Research on Bearing Capacity of High Pile Cap with Coupling Beam Based on Finite Element Method

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Abstract: In the construction project, the foundation of multiple pile caps and connecting beams is used to solve the problem of insufficient horizontal bearing capacity and excessive displacement. However, there is no very clear theory to analyze the calculation theory, bearing capacity calculation, and displacement calculation of connecting beams. Therefore, in the paper, the finite element method is used to model and analyze the influence of horizontal bearing capacity, the top of the pile foundation and the connection beam on the internal force. Meanwhile, the influence of horizontal displacement, the selection of the connecting beam size and the position of the connecting beam on the bearing capacity is analyzed as well. Besides, a concise calculation method and an assessment on the bearing capacity of the actual engineering foundation are gained. The experiment proves that the research method in the paper can well simulate the vertical compression static load test of high piles with connecting beam caps.

1. Introduction

In the finite element analysis, the characteristics of the soil and the contact characteristics between the pile and soil have a great influence on the results. Therefore, most researchers use the Mohr-Coulomb elasto-plastic constitutive relationship and the Drucker-Prager elasto-plastic constitutive relationship that are easily obtained by the soil material parameters in experiment. Besides, some adopts the revised Cambridge model that requires more soil parameters, and result that is in good agreement with the test results of pile testing is obtained. Additionally, the friction coefficient is usually a comprehensive friction coefficient, which is used for all soil layers, and the numerical value is calculated based on the test results[1-2].

When adopting the elasto-plastic constitutive relationship, most researchers directly give the elastic modulus of the soil without mentioning the relationship between the most common compression modulus and elastic modulus in geological reports. Moreover, the general finite element program ABAQUS is used to carry out numerical simulation of the vertical compressive static load test of high piles with connecting beam caps in the construction of substations. Besides, the study found that the elastic modulus in the elasto-plastic relationship has an important influence on the analysis results. Meanwhile, through research, it is found that the finite element model used in the paper can effectively simulate the static load test of high piles with connecting beam caps[3-5].

2. Finite Element Model Analysis

2.1 Finite Element Model

Unit division: The solid unit C3D8 is used for the pile, and the solid unit C3D8 is used for the soil
body. What’s more, the soil body is subdivided within a range of 5.0m in diameter around the pile body. Unit division is shown in Figure 1.

![Figure 1. Division of high-pile unit with connecting beam cap](image)

The specific parameters of the soil layer and rock layer of the specific site are shown in Table 1[6].

| Statistics project | 1\(^{st}\), \(Q=1327\text{ kN}\) | 2\(^{nd}\), \(Q=1314\text{ kN}\) | 3\(^{rd}\), \(Q=1318\text{ kN}\) |
|--------------------|-------------------------------|-------------------------------|-------------------------------|
| Axial force before pile enters bearing layer / kN | 607.1 | 597.6 | 585.7 |
| Pile bottom axial force / kN | 543.7 | 541.2 | 531.7 |
| Side friction resistance in front of the holding layer / kPa | 33.4 | 32.7 | 31.8 |
| Friction resistance at the bottom of the pile / kPa | 121.7 | 113.4 | 113.7 |

The general finite element software ABAQUS is used to establish the pile-soil model, and the symmetry is utilized to constructed the three-dimensional model of the semi-cylinder. The pile diameter is 120 cm and the soil diameter is 20 m, as shown in Figure 2.

![Figure 2. Schematic diagram of pile foundation stress](image)

The structural load and the dead weight of the bearing platform and the soil body on the bearing platform can be converted into vertical force \(\sum N\), horizontal force \(\sum H\) and moment \(\sum M\).
acting on the origin of the coordinates of the bottom surface of the bearing platform. In principle, these loads are shared by the pile group and the soil body under the side and bottom of the platform. All the loads are balanced with the pile top reaction force of each pile, and the soil resistance at the side of the platform and the soil reaction force at the bottom of the platform. In addition, the resistance of the soil on the side of the platform and the reaction force of the bottom soil of the platform can only be exerted stably and reliably under certain conditions, while for bridge engineering, the reaction force of the bottom soil is not considered. When subjected to these loads, both the bearing platform and the pile foundation will produce vertical displacement, horizontal displacement and rotation angle. Meanwhile, as shown in Figure 3, for each high pile with connecting beam cap, there are axial force $N_i$, horizontal force $Q_i$, and bending moment $M_i$, transmitted from the bearing platform, which is called pile top load or pile top internal force. Besides, the additional bending moment of the pile section caused by the axial force $N_i$ is not considered in the calculation, and the force and displacement of each pile are calculated[7-9].

