

Nonlinear optimization design of pile foundation based on settlement control principle

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Abstract. How to take certain measures to minimize the differential settlement of buildings is one of the urgent problems to be solved in the current pile-raft foundation design. In this paper, the nonlinear optimization design of pile foundation based on the principle of settlement control is developed. For the soil around the pile group, considering its nonlinear characteristics, when it yields, the ideal elastic-plastic model is adopted for calculation. Through numerical simulation, combined with the results of model test and field observation, some practical research results are obtained: the smaller the elastic modulus coefficient is, the flatter the load-settlement curve of CPF (Composite pile foundation) is, and the larger the fixed value is, the load-settlement curve is abrupt. Using settlement control to design rigid pile composite foundation has clear settlement. As a supplement to the insufficient bearing capacity of foundation soil, pile foundation makes full use of the bearing capacity of soil between piles. The design scheme is more economical, and it is a good nonlinear optimization method of pile foundation.

Keywords: Settlement control, Composite pile foundation, Nonlinear optimization.

1. Introduction

According to the traditional design method, the pile foundation works within the allowable bearing capacity, which is about half of the ultimate bearing capacity [1]. Moreover, once the pile foundation is adopted, the original bearing capacity of the natural foundation will be abandoned and not utilized. It can make full use of the bearing capacity of natural foundation and save the cost of foundation treatment [2-3]. Settlement is also the root cause of the increase of internal force of foundation and secondary stress of superstructure, and the increase of plate thickness and reinforcement. Therefore, how to take certain measures to minimize the differential settlement of buildings is one of the problems of nonlinear optimal design of pile foundation at present.

2. Research method

2.1. Analysis of settlement mechanism of composite pile foundation

Composite pile foundation analysis can be divided into three parts: pile group calculation, pile cap (raft) calculation and foundation soil load calculation. Among them, pile group calculation theory is the most important part. On the basis of pile group calculation theory, the interaction theory of CPF (Composite pile foundation) can be established by taking into account the action of pile cap (raft) and soil with appropriate methods.

For the design of CPF, it is generally required that the pile spacing is greater than or equal to $6d$, and the shared load of pile groups is transmitted to the soil by the pile side friction and pile tip resistance. Therefore, the stress superposition between piles can be ignored, and the friction and distribution of the soil between piles and the pile tip soil resistance are equal to those of single pile [4].

When calculating the settlement of CPF, some calculation methods of conventional pile foundation can be directly applied in combination with empirical coefficient. Taking the pile end plane as the

acting surface, the projection A of the pile cap as the acting area, and the additional stress p_0 at the acting surface as the acting load, the vertical stress in the soil is calculated according to Boussinesq solution, which is solved by layered summation method.

$$S = \psi_s S' = \psi_s \sum_{i=1}^n \frac{p_0}{E_{S_i}} (z_i a_i - z_{i-1} a_{i-1}) \quad (1)$$

$$p_0 = \frac{Q + G'}{A} - \sigma_{cz_0} \quad (2)$$

Where, p_0 is the additional stress at the pile end; σ_{cz_0} is the self-weight stress of the soil at the pile end; Q is the sum of the vertical force from the superstructure to the top of the pile cap, the dead weight of the foundation and the weight of the covering soil on the foundation when corresponding to the standard combination of load effect; G' is the total weight of soil and pile within the range of pile length.

There is an internal force in the main structure of the project under load, which is directly related to the stress of the organizational structure [5-6]. At this time, the foundation steel plate used in the construction is too thick or the number of steel bars is significantly increased. These differences are the main reasons that lead to or affect the settlement of buildings. Considering that there are obvious construction limitations between the superstructure and the geological environment in the process of building construction, the top pile can be deformed to ensure the coordination of construction, thus ensuring the expansion of the application scope of the project.

In recent years, in the design, research and construction of pile foundation, the consolidation of the soil under the bearing platform is the cause of large total settlement and differential settlement of the foundation. Excessive settlement deformation will inevitably lead to the increase of internal stress of foundation, especially in soft soil foundation. With the increase of the load, the foundation will settle, the surrounding loose sand cushion will begin to be compacted, and the soil under it will begin to bear part of the load. When the load reaches a certain level, the whole bottom area of the foundation will take part in the subsequent load, forming a roughly uniform reaction force.

The bottom reaction force redistributes and concentrates in the middle of the foundation, and the distribution of the base reaction force after the treatment of variable stiffness cushion is obviously more reasonable than that without treatment. It can be seen that the setting of variable stiffness cushion improves the working behavior of foundation soil, delays the failure time of foundation soil, and thus improves the bearing capacity of foundation.

