Analysis of soil movement around a loaded pile induced by deep excavation

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Abstract. The change of the bearing capacity of an adjacent pile induced by the excavation of a foundation pit involves the complex interaction between the retaining structure, soil, and loaded pile. Thus, the study of the displacement field of the soil around the pile is very important. A three-dimensional finite element model was established and the influence of pile spacing and pile-cap spacing on the displacement of soil around the pile was analyzed. The pile foundation could restrain the settlement of the soil around the pile. In addition, the soil within 20 m below surface was obviously affected with an influence coefficient of 0.7. The results show that when the pile-cap spacing is less than 50 m, the soil settlement coefficient changes approximately linearly. Moreover, an empirical formula is obtained for the reduction coefficient.

1. Introduction

With the deepening of underground space development, urban railway transit projects, which are the focus of underground space development, have received increasing attention. Urban railway metro stations require the construction of a large number of subway stations. At present, the area of excavation is increasing in volume and depth. The foundation of excavation project presents larger, deeper, and tighter features [1]. Frequent occurrence of accidents have also been reported because of the engineering of deep and large foundation pits, leading to deformation, destruction, and even collapse of adjacent buildings. For the soft-soil areas in southeast China, the problem of deformation and even damage of adjacent pile foundations caused by excavation should not be underestimated. The relationship between deep excavation and displacement field of adjacent soil is shown in Figure 1.

Scholars have studied the law of displacement field around deep-excavation areas, for example, Peck [2], Blackburn and Finno [3], Wang et al. [4], Ou et al. [5], and Moon et al. [6]. Schuster et al. [7] combined the previous research experience and conducted a comparative study on the lateral and vertical displacement of different types of walls. Mu and Huang [8] used the finite element method to study the surrounding soil formed by the excavation. The hardening-soil model was adopted as the soil constitutive model. By conducting back analysis of the measured data of an excavation project in Chicago, different calculation formulas were proposed for the three-dimensional (3D) soil-
displacement field caused by the excavation. Leung et al. [9] used centrifugal tests to discuss the effects of excavation on foundations of adjacent buildings without support.

Figure 1. Displacement field around the pile induced by excavation.

The present research focuses mainly on the law of the soil-displacement field when there is no building facility around the retaining structure. When there is a pile foundation structure around the retaining structure, the presence of the pile foundation will change the force state in the active zone. The loaded pile foundation transfers part of the load to the retaining structure; this involves the complex interaction between the retaining wall, soil, and pile foundation. The law of the soil-displacement field under this condition needs to be further clarified.

2. Interaction mechanism between retaining structure, soil, and pile
The displacement field around the soil is related to the existence of the pile foundation around the retaining wall, and is generally reflected in the following aspects. (1) If the pile foundation around the enclosure is in service, the load is transmitted to the retaining wall. (2) If a pile foundation exists around the envelope structure, the soil displacement behind the pile is limited by the pile foundation. (3) Owing to the limitation and influence of the pile foundation, the soil behind the pile is strengthened. Therefore, the excavation of a foundation pit involves a complex interaction between the retaining structure, soil, and pile foundation.

3. Establishment of a finite element model
The influence of the pile foundation on the displacement field around the retaining structure is study. Meanwhile, the distance between the pile platform is divided into 10 and 20 m; the pile spacing is divided into 2, 3, and 4 m, respectively. A four-pile cap was used with dimensions of 4 m × 4 m. Moreover, the uniform load value was 1000 kN/m² and the pile length was 50 m, which was approximately 2 times the depth of excavation. Further, the pile diameter was 1 m. Figure 3 shows the plaxis 3D finite element calculation model.
4. Analysis of numerical results

4.1. Influence of pile foundation on soil-settlement value around the pile

The soil around the pile 10 and 30 m away from the retaining structure was selected as the research object. Figure 4 shows the soil settlement at different locations.

