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Technical Communication

Evaluation of vertical effective stress and pile tension capacity in sands considering scour-hole dimensions

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ABSTRACT

Evaluation of vertical effective stress of soils around piles is essential to calculation of pile capacities. However, the widely-used design manuals such as FHWA and API recommend different methods for calculating the vertical effective stress under scour conditions, which thus lead to different calculations of pile capacities. This paper was to evaluate the suitability of the existing methods and the proposed analytical solution for estimation of pile tension capacity by comparing them with FE analyses under different scour-hole dimensions. Based on the comparisons, recommendations were developed for selecting an appropriate method to calculate pile tension capacity under different scour-hole conditions.

1. Introduction

Pile foundations in river and ocean can suffer enormous loss of soil supports due to scour. To ensure the safety of bridges and marine structures, pile foundations should be designed with adequate capacities against scour in floods or hurricanes. Scour generally consists of general scour (erosion across the riverbed) and local scour (developing a scour hole at the foundation). General scour causes the uniform reduction of vertical effective stress in the remaining (or unscoured) soils; however, the stress reduction due to local scour is nonuniform and highly dependent on the dimensions of a scour hole. Currently, the widely used design manuals including American Petroleum Institute (API) [1], US Federal Highway Administration-Driven Piles (denoted as FHWA-DP) [2], and FHWA-Drilled Shafts (denoted as FHWA-DS) [3] specify different methods to estimate vertical effective stress of remaining soils at piles under local scour [4]. The different stress calculations lead to the pronounced difference in calculated pile lateral or axial capacity, which thus confuses the engineer on selecting an appropriate method for the design. Lin and Wu [4] compared the existing methods (i.e., FHWA-DP, FHWA-DS, and API) with their proposed closed-form solution and quantified the difference in terms of pile lateral capacity. They found that FHWA-DP and FHWA-DS overestimated pile lateral capacity by 34–47% and 12–22%, respectively, while API gave the most agreeable estimation but was only applicable in limited scour-hole conditions.

Extensive research efforts have been focused on scour effects on the behavior of laterally loaded piles considering various scour-hole dimensions [5–10]. However, limited attention has been paid to variations of pile axial capacity including both compression and tension capacities with scour-hole dimensions. In particular, almost no effort has been made to evaluate the difference in pile compression or tension capacity due to the different stress calculations recommended by the existing methods.

The objective of this paper was to investigate how the different stress calculations by the existing methods (i.e., FHWA-DS, FHWA-DP, and API) and an analytical solution proposed by the authors [11] would affect the calculations of pile tension capacity under local scour. A series of FE analyses (65 cases) was run on single piles in both loose and dense sands under a wide range of scour-hole dimensions. The FE results including vertical effective stress and pile tension capacity were compared with those from the existing methods and the analytical solution [11]. Based on the comparisons and discussions, recommendations for selecting a proper method were developed.

2. Pile tension capacity under local scour conditions

In general design practices, pile tension capacity is often estimated as the ultimate tensile load according to various design methods such as Reese and O'Neill [12] and Fleming et al. [13]. In this study, the method of Fleming et al. [13] was adopted as it yielded the agreeable prediction to in-situ testing data for bored piles [14]. It can be expressed as

$$R_s = \int_0^{L_e} (\pi D K \sigma_v{}' \tan\delta) dz \tag{1}$$

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Nomenclature

D	pile diameter
e_{int}	initial void ratio of soils
E_s	Elastic modulus of soils
E_p	Elastic modulus of piles
K	coefficient of lateral earth pressure at piles
L	pile length
L_e	embedded length of piles
R_s	ultimate tension capacity
S_{wt}	top width of scour hole (Fig. 1)
S_{wb}	bottom width of scour hole (Fig. 1)
S_d	scour depth due to local scour (Fig. 1)
z	depth below post-scour ground level (Fig. 1)
Z	depth below pre-scour ground level, equal to $S_d + z$ (Fig. 1)
z_i	influence depth below which the reduction of vertical effective stress due to local scour vanishes and the effective stress is computed from the pre-scour ground level
β	scour-hole slope angle (Fig. 1)
δ	friction angle of soil-pile interface
ϕ	friction angle of soil
ψ	dilation angle of soil
γ'	effective unit weight of soils
γ_s	saturated unit weight of soils
γ_p	total unit weight of piles
ν_s	Poisson's ratio of soils
ν_p	Poisson's ratio of piles
σ_v'	vertical effective stress of soils at piles
σ_{va}'	vertical effective stress of soils at piles after scour
σ_{vb}'	vertical effective stress of soils at piles before scour
$\sigma_{va}'/\sigma_{vb}'$	stress ratio, or normalized vertical effective stress

The value of K is typically chosen as 0.9 for sands and 0.6 for silts. The value of δ was chosen as peak friction angle of soils in this study [14], equal to 28° and 39° for loose and dense sands, respectively. The detailed soil and pile properties are summarized in Table 1. It should be noted that the present study was focused on the effect of scour-hole dimensions on pile tension capacity and the effect of stress history changes in remaining soil due to scour on soil properties (e.g. K and ϕ') and pile capacities [15–18] was not considered in this study. The value of σ_v' was chosen as $\sigma_{vb}^{'} = \gamma' Z$ before scour occurred but as σ_{va}' after scour occurred. The value of σ_{va}' for local scour conditions was determined using FHWA-DP, FHWA-DS, API, and the analytical solution [11] as discussed later. The value was taken as $\sigma_{va}^{'} = \gamma' z$ when local scour evolved into general scour (i.e., $S_{wb} = \infty$).

