Numerical analysis of bearing characteristics of composite foundation with variable diameter rigid pile

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Abstract. Variable diameter rigid pile composite foundation are proposed for the multi-layer foundation. The bearing characteristics of composite foundation with variable diameter rigid pile under vertical load are numerically calculated and analysed. The research content of this paper focuses on the variation law of load and settlement of composite foundation, pile axial force, pile lateral friction resistance and distribution law of soil internal force between piles under different diameter ratios etc. The results showed that Variable diameter of rigid pile composite foundation can effectively improve bearing capacity and control settlement and reduce the stress level of soil; negative skin friction section at the top of pile decreases with variable diameter ratio D/d increases, Zero skin friction section in diameter produced and increases with variable diameter ratio D/d increases; Optimal diameter ratio of pile in the variable diameter rigid pile composite foundation should be at about 1.75.

1. Introduction

In the foundation reinforcement of multi-storey and high-rise buildings, the technology of rigid pile composite foundation has been widely applied, and engineers and technicians have also conducted a lot of research on its stress mechanism, bearing capacity and deformation characteristics [1-4]. In engineering practice, we often need to reinforce multi-layer foundation [6-9]. In order to obtain a higher bearing capacity of composite foundation, it is generally necessary to increase the pile diameter and pile length by the whole pile to improve the bearing capacity of a single pile, or to adopt the technical means of increasing the number of piles and the replacement rate of pile body area to achieve the goal. Under the action of large load, measures such as increasing pile number, pile length, pile diameter and so on are taken to improve the project cost. Because the large difference of stiffness between pile and soil is the relative displacement between pile and soil, the negative friction area [10] on the top of pile can be formed to expand downward, thus reducing the bearing capacity of single pile in composite foundation.

In recent years, engineers have carried out a series of theoretical analysis and model tests on variable-diameter piles. The author puts forward a new method of reinforcing multi-layer foundation with composite foundation with variable diameter rigid pile. In this paper, Plaxis geotechnical engineering finite element software is used to establish the numerical model of the composite foundation with variable diameter rigid pile, and the performance of the composite foundation under different variable-diameter ratio is analyzed and studied.
2. Analyze scheme design

2.1 Analysis methods and basic assumptions

Using Plaxis geotechnical engineering finite element analysis software, the axisymmetric geometric models of single pile and single pile composite foundation were established respectively, and the bearing characteristics of single pile with variable diameter and single pile with variable diameter composite foundation were compared and analyzed according to the two-dimensional problem.

The pile, soil and mattress were all constructed with 15-node triangular element, the mohr-coulomb elasto-plastic constitutive model was used for the double-layer soil, and the linear elastic constitutive model was used for the pile and mattress. It is assumed that the soil is normally consolidated and fluid-solid coupling is not considered. Interface units are set between piles and soils to simulate the sufficient interaction between piles and soils. The calculation parameters are shown in table 1.

Table 1. Material properties for numerical modeling

| material            | γ (kN·m⁻³) | E_ref (MPa) | ν   | C (kPa) | φ (°) | R_inter |
|---------------------|------------|-------------|-----|---------|-------|---------|
| pile                | 24         | 2.5E+4      | 0.2 |         |       |         |
| Mattress layer      | 20         | 80          | 0.3 |         |       |         |
| The upper clay      | 19.5       | 15          | 0.35| 20      | 10    | 0.70    |
| The lower sand      | 20         | 40          | 0.3 | 1       | 40    | 0.85    |

2.2 Establishment of model

Calculate the horizontal direction 6m and the vertical direction 10.3m. From top to bottom, the thickness of mattress is 0.3m, the thickness of upper clay is 2m, and the thickness of lower sand is 8m. With the diameter d=0.4m, L=7.5m pile as the benchmark, the diameter expansion d= 0.6m, 0.7m, 0.8m, 0.9m in the upper clay, that is, the diameter ratio D/d= 1.5, 1.75, 2.0, 2.25, the diameter expansion pile segment extends into the lower sandy soil 0.5m. The geometric model of single pile and composite foundation and the element meshing are established respectively. The meshes of cushion, pile and nearby soil are fine, and the meshes of soil far away from pile are thick. The top boundary of the model is free, the bottom boundary is fixed, and the horizontal displacement is limited by the boundary at both ends. FIG. 1 shows a numerical model grid with variable diameter ratio D/d =1.75.

