Bearing characteristics of large-diameter hollow composite pile

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Abstract: Large-diameter hollow composite pile is a new type of pile which is composed of hollow pile, cement mixing pile around the pile and grouting soil around the pile. In order to analyze the influence degree of soil grouting and cement mixing pile around the pile on the improvement of pile foundation bearing capacity, the vertical and horizontal load-bearing characteristics of large-diameter hollow composite pile are studied by numerical simulation, and the structural practicability of the new foundation is analyzed. Research shows that grouting around piles and grouting around piles + cement mixing piles have obvious effects on the improvement of pile bearing capacity, the vertical bearing capacity increased is by 7.4% and 12.1% respectively, while the horizontal bearing capacity is increased by 7.2% and 14.4% respectively. Compared with solid group piles of the same pile side area, the bearing capacity of large-diameter hollow composite pile foundation is increased by 19.1%. The research results can provide theoretical basis and technical support for the design and construction of large-diameter hollow composite pile foundation.

1. Introduction

With the rapid development of transportation in China, the improvement of highway grade and the increasing of overload, the current design and construction of existing highway and bridge have higher and higher requirements on the the bearing capacity of pile foundation, resulting in larger and larger pile foundation diameter and buried depth [1]. This raises many questions. On the one hand, pile deadweight accounts for more and more pile bearing capacity, and the reduction of effective load rate makes the project uneconomical. On the other hand, the construction technology of large-diameter long pile foundation is complex and the cost is high, pore-forming, but construction quality cannot be guaranteed [2]. The appearance of large-diameter hollow pile can effectively solve the above problems [3-6].

Large-diameter hollow pile is a new pile foundation technology. It was an important scientific and technological project of the Ministry of Communications in the “Seventh Five-Year Plan” which was promoted and applied in China since 1992[7]. Zhang initially studied the construction of large-diameter hollow pile, and proposed the calculation formula of the bearing capacity of it according to the ultimate stress method [8]. Liu, Shang Guan et al. introduced the key technology of large-diameter PC hollow pile in bridge construction in Hunan province, and pointed out that it has the characteristics of rapid construction speed, low labor intensity and reduced engineering cost [9-10]. At present, the study on bearing capacity of large-diameter hollow pile foundation mainly focuses on finite element analysis and indoor model test. Li et al. used MARC finite element software to conduct
a series of studies on the load-bearing characteristics of large-diameter hollow pile, and the results showed that the soil parameters, the grouting effect and the pile body parameters all had different degrees of influence on the vertical bearing capacity of the pile, and according to the limit equilibrium theory, the calculation formula of eccentric compression load of large-diameter hollow pile was deduced [11-14]. Chen et al. studied the influencing factors of large-diameter hollow pile bearing capacity by using ANSYS finite element and APDL parameterization technology [15]. The author also systematically studied the bearing capacity of large-diameter hollow pile through laboratory model test and numerical simulation, and presented the criterion for defining rigidity and flexibility of large-diameter hollow pile, established the internal force formula of large-diameter hollow pile under eccentric load and the bearing capacity formula under vertical load, obtained a relatively complete design and calculation method for large-diameter hollow pile.

On the basis of the development of large-diameter hollow pile, a new type of large-diameter hollow composite pile structure, is proposed, which is mainly composed of hollow pile, cement mixing pile and grouting soil around the pile. The pile and pile side soil grouting, pile and cement mixing piles on the outside of pile side soil grouting of large-diameter hollow composite pile foundation reinforced the soil around the pile, and they can greatly improve the engineering characteristics of the soil around the pile and the pile-soil interaction, but how this effect improves the pile bearing capacity (vertical and horizontal) directly determines the design calculation method and calculation parameters of the new technology, as well as the selection of its design technology and parameters. Therefore, in order to explore the interaction mechanism of hollow pile - grouting soil - cement mixing pile, and clarify the improvement of pile bearing capacity of soil grouting around the pile and cement mixing pile, and the bearing characteristics of large-diameter hollow composite pile is developed by using MARC finite element simulation software.

2. Introduction of large-diameter hollow composite pile

The large-diameter hollow composite pile is composed of hollow pile, reinforced concrete thick plate at pile end, cement mixing pile and grouted soil around pile, it is a new type of pile that combines the advantages of precast pile, drill pile and composite pile. Its structure is shown in Figure 1.

Compared with ordinary pile, it has the following characteristics:

1. The pile has a larger diameter (more than 2.5m) and is made of hollow pile, which makes the pile section layout more reasonable and effective, compared with solid piles of the same diameter, it not only saves a lot of concrete, but also increases the bearing capacity of pile relatively because of the improvement of concrete quality and the reduction of dead weight.