In finite element (FE) analyses, two-dimensional axisymmetric FE models were built in the commercial software, Plaxis. The vertical boundary was set 50D from the pile center and the bottom horizontal boundary was 20D below the pile tip. These boundaries were found to have a negligent effect on the results of numerical modelling. A "medium size" meshing function in Plaxis was selected, which automatically created a large number of 15-node triangular elements (approximately 1500–3500). The computational results become less sensitive to meshing density when soil-pile interface is created [19]. In the FE models, soil-pile interface was established and the "medium-size" mesh was sufficient to achieve computational accuracy. In the soil-pile interface, shear strength was chosen as that of the adjacent soil (i.e., $R_{int} = 1.0$ in Table 1). Soils were simulated using the elastic perfectly plastic Mohr-Coulomb model and piles as an elastic material. Soil parameters used in FE analyses varied with the density of sands. As shown in Table 1, a larger elastic modulus, a slightly higher unit weight, and a lower void ratio were used for dense sand than loose sand. Dilatancy was considered in dense sand but not in loose sand. The dilatant angle was computed using $\Psi = \phi^{'} - 30°$ as suggested by Plaxis. The numerical calculation proceeded with the initial equilibrium of the model, followed by imposing tensile displacement on the pile head. The pile tensile loads were computed at the corresponding imposed tensile displacements. The pile tension capacity was taken as the tensile load that corresponded to a pile tensile displacement of 5%D. The shaft resistance is typically mobilized at a pile axial displacement of 0.5–2%D [20,21]. The higher pile displacement of 5%D was chosen herein mainly to account for the potential rebound of piles after scour.

As described previously, pile tension capacity determined by FEM was based on the serviceability limit state, which is different from the ultimate limit state used in Eq. (1) [13]. To make the results computed by both methods comparable, tension capacity ratio was used instead of the absolute value of tension capacity. It is defined as a ratio of pile tension capacity calculated after scour to that before scour, i.e., $\text{tensioncapacityratio} = R_{s(post-scour)}/R_{s(pre-scour)}$.

3. Methods for calculating vertical effective stress at piles under local scour

Local scour forms a scour hole around the piles. In general design practices, the scour hole is simplified as an inverted truncated cone with the dimensions defined by S_d, S_{wb}, and β in Fig. 1(a). For foundations in river, FHWA HEC-18 [22] recommends the top width of scour hole be twice the scour depth (i.e., $S_{wt} = 2S_d$) which corresponds to $S_{wb} = 0$ and $\beta = 26.7°$, and the value of S_d can be varied. For foundations in ocean, similar dimensions of the scour hole (i.e., $S_{wb} = 0$ *and* $\beta = 30°$) are used [23] but $S_d = 1.5D$ is often suggested [1].

The formation of a scour hole reduces the vertical effective stress in the remaining soils around piles and the reduction rate of the stress becomes smaller at greater depths. The existing methods account for this in different ways. FHWA-DP ignores the scour-induced stress reduction, so its vertical effective stress follows a linear line calculated from the pre-scour ground as illustrated in Fig. 1(b), whereas FHWD-DS and API consider the stress reduction but only to a limited depth, so their vertical effective stress follows two lines. Before the limited depth, the stress is calculated from the post-scour ground; however, below this depth, no further reduction in the stress occurs and therefore the stress is calculated from the pre-scour ground in Fig. 1(b). Lin and Wu [4] defined this limited depth as the influence depth. It is equal to $1.5S_d$ below the post-scour ground according to FHWA-DS (i.e., $z_i = 1.5S_d$) and 6.0D below the pre-scour ground according to API. Since API recommends $S_d = 1.5D$, its influence depth is $z_i = 3S_d$ below the post-scour ground. The detailed stress calculation using the existing methods

Table 1
Soil and pile parameters.

Soil parameters	Loose sand	Dense sand
Soil (Mohr-Coulomb)		
Saturated unit weight, γ_s (kN/m^3)	19	21
Elastic modulus, E_s (MPa)	20	100
Poisson's ratio, ν_s	0.3	0.3
Void ratio, e_{int}	0.7	0.4
Effective friction angle, ϕ' (°)	28	39
Dilatant angle, ψ (°)	0	9
Soil-Pile Interface		
Reduction factor, R_{int}	1	
Pile (Linear elasticity)		
Saturated unit weight, γ_p (kN/m^3)	24	
Elastic modulus, E_p (MPa)	24,000	
Poisson's ratio, ν_p	0.15	
Pile diameter, D (m)	1	
Pile length (fully embedded), L (×D)	20	