Compute the column skew factor, K_α, with Eq. (9).

$$K_\alpha = \frac{b_{col}\cos(\alpha) + l_{col}\sin(\alpha)}{b_{col}} \tag{9}$$

(5) Compute the weighted average value of the pile cap extension, f, using Eq. (10).

$$f = \begin{cases} \dfrac{3f_1 + f_2}{4} & \text{for } \alpha \leq \dfrac{\pi}{4} \\ \dfrac{3f_2 + f_1}{4} & \text{for } \alpha > \dfrac{\pi}{4} \end{cases}, \tag{10}$$

where f_l and f_2 are the front and side overhangs of pile cap.

(6) Compute the pile cap extension coefficient, K_f, using Eq. (11).

$$K_f = -0.24\left(\frac{f}{b_{col}}\right)^2 - 0.02\left(\frac{f}{b_{col}}\right) + 1. \tag{11}$$

(7) Compute the effective diameter for the column, D^*_{col}, with Eq. (12).

$$D^*_{col} = K_s K_\alpha K_f b_{col}\left[0.16\left(\frac{H_{col}}{y_{0(max)}}\right)^2 - 0.39\left(\frac{H_{col}}{y_{0(max)}}\right) + 0.25\right] \tag{12}$$

The procedure for computing the effective diameter of the pile cap, D^*_{pc}, is presented in steps (8)-(12).

(8) Calculate $y_{0(max)}$ for the pile cap with Eq. (13).

$$y_{0(max)} = \begin{cases} 2.5\, b_{pc}\left(\dfrac{T}{y_0}\right)^{0.4} & y_o \geq 2.5\, b_{pc}\left(\dfrac{T}{y_0}\right)^{0.4} \\ y_o & y_o < 2.5\, b_{pc}\left(\dfrac{T}{y_0}\right)^{0.4} \end{cases} \tag{13}$$

(9) Determine if the pile cap contributes to the complex structure total effective diameter. If $H_{pc} \geq y_{o(max)}$, the pile cap will not contribute to the effective diameter (proceed to step (13)), otherwise continue to step (10).

(10)Compute the pile cap shape factor, K_s, using Eq. (14).

$$K_s = \begin{cases} 1 & \text{for circular pile caps} \\ 0.86 + 0.97\left|\dfrac{\pi}{\alpha}\right|^4 & \text{for square pile caps} \end{cases} \tag{14}$$

(11)Compute the pile cap skew factor, K_α, with Eq. (15).

$$K_\alpha = \frac{b_{pc}\cos(\alpha) + l_{pc}\sin(\alpha)}{b_{pc}} \tag{15}$$

(12)Compute the effective diameter of the pile cap, D^*_{pc} , using Eq. (16) and noting that the values of $H_{pc} / y_{o(max)}$ and $T / y_{o(max)}$ should not exceed 1.

$$D^*_{pc} = K_s\, K_\alpha\, b_{pc} \exp\left[-1\ -1.8 \exp\left(\frac{H_{pc}}{y_{0(max)}} \right) + 1.7 \left(\frac{T}{y_{0(max)}} \right)^{\frac{1}{2}} \right] \tag{16}$$

The procedure for computing the effective diameter of the pile group, D^*_{pg} , is presented in steps (13)-(22). The scour created by the upper components is added to the height of the pile group, H_{pg}, and water depth, y_o.

(13)Calculate the effective diameter of the column and pile cap, $D^*_{(col+pc)}$, using Eq. (17).

$$D^*_{(col+pc)} = D^*_{col} + D^*_{pc} \tag{17}$$

(14)Compute the scour due to the column and pile cap, $d_{s(col+pc)}$, using Eqs. (1)–(5) .

(15)Compute H'_{pg} and y'_o using Eqs. (18) and (19).

$$H'_{pg} = H_{pc} + d_{s(col+pc)} \tag{18}$$

$$y'_o = y_o + d_{s(col+pc)} \tag{19}$$

(16)Compute the pile group shape factor, K_s, using Eq. (20) and Eq. (21).

$$K_s = \frac{K_{s\,(pile)} - K_{s\,(pile\ group)}}{9} \left(\frac{s}{b} \right) + K_{s(pile)} - \frac{10}{9} \left(K_{s\,(pile)} - K_{s\,(pile\ group)} \right) \tag{20}$$

$$K_{s(pile\ or\ pile\ group)} = \begin{cases} 1 & \text{for circular piles or pile group arrays} \\ 0.86+0.97 \left| \dfrac{\pi}{\alpha} \right|^4 & \text{for square piles or pile group arrays} \end{cases} \tag{21}$$

(17)Compute the non-overlapping projected width of the pile group, W_p, using only the first 2 rows and the first column.

