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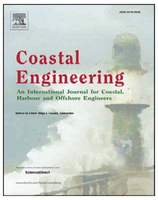

Prediction of current-induced local scour around complex piers: Review, revisit, and integration

Danial Amini Baghbadorani [a], Behzad Ataie-Ashtiani [a,b], Aliasghar Beheshti [c,*], Mahmoud Hadjzaman [a], Mirmosadegh Jamali [a]

[a] Department of Civil Engineering, Sharif University of Technology, P.O. Box 11155-9313, Tehran, Iran
[b] National Centre for Groundwater Research & Training, College of Science & Engineering, Flinders University, GPO Box 2100, Adelaide, South Australia 5001, Australia
[c] Water Science and Engineering Department, Ferdowsi University of Mashhad, P.O. Box 91775-1163, Mashhad, Iran

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ABSTRACT

Complex piers (CPs), consisting of a column, pile cap and pile group, are commonly built as foundations for hydraulic and marine structures. Scour-hole development around CPs is studied in this paper. A total of 52 tests is carried out on 4 CP models, with experiments durations ranging from 24 to 120 h. All of the available experimental data for clear-water scour around CPs including the collected data of the present study and those previously published are reviewed and combined into a database. A special case of bridge piers with deep foundation or caisson instead of pile caps is also considered, which is herein called compound piers. The database contains 367 experiments for CPs and 162 experiments for compound piers. The predictive equations of the maximum scour-hole depth at complex piers including HEC-18 and FDOT equations are revisited and a new equation is proposed. Comparisons of the prediction equations shows that for CP data, the absolute error is 28%, 79% and 108% for the proposed, HEC-18 and FDOT equations, respectively. Underestimation below −20% error line occurs for 11%, 15%, and 7% of the cases in the proposed, HEC-18, and FDOT equations, respectively. For compound piers, the proposed equation has 41% absolute error while HEC-18 equation has 93% absolute error.

1. Introduction

A complex pier (CP) is a type of foundation that is used to support hydraulic and marine structures. It is composed of a column resting on a pile cap (or shallow footing) which is supported by a group of piles. Compound piers are a special type of CPs without pile groups and typically with thicker pile cap, which are also referred to as column on caisson foundations. Erosion of surface topsoil in river sites where bridges are located forces designers to use deep foundations such as pile groups or caissons (Bowles, 1997). Due to the advances in construction procedures and the architectural elegance of contemporary structures, and the need for deep foundations, complex and compound pier foundations are frequently utilized.

Complex piers are prone to the loss of performances, the risk of instability, and even failure due to the current-induced scour around their foundations. A required step in the design of complex and compound piers is to find the maximum scour-hole depth (SHD) to ensure that the load-bearing capacity of the foundation is maintained during flood events and after exposure to steady current for long period of time. Due to general or contraction scour, the pile cap position may be changed with respect to the bed level during the life of a bridge, which will add to complexities. Many studies present experimental data of CP scour vs. pile cap elevation (Oliveto et al., 2004, 2006; Ataie-Ashtiani et al., 2010; Oliveto, 2012; Ferraro et al., 2013; Amini et al., 2014; Moreno et al., 2016). Empirical relationships have been proposed to estimate scour depth. The method of Hydraulic Engineering Circular No. 18 (HEC-18) as reported in Arneson et al. (2012) and the method of Florida Department of Transportation (FDOT) as reported in Sheppard and Renna (2005) are often used for design purposes. Both HEC-18 and FDOT methods apply superposition principle to combine the effect of each substructure of complex piers for calculations of scour depth. On the other hand, Coleman (2005) and, recently, Moreno et al. (2016) give equations that, by combining an equivalent width approach with a single-pier scour equation, can lead to SHD prediction for complex piers. Ataie-Ashtiani et al. (2010) proposed correction factors for SHD estimation using HEC-18 and Coleman (2005) equations. However, the existing methods such as

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* Corresponding author.
E-mail addresses: danial.amini@gmail.com (D. Amini Baghbadorani), ataie@sharif.ir (B. Ataie-Ashtiani), beheshti@ferdowsi.um.ac.ir (A. Beheshti), m.hadjzaman@gmail.com (M. Hadjzaman), jamali@sharif.edu (M. Jamali).

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Coleman (2005) suffer from problems such as overestimation as pointed out by Ataie-Ashtiani et al. (2010) and Ferraro et al. (2013). It is therefore necessary to provide new predictive equations with higher accuracy that lead to an improved, indulgent and more economical design of complex pier foundations.

Despite the previous efforts, there are no categorical comparisons among the equations for scour depth prediction. More importantly, the data of the former physical experiments have not been integrated and used all together. The main objectives of this work are to produce a new set of data for scour around CP, to review and integrate all previous experimental works, establishing a comprehensive database which is used for a comparative study of the available equations for SHD estimations, and to suggest a new equation that correctly accounts for important variables such as pile cap elevation and thickness without suffering from excessive overestimation.

2. Dimensional analysis

A schematic for flow-induced scour around a CP is shown in Fig. 1. The CP is placed in a flume having water depth of y and depth-averaged approach flow velocity of V, and the bed is covered with cohesionless sediment having the median particle diameter of d_{50}. The column is rectangular in shape with rounded nose, having the width of b_{col} and length of l_{col}. The pile cap is rectangular in shape, having the width of b_{pc}, length of l_{pc}, and thickness of T. The frontal and side extensions of the pile cap with respect to the column are f_1 and f_2, respectively. The elevation of the pile cap top and bottom with respect to bed level are h_1 and h_0, respectively (h_1 is positive in the direction above the initial bed level). The pile group consists of $n \times m$ cylindrically shaped piles with diameter of b_p, where n is the number of piles perpendicular to the flow and m is the number of piles inline with the flow (e.g. $n \times m = 2 \times 3$ in Fig. 1). The center-to-center spacing of piles perpendicular to and inline with the flow are S_n and S_m, respectively. The scour hole has a maximum depth of y_s. The CP model is placed in a flume having the width of B_{flume}. The flow angle of attack with respect to CP is zero in all experiments.