Figure 4 shows that there is a significant difference in the settlement pattern at distance of 10 and 30 m from the retaining wall. In addition, the change patterns of the soil settlement with and without the pile foundation are different. At the distance of 10 m from the retaining structure, the soil settlement, in the presence of the pile foundation, remains unchanged with the increase of depth in the range of 0–20 m (0–1.0 $H_e$). At the depth of 20–35 m (1.0–1.75 $H_e$), the soil settlement decreases linearly. At the distance of 30 m from the retaining structure, the settlement of the soil behaves in a “cantilever” manner, that is, with the increase in depth, the settlement of the soil decreases approximately linearly. When the pile foundation exists, the surface settlement value is 0.5 times that of the surface settlement with no pile foundation. According to the above-mentioned analysis, when the pile spacing is 20 m, the soil settlement has a certain reduction when the pile foundation exists compared with no pile foundation. The reduction coefficient is approximately 0.7 in the first row, and the reduction coefficient of the second row is approximately 0.5 times that of the first row. Therefore, the reduction in the soil settlement in the second row can be seen as the accumulation of the reduction factor.
4.2. Influence of pile-cap spacing and pile spacing on soil settlement

To better study the variation law of soil settlement around the pile foundation, soil settlements between the retaining structure and pile cap, between loaded piles, and behind the pile cap were extracted from the Plaxis calculation results (Figure 5).
When there is no pile foundation around the retaining structure, the soil settlement increases first, and then decreases with the increase in depth. At the depth of 10 m (0.5 $H_e$) from the surface, the soil settlement reaches its maximum value. Figure 6 shows that when the pile foundation exists, the settlement of the soil around the pile foundation first remains unchanged and then decreases to 0. Therefore, the trend of the soil settlement around the pile can be approximated as shown in Figure 6.

To study the influence of soil settlement on the bearing capacity of pile foundation, the average value of soil settlement at different locations was studied. The comparison of Figures 5 (a), (c), and (e) shows that when the pile spacing is 10 m, it has a slight effect on the settlement value and trend of the soil. At the depth of 0–20 m (1.0 $H_e$), the average settlement of the soil is maintained at approximately 12 mm. At 20–35 m (1.0–1.75 $H_e$), the soil settlement is reduced from 12 to 0 mm. Similarly, the comparison of Figures (b), (d), and (f) shows that at 0–20-m depth (1.0 $H_e$), the average settlement of the soil is maintained at approximately 14 mm, and at a depth of 20–35 m (1.0–1.75 $H_e$), the soil settlement decreased from 14 to 0 mm.

Figure 7 shows that the influence of the pile-cap spacing on the settlement of the soil is greater than the influence of the pile spacing on the soil settlement. To better study the influence of the bearing spacing on the soil settlement, Figure 7 analyzes the influence of the pile-cap spacing on the settlement-reduction coefficient. The reduction factor is defined as the ratio of the settlement value of the soil around the pile to that without the pile foundation. When the spacing between the caps is 0 m, the reduction factor is 0.5. When the pile spacing is large enough, the reduction factor is 1, that is, the pile foundation has no effect on the soil settlement value. The formula for the reduction factor and pile-cap spacing can be simplified as

$$\beta = \begin{cases} 0.5 + 0.01D, & D \leq 50 \\ 1.0, & D > 50 \end{cases}$$

where $D$ is the pile-cap spacing.
5. Conclusion
By establishing a 3D finite-element-calculation model, the influence of the pile-cap spacing and pile spacing on the law of the displacement field around the retaining structure was analyzed. The following main conclusions were drawn from this study.

1. The exist of pile foundation hinder the settlement of the soil around the pile. The pile foundation has a great influence on the soil movement within 20 m below the surface, and the soil reduction coefficient is 0.7.
2. The pile-cap spacing has a great influence on the soil around the piles. According to the parameter analysis, when the spacing between the piles is less than 50 m, the soil-settlement coefficient decreases linearly and an empirical calculation formula was obtained for the reduction factor.

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