(18)Compute the pile spacing coefficient, K_{sp}, for the pile group using Eq. (22).

$$K_{sp} = 1 - \frac{4}{3} \left(1 - \frac{w_{pi}}{W_p} \right) \left(1 - \frac{1}{\left(\dfrac{s}{w_{pi}} \right)^{0.6}} \right), \tag{22}$$

where w_{pi} is the projected width of a single pile.

(19)Compute K_m (accounts for the number of piles inline with the flow) for the pile group using Eq. (23). If the skew angle is greater then 5 degrees, K_m =1.

$$K_m = \begin{cases} 0.045(m) + 0.96 & |\alpha| < 5, \text{and } m \leq 5 \\ 1.19 & |\alpha| < 5, \text{and } m>5 \\ 1 & |\alpha| \geq 5 \end{cases} , \tag{23}$$

where m is the number of piles along the axis of the pier.

(20) Compute $y_{0(max)}$ for the pile group using Eq. (24).

$$y_{0(max)} = \begin{cases} y_0' & \text{for } y_0' \leq W_p K_{sp} K_m \\ 2.5\ W_p K_{sp} K_m & \text{for } y_0' \geq W_p K_{sp} K_m \end{cases} \tag{24}$$

(21) Compute the pile group height coefficient, K_h, using Eq. (25).

$$K_h = 0.86 \tanh\left(1.8\sqrt{\frac{H_{pg}'}{y_{0(max)}}}\right) \tag{25}$$

note: $0 \leq K_h \leq 1$ and that $0 \leq \frac{H_{pg}'}{y_{0(max)}} \leq 1$.

(22) Compute the effective diameter for the pile group, D_{pg}^*, using Eq. (26).

$$D_{pg}^* = K_s K_{sp} K_m K_h W_p \tag{26}$$

The effective diameter for the complex pier is calculated by summing up the individual effective diameters using Eq. (6). The total scour for the complex pier is determined by substituting the D^* for the complex pier into Eqs. (1)-(5).

1.1.2. Case 2 Complex Pier Local Scour Prediction Procedure

This section outlines the procedure for computing local scour depths for Case 2 complex piers as illustrated in Fig (2).

(1) Calculate the effective diameter of the column [following steps (1) through (7) in Sec. *1.1.1.*

The procedure for computing the effective diameter of the pile cap, D_{pc}^*, is presented below in steps (2)-(14). The effective diameter calculation for the Case 2 complex pier requires an iterative scheme to determine how much of the pile cap is exposed. The subscript "i" refers to the number of iterations (e.g. i = 1 for the first iteration, 2 for the second, etc.).

(2) Calculate the scour due to the column, $d_{s(col)}$ using the effective diameter of the column calculated in step (1).

(3) Compute the pile cap shape factor, K_s, using Eq.(14) in Sec. *1.1.1.*

(4) Compute the pile cap skew factor, K_α, using Eq. (15) in Sec. *1.1.1.*

(5) Compute H_{pc}' and T' using Eqs.(27) and (28), and noting that T' is always positive and $H_{pc}' \leq 0$ for Case 2 complex piers.

$$H'_{pc} = -d_{s(col)} \tag{27}$$

$$T' = T + H'_{pc} \tag{28}$$

(6) Calculate $y_{0(max)}$ for the pile cap using Eq. (29).

$$y_{0(max)} = \left\{ \begin{array}{ll} 2.0\, b_{pc} \left(\dfrac{T'}{y_0 + \left| H'_{pc} \right|} \right)^{0.4} & y_o \geq 2.0\, b_{pc} \left(\dfrac{T'}{y_0 + \left| H'_{pc} \right|} \right)^{0.4} \\ y_0 + \left| H'_{pc} \right| & y_o < 2.0\, b_{pc} \left(\dfrac{T'}{y_0 + \left| H'_{pc} \right|} \right)^{0.4} \end{array} \right\} \tag{29}$$

