Study on Influence of Soil Hardness Change on Pile Bearing Capacity and Settlement in Single Bearing Layer of Pile End

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Abstract. The bearing capacity and settlement of the pile are indispensable in the calculation and verification of the pile footing, and the diverse bearing layers of the pile foundation will have different effects on the ultimate strength of the pile and the pile’s settlement. Because of the selectivity and transformability of stratum structure, how to optimize the selection and reinforcement of stratum structure is of great significance to the economy and safety of engineering. Therefore the FEM is used to analyze the Sutong Bridge (large-diameter super-long bored pile) as an example, and then the influence of soil hardness change on pile bearing capacity and settlement is studied.

1. Introduction

The stratigraphic structure is a superimposed, stacked or spatially combined state of the strata within the stratigraphic sequence. The concept of stratigraphic is mainly used to study and describe the vertical and horizontal total (or dominant) accumulation of rock formations in the bottom interval of the equivalent or slightly less than one system domain. “Geophysical stratigraphic effect” means that the stratum structure has an important influence on the stress, deformation and stability or safety and economy of various geotechnical projects. The same project can be selected in different stratum structures, or The selected stratum structure is artificially modified to make it more suitable or more conducive to the project\textsuperscript{[1]}.

A large amount of data shows that after changing the properties of the pile end soil, the relationship between the pile bearing capacity and the pile end resistance will change\textsuperscript{[2]}. In this paper, the piles are selected. Because of the simple and light construction equipment, such piles are easy to relocate in mountainous areas and rural areas with inconvenient transportation, and the prices are relatively low. From micro piles to giant piles, it can be constructed from soft soil foundation. It can be piled into hard rock and has a wide range of applicability. Therefore, studying the hardness change of the soil at the pile end has important theoretical significance and practical value for the bearing capacity and settlement of the pile.

At present, the static load test method, in-situ test method and empirical parameter method are generally adopted for the ultimate bearing capacity of a single pile in engineering. Load transfer analysis method, layered sum method, elastic theory calculation method and shearing are generally adopted for single pile settlement. The cutting deformation transfer calculation method and the simplified algorithm proposed by the specification. However, most of the above methods are cumbersome and have large errors. Therefore, based on the elastoplastic theory, the FEM is used to numerically imitate the rigid large-diameter and extra long bored piles.
2. Elastic-plastic finite element model analysis and determination of ultimate bearing capacity and corresponding settlement

2.1. Project example

The Sutong Bridge test pile project consists of 6 bored piles. To verify the feasibility of the FE Model, this article numerically simulates the pile foundation loads and settlement of the N1 pile on the North Shore.

According to the field measured data[3], the geometric calculation data is shown in Table 1 and Table 2 below. The radius of the soil is taken as 100m, which is much larger than the radius of the pile; the lateral pressure coefficient is 0.85.

Table 1. N1 pile parameters.

| Test pile number | Diameter (m) | The top elevation of pile (m) | The bottom elevation of pile (m) | The length of pile (m) | Young’s Modulus (Gpa) | Poisson’s ratio |
|------------------|--------------|-------------------------------|-------------------------------|-----------------------|-----------------------|----------------|
| N1               | 1            | 2.2                           | -73.8                         | 76                    | 30                    | 0.2            |

Table 2. Soil parameter.

| Number of layers | The name of the soil | Density (g/cm³) | Modulus of deformation (MPa) | Poisson’s ratio | Cohesion (kPa) | Angle of friction (°) | The elevation of bottom |
|------------------|---------------------|-----------------|------------------------------|-----------------|-----------------|------------------------|------------------------|
| 1                | Silt and sub-clay   | 1.89            | 20.57                        | 0.37            | 15.0            | 25.8                   | -21.8                  |
| 2                | Silt                | 1.91            | 23.85                        | 0.33            | 9.0             | 31.1                   | -29.2                  |
| 3                | Sub-clay            | 2.05            | 24.13                        | 0.41            | 83.0            | 18.4                   | -50.8                  |
| 4                | Silt                | 1.93            | 30.83                        | 0.31            | 32.5            | 31.3                   | -58.8                  |
| 5                | Fine sand           | 1.96            | 32.12                        | 0.32            | 32.0            | 32.3                   | -100.0                 |

2.2. Feasibility verification of finite element model

The accuracy of the calculation results mainly depends on the rationality of the finite element model and the accuracy of the constitutive model and the calculated parameters. For the vertical analysis of large-diameter super-long piles, this paper uses the three-dimensional model for calculation[4]. In order to improve the calculation efficiency, the cell mesh is thinner near the contact surface of the pile and soil, while the mesh is relatively sparse in the soil away from the contact surface.

