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On the behaviour of pile groups under combined lateral and vertical loading

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ABSTRACT

The effect of vertical loads on the lateral response of a 3×5 pile group embedded in sandy and clayey soils is studied through 3D finite differences analyses using the computer code FLAC3D. In the numerical model, the piles were treated as a linear elastic material and the soil was idealized using the Mohr-Coulomb constitutive model with a non-associated flow rule. Vertical loads, inducing a vertical pile head displacement of 0.01-pile diameter, were applied prior to the application of the lateral loads. Numerical results showed that the lateral resistances of the piles installed in sandy soil increase with vertical loads. However, the presence of vertical loads on piles embedded in clay reasonably decreases their lateral capacities. The increase and decrease in the lateral stress in the sandy and clayey soils, respectively, are the major driving factors to contribute the change in the lateral resistance of piles, depending on the pile position in the group and its lateral deflection. 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 are extensively used to support various structures built on loose/soft soils, where shallow foundations would undergo excessive settlements or have low bearing capacity. These piles are not only used to support vertical loads, but also lateral loads and combination of vertical and lateral loads. Yet, the vertical and lateral responses of piles are often evaluated separately without considering their possible interactions. This approach is valid only for small lateral loads (Christenson and Scott, 1983; Brown et al., 1988), however, in case of pile groups, the lateral loads are significantly high and in the order of 10–20% of the vertical loads. In such cases, studying the interaction effects and the pile group behaviour (i.e. lateral capacity and bending moment) due to combined vertical and lateral loads is very essential. In general, the pile group should not be only designed or analyzed to support vertical loads or lateral loads separately but always a simultaneous combination of the vertical and lateral loads.

Piles are always constructed within a group and the position of pile within the group directly affects the pile performance especially its lateral behaviour (Brown et al., 1988; Rollins et al., 1998). For example, the piles in trailing (back) rows are thought to exhibit less lateral resistance because of interference with the failure surface of the row of piles in front of them (Rollins et al., 2006). This group interaction effect is expected to become more significant as the spacing between piles decreases because there is more overlap between adjacent failure planes (Rollins et al., 2006). The method accounting for the group reduction effects is to reduce the modulus or the soil resistance, *p*, from a single pile *p-y* curve using a constant reduction factor or p-multiplier (*fm*) first introduced by Brown et al. (1988). This simple approach has provided relatively good estimates of measured pile group response (Brown et al., 1988; Rollins et al., 1998). However, the values of the p-multiplier always depend only on the magnitude of lateral load.

Many investigators have studied assessments of the behaviour of laterally loaded pile group using three dimensional (3D) finite element (FE) or finite differences (FD) method (Muqtadir and Desai, 1986; Trochanis et al., 1991; Kimura et al., 1995; Hazzar et al., 2013a). On the other hand, little numerical work has been devoted to the behaviour of pile group (and even single pile) subjected to combined effects of vertical and lateral loads. A series of 3D FD analyses is conducted by Hazzar et al. (2016) to evaluate the influence of vertical loads on the lateral performance of single pile. Numerical results showed that the lateral resistance of the piles does not appear to vary considerably with the vertical load in sandy soil. However, the presence of a vertical load on a pile embedded in homogeneous or inhomogeneous clay is detrimental to its lateral capacity, and it is unconservative to design piles in clays assuming that there is no interaction between vertical and lateral loads. Hussien et al. (2012, 2014), using two dimensional (2D) FE models, reported a little increase in the lateral capacity of free-head group pile installed in sandy soil due to the presence of vertical loads

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and attributed this increase to the increase in the confining pressures in the sand deposit surrounding the upper part of the pile. Achmus and Thieken (2010) used the 3D FEM to investigate the behaviour of single pile in sandy soil under combined lateral and vertical loading, and they reported that the combined loading on piles induces interaction effects due to simultaneous mobilization of passive earth pressure due to lateral loads and pile skin friction due to vertical loads. Karthigeyan et al. (2006, 2007) showed through a series of 3D FE analyses on single piles that the presence of vertical loads increases the lateral load capacity of piles in sandy soil and decreases it in clayey soil.

In view of the above mentioned issues, all lateral response on pile groups were studied by non-simultaneous actions of both axial and lateral loads. Thus, this study aims to assess the influence of simultaneous load combinations on the lateral pile group action using 3D FD approach in FLAC3D software (Itasca, 2009). Two types of soil (a sand and a clay) were used for comparison. Numerical models are validated with results from full scale lateral load test of a 3×5 pile group and then analyses were carried out to investigate the influences of vertical loads on the lateral capacity and bending moment of piles. The main intention of this paper is to improve our understanding of and ability to evaluate the effect of vertical loads on the lateral resistance and the group reduction effects in sandy and clayey soils. Combined load analyses were performed for vertical loads equal to 100% of the ultimate vertical load capacity of the pile.