(7) Compute the pile cap effective diameter using Eq.(30), noting that the values of $H'_{pc} / y_{o(max)}$ and $T' / y_{o(max)}$ can not exceed 1.

$$D^{*}_{pc} = K_s\, K_\alpha\, b_{pc} \exp\left[-1 \; - 1.8 \exp\left(\frac{H'_{pc}}{y_{0(max)}} \right) + 1.7 \left(\frac{T'}{y_{0(max)}} \right)^{\frac{1}{2}} \right] \tag{30}$$

(8) Compute the effective diameter for the column and pile cap combination, $D^{*}_{(col+pc)}$, using Eq. (17).

(9) Compute the scour depth for the column and pile cap combination, $d_{s(i)}$ using Eqs. (1)-(5).

(10) Compute H'_{pc} and T' using Eqs. (31)-(32).

$$H'_{pc} = \left\{ \begin{array}{ll} H_{pc} & d_{s(i)} \geq \left| H_{pc} \right| \\ -d_{s(i)} & d_{s(i)} \leq \left| H_{pc} \right| \end{array} \right\} \tag{31}$$

$$T' = \left\{ \begin{array}{ll} T & y_{s(i)} \geq \left| H_{pc} \right| \\ T + H'_{pc} & y_{s(i)} \leq \left| H_{pc} \right| \end{array} \right\} \tag{32}$$

(11) Check for convergence using Eq.(33).

If $i = 1$ proceed to step (5) above
If $i > 1$

$$\text{1) Compute } \Delta \equiv \frac{d_{s(i)} - d_{s(i-1)}}{d_{s(i-1)}} \tag{33}$$

$$\text{2) If } \left\{ \begin{array}{l} \Delta \;\leq\; 0.05 \text{ proceed to step (12) below} \\ \Delta \;>\; 0.05 \text{ proceed to step (5) above} \end{array} \right.$$

(12) Determine if the pile group has been exposed using Eq. (34).

$$\text{If } \begin{cases} d_{s(col+pc)} \leq \left|H_{pg}\right| & \text{proceed to step (13)} \\ d_{s(col+pc)} > \left|H_{pg}\right| & \text{proceed to step (14)} \end{cases} \tag{34}$$

(13) The pile group is not uncovered and hence the pile group effective diameter is zero. The complex pier's total effective diameter is computed with Eq. (6) noting that $D^*_{pg} = 0$.

(14) Compute D^*_{pg} following steps (13) - (22) for case 1 piers (Sec. *1.1.1*).

The effective diameter for case 2 complex piers is the sum of the component effective diameters [Eq.(6)]. The equilibrium scour depth is then computed using D^* in Eqs. (1)-(5).

1.1.3. Case 3 Complex Pier Local Scour Prediction Procedure.

This section details the procedure for computing local scour depths for Case 3 complex piers as shown in Fig. (2). The procedure for computing local scour depths for Case 3 complex piers is outlined below in steps (1) through (14).

Compute the effective diameter of the column.

(1) Calculate K_s and K_α for the column following steps (3) and (4) in Sec. *1.1.1*.

(2) Compute an effective diameter for the column using Eq. (35).

$$D^*_{col} = K_s\, K_\alpha\, b_{col} \tag{35}$$

(3) Compute the scour depth for the column, $d_{s(col)}$ as if it were an infinitely deep single pile using Eqs. (1)-(5). Compare this scour depth with the height of the column using Eq. (36).

$$\text{If } \begin{cases} d_{s(col)} \leq \left|H_{col}\right| & D^* = D^*_{col} \text{ and } D^*_{pc} = D^*_{pg} = 0 \\ d_{s(col)} > \left|H_{col}\right| & \text{pile cap exposed, proceed to step (4)} \end{cases} \tag{36}$$

(4) Compute f and K_f using Eqs. (5) and (6) in Sec. *1.1.1*.

(5) Compute the attenuated column effective diameter, $D^*_{col(f)}$, using Eq. (37).

$$D^*_{col(f)} = K_f K_s K_\alpha b_{col} \left[-.75\left(\frac{H_{col}}{d_{s(col)}}\right)^2 + 0.25 \right] \tag{37}$$

(6) Compute the minimum effective diameter of the column that will produce a scour depth to the base of the column, $D^*_{col(min)}$. $D^*_{col(min)}$ is computed by setting $d_s = \left|H_{col}\right|$ in Eqs. (1)-(5) and solving for D^* .

