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Effect of vertical load on the lateral response of offshore piles considering scour-hole geometry and stress history in marine clay

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ABSTRACT

Scour induces the loss of soil support around the pile foundations for the offshore and coastal structures, and thus increases their bending moments and lateral deflections, which may change the vertical loads effect on the lateral response of piles applied in such cases. In this paper, the stress changes of the remaining soils at the corresponding pile location due to the three-dimensional scour-hole formation are first determined based on the Mindlin's elastic solutions. Then, the calculated new soil stresses are adopted to re-examine the Young's modulus of the remaining soils undergoing a stress history due to scour. With this key soil parameter that have been modified appropriately to reasonably reflect the effects of three-dimensional scour-hole geometry and the stress history of the soils simultaneously, an analytical model based on the principle of minimum potential energy is further developed to investigate the influence of vertical loads on the lateral responses of offshore piles in marine clay under scour conditions. The influence of related parameters including the lateral displacement level and the vertical load level with different scour-hole dimensions (i.e., scour depth, scour width and scour-hole slope angle), considering or ignoring stress history effect, have also been analyzed based on a case study. The results show that scour depth plays the most important role among the various scour-hole dimensions in influencing the responses of scoured piles under combined vertical and lateral loading. Although still possessing some limitations (e.g., the simplistic assumption of linear-elastic behavior for the soil and the approximate allowance made to account for the gapping effect), the simplicity and relative ease of utilization offered by this proposed analytical model make it a good alternative approach for estimating the deflection and moment responses of the scoured pile foundations subjected to combined lateral and vertical loading.

1. Introduction

Pile foundations supporting the offshore and coastal structures are not only subjected to vertical loads from the superstructures, but also lateral loads due to wind or wave actions. In such cases, the effect of vertical loads on the pile's lateral responses (i.e., bending moments and lateral deflections) is to be expected. In addition, scouring of soil around pile foundations of offshore structures can significantly increase their bending moments and lateral deflections and sometimes pose a risk to structural stability (Briaud et al., 1999; Richardson and Davis, 2001; Wardhana and Hadipriono, 2003), which may change the influence of vertical loads on the lateral responses of pile foundations.

Yet, the literature available on this topic is scanty, and the results available in the limited literature are somewhat inconsistent with respect to the effect of vertical loads on the lateral responses of piles (Hussien et al., 2014). For the pile embedded in sand, some experimental (Jain et al., 1987; Lee et al., 2011, 2013) and analytical (Goryunov 1973; Levy et al., 2005) studies indicated that the presence of a vertical load increases the lateral deflection while other experimental (Pise, 1975; Karasev et al., 1977; Zhang et al., 2002) and numerical (Karthigeyan et al., 2006; Achmus and Thieken, 2010a; 2010b; Achmus et al., 2009) investigations suggested a decrease in lateral deflection with the combination of vertical loads. Similarly, model (Anagnostopoulos and Georgiadis, 1993) and field (Zhukov and Balov, 1978; Sorochan and Bykov, 1976) tests as well as theoretical studies (Liang et al., 2012; Karthigeyan et al., 2007; Madhav and Sarma, 1982) reached opposite conclusions for the pile embedded in clay. The contradiction regarding the effect of vertical loads on the lateral responses of piles found in the

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experimental results was considered to stem from the restraint condition of the pile head during loading (Lee et al., 2011, 2013), and other possible reasons for this contradiction, such as the soil properties (i.e., for the pile embedded in sand, the confining stress increases with vertical loads, while the interface between the pile and the surrounding clayey soils fails early in the presence of vertical loads) and the lateral load level (i.e., for higher load levels and thus larger lateral displacements, the importance of the favorable influence of the vertical load on the pile's lateral response decreases due to geometrical non-linearity), were given by Karthigeyan et al. (2007), Achmus and Thieken (2010b) and Liang et al. (2015a) in theoretical studies.

Moreover, when studying the vertical loads effect on the lateral responses of pile foundations under scour conditions, another significant difficulty is that scour holes formed around the piles usually involve certain shapes and sizes and meanwhile, the remaining soils have undergone an unloading process associated with new stress states. The latter of unloading produces the changes of stress history of the remaining soils and hence their resistances provided to the pile foundations as well. Although limited number of studies have been conducted to investigate the behavior of laterally loaded piles under scour conditions (Daniels et al., 2007; Bennett et al., 2009; Lin et al., 2010b, 2014a; 2014b, 2016; Li et al., 2013), however, most of them have been largely limited to ignoring either the effect of scour-hole geometry, or that of the stress history characterized by the over-consolidation ratio (OCR).

The objective of this paper is to present a simplified analysis procedure to investigate the influence of vertical load on the lateral responses of offshore piles considering scour-hole geometry and stress history of marine clay. The major contribution to this procedure included (1) the application of a variational approach proposed by the authors in Liang et al. (2015a) for the analysis of vertical loads effect on the lateral response of fully embedded piles to further consider the exposure of the pile due to scour, in which the combined effect of the lateral reaction pressure, the vertical shear stress along the pile shaft, and the normal stress at the pile base are accounted for; and (2) the modification of the key soil parameter given in the proposed model (i.e., the Young's modulus of marine clay) to account properly for the effects of the three-dimensional scour-hole geometry as well as of the stress history of the soils, whose procedures are similar to those presented by the authors in Zhang et al. (2017). With the simplified procedure, a case study is subsequently used to analyze the scour-affected behavior of laterally loaded piles in marine clay with the combination of vertical load.

2. Analysis procedure

A pile having length l and diameter d, subjected to lateral load H_t, bending moment M_t and vertical load P_t at the head simultaneously, is assumed to be embedded in a normally consolidated homogenous marine clay before the scour event as shown in Fig. 1. In this figure, a typical scour hole with the dimensions defined by the scour depth S_d, width S_w and slope angle α, which has been successfully used by Zhang et al. (2017) for a laterally loaded single pile under scour condition, is assumed to be formed around the pile for the demonstration purposes, and the center of the scour hole at the ground surface is set to be the origin of the axisymmetrical cylindrical coordinate system (r, θ, z).

The effect of vertical load on the lateral response of pile foundation under scour conditions, which has not been studied before, is analyzed by means of the analytical model proposed by the authors in Liang et al. (2015a). Further, in the analysis procedure, to satisfy the scour conditions (including scour-hole dimensions and stress history effect), the embedded length of the pile is altered, and the key soil parameter of the analytical model and other corresponding soil properties are modified appropriately based on the framework developed by the authors in Zhang et al. (2017). The main analysis procedures are outlined briefly for completeness in the following.

2.1. Description of the analytical model proposed by the authors in Liang et al. (2015a)

The analytical model summarized herein was proposed by the authors in Liang et al. (2015a) for the analysis of vertical loads effect on the lateral response of offshore pile without any scour ($S_d = 0$). For a single pile subjected to both the lateral and vertical loads, the total potential energy π_p can be written as

$$\pi_p = U_p + \frac{1}{2}\iint_S \tau_z w_z \mathrm{d}s + \frac{1}{2}\int_l p_z \rho_z \mathrm{d}dz + \frac{1}{2}\iint_A \sigma_b w_b \mathrm{d}A - P_t w_t - H_t \rho_t - \frac{\partial \rho_t}{\partial z} M_t \tag{1}$$

In Eq. (1), the first term U_p equals elastic strain energy of the pile (see Liang et al., 2015a). The second and third terms are, respectively, the work done by the vertical shear stress τ_z and the lateral reaction pressures p_z along the pile shaft, where w_z and ρ_z are, respectively, the vertical and the lateral displacements of the pile at depth z and S is the surface area of the pile. The fourth term is the work done by the normal stresses σ_b at the pile base, where w_b is the vertical displacement at the pile base and A denotes the cross-sectional area of the pile. The last three terms are the works done by the vertical load P_t, by the lateral load H_t, and by the applied moment M_t at the pile head, where w_t and ρ_t are, respectively, the vertical and lateral displacements of the pile at the pile head.

By using Gauss integration and assuming uniform σ_b and w_b at the pile base, Eq. (1) can be rewritten as

$$\pi_p = U_p + \frac{1}{2}\{\rho w\}^T [k_s] \{\rho w\} - P_t w_t - H_t \rho_t - \frac{\partial \rho_t}{\partial z} M_t \tag{2}$$

where $\{\rho w\}$ is the vector that include the lateral displacements (ρ_{qi}) and the vertical displacements (w_{gi}) of the pile at the Gauss points as well as the vertical displacement w_b at the pile base. Here ng and nq are the number of Gauss points chosen for the pile along its shaft. $[k_s]$denotes the soil stiffness matrix, which is described in a subsequent section.

The lateral and the vertical displacements of the pile, which can be represented by finite series as given by Liang et al. (2015a), can be written as

$$\rho_z = \{Z_{hm}\}^T \{\beta_{hm}\}, . w_z = \{Z_v\}^T \{\beta_v\} \tag{3}$$

where $\{Z_{hm}\}$ and $\{Z_v\}$ are the vectors related to only the depth coordinate z; $\{\beta_{hm}\}$ and $\{\beta_v\}$ containing undermined constants. Thus, with the application of the principle of minimum potential energy, Eq. (2) can be reduced as

$$\frac{\partial U_p}{\partial \delta_j} + \left\{\frac{\partial \rho w}{\partial \delta_j}\right\}^T [k_s]\{\rho w\} = \left\{\frac{\partial w_t}{\partial \delta_j}\right\}^T P_t + \left\{\frac{\partial \rho_t}{\partial \delta_j}\right\}^T H_t + \left\{\frac{\partial\left(\frac{\partial \rho_t}{\partial z}\right)}{\partial \delta_j}\right\}^T M_t \tag{4}$$

where δ_j are the coefficients in the vectors $\{\beta_{hm}\}$ and $\{\beta_v\}$.

The soil load-deformation relationship (i.e., the soil stiffness matrix $[k_s]$ described in Eq. (2)) can be determined based on the point-load solution by Mindlin (1936). Specifically, the lateral reaction pressures and the vertical shear stresses at depth z are first approximated by the following two finite series (see Liang et al., 2015a)

$$p_z = \{Z_p\}^T \{\alpha_p\}., \tau_z = \{Z_\tau\}^T \{\alpha_\tau\} \tag{5}$$

where $\{Z_p\}$ and $\{Z_\tau\}$ are the vectors related to only the depth coordinate z; $\{\alpha_p\}$ and $\{\alpha_\tau\}$ containing undermined constants. Then, the vector $\{\rho w\}$ in Eq. (2), which represent the displacement of the pile, can be rewritten as

$$\{\rho w\} = [f]\{\alpha\} \tag{6}$$