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Analysis of laterally loaded piles in soft clay considering scour-hole dimensions

Cheng Lin [a], Jie Han [b,*], Caroline Bennett [c], Robert L. Parsons [d]

[a] Terracon Consultants, Inc., 2201 Rowland Ave., Savannah, GA 31404, USA
[b] The University of Kansas, Civil, Environmental, & Architectural Engineering (CEAE) Department, 2150 Learned Hall, 1530 W. 15th Street, Lawrence, KS 66045-7609, USA
[c] The University of Kansas, CEAE Department, Lawrence, KS 66045, USA
[d] The University of Kansas, CEAE Department, Lawrence, KS 66045, USA

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ABSTRACT

Scour is a process of soil erosion around foundations, resulting in a reduced capacity of the foundations or even failure of the structures. When there are isolated foundations in the midst of water currents, scour holes are formed around the foundations. In practice, scour effects on the foundations are evaluated or designed by ignoring the scour-hole geometry. Instead, scour effects are considered by simply removing the whole soil layer to the scour depth. However, scour-hole dimensions include not only scour depth but also scour-hole width and slope angle. To date, the widely used *p–y* method for analyzing laterally loaded piles cannot consider three-dimensional scour-hole dimensions. For this reason, a simplified method was developed in this study for the analysis of laterally-loaded piles in soft clay under scour conditions by modifying the *p–y* curves. The simplified method was used to evaluate the effects of scour-hole dimensions on responses of laterally loaded piles in soft clay. The computed results were compared with those from the 3D finite difference method. The analysis indicated that ignoring the scour-hole dimensions could result in 10–19% larger lateral pile-head displacements and 6–8% larger bending moments than what would be computed while considering them.

1. Introduction

Scour is a major concern for the safety of structures in water, such as bridges, offshore wind farms, offshore platforms, and similar structures. By removing soils in the vicinity of the foundations, scour results in a significant decrease of foundation capacities and poses a risk to structural stability. Wardhana and Hadipriono (2003) conducted a survey of bridge failures in the United States from 1989 to 2000 and found that flood and scour were responsible for nearly 50% of the total number of bridge failures in that time period. Scour damaged over 500 bridges on the Georgia highway system during the 1994 flood, causing a financial loss of $130 million (Richardson and Davis, 2001). The above mentioned historical losses due to scour clearly indicate the importance of scour assessment and mitigation.

A limited number of studies (Avent and Alawady, 2005; Daniels et al., 2007; Lin et al., 2010; Li et al., 2013; Sørensen and Ibsen, 2013; Lin et al., 2014a; Wang et al., 2014; Liang et al., 2015) have examined the effects of scour on pile foundations, bridges, and offshore structures. When water flows around a stationary object (e.g., a bridge pier supported by a pile foundation), it induces a scour hole around the pile foundation. When the behavior of the pile foundation under the scoured condition is analyzed, common practice is to completely remove the soil around the pile foundation to a scour depth and ignore the shape and dimensions of the scour hole. To evaluate the effects of scour-hole dimensions on pile behavior, three-dimensional (3D) numerical methods were utilized by several researchers (Li et al., 2009; Achmus et al., 2010; Li et al., 2013). However, 3D numerical methods, such as the finite element method (FEM) or finite difference method (FDM), are complicated to use and require long computation time. To overcome these shortcomings, Lin et al. (2014b) developed a simplified method to analyze the effects of scour-hole dimensions on laterally-loaded piles in sand by modifying the widely-used *p–y* curve for piles in sand. This simplified method is only valid for laterally-loaded piles in sand, and a method is still needed for piles in clay.

* Corresponding author.
E-mail addresses: clin@terracon.com (C. Lin), jiehan@ku.edu (J. Han), crb@ku.edu (C. Bennett), rparsons@ku.edu (R.L. Parsons).

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The objective of this study was to develop a simplified method for laterally-loaded piles in soft clay under a scoured condition considering the effects of scour hole dimensions. The simplified method was developed by modifying the p–y curves proposed for soft clay by Matlock (1970). In the following sections, the simplified method is first derived; then the computed results are compared with those obtained from the commercial 3D finite difference software *FLAC*^{3D} (Fast Lagrangian Analysis of Continua). The 3D finite difference modeling was used to verify the simplified method. Finally, the effects of scour-hole dimensions on the laterally loaded piles are discussed based on the computed results from both the simplified method and the 3D finite difference method.

2. Definition of scour-hole dimensions

The scour-hole dimensions refer to scour depth, width, and slope angle, as depicted in Fig.1. Scour depth, S_d, is the distance between the pre-scour and post-scour ground surfaces. Scour width refers to the top width or bottom width in the scour hole, which is measured from one side of the footing to the edge of the scour hole. For simplicity, scour width, S_w, only refers to the bottom width of the scour hole throughout this study. Scour-hole slope angle, θ, is the slope formed inside the scour hole.