(7) Compute the effective diameter of the column using Eq. (38).

$$D^*_{col} = \begin{cases} D^*_{col(f)} & \text{if } D^*_{col(f)} \geq D^*_{col(min)} \\ D^*_{col(min)} & \text{if } D^*_{col(f)} < D^*_{col(min)} \end{cases} \tag{38}$$

The procedure for computing the pile cap effective diameter, D^*_{pc}, is presented below in steps (8)–(15)

(8) Perform steps (2) – (4) in Sec. *1.1.2*.

(9) Compute the buried pile cap attenuation coefficient, K_{bpc}, using Eq.(39).

$$K_{bpc} = a\left(\frac{H_{col}}{d_{s(col)}}\right)^2 + b\left(\frac{H_{col}}{d_{s(col)}}\right) + c\ , \tag{39}$$

where a = 0.21(f/b_{pc}) - 0.77, b = 0.028(f/b_{pc})^2 - 0.84(f/b_{pc}) - 0.12 and c = -0.25(f/b_{pc}) + 0.95.

(10) Perform steps (5) and (6) in Sec. *1.1.2.*

(11) Compute the pile cap effective diameter using Eq.(40), noting that the values of $H'_{pc} / y_{o(max)}$ or $T' / y_{o(max)}$ can not exceed 1.

$$D^*_{pc} = K_s\, K_\alpha K_{bpc}\, b_{pc} \exp\left[-1\ - 1.8 \exp\left(\frac{H'_{pc}}{y_{0(max)}}\right) + 1.7\left(\frac{T'}{y_{0(max)}}\right)^{\frac{1}{2}}\right] \tag{40}$$

(12) Perform steps (8) – (10) in Sec. *1.1.2*.

(13) Check for convergence using Eq. (41).

If i = 1 proceed to step (10) above

If i > 1

$$\text{1) Compute } \Delta \equiv \frac{d_{s(i)} - d_{s(i-1)}}{d_{s(i-1)}} \tag{41}$$

$$\text{2) If } \begin{cases} \Delta \leq 0.05 \text{ proceed to step (14) below} \\ \Delta > 0.05 \text{ proceed to step (10) above} \end{cases}$$

(14) Determine if the pile group has been exposed using Eq.(42).

$$\text{If } \begin{cases} d_{s(col+pc)} \leq \left|H_{pg}\right| \text{ proceed to step (16)} \\ d_{s(col+pc)} > \left|H_{pg}\right| \text{ proceed to step (17)} \end{cases} \tag{42}$$

(15) The pile group is not uncovered and hence the pile group effective diameter is zero. The complex pier’s total effective diameter is computed with Eq. (6) noting that $D^*_{pg} = 0$.

The procedure for computing the pile group effective diameter, D^*_{pg}, is presented below in steps (17)-(20).

(16) Perform steps (13) - (21) in Sec. *1.1.1*.

(17) Compute the buried pile group attenuation coefficient, K_{bpg} using Eq. (43).

$$K_{bpg} = \frac{H'_{pg}}{d_{s(col+pc)}} + 1 \tag{43}$$

note: $-1 \le \frac{H'_{pg}}{d_{s(col+pc)}} \le 0$ and $0 \le K_{bpg} \le 1$

(18) Compute the effective diameter for the pile group, D^*_{pg}, using Eq. (44).

$$D^*_{pg} = K_s K_{sp} K_m K_h K_{bpg} W_p \tag{44}$$

The effective diameter of the complex pier is computed by summing the effective diameters of the components using Eq. (6). The total scour for the complex pier is computed using D^* in Eqs. (1)-(5).

2 Predicted versus Measured Scour Depths

Predictions using the methods in HEC-18 version 4 and the methods outlined in this paper for the conditions in three different laboratory data sets were made and compared with the measurements. The piers used in Sheppard's and Coleman's experiments were composed of a column, pile cap and pile group. The piers in Jones' experiments consisted of a column and pile cap (footer). Sheppard's experiments were performed in the live-bed scour range while Coleman's and Jones' experiments were in the clear-water scour range. Figs. 4-6 compare the predicted and measured scour depths for the three sets. The average error and standard deviation for the two prediction methods are given in Table 1 by data set.