\[ N_i \quad Q_i \quad M_i \]

Figure 3. Schematic diagram of pile position

In Figure 3, $N_i$ is transmitted to the foundation in the way of pile side friction resistance and pile end resistance, which is equal to the total friction resistance and total end resistance. Moreover, $Q_i$ and $M_i$ will cause the pile body to flex and deform, and there will be horizontal displacement at each point of the pile body, which is generally balanced by the soil resistance of the pile.

2.2 Model Boundary Conditions

The top of the soil model is a free edge without constraints, and the bottom is a fixed edge constraining all displacements. What’s more, the circular arc surface constrains the horizontal displacement, and the semicircular straight surface is symmetrical. Moreover, the top of the pile is free and unconstrained, and the bottom surface is bonded to the soil. Besides, the arc surface is in frictional contact with the soil, the normal to the contact surface is hard contact, and the tangential direction is Coulomb friction. In order to simplify the calculation, a uniform friction coefficient is used for each soil layer. After trial calculation and comparison with the test results, the friction coefficient is 0.45, and the semicircular straight line surface is a symmetric constraint. Load calculation steps: The stress process of the static load test on the simulated bored pile is as follows[10].

(1) Soil stress self-balance analysis simulating the original state of the soil is to remove the piles in the model, and only self-balance analysis is performed on the soil to apply horizontal displacement constraints to the contact surface, namely side and bottom of the pile with the soil. Additionally, the self-weight load is applied to the soil, and the Geostatic included in the program is used to calculate the self-balance of the soil stress. Besides, the self-balance convergence condition is that the soil displacement is less than 10-5m.

(2) Calculation of pile-soil contact simulating the load action of the soil on the pile after pile formation is to add the pile to the model and release the first step to impose horizontal displacement constraints on the contact surface of the pile and the soil, so that the pile and soil contact can be
achieved. Meanwhile, the load of the soil is applied to the pile, and the influence of the pile's own weight is taken into account.

(3) A uniform load simulating the loading state of the pile is applied on the top of the pile, and a downward uniform load of 5.66MPa is imposed on the top of the pile. In addition, the top pressure of the pile is 1600kN, and the stress and deformation performance of the pile and soil under the load of the pile top are calculated.

(4) A uniform load simulating the unloading state of the pile on the top of the pile is distributed to calculate the stress and deformation performance of the pile and the soil under the load on the pile.

3. Finite Element Analysis Results

The finite element analysis simulates the static load test to obtain the Q-s curve of the load and settlement of the pile top during loading and unloading. The comparison with the test results is shown in Figure 4.

![Figure 4 Comparison of Q-s curve between finite element and test result](image)

It can be seen from Figure 4 that the results of the finite element are consistent with the test results at most stages of the loading process, and the difference appears only after the load on the pile top reaches 1200kN. Moreover, the settlement of the finite element result is slightly larger, and the finite element unloading process is almost elastic unloading, which is somewhat different from the test results, but it can be seen that the slope of the unloading curve is very close. In addition, from the perspective of specific data, the maximum pile settlement at the finite element result is 12.38mm, the test result is 10.77mm, and the difference is 1.61mm. Besides, the residual settlement after the finite element unloading is 7.50mm, the test residual settlement is 5.74mm, and the difference is 1.76mm.

4. Conclusion

(1) The finite element model in the paper can well simulate the vertical compressive static load test of high piles with connecting beam caps. A small amount of static load test can be used in general, and the elastic modulus and friction coefficient of the soil can be deduced by the finite element method. Finally, these parameters can be applied to the determination of the bearing capacity of other piles.

(2) There is a limit value for the side friction resistance of the pile. The increase in the pile top load will not exceed the limit value. After the pile side friction resistance reaches the limit value, the side friction resistance will no longer increase as the pile top load increases.

(3) When the pile top load is small, the Q-s curve is almost linear. As the pile top load increases, the pile side frictional resistance gradually reaches the limit from the pile top. At this time, the Q-s curve enters a nonlinear phase. In the linear phase, the load of the pile is mainly resisted by side friction resistance, and the resistance at the pile end begins to play a greater role after entering the nonlinear phase.
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