2. Compared with solid piles of the same section area, the girth and equivalent width of the section are greatly improved, as a result, the contact area between pile and pile side soil is greatly increased, and the ultimate lateral resistance and lateral soil resistance of pile increases, the bearing capacity is greatly improved, which can often replace multiple solid piles.

3. The grouting around the pile makes the pile and soil around the pile close together, which greatly increases the frictional resistance of the pile. The high-pressure grouting at the bottom of the pile makes the soil at the bottom of the pile compact and reinforced, and the bearing capacity of the pile end is effectively exerted.

4. The outermost cement mixing pile provides a strong guarantee for hole forming safety during construction period, which can also enhance the bearing capacity of the pile during operation period and make the secondary utilization economical and efficient.

5. It can overcome the problems such as breaking pile and reducing diameter which are easy to occur in underwater concrete pouring.
3. Numerical simulation analysis

3.1 Model establishment and scheme design

3.1.1 Model establishment and parameter selection.

1. Geometric model.

The large-diameter hollow composite pile adopts the structure of one pier, one column and a vacant pile cap. The surrounding rock soil is a semi-infinite spatial body, which adopts the three-dimensional spatial model. The surrounding rock soil of the pile is within the range of 8 times the diameter of the pile (40m on the pile side), and the thickness of bearing layer below the pile bottom is within the range of 20m. The geometric dimension of pile is determined by referring to actual design data, in which the outer diameter of hollow pile is \( D = 5 \)m, inner diameter \( D' = 4 \)m, wall thickness \( b = 0.5 \)m and pile length is 28m, in addition, 3m thick reinforced concrete is provided at the bottom of the hollow pile. The grouting body at the side of the pile is substituted by the hollow cylinder with wall thickness of 0.5m, length of 30m and inner diameter of 5m. In order to make the calculated results more convergent and the model more simplified, the cement mixing pile on the pile side is simplified to a hollow cylinder with a wall thickness of 0.5m, a pile length of 30m and a pile inner diameter of 5.5m.

2. Material constitutive model.

In this paper, elastomer analysis is adopted for piles, elastoplastic analysis is adopted for soil around piles, and the Mohr-Coulomb yield criterion applicable for geotechnical materials is selected.

3. Cell grid partitioning.

Eight nodal hexahedron and six nodal pentahedral elements are selected for mesh division. The geometric model of large-diameter hollow composite pile is shown in Figure 2.
4. Model parameter selection.

Based on the geological exploration data along the Huaihe river in Anhui province, among them, the soil layer is distributed from top to bottom, including mixed earth, clay, clay with silty clay, silty clay with silty soil, silty soil and fine sand with silty soil. However, as piles mainly pass through clay layer and silty soil layer, clay is used as the overlying soil layer with a thickness of 12m and silty soil as the holding soil layer in the calculation, and the depth of pile tip under the holding layer is 16m. The calculated parameter values of the model are shown in Table 1.

| Material name            | Deformation modulus (MPa) | Poisson ratio | Cohesion (kPa) | Internal friction angle (°) |
|--------------------------|----------------------------|---------------|----------------|-----------------------------|
| Reinforced concrete      | $3 \times 10^4$           | 0.2           | -              | -                           |
| Cement mixing pile       | 75                         | 0.25          | 136            | 32                          |
| Pile side grouting body  | 65                         | 0.25          | 97             | 30                          |
| Clay                     | 10.5                       | 0.27          | 28             | 25                          |
| Silt                     | 13.8                       | 0.25          | 21             | 16                          |

3.1.2 Simulation scheme design. In order to study the improvement of the bearing capacity of hollow pile by grouting soil around the pile and cement mixing pile, according to the different treatment methods of soil around the piles, modeling is divided into three kinds of working conditions, namely, non-treatment of soil around the piles of hollow piles (hollow piles), grouting and reinforcement treatment of soil around the piles of hollow piles (hollow piles + grouting body), and reinforcement treatment of soil around the piles of hollow piles + cement mixing piles (composite piles), then we compare and analyze the vertical and horizontal load bearing characteristics of the pile under three kinds of working conditions.

3.2 Numerical simulation results analysis

3.2.1 Analysis of bearing capacity of vertical pile foundation. The load-settlement curves of piles under three kinds of working conditions are shown in Figure 3.
The vertical ultimate bearing capacity of pile foundation is controlled by deformation, and the vertical ultimate bearing capacity of single pile is taken as the corresponding load of settlement of pile top is 40mm.