Table 1. The average error and standard deviation for the two prediction methods.

Data	Revised Methodology		Existing HEC-18 Methodology	
	Average error	Standard Deviation	Average error	Standard Deviation
Coleman	20%	16%	21%	54%
Jones	3%	17%	13%	14%
Sheppard_2	13%	12%	78%	32%

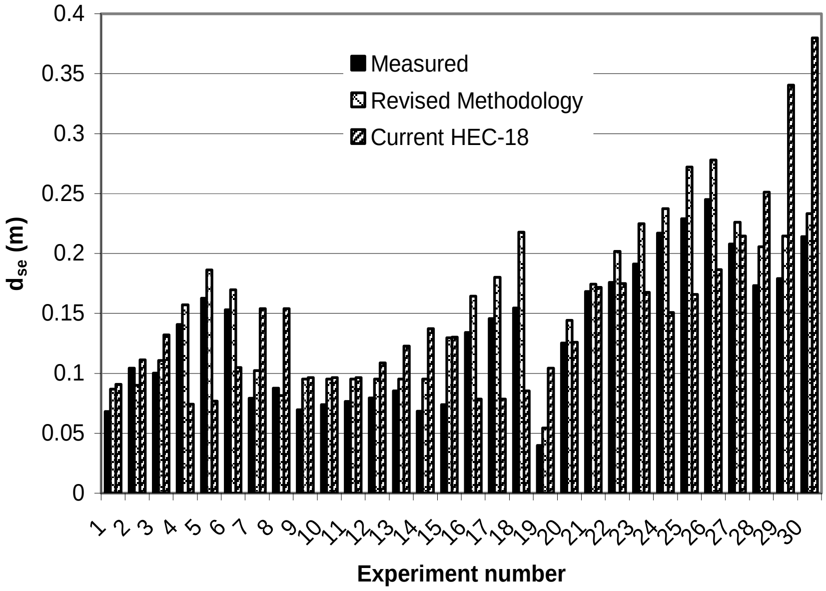

Figure 4. Predicted versus Coleman's measured scour depth for a three component complex pier.

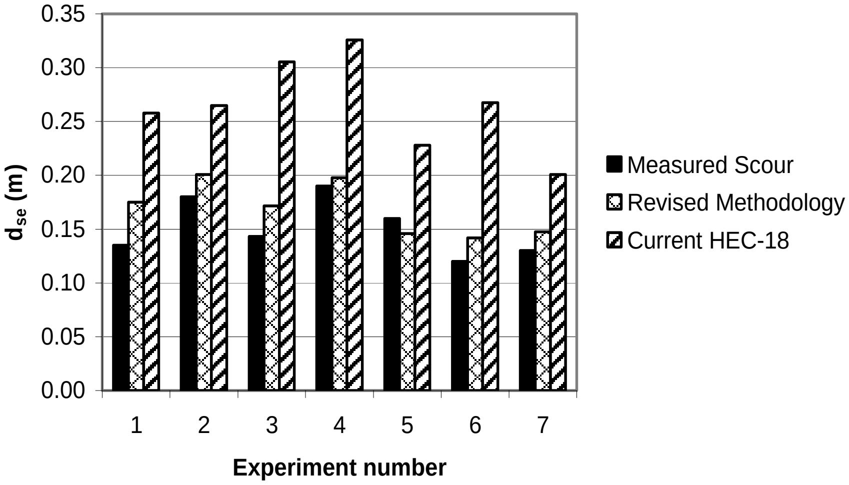

Figure 5. Predicted versus Sheppard's measured scour depth for a three component complex pier under live-bed scour conditions.

