Numerical calculation and analysis of parameters of collapsible loess treatment on composite foundation based on FLAC\textsuperscript{3D}

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Abstract. Combined composite foundation technology is one of the research directions for dealing with collapsible loess foundation in the northwest region. Under the vertical load of rigid-flexible composite foundation reinforcement, considering the relevant factors of rigid pile, flexible pile, cushion, etc., a FLAC\textsuperscript{3D} finite element model was established for numerical analysis. The results of the research show that the length of rigid piles is the main factor affecting bearing capacity and settlement, and the main function of flexible pile lengths is to improve the strength of shallow soils and eliminate the collapsibility of loess. This paper provides a reference basis for the study of the combined composite foundation mechanism.

1. Introduction
The technical treatment and theoretical research of collapsible loess foundation is one of the most important issues of civil engineering construction. The combined composite foundation technology\cite{1} can fully utilize the advantages of a variety of pile composite foundation. The engineering characteristics of pile material can solve the requirements of foundation bearing capacity and settlement control economically and reasonably, which has a good application prospect\cite{2}.

Many scholars at home and abroad have done a lot of research. Zhu Xiaoyou\cite{3} used cement powder sprayed piles to successfully reinforce the bearing capacity of the original cast-in-situ piles, and proved that the composite piles can improve the bearing capacity; Guo Peihong\cite{4} solves the problem of the foundation design of the new building on the old piles foundation through the method of the original sinking pipe pile combined with the deep cement mixing pile. Jianhua and Zhang Tao\cite{5} proposed the calculation formula of the standard value of the bearing capacity of the combined composite foundation of the rigid pile and the flexible pile; Zhang Zhongmiao\cite{6} et al. Based on the CM pile test of BaiDanghai community, the idea of CMG composite pile foundation was proposed. The current research is mainly in the aspects of theoretical analysis, experimental research and engineering measurement, etc. This paper analyzes and evaluates various influencing factors of composite foundation based on FLAC\textsuperscript{3D} finite element simulation software.

Combined with a certain engineering project, the field test of rigid-flexible pile composite foundation is carried out, and the calculation model of composite foundation is established according to its stress characteristics, combined with the existing research data and the results of foot test\cite{7-8}, in order to provide reference for the study of composite foundation treatment.
2. Numerical model of composite piles

2.1. Calculation software introduction

FLAC\textsuperscript{3D} is an international general professional analysis software developed for the field of geotechnical engineering. It is a numerical analysis method based on explicit finite difference technology. It is suitable for the solution of continuum mechanical problems with multiple material models and complex boundary conditions. Following the assumption of continuous media, the differential format is used to solve the problem in time-step integration. The coordinates are continuously updated as the configuration changes, and the incremental displacement is accumulated into the coordinate system, allowing large deformation of the media.

2.2. Calculation parameters and boundary conditions

This analysis model is a composite foundation of gravel piles and cement fly ash gravel piles. The model is simplified without affecting the calculation results: the pile and the cap are both linear Elastic materials; the soil is homogeneously layered and isotropic, simulated by an ideal elastoplastic model. Using the principle of area equivalence, the round pile is simplified into a square pile, and the side length of the square pile: \( l = \sqrt{\pi D/2} \) (D is the diameter of the round pile). The analysis model is shown in Figure 1.

The calculation parameters of the model are: cushion: thickness \( d=0.3\)m, Poisson’s ratio, elastic modulus \( E=30\)MPa; rigid pile: length \( h=8\)m, diameter \( D=0.4\)m, elastic modulus \( E=3\times10^5\)MPa; flexibility Pile: length \( h=7\)m, diameter \( D=0.4\)m, elastic modulus \( E=150\)MPa; lime-soil compacted pile, pile diameter 400mm, pile spacing 950mm, plum-shaped arrangement. In this paper, the numerical calculation of the soil adopts the elastoplastic constitutive model and the Mohr Coulomb failure criterion. The cushion, rigid pile and flexible pile adopt the elastic constitutive model. The specific physical and mechanical parameters are shown in Table 1.

| Foundation soil, soil between piles or pile type | unit weight of soil (KN/m\(^3\)) | Poisson ratio | the cohesion value (kPa) | The angle of internal friction (°) | modulus of rigidity (MPa) | bulk modulus (MPa) |
|-------------------------------------------------|-------------------------------|---------------|-------------------------|-------------------------------|------------------------|-----------------|

Figure 1. FLAC\textsuperscript{3D} analysis model diagram
3. Numerical simulation results and analysis