3. Simplified method

3.1. Description of the p–y method for a pile in soft clay

In the p–y method, lateral soil resistance to a pile is treated as a series of independent nonlinear Winkler springs. The solution for the response of the laterally-loaded pile in the soil was obtained from the governing equation for a beam supported by the Winkler springs. The governing beam equation was developed by Hetényi (1946) and used to evaluate the response of a pile under lateral loading (Reese and Van Impe, 2001) as follows:

$$\frac{d^2}{dx^2}\left(R_h\frac{d^2y}{dx^2}\right)+P_t\frac{d^2y}{dx^2}+p-W=0 \tag{1}$$

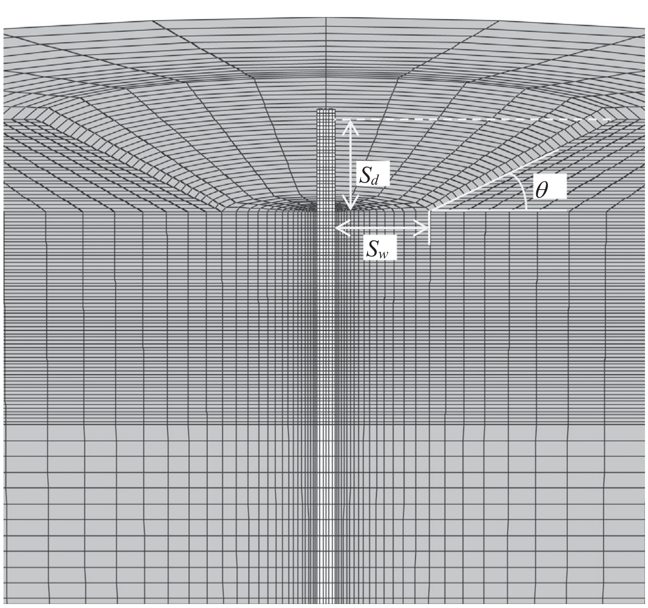

Fig. 1. Three dimensional model of a scour hole (S_d=scour depth, S_w=scour width, θ=scour-hole slope angle).

where R_h is flexural stiffness of the pile, equal to E_pI_p; E_p is elastic modulus of the pile; I_p is moment of inertia of the pile; P_t is vertical load on the pile; p is lateral soil resistance per unit length; W is distributed lateral load along the pile length; x is depth below the pile head; and y is lateral displacement of the pile.

Eq. (1) can be solved when the relationship between p and y is known. If the p–y relationship is assumed to be linear, a closed-form solution is readily available (Hetényi, 1946). If the p–y relationship is nonlinear, numerical techniques, such as FDM and FEM, have been used to solve for the nonlinear problems. This effort leads to the development of the widely-used commercial software, such as *LPILE* (an FDM code) and *FB-Multipier* (an FEM code). Alternatively, the p–y relationship can be developed based on the full scale tests on piles under lateral loading. Different p–y relationships have been used to characterize the piles in different types of soils (e.g. sand, soft clay, stiff clay, and rock).

The p–y curves adopted in this study for piles in soft clay were proposed by Matlock (1970) based on short-term static loading of piles in soft clay, and are formulated as follows:

$$\frac{p}{p_{ult}}=0.5\left(\frac{y}{y_{50}}\right)^{1/3} \tag{2}$$

In Eq. (2), y_{50} is lateral displacement at half the maximum soil stress and can be determined by Eq. (3) and p_{ult} is ultimate soil resistance per length, which is equal to the smaller value of p_{ult1} and p_{ult2} calculated in Eqs. (4) and (5) respectively. When y is greater than $8y_{50}$, p is equal to a constant value of p_{ult}.

$$y_{50}=2.5\varepsilon_{50}D \tag{3}$$

$$p_{ult1}=\left(3+\frac{\gamma'}{C_u}z+\frac{J}{D}z\right)C_uD \tag{4}$$

$$p_{ult2}=9C_uD \tag{5}$$

In Eqs. (3)–(5), ε_{50} is the strain at one-half the maximum stress; D is pile diameter; p_{ult1} is ultimate soil resistance per length near the ground surface; p_{ult2} is ultimate soil resistance per length at depths; γ' is effective unit weight of the soil; J is a constant value (typically using 0.5); z is depth below the existing grade (the existing grade refers to the pre-scour surface when no scour occurs or the post-scour ground surface when scour occurs); C_u is undrained shear strength of the soft clay.

3.2. Derivation of the Simplified Method

The simplified method is developed by establishing an imaginary equivalent wedge failure model without a scour hole (the right part of Fig. 2) which has the same ultimate soil resistance as the wedge failure model having a scour hole (the left part of Fig. 2). The equivalent wedge is mainly characterized by the equivalent soil depth, Z. The value of Z is back-calculated from the ultimate soil resistance which is quantitatively equal to the one computed from the wedge considering the scour-hole dimensions. The simplified method is then developed by substituting Z for z in Eq. (4) to modify the Matlock p–y curves. For simplicity, the above process approximates the scour-hole surface in front of pile as a planar scour-hole slope surface and the possible errors resulting from the use of the planar surface are assumed to be minimal. According to Eq. (5), the plane failure in the soft clay at depths well below the ground surface is independent of the overburden stress. As such, the effects of the scour-hole dimensions are not considered for the soil at depths well below the ground surface.

For the equivalent wedge without a scour hole (the right one in Fig. 2), the ultimate soil resistance, F_u, can be determined below