![Numerical model grid with variable diameter ratio](image)

2.3 Calculation of operating conditions and load application

According to the diameter change ratio D/d =1.0, 1.5, 1.75, 2.0, 2.25, and a total of 10 analysis models of single pile and composite foundation, the following steps shall be followed:(1) initial stress, when the pile does not exist, attributes are assigned according to the corresponding class group;(2) pile formation and neglect of pile formation process;(3) apply vertical load.
The applied load is realized by means of forced displacement, that is, the vertical displacement of 20mm is applied to the pile top of a single pile, and the settlement of 20mm is simulated under the action of load. A 20mm displacement is applied to the surface of the 1m width range of the cushion of the composite foundation, and a 20mm settlement is generated under the vertical load of the single-pile composite foundation when the pile spacing is simulated to be 2m.

3. Analysis results

3.1 Analysis of single pile bearing characteristics

FIG. 2 shows the load (Q) - settlement (S) curves characterizing the bearing capacity of single pile with variable diameter. The curves all have the characteristics of nonlinear and steep drop, and the inflection point of the ultimate bearing capacity is obvious. Under the same load, with the increase of variable diameter ratio D/d, the settlement of pile S decreases and the bearing capacity Q increases. With the increase of variable diameter ratio D/d, the curve of load is relatively gentle when the load is very small, and the settlement amount corresponding to the inflection point position is also smaller, indicating that the pile with a large variable diameter ratio effectively reduces the settlement of the pile, and at the same time reaches the ultimate bearing capacity at a small settlement.

By analyzing the stress diagram of variable-diameter piles in FIG. 2, the bearing capacity of piles is composed of four parts: lateral friction resistance q_s1 in the expansion section, lateral friction resistance q_s2 in the standard diameter section, end resistance q_d1 at the bottom of the expansion section and pile end resistance q_d2. Compared with the equal diameter pile, the side surface area of the enlarged pile increases, which increases the contribution of pile side friction resistance to the bearing capacity of a single pile. For the same pile length, with the increase of D/d, the bearing capacity of single pile increases, with the increase of 1.3~1.6 times.

FIG. 3 show the displacement cloud diagram of pile with diameter ratio D/d = 1, 1.5, 1.75, 2 in the limit state. It can be seen from the analysis that: with the diameter of the expansion section gradually increasing, the plastic zone of pile side gradually shows a large value near the variable section of pile body, the foundation below the variable section appears the elastic soil core, the position of the variable section has the phenomenon of transferring the load to the good bearing layer, but it also shows that the settlement increases with the diameter of the expansion section.

3.2 Analysis of bearing characteristics of composite foundation

In FIG. 4, the load-settlement curves of composite foundation all show a slow variation without obvious inflection point. The curves of D/d >1 all lie above D/d =1, indicating that the bearing capacity of the composite foundation with variable diameter piles is greater than that of the composite foundation with equal diameter piles. The flatness of the curve decreases with the increase of D/d, and the slope of the curve with D/d =2 and 2.25 increases at s=10mm, intersecting with the curve with D/d =1.75. When settlement S reaches 20mm, the bearing capacity of composite foundation presents the rule of (D/d =1.75) > (D/d =2.0) > (D/d =2.25) > (D/d =1.5) > (D/d =1.0).
Composite foundation by share the upper load of pile and soil, due to differences in stiffness of piles and soil, produce relative displacement between pile soil, the settlement of soil is more than the settlement of pile, pile at the top of a range of negative friction caused by area, the bigger the pile body surface area, at the same depth of the negative friction zone of negative friction resistance, the greater the bearing capacity of single pile composite foundation can't give full play to the curve as shown in figure 3, formed a composite foundation \( Q-s \) curve intersection phenomenon. In addition, with the increase of variable diameter ratio, the load of variable diameter pile also increases, which also causes the increase of settlement. When the variable diameter ratio \( D/d = 1.75 \), the bearing capacity of the composite foundation is the largest, indicating that there is an optimal variable diameter ratio in the composite foundation with variable diameter piles, and the value should be about 1.75.

3.3 Distribution of pile lateral friction resistance in composite foundation

FIG. 5 is the distribution curve of pile lateral friction resistance in composite foundation when 5mm load is applied on the top of composite foundation. Lateral friction resistance \( q_s \) increased with the increase of \( D/d \), and the negative friction section at the top of pile decreased with the increase of \( D/d \).
The zero-friction section of the variable diameter pile appeared at the diameter change, and its range increased with the increase of $D/d$.

