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Research Paper

Settlement and load transfer mechanism of a pile group adjacent to a deep excavation in soft clay

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ABSTRACT

Three-dimensional coupled consolidation analysis is conducted to gain insight into the response of a 2 × 2 floating pile group adjacent to deep excavation in soft clay. By using a validated finite element model, the influence of the excavation depth, pile length, pile group location from excavation, the supporting system stiffness, soil state and permeability, and working load are systematically studied. The analysis revealed that the maximum settlement occurs when the pile group is founded at the excavation level and at a distance of 0.75-times the excavation depth, although the induced bending moment is minimum. In contrast to pile group settlement, tilting is maximum when it gets closer to the wall and minimum at a distance of 0.75-times the excavation depth. It is also observed that the influence of system stiffness is more pronounced for the flexible wall and when the pile group is located at the excavation level. Applied working load influences pile group settlement but has relatively minor effects on pile group tilting. Excess negative pore water pressures are generated in the soil elements due to excavation. Pile group experiences progressive long term settlement with the dissipation of excess negative pore water pressure.

1. Introduction

The development of underground space induces ground movements and stress relief in the surrounding soil, which might affect the existing structures. These underground infrastructures are usually constructed in the proximity of high-rise buildings and bridge foundations, which are normally supported by pile foundations [1,2]. Most of the earlier researchers estimated the buildings settlement and tilting considering wall movements and ground surface settlement trough using empirical approaches. The performance of pile foundation depends on the stress state of the soil and the surrounding sub-surface soil movements [3]. In addition, deep excavation in soft clay induces negative excess pore water pressure [4], which induces long-term pile group settlement with the dissipation of excess pore water pressure. Therefore, it is essential to investigate the pile group settlement and load transfer mechanism adjacent to deep excavation in soft soils.

To understand the soil-structure interaction mechanism for deep excavations, many researchers have investigated field monitoring case studies and numerical modelling studies [5–8]. Moreover, to comprehend the pile-soil-excavation interaction mechanism, Finno et al. [1] and Goh et al. [2] reported case studies in granular soil and alluvial residual soil, respectively. They demonstrated that lateral soil movements due to excavation can be detrimental to nearby existing piles. Apart from field monitoring, a number of centrifuge tests were conducted to investigate the response of a single pile [9] and pile group in soft Kaolin clay [10]. The researchers concluded that the induced bending moment and lateral deflection of piles are highly influenced by distance from wall and pile head condition. In these studies, the lateral response of end-bearing piles without initial applied load was reported. However, pile group in soft clay behaves as a floating pile group and is subjected to initial axial load from the superstructure. Poulos and Chen [11] developed design charts to compute the lateral behaviour of a single pile adjacent to deep excavation in soft ground. Liyanapathirana and Nishanthan [12] and Nishanthan et al. [13] studied the response of a single pile and pile group adjacent to deep excavation by using numerical modelling. The focus of these studies was to investigate the lateral deflection of pile foundation due to excavation. Korff et al. [14] developed an analytical model to investigate the reduction in pile capacity and excavation-induced settlement. In this model, the effect of working load and soil pile-relative movement were considered. They concluded that pile settlement induced by pile soil-relative movement and settlement can be assessed on the basis of soil movement at the interaction level. In this approach, excavation induced stress release and soil-pile interaction were not considered.

Most of the previous studies focused on the lateral response of a single pile foundation. The settlement and load transfer mechanism of

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floating pile group combined with the applied working load adjacent to deep excavation in soft clay have not been studied systematically. Moreover, in soft clay, progressive changes in excess pore water pressure with time and consolidation settlement of pile group needs more attention to investigate the long-term response.

In this study, three-dimensional coupled consolidation finite element analysis (FEA) was conducted to investigate the settlement and load transfer mechanism of pile group in soft Kaolin clay due to adjacent excavation. Prior to performing the multi-strutted deep excavation, calibration of numerical model and its soil parameters was conducted using the centrifuge test results reported by Ong et al. [10] and triaxial test reported by Benz [15], respectively. This study aimed to give an insight into the settlement and tilting behaviour of pile group by varying excavation depth, pile length, pile group location from excavation, the supporting system stiffness, soil state, permeability, and initial working load. Also, the progressive changes in excess pore water pressure and long-term settlement of pile group having different pile toe positions relative to the final excavation level are studied.