In order to reduce the number of parameters, the equivalent width approach is used in this study. All parameters relating to geometry and position of CP are represented with equivalent width or b_e via the following relationship:

$$\frac{b_e}{b_{col}} \text{ or } \frac{b_e}{b_{pc}} \text{ or } \frac{b_e}{nb_p} = \text{function}\left(K_{s,col}, K_{s,pc}, K_{s,pg}, \frac{b_{col}}{l_{col}}, \frac{b_{pc}}{l_{pc}}, \alpha, \frac{h_1}{y}, \frac{h_0}{y}, \frac{T}{y}, \frac{f_1}{b_{col}}, \frac{f_2}{b_{col}}, \frac{b_{col}}{b_{pc}}, \frac{b_p}{b_{pc}} \text{ or } \frac{W}{b_{pc}}, m, n, \frac{S_n}{b_p}, \frac{S_m}{b_p}, \frac{h_1}{b_{pc}}\right) \tag{1}$$

Here $K_{s,col}$ is shape factor for column, $K_{s,pc}$ is shape factor for pile cap, $K_{s,pg}$ is shape factor for pile group, W is projected width of the pile group ($W = nb_p$ for aligned flow), and α is angle of attack. Pile group parameters are eliminated and replaced by b_{pg} which is equivalent width of full depth pile group.

The effect of flow, sediment and other factors that influence scour are typically considered via dimensionless groups. Therefore scour is a function of dimensionless groups including: flow intensity as V/V_c, Froude number as $\boldsymbol{F}_r$, time group as Vt/b_e, relative sediment size b_e/d_{50}, flow shallowness y/b_e, and geometric standard deviation of sediments σ_g. These parameters are incorporated in common single pier scour equations. In the above groups, V_c is the average critical velocity of cross section for initiation of sediment motion, $\boldsymbol{F}_r$ is considered as approach flow Froude number which is $V/(gy)^{0.5}$, t is time, and d_{50} is median sediment size.

3. Review of equations for complex piers scour estimation

The existing equations for prediction of complex pier scour depth are reviewed here. All of the existing CP scour equations utilize single pier scour equations during their calculations. The most popular methods are HEC-18 and FDOT.

3.1. Coleman (2005) method

Coleman (2005) method proposed equations for calculating b_e (equivalent width of complex pier) based on pile cap position, expressed by:

$$\begin{aligned} & b_e = b_{col} \quad \text{for } h_1 \le -b_{col} \\ & b_e = b_{col} \times \left(b_{col}/b_{pc}\right)^{\left\{\left(b_{col}/b_{pc}\right)^3 + 0.1 - \left[0.47\left(0.75 + h_1/b_{col}\right)^{0.5}\right]\right\}} \quad \text{for } 0 < h_1 \le T/2 \\ & b_e = \frac{0.52Tb_{pc} + (y - 0.52T)b_{pg}}{y} \quad \text{for} \quad h_1 = y \\ & b_e = b_{pg} \quad \text{for } h_1 \ge y + T \end{aligned} \tag{2}$$

The value of b_e is then substituted in the single pier scour equation of Melville and Coleman (2000), defined as

$$y_s = K_{y,b} K_d K_I K_t K_s K_\alpha \tag{3}$$

here $K_{y,b} = 2(yb_e)^{0.5}$ for $0.2 < y/b_e < 1.43$, $K_d = 1$ for $b_e/d_{50} > 25$, $K_I = V/V_c$ for clear-water conditions with uniform sediments, $K_t =$ time factor, $K_s =$ shape factor, and $K_\alpha =$ factor for angle of attack which is $K_\alpha = 1$ in this study. Finally, a correction factor considering protection effect of pile cap frontal extension parameter, f_1/b_{col} is applied for $0 < h_1 \le T/2$ which yields the corrected value of scour depth, $y_{s,new}$.

$$\frac{y_{s,new}}{y_s} = 1 - 0.083\left(\frac{f_1}{b_{col}}\right)^{2.76} \quad \text{for } \frac{f_1}{b_{col}} < 2.5, \quad \text{otherwise } y_{s,new} = 0 \tag{4}$$

3.2. Method of FDOT

The method of Sheppard and Renna (2005), referred to as the FDOT method herein, calculates scour using superposition, expressed by:

$$b_e = b_{e,col} + b_{e,pc} + b_{e,pg} \tag{5}$$

here $b_{e,col} =$ equivalent width of column, $b_{e,pc} =$ equivalent width of pile cap and $b_{e,pg} =$ equivalent width of pile group. FDOT method considers three cases including pile cap submerged in the flow, pile cap partially buried in the bed, and pile cap completely buried in the bed. The calculation of $b_{e,col}$, $b_{e,pc}$ and $b_{e,pc}$ for case of submerged pile cap are explained in the supplementary materials. The final step is to substitute b_e as pier diameter b in the FDOT single pier equation, which for clear-water scour condition can be expressed by:

$$\begin{aligned} \frac{y_s}{b} = 2.5 \tanh\left[\left(\frac{y}{b}\right)^{0.4}\right]\left\{1 - 1.2\left[\ln\left(\frac{V}{V_c}\right)\right]^2\right\} \\ \times \left\{\frac{b/d_{50}}{0.4(b/d_{50})^{1.2} + 10.6(b/d_{50})^{-0.13}}\right\} \quad \text{for } 0.4 \le \frac{V}{V_c} \le 1 \end{aligned} \tag{6}$$