It can be seen from Figure 3 that, with the increase of pile top load, the variation rules of the P-s curves of pile foundation under three kinds of working conditions are basically the same, all of which are of gradual variation. When the load is small, the P-s curves increase approximately linearly, with the increase of load reaching a certain limit value, the settlement curves appear inflection point successively, and show different degrees of bending, and the settlement amount increases sharply. When pile top load is less than 12MN, vertical settlement of pile top is basically the same under three kinds of working conditions, differential settlement begins to occur when pile top load is greater than 12MN, and the differential settlement increases with the increase of load. The vertical ultimate bearing capacity of pile foundation is high under three kinds of working conditions, all above 15500kN. Compared with untreated hollow piles at the pile side, after the two methods of reinforcement, namely pile-side grouting and pile-side grouting + cement mixing piles, the vertical ultimate bearing capacity of piles increased by 1150kN and 1887kN, with an increase of 7.4% and 12.1% respectively.

3.2.2 Analysis of horizontal load bearing characteristics. The H-y curves of pile foundation under three working conditions are shown in Figure 4.

In order to satisfy the safety of structural and pile-soil deformation conditions, the load corresponding to the horizontal displacement of pile at ground level of 6mm is taken as the horizontal ultimate bearing capacity.

As can be seen from Figure 4, with the increase of lateral load on pile top, the horizontal displacement of pile top under three working conditions all presented non-linear growth, H-y curves appear upper curve of different degrees, and the displacement increment are gradually increased under the same load increment. However, the load corresponding to the horizontal displacement of pile top 6mm under three working conditions are very small, about 600~700kN, which are still in the linear change stage, indicating that there is still great potential for horizontal bearing capacity of pile foundation under three working conditions. With the improvement of soil properties of pile side, the
horizontal ultimate bearing capacity of pile foundation has been improved significantly, compared with untreated hollow pile at the pile side, the lateral ultimate bearing capacity of the pile increased by 44kN and 88kN respectively after being treated and reinforced by grouting at the pile side and grouting at the pile side + cement mixing pile respectively, with an increase of 7.2% and 14.4% respectively.

4. Practical analysis of large-diameter hollow composite pile

The large-diameter hollow composite pile foundation can realize the lightening of bridge foundation structure, which lays a good foundation for its popularization and application in solid engineering. However, compared with the existing pile foundation, the structural practicability of the pile foundation is worthy of further study. In order to reduce the error degree of comparative analysis, when analyzing the practicability of composite pile structure, the hollow pile and solid group pile need to be compared first, and then analyze the mechanical behavior of composite pile under vertical load.

Select 4 solid group piles whose pile length is equal to that of hollow pile, and ensure that the pile lateral resistance remains unchanged, the mechanical behavior of hollow pile and solid group pile under vertical load is compared and analyzed. The length of the hollow pile is 30m, the diameter is 5m, and the solid group pile foundation is shown in Figure 5. The soil parameter of the pile side and concrete mark in the solid pile group model are consistent with the hollow pile. The established geometric model is shown in Figure 6. The P-s curves of the top of hollow pile and solid group pile are shown in Figure 7.

As shown in Figure 7, when the load is less than 15MN, the p-s curve of hollow pile and solid group pile basically coincide, when the load is greater than 15 MN, the bearing capacity of hollow pile is significantly higher than that of solid pile group, and the settlement of pile top of solid pile group increases sharply. Under the condition of equal pile side area, the bearing capacity of hollow pile and composite pile is 6.2% and 19.1% higher than that of solid group pile, and the vertical ultimate bearing capacity increased by a large margin.
5. Conclusion
1. Pile side grouting or pile side grouting + cement mixing piles can significantly increase the vertical ultimate bearing capacity of hollow piles by 7.4% and 12.1%, respectively.
2. After the treatment of pile side grouting or pile side grouting + cement mixing pile, the lateral bearing capacity of pile increases significantly, increasing by 7.8% and 14.5%, respectively.
3. The influence range of the pile under different treatment methods on the pile side soil is slightly different, the influence range of pile lateral grouting + cement mixing pile is larger than that of pile side grouting body and larger than that of hollow pile.
4. Compared with ordinary solid group pile foundation, large-diameter hollow composite pile foundation has higher bearing capacity. In the case of equal pile side area, the bearing capacity is 19.1% higher than that of ordinary group piles, which is highly practical and suitable for popularizing and applying in bridge field.

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