The design of rigid pile composite foundation is mainly based on the code design [7-8], and its bearing capacity calculation formula is mainly based on strength control, and the relationship between pile and soil deformation is not considered when calculating the bearing capacity. Moreover, the bearing capacity exerting coefficient β in the formula is generally based on experience, lacking a quantitative method with theoretical basis, and its calculation formula is as follows:

$$f_{spk} = m \frac{R_a}{A_p} + \beta(1-m)f_{sk} \quad (3)$$

f_{spk} is the characteristic value of bearing capacity of single pile composite foundation; m is the replacement rate of composite foundation; R_a is the characteristic value of vertical bearing capacity of single pile; A_p is the area of the pile; β is the reduction coefficient of the bearing capacity of the natural foundation of the soil between piles, or the play coefficient. If the bearing capacity coefficient β of the soil between piles fails to reach the design value, the load shared by piles will be larger than the design value, and there is a safety risk.

2.2. Nonlinear optimization design of CPF

Mohr-Coulomb constitutive model is ideal elastic-plastic. It considers the change of strength with confining pressure, and its yield surface is an irregular hexagonal cone in the principal stress space. This model is widely used for numerical analysis of geotechnical engineering problems. In general, piles are made of linear elastic materials, and the section of pile body is constant along the unit, and there is no yield limit. Of course, if necessary, plastic hinges can be defined between two sections of pile units. Because the normal direction is not the main research direction, and through trial calculation, the parameters in the normal direction have little influence on the results, which can be ignored. Therefore, the parameters in the normal direction also follow the principle of the parameters in the tangential direction [9].

Plexiglas rod and plexiglass plate are selected for the pile and the pile cap plate respectively. Two-way slotted strain gauges are attached to the side of the plexiglass rod. The surface of the strain gauges is protected by silica gel and then filled with epoxy resin. In order to make the side wall of the pile reach a certain roughness, a layer of fine sand is glued on the surface of the plexiglass rod with epoxy resin. In fact, the upper load is shared by the pile, the pile cap and the foundation, and ignoring the joint action of the three will cause huge waste.

In a certain time domain, the static equilibrium problem can be solved by the following equilibrium equation:

$$\sigma_{ij,j} + \rho B_i = 0 \quad (4)$$

ρ is the density of the medium, and B_i is the volume force.

In the fast Lagrangian analysis, assuming that the velocity in time Δt is constant, the incremental constitutive equation can be expressed as:

$$\Delta \tilde{\sigma}_{ij} = H_{ij}^*(\sigma_{ij}, \xi \Delta t) \quad (5)$$

$\Delta \tilde{\sigma}_{ij}$ is the co-rotating force increment, and H_{ij}^* is a given function.

Let the differential settlement equation of pile foundation be D , and the formula (6) can be obtained.

$$D = \lim_{t \rightarrow \omega} \frac{\lg f_0}{\lg t} \quad (6)$$

ω represents the rigidity of the superstructure; f_0 represents the stiffness of foundation; t represents the monitoring time of differential settlement deformation of pile foundation. Through formula (6), the differential settlement of the pile foundation is obtained, and the obtained differential settlement of the pile foundation is input into the deformation adjusting device, so that the supporting stiffness of the pile foundation can be evenly distributed, and then the structural parameters of the pile foundation are optimized based on differential settlement control.

Because the pile in the CPF, the soil between piles and the soil around the pile group have different working characteristics under stress, different constitutive models are adopted for the soil in actual calculation. For piles and soil between piles, considering its elastic properties, the elastic matrix is constant; For the soil around the pile group, considering its nonlinear characteristics, when it yields, the ideal elastic-plastic model is adopted for calculation.

Considering the material characteristics of soil, the Drucker-Prager model is selected, and the expression of yield criterion is:

$$F = \sqrt{J_2} - \alpha I_1 - k = 0 \quad (7)$$

$$\alpha = \frac{\sin \varphi}{\sqrt{3(3 + \sin^2 \varphi)}}, \quad k = \frac{\sqrt{3}C \cos \varphi}{\sqrt{3 + \sin 2\varphi}}, \quad J_2 \text{ are the second invariant of stress tensor, } I_1 \text{ is the first invariant of stress tensor, and } \alpha, k \text{ is the parameter of yield function; } C \text{ is cohesion; } \varphi \text{ is the internal friction angle. When } F < 0, \text{ the soil is in the elastic stage.}$$

3. Example analysis

To verify the effectiveness of the method proposed in this paper, the following engineering examples are used for verification: a building with 10 floors above the ground, a frame structure and an underground floor, the excavation depth of the foundation pit is 5.0m, the size of the basement floor is about 65×15m, the standard value of building load (accumulated maximum column load) totals 191,831kN, and the load distributed according to the building base area is about 331k Pa. The method of this paper is used to optimize the design of this project. The constructed pile is used as the pile foundation in the rigid pile composite foundation, and the pile-soil stress ratio is adjusted through the cushion. The design is optimized according to the settlement control introduced above.

Considering the influence of different soils on the stress and deformation of CPF, the elastic modulus coefficient k of foundation soil is 