2. Three-dimensional numerical analysis

Three-dimensional coupled consolidation numerical analysis was performed to investigate the response of an axially loaded pile group adjacent to multi-strutted deep excavation by using Plaxis 3D 2013 [16], a commercially available software package. Typical excavation geometry that is commonly used in modern urban development is shown in Fig. 1. The final excavation depth (H_e) was 20 m and supported by 1-m-thick and 40-m-deep diaphragm wall with ten levels of struts. The struts were spaced 2 m vertically and 3 m horizontally. Steel pipes were used as struts in the analysis, having an outer diameter of 600 mm and thickness of 25 mm. The axial rigidity of the struts was 9.03×10^6 kN. Bottom up excavation supported by struts was adopted in this study, which is commonly used in the industry. Two by two elevated pile group was selected for this fundamental study. Piles were rigidly connected to the pile cap. Elevated pile group was selected to ignore the load transfer through pile cap, which will not affect the fundamental findings of this study. The distance between the wall and front pile (P1) was 5 m and centre to centre spacing between the piles was 5 times the pile diameter (d_p = 1 m). Two pile groups of 1-m-diameter (d_p) piles were selected, which were similar in geometry except for the difference in pile lengths (L_p). One pile group consisted of 20-m-long piles, which were referred as case-A pile group (L_p/H_e = 1), while the other one comprised 40-m-long piles referred as case-B pile group (L_p/H_e = 2). The thickness of the concrete pile cap was 1 m and subjected to uniformly distributed axial load. To investigate the effects of excavation-induced ground movements on floating pile group in normally consolidated Kaolin clay, a total of 20 numerical analysis were conducted as summarized in Table 1.

2.1. Finite element mesh and boundary conditions

Fig. 2 shows the three-dimensional finite element model mesh and boundary conditions adopted in this study. Only half of the excavation width was modelled because of geometrical symmetry. The mesh size 80 m (length along Y-axis), 30 m (width along X-axis), and 80 m (depth along Z-axis) was adopted in this study. The dimensions of the model were large enough to minimize the effect of boundary conditions and capture the primary influence zone of settlement trough induced by deep excavation [17–19]. Soil was modelled using a 10-node tetrahedral element. Waller beam and fixed end anchor were modelled as a 3-node line element. Diaphragm wall and cap were modelled using a 6-node triangular plate element. Diaphragm wall interface was modelled using a 12-node interface element that is built-in available in Plaxis-3D. It consists of a pair of nodes, which is compatible with a 6-node triangular side of soil element or plate element. The details about the elements and interface properties can be found in Plaxis 3D 2013 [16]. The mesh consisted of 45,631 soil elements and 66,823 number of nodes. The soil mesh surrounding the pile group was refined (relative element size factor was 0.25 and element size was 0.595 m) and become coarser further away from the pile group (relative element size factor of 1 and average element size is 1.596 m). Fig. 2 illustrates the boundary conditions adopted in this analysis. Regarding displacement boundary conditions, all the vertical sides were fixed horizontally by providing roller support, while the base was restricted in all the directions by using pin support. The top of the model was allowed to move in any direction. Hydraulically, throughout the analysis no change in pore

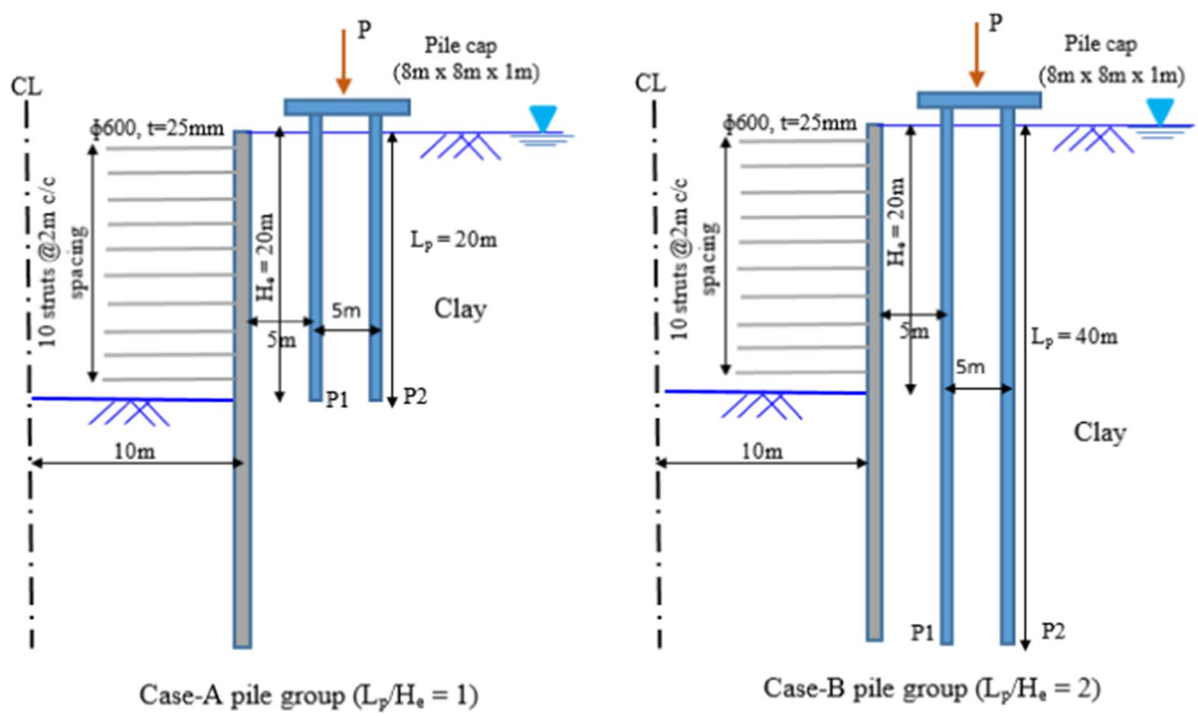

Fig. 1. Typical geometry problem selected in the analysis.