With the increase of $D/d$, the $m$ value in formula (1) of the bearing capacity of composite foundation increases, and the load shared by pile increases. In this way, the settlement difference between pile and soil is reduced, and the negative friction area at the top of pile gradually decreases. However, there is no relative displacement between pile and soil in the local area at the end of the diameter expansion, resulting in the zero friction area. The variable diameter piles in the composite foundation reduce the range of the negative friction zone at the top of the pile, so that the bearing capacity of the pile can be given full play. In practical application, it should be noted that it is not the bearing effect of composite foundation that the larger the diameter ratio is, the better the bearing effect is.

$$f_{spk} = m \frac{R_a}{A_p} + \beta(1 - m)f_{sp}$$

(1)

3.4 Pile stress distribution

FIG. 6 shows the pile stress distribution curve in composite foundation when 5mm load is applied on the top of composite foundation. The pile stress distribution in $D/d =1$ is a typical pile stress distribution curve in composite foundation: the pile stress in the negative friction zone at the top increases gradually, reaches the maximum value near the neutral point, and then decreases gradually. $D/d=1.5, 1.75, 2.0$ and $2.25$ showed the same distribution curve as $D/d =1$ in the variable diameter section, but the stress suddenly increased at the variable diameter, resulting in sudden stress mutation. Although it increased with the increase of $D/d$, the increment after $D/d >2$ was not significant. The above curve characteristics show that the variable-diameter pile shares more upper load and gives play to higher bearing capacity of single pile, resulting in stress mutation at the variable-diameter pile with reduced cross-sectional area. However, the stress increment was not significant after $D/d =2$, indicating that the bearing capacity of single pile increased by a little.

3.5 Additional stress distribution in soil

FIG. 7 shows the curve of additional stress in soil with the change of settlement amount of composite foundation. The additional stress curves of $D/d=2.0$ and $2.25$ in the soil showed a steep drop at a small settlement amount and still increased after that, but the extreme values were smaller than those of $D/d =1.0, 1.5$ and $1.75$. The additional stress curves of $D/d=1.0, 1.5$, and $1.75$ are relatively consistent, that is, with the increase of settlement, they gradually reach the extreme value, and then no increase. The value of additional stress in $D/d=1$ is the largest, which is about 10% larger than that in $D/d =1.5$ and $1.75$, and about 25% larger than that in $D/d =2.0$ and $2.25$. 

Figure 6. The distribution curve of stress of pile

Figure 7. The curves of subsidiary stress in soil with the settlement
The results show that the stress in the soil of the composite foundation with variable diameter piles with variable diameter ratio $D/d = 1.5, 1.75, 2.0$ and $2.25$ is all less than that of the composite foundation with equal diameter piles with variable diameter ratio $D/d = 1$. When the diameter change is relatively large ($D/d = 2.0, 2.25$), the pile shares more load, inhibits the total settlement of the composite foundation, and the bearing capacity of the soil is not fully developed. However, when the diameter change is relatively small ($D/d = 1.5, 1.75$), the load sharing of pile and soil is relatively reasonable, and the bearing capacity of soil is given full play.

4. Conclusion
The finite element software is used to simulate and analyze the bearing characteristics of the composite foundation with variable diameter piles. The following conclusions are drawn through the analysis of the load settlement curve, pile stress curve, soil stress curve and pile lateral friction resistance distribution curve of the composite foundation: 1) variable diameter rigid pile composite foundation can effectively improve the bearing capacity and control settlement, and reduce the stress level of soft soil foundation; 2) the negative friction section on the top of the tapered pile in the composite foundation decreases with the increase of $D/d$, and the zero friction section increases with the increase of $D/d$ at the tapered section. 3) although the bearing capacity of single pile of variable diameter pile increases with the increase of $D/d$, its bearing capacity cannot be fully exerted in composite foundation due to the joint action of pile and soil. The optimal variable-diameter ratio of the pile in the composite foundation with variable diameter rigid pile is about 1.75. 4) the maximum stress of the variable-diameter pile in the composite foundation occurs at the variable-diameter site, and sufficient attention should be paid to its engineering application.

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