The grid of the soil is shown in Figure 1. The elastic analysis is used for the pile body, and the soil is analyzed by the elastoplastic body, and we used the Mohr-Coulomb mode to study it. In the contact simulation of ABAQUS, a contact pair is established on the upper surface of the component, and a master-slave contact is used. The model calculation results are shown in Figures 2a and 2b.
As can be seen from the figure, the finite element calculation results are basically close to the experimental results. Therefore, the finite element simulation method is feasible at the level of this research.

2.3. Determination of ultimate load and corresponding sedimentation of pile foundation

The ultimate compressive ultimate bearing capacity of a single pile can be determined according to the characteristics of the settlement with load changes[5]:

① For the curve of steep drop Q-S, the load value at the starting point where the steep drop occurs and the corresponding settlement should be taken.

② For the curve of slowly Q-S, the load value where S=40mm should be taken according to the total deposition of the pile top; for the pile with the diameter not less than 800mm, the load value corresponding to S=0.05D (D is the diameter of the pile end) can be taken; If the length is greater than 40m, the elastic compression of the pile body should be considered.

3. Case Analysis

3.1. Establishment of pile-soil model

In order to study the influence of hardness change of bearing soil on pile bearing capacity and settlement, taking the Sutong Bridge N1 test pile as an example, three kinds of working conditions are
set in the soil of the bearing layer for analysis, and the other parameters are unchanged (see Table 1 and Table 2).

1. The holding layer is general soil
   Physical and mechanical parameters of the general soil layer: Modulus of deformation $E$ is $5.8 \times 10^4 \text{kPa}$, Cohesion $c$ is $26 \text{kPa}$, The angle of friction $\phi$ is $24^\circ$, Poisson's ratio is 0.36, severe is $19.3 \text{KN/m}^3$.

2. The holding layer is soft soil
   Physical and mechanical parameters of the general soil layer: Modulus of deformation $E$ is $2.0 \times 10^3 \text{kPa}$, Cohesion $c$ is $6 \text{kPa}$, The angle of friction $\phi$ is $5^\circ$, Poisson's ratio is 0.40, severe is $15 \text{KN/m}^3$.

3. The holding layer is hard soil
   Physical and mechanical parameters of the general soil layer: Modulus of deformation $E$ is $9.6 \times 10^3 \text{kPa}$, Cohesion $c$ is $60 \text{kPa}$, The angle of friction $\phi$ is $36^\circ$, Poisson's ratio is 0.31, severe is $19.8 \text{KN/m}^3$.

3.2. Model calculation result
Figure 3 shows the pile top bearing capacity and pile top settlement $Q$-$S$ curves obtained under three working conditions.

![Figure 3. Comparison of three working conditions Q-S curves.](image)

It can be seen from the figure that when the bearing layer is general soil, the $Q$-$S$ curve is steeply descending, the limit load in structure of the pile foundation is 17500KN, and the corresponding displacement is 25mm; when the bearing layer is soft soil, the $Q$-$S$ curve is linear, the pile The bearing capacity of the foundation is extremely poor; when the bearing layer is hard soil, the $Q$-$S$ curve is a slowly changing type, and the ultimate bearing capacity of the pile foundation is 23000 KN when the displacement is 0.05 m.

4. Conclusion
Through the research in this paper, we can draw the following conclusions:

(1) The finite element is calculated based on the nonlinear elastoplastic theory and can apply enough force to bring the pile to a destructive state. When other conditions are certain, assuming the hardness of the soil in different bearing layers, the finite element method can be used to calculate the
pile footing’s ultimate load and settlement under certain conditions. Therefore, using the finite element method to calculate the effective length of large-diameter super-long piles has certain advantages.

(2) Under other conditions, the greater the soil’s elastic modulus in the bearing layer, that is, the greater the hardness, the stronger the ultimate load of the pile footing and the greater the ultimate bearing capacity.

(3) Soft soil is very unsuitable as a bearing layer for piles. Under the same load, the settlement of the bearing layer for hard soil and general soil is much smaller than that of soft soil.

(4) Regarding how to choose the bearing layer as general or hard soil, it is necessary to consider how much bearing capacity will be applied to the pile foundation in the actual project.

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