3.1 Effect of rigid pile parameters on characteristics of composite foundation

3.1.1 Influence of rigid pile modulus

| Material                  | Modulus (MPa) | Poisson's Ratio | Young's Modulus (GPa) | Compressive Modulus (GPa) | Rigid pile Modulus (GPa) |
|---------------------------|---------------|-----------------|------------------------|----------------------------|--------------------------|
| Loess-like silt           | 1520          | 0.32            | 14                     | 26                         | 5.3                      |
| Plain soil between piles  | 1797          | 0.3             | 26                     | 30.6                       | 7.95                     |
| Rigid pile                | 2500          | 0.2             |                        |                            | 8.3e3                    |
| Flexible pile             | 1900          | 0.25            |                        |                            | 62.5                     |

It can be seen from Fig. 2 that with the increase of the elastic modulus of the rigid pile, the displacements of the top of the rigid and flexible piles and the vertical displacement of the cushion have a tendency to decrease, and the reduction of the rigid pile is the largest. Figure 3 shows that as
the rigid pile modulus increases, the trend is to increase and then decrease, and the total settlement and the settlement at the bottom of the pile reach their maximum values at 20,000 MPa.

3.1.2 Effect of rigid pile length
It can be seen from Figure 4: With the growth of the pile length, the displacement of the top of the rigid flexible pile and the vertical displacement of the cushion first increase and then tend to stabilize. The bottom displacement and total displacement of rigid piles have a tendency to decrease, and as the pile length increases, the slope of the curve decreases, that is, tends to be stable, indicating that the rigid pile has an effective pile length. In addition, it can be known that the increase of rigid pile length has a significant effect on reducing the average settlement and differential settlement.

![Figure 4: Curve of vertical displacement of rigid and flexible piles and cushion with the length of rigid piles](image)

![Figure 5: Variation curve of rigid pile, flexible pile and cushion vertical displacement rigid pile length](image)

3.2 The influence of flexible pile parameters on the characteristics of composite foundation

3.2.1 Effect of elastic modulus of flexible piles
It can be seen from Figure 6a that with the increase of the elastic modulus of the flexible pile, the displacement of the top of the rigid and flexible piles and the settlement of the cushion are decreasing, and the settlement of the displacement of the top of the rigid pile is more obvious, with the largest amplitude. It shows that the increase of the elastic modulus of the flexible pile effectively improves the bearing characteristics of the flexible pile, eases the axial force of the rigid pile and adjusts the stress state of the rigid pile.

It can be seen from Figure 6b that with the increase of the elastic modulus of the flexible pile, the vertical settlement and the total settlement at the bottom of the pile are reduced to varying degrees, which also shows that the flexible pile exerts its bearing characteristics and is flexible. The load sharing ratio of the pile increases. The load sharing ratio of rigid piles may be reduced. Therefore, we can adjust the load sharing ratio of rigid-flexible piles in composite foundations of rigid-flexible piles by improving the material ratio of the flexible piles or the construction process, so that the two can give full play to their respective advantages and work together.

3.2.2 Influence of flexible pile length

Figure 7. Variation curve of vertical displacement of rigid, flexible piles and cushion with length of flexible piles
Figure 8. Curves of displacement and total displacement of rigid pile with flexible pile length

It can be seen from Figure 7: With the growth of the pile length, the displacement of the rigid flexible pile top and the vertical displacement of the cushion first increase and then tend to stabilize. It can be seen from Fig. 8: With the increase of the length of the rigid pile, the displacement of the bottom of the rigid pile and the total displacement have a tendency to decrease, and as the length of the pile increases, the slope of the curve decreases, and when the length of the pile reaches a certain length, the slope of the curve is more Small, that is, tends to be stable, indicating that the flexible pile and rigid pile have an effective pile length for synergy, and this effective pile length is the best combination of the two.

3.3 Influence of cushion parameters on characteristics of composite foundation

3.3.1 The effect of cushion modulus

Figure 9. Curves of vertical displacement of rigid and flexible piles and cushion with elastic modulus of cushion

It can be seen from Figure 9a that as the elastic modulus of the cushion layer increases, the displacement of the top of the rigid and flexible piles and the vertical displacement of the cushion layer decrease, which is due to the increase in the elastic modulus of the cushion layer and the increase in stiffness. Due to the large size, with the increase of stiffness, the stress concentration of rigid piles is more obvious, and its bearing characteristics can be fully exerted. According to Fig. 9b, it can be seen that as the modulus of the cushion layer increases, the bearing deformation characteristics of the
rigid-flexible pile composite foundation tend to be gentle, indicating that when the modulus of the cushion layer increases to a certain degree, it can be adjusted by changing the rigidity of the cushion layer. The pile-soil stress is of little significance.

