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On the influence of vertical loads on the lateral response of pile foundation

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ABSTRACT

The influence of vertical loads on the lateral response of group piles installed in sandy soil and connected together by a concrete cap is studied through finite elements analyses. The analyses focus on the five piles in the middle row of 3×5 pile groups. The vertical load is applied by enforcing a vertical displacement equivalent to 2% of the pile diameter through the pile cap prior to the application of the lateral loads. The results have shown that the lateral resistance of the leading pile (pile 1) does not appear to vary considerably with the vertical load. However, the vertical load leads to 23%, 36%, 64%, and 82% increase in the lateral resistance of piles 2–5, respectively. The increase in the lateral pressures in the sand deposit is the major driving factor to contribute the change in the lateral resistance of piles, depending on the position of the pile in the group. The distribution of lateral loads among piles in the group tends to be more uniform when vertical loads were considered leading to a more economical pile foundation design.

1. Introduction

Pile foundations have been used for many years in building and bridge structures to support vertical and lateral loads. Studies on these foundations may be categorized into those on the behavior of pile foundations under vertical loads [1–4] and those under pure lateral loads [5–9]. The former category of studies led to the methodologies to evaluate bearing capacities and settlements of piles, while the latter led to evaluate bending moments and deflections. The results of these extensive studies have formed the basis for the current design practice of pile foundations, where vertical and lateral loads were assumed to act independently, and the interaction between these loads was not significant. This is obviously not true, as the pile foundations for several types of structures are often subjected to simultaneous vertical and lateral loading. The separate consideration of the vertical and lateral loading therefore cannot be expected to account properly for the pile behavior.

Only a few experimental studies have been conducted to investigate the behavior of piles under combined loading. Meyerhof et al. [10] and Meyerhof and Yalcin [11] investigated through model tests the effects of lateral loads and bending moments on the vertical bearing capacity of single and group piles and they suggested a significant decrease in the vertical bearing capacity due to the presence of lateral loads or bending moments. On the other hand, the results available in the literature are inconsistent with respect to the effects of vertical loads on the lateral response of piles. Early analytical investigations [12,13] reveal that for a given lateral load, the lateral deflection increases with the combination of vertical load. However, recent studies based on experimental investigations [14] and numerical analyses [15–18] suggest a decrease in lateral deflection with the combination of vertical loads. In fact, the scopes of these recent studies were limited to the behavior of free-head single and group piles. Yet, little work has been devoted to investigate the effect of vertical loads on the lateral response of piles in groups where reinforced concrete caps attached to ground surface and fastened at piles-heads to connect the piles together in the group.

The objective of this study is to investigate numerically the influences of vertical loads on the deformation and internal forces of both free-head and capped pile groups. The three-dimensional (3D) analysis based on finite elements (FE) or finite differences (FD) methods is the most appropriate numerical method for the analysis of the soil–pile system. However, it is computationally

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intensive and time consuming. Therefore, several investigators attempted to develop new procedures to simplify these rigorous 3D FE and FD models. For example, Ozutsumi et al. [19] proposed a simplified approach to idealize the soil–pile interaction in 3D type into the two-dimensional (2D) analysis using soil–pile interaction springs with non-linear load-displacement relationships. In this paper, a 2D FE analysis based on a multi-shear mechanism constitutive relationship, FLIP [20] was used. The interaction between a pile and the surrounding soil in 3D type was idealized in the 2D analysis using the soil–pile interaction springs concept proposed by Ozutsumi et al. [19]. The constitutive model used in FLIP has a potential capability to take into account the stress change induced in the soil due to vertical loads applied to piles prior to the application of lateral loads. In this model, directional shear stress contributions due to contact forces between soil particles are idealized by evenly distributed multiple springs, whose property is characterized by a non-linear load-deformation relationship. The model automatically accommodates the principal stress rotation, which has a significant effect on the strength and deformation behavior of soils. In addition, the applicability of the computer code FLIP to the analysis of pile groups under lateral loads has been confirmed through a study based on a full scale test of a 3×5 pile group at the Salt Lake City International Airport.

After the description of the multiple shear mechanism model for soil used in this study, a brief review is given to the applicability of the model to the full scale lateral load test of a 3×5 pile group. This paper then presents the initial part of the study that analyses the effect of vertical loads on the lateral resistance of free-head and capped single piles; to be followed by the main part of the study with respect to the behavior of free-head and capped pile groups under combined loads. The primary findings from this study were summarized as conclusions.