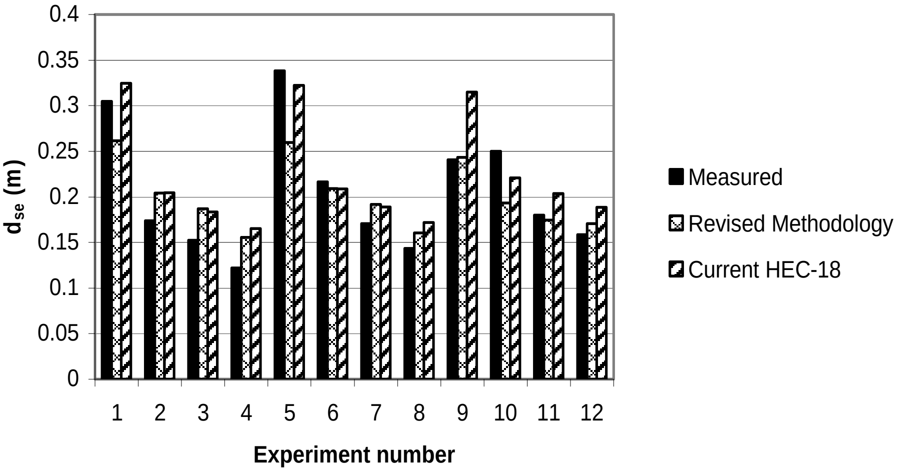

Figure 6. Predicted versus Jones' measured scour depths for complex piers with a column and pile cap.

3 Discussion

The revised procedure outlined in this paper has been extended to complex piers with partially or fully buried pile caps (footers). The procedure was developed using both clear-water and live-bed scour data. The method used by Sheppard to extrapolate measured scour depths to equilibrium values is conservative (i.e. the extrapolated equilibrium values are most likely larger than the actual values). The revised method presented here appears to more accurately predict scour depths than the methods presented in the current version of HEC-18. The revised procedure is more accurate at predicting scour depths during live-bed flow conditions, and at predicting the scour for partially buried and fully buried pile caps. It is noteworthy that for the situations covered in Coleman's Experiments 5, 6, 7, 25 and 26 the current HEC-18 method under predicts the measured scour depth. All of these tests were with three component piers with buried or partially buried pile caps.

References

Coleman, S.(2001), Personal communication by e-email to D.M. Sheppard.

Jones, J.S. (2000). In personal communication by e-mail to D.M. Sheppard.

Sheppard, D.M., and Jones, J.S. (1998) "Scour at complex pier geometries." Compendium of scour papers from ASCE Water Resources Conferences, Eds. E.V. Richardson and P.F. Lagasse, ASCE, New York.

Sheppard, D. Max, and Sterling Jones. (2000) "Local Scour at Complex Piers," Proceedings for the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management Conference, Minneapolis, MN, July 30-August 2, 2000.

Sheppard, D. Max and Rick Renna, (2001), "Florida Bridge Scour Manual" Published by Florida Department of Transportation, 605 Suwannee Street, Tallahassee, FL 32399-0450.

Sheppard, D. Max, Mufeed Odeh and Tom Glasser (2004),"Large Scale Clearwater Local Pier Scour Experiments", J. Hydr. Engrg., ASCE, 114, No. 10, 1210-1226.

Acknowledgments

The authors thank Rick Renna, Shawn McLemore and Richard Long with the Florida Department of Transportation (FDOT) for supporting this research. Thanks to Bruce Melville and his staff, Jim Beckner and Raymond Hoffmann and University of Auckland graduate students Sjoerd van Ballegooy and Thomas Macdougal Clunie for running the tests. Thanks also to Stephen Coleman (University of Auckland) and Sterling Jones (U.S. Federal Highway Administration) for use of their data.

Notation

b = circular pile diameter,
b_{col} = width of column,
b_{pc} = width of column,
D^* = effective diameter of the complex pier,
D^*_{col}= effective diameter of the pier column,
$D^*_{co(f)l}$= effective diameter of the pier column attenuated by K_f,
$D^*_{col(min)}$ = smallest value for a case 3 column effective diameter
D^*_{pc} = effective diameter of the pier pile cap,
D^*_{pg}= effective diameter of the pier pile group,
D_{50} = median sediment grain diameter,
d_{se} = equilibrium scour depth,
H_{col} = height of column base from bed,
H_{pc} = height of pile cap base from bed,
H_{pg} = height of top of piles above bed,
K_{bpc} = buried pile cap coefficient
K_{bpg} = buried pile group coefficient
K_h = submerged pile group coefficient,
l_{col} = length of column,
l_{pc} = length of pile cap
f_1 = pile cap extension beyond the front of the column,
f_2 = pile cap extension beyond the side of the column,
V = depth averaged velocity,
V_c = sediment critical depth averaged velocity,
V_{lp} = live-bed peak scour velocity (velocity where the bed planes out),
y_0 = approach water depth.