3.3.2 Influence of the thickness of the cushion layer on the bearing deformation characteristics of the rigid-flexible composite foundation

According to previous research results [9]: With the change of the thickness of the cushion, the distribution of the reaction force of the soil under the platform is generally reversed along the axis, that is, the reaction force in the middle is large and the reaction force in the corner is small. This is due to the tendency of the slab to lift under the effect of the upper load, so the presence or absence of cushions will have a significant impact on the bearing deformation characteristics of the rigid-flex pile composite foundation. There will be different stress states for the composite foundation without cushion and the composite foundation with cushion. The stress increase of the composite foundation without cushion is relatively large near the edge of the foundation. In addition, the stress state of the foundation soil also follows the cushion. The thickness varies, and generally, the soil reaction force increases with the thickness of the cushion layer. When there is no cushion, the soil reaction force is significantly reduced.

Figure 10. Vertical displacement of rigid-flexible pile top, cushion and pile bottom as a function of cushion thickness

Figure 10 is the load-bearing deformation characteristics of composite foundation with rigid-flexible piles under a load of 120kPa. It can be seen from the figure that as the thickness of the cushion layer increases, the displacement of the top of the rigid-flexible pile and the vertical displacement of the cushion layer tend to be stable. In the case of this calculation example, when the thickness of the cushion layer is 20 cm, the settlement of rigid piles, flexible piles and foundation soil tends to be stable. It shows that for a specific load or a specific project, there is an optimal cushion thickness. This thickness of cushion layer can relieve the stress concentration of rigid piles, and can coordinate the rigid and flexible piles, and the soil between the piles to work together to give full play to their respective advantages.

4. Summary

The rigid pile modulus has little effect on the bearing deformation characteristics of the composite foundation. The rigid pile is the main control pile of the composite pile composite foundation, and its pile length has a critical value. When the length of the rigid pile changes within the range of less than the critical pile length, the pile body stress and the bearing capacity of the pile increase with the continuous increase of its length. When it is greater than the critical pile length, the increase of the pile length affects the lower part of the pile. The stress has no effect and the bearing capacity of the pile
will not increase.

The existence of flexible piles has an effect on the effective pile length. When the pile length reaches a certain level, the pile length that continues to increase does not contribute much to the bearing capacity. The length of the flexible pile has a significant effect on the average score, and has little effect on the difference ratio. The change of the flexible pile modulus on the rigid and flexible pile composite foundation characteristics is mainly limited to the shallow part, and has basically no effect on the lower conveying deformation characteristics.

The soil quality of the reinforcement layer is the most important factor affecting the bearing characteristics. The increase of the soil modulus can fully exert the bearing contribution of the soil, and the alternating sharing ratio of the soil increases.

According to the above analysis, rigid pile length is the main factor affecting bearing capacity and settlement in flexible and rigid pile composite multiple composite foundation. Relatively speaking, the flexible pile length has little influence on the bearing capacity, and its function is mainly to improve the strength of shallow soil and reduce the settlement deformation.

References
[1] Zheng Junjie, Ou Jianhua, Wu Shiming, Yuan Neizhen. Theory and Practice of Multi-element Composite Foundation [J]. Chinese Journal of Geotechnical Engineering, 2002 (02): 208-212.
[2] Chen Changfu, Xiao Shujun, Niu Shunsheng. Research on optimization design method of composite foundation with long and short piles [J]. Journal of Engineering Geology, 2006 (02): 229-232.
[3] Zhu Xiaoyou, Yin Hualian. Binary composite pile foundation and its application in high-rise buildings, 1999 (12)
[4] Guo Peihong. Discussion on utilization of original pile foundation in old house reconstruction. [J] Journal of Fuzhou University (Natural Science Edition), 1999, 27 (3)
[5] Wu Jianhua, Zhang Taosu. Design of composite foundation with concrete pile, cement soil pile and soil working together, 1999 (01)
[6] Zhang Zhongmiao, Tang Chaowen. On the technical points of grouting behind the pile bottom. [J] Journal of Rock Mechanics and Engineering, 2002, 21 (11)
[7] Chen Qiang, Huang Zhiyi, Xu Renping. Stress characteristics analysis of piles, soil and cushion in ternary composite foundation [J]. Zhejiang Architecture, 2001 (04): 26-28.
[8] Wu Jianhua, Zhang Tao, Zhou Yajun. A practical design method for joint work of plain concrete piles, cement soil piles and soil [J]. Scientific Research of Water Conservancy and Water Transportation, 1998 (04): 410-415.
[9] Huang Cheng. The effect of cushion thickness on the bearing capacity of composite foundation [J]. Gansu Science Journal, 2017, 29 (03): 53-57.