2. 3D FD modelling and parameter identification

2.1. FD mesh and boundary conditions

The 3D FD program *FLAC^{3D}* (Itasca, 2009) was employed to study the behaviour of free-head single and group piles corresponding to a given soil profile and pile dimension under combined lateral and vertical loads. Steel pipe piles with an embedment depth of 11.6 m, a 0.324 m outside diameter, *D*, and a 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* from center to center in the lateral loading direction and of a 3.29*D* perpendicular to the loading direction (Fig. 1). The 3D FD analysis focused on the single pile and the 15 piles of the group. A grid generator subroutine has been implemented using the *FISH* built in programming language providing the possibility of mesh refinement and geometry variation according to the specific group configuration. Fig. 2 illustrates the finite difference grid of a 3×5 pile group. The soil-pile system was meshed with 8-node brick elements, and the soil elements are fairly small adjacent to the pile

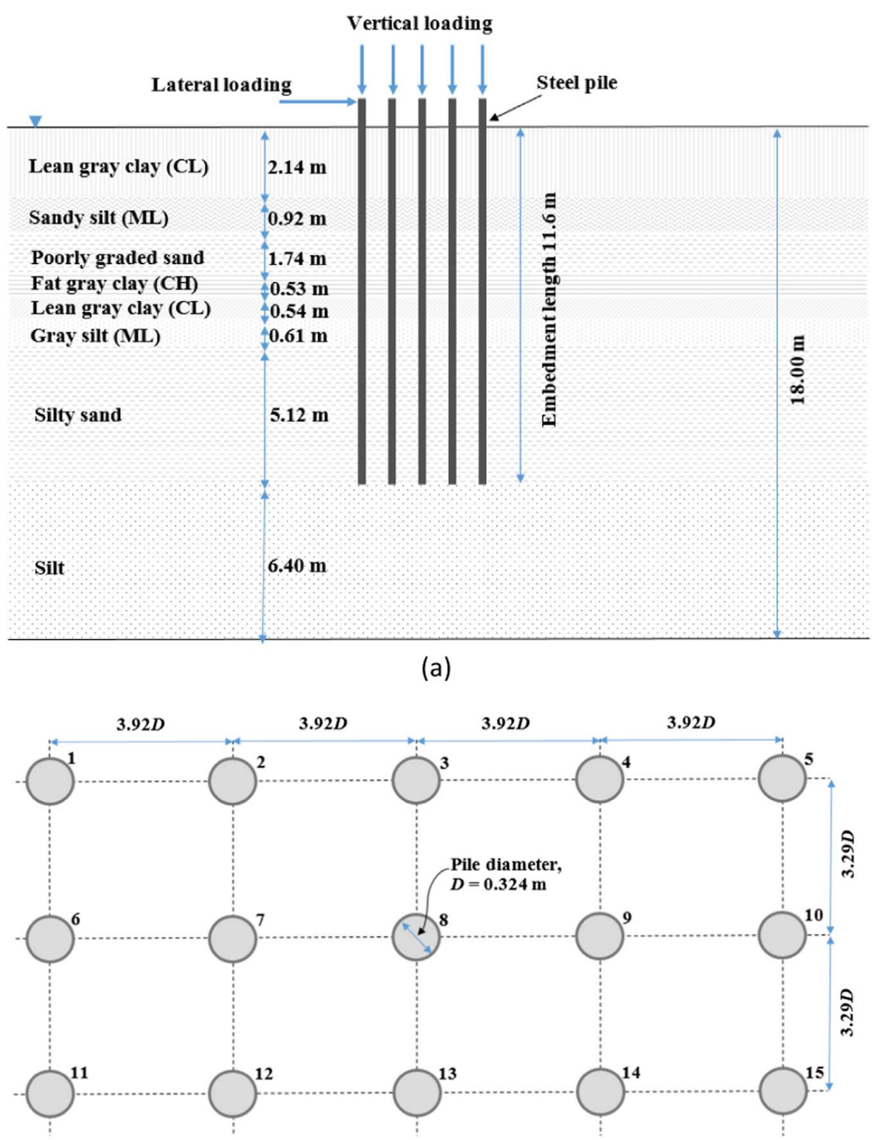

Fig. 1. Pile group configuration: (a) longitudinal section corresponding to the middle of the pile group and (b) plan view of the pile group.