2. Finite element modeling and parameter identification

2.1. Finite elements

The 2D FE program FLIP was employed to study the behavior of free-head and capped pile groups under combined loading. Steel pipe piles with a 0.324 m outside diameter and wall thickness of 9.5 mm were considered. The piles in the group were arranged in a 3×5 pattern with a nominal spacing of a 3.92*D* (*D* = pile diameter) from center to center in the lateral loading direction and of a 3.29*D* perpendicular to the loading direction. The 2D FE analysis focused on the five piles in the middle row of the group. Two cases of numerical analyses were primarily considered: a free-head pile group case, in which the top and bottom of the piles were set as displacement and rotation free, and a capped pile group case in which a concrete cap with 0.495 m thickness attached to the ground surface is added above the piles-heads. Fig. 1 shows the general layout and meshing of the FE model with a concrete cap attached to the ground surface. Side boundary displacements were fixed in the horizontal direction, while those at the bottom

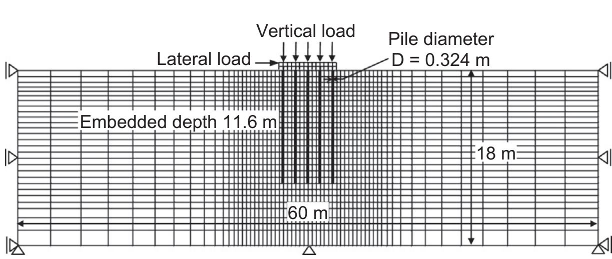

Fig. 1. General layout and meshing of the finite element model for the capped pile group case.

boundary were fixed in both the horizontal and vertical directions. Prior to the analysis of pile group behavior, analyses of free-head and capped single piles were performed as references in order to discuss the specific behavior of the pile group under combined loads. The same meshing of the soil profile was used to analyze the single piles. Dimensions of pile caps in both single and group pile cases considered in the analyses are shown in Fig. 2.

A total of 8 cases including single and group piles with and without pile caps were considered. Pure lateral loads were considered in half of these cases while a combination of vertical and lateral loads was considered in the others. For both single and grouped pile cases, the combined loads are applied in two stages. In the first stage, a vertical working load (i.e. a vertical load equals to 33% of the ultimate vertical load capacity of the pile, given a factor of safety of 3) inducing a vertical displacement (*V*) of 0.02*D* was applied on the pile head or through the pile cap. The ultimate vertical load capacity was evaluated a priori by a separate numerical analysis of single pile subjected to a pure vertical load and it was estimated as 490 kN (corresponding to the point with maximum curvature on the vertical load-settlement response). In the second stage, a lateral load was applied until a target lateral displacement of 80 mm was achieved. The target lateral displacement of 80 mm corresponds to the maximum attainable pile head displacement without numerical instability. The maximum vertical applied displacement at the pile head or through the pile cap was kept constant during the application of the lateral displacement.

2.1.1. Soil model

The soil model used in this study consists of a multiple shear mechanism [20]. The model is formulated based on the concept of contact forces in granular media. In this model, contact forces between soil particles are idealized by evenly distributed multiple springs as shown in Fig. 3, whose property is characterized by a non-linear load-deformation relationship. The multiple shear mechanism soil model is now widely used in design practice, especially for designing geotechnical structures in port and harbors in Japan [21]. In what follows, the core of the soil modeling is briefly introduced. Let us consider the following vectors of stresses and strains:

$$\{\sigma'\}^T = \{\ \sigma'_x \quad \sigma'_y \quad \tau_{xy}\ \} \tag{1}$$

$$\{\varepsilon\}^T = \{\ \varepsilon_x \quad \varepsilon_y \quad \gamma_{xy}\ \} \tag{2}$$

where σ'_x and σ'_y are normal stresses. ε_x and ε_y are normal strains in x and y directions, respectively. τ_{xy} and γ_{xy} are shear stress and shear strain, respectively. The incremental form of the constitutive relationship can be written as

$$\{d\sigma'\} = G_{L/U}\{n_{L/U}\}\{n\}^T\{d\varepsilon\} \tag{3}$$

where the vector $\{n_{L/U}\}$ specifies direction of stress increment, the scalar $G_{L/U}$ defines the magnitude of stress increment per unit strain increment along the direction $\{n\}$, and vector $\{n\}$ gives the direction of strains. The subscripts L/U indicate that the components are different in the directions of loading L and unloading U. Iai et al. [20] postulated that the incremental constitutive relation, Eq. (3), is given by $I+1$ separate mechanisms for $i = 0$ to I in associated form (i.e. $\{n_{L/U}\} = \{n\}$) as

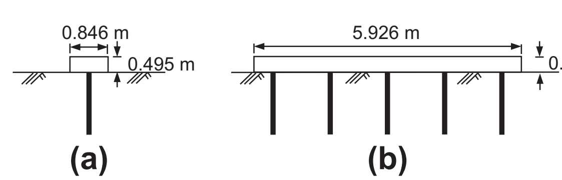

Fig. 2. Pile cap dimensions: (a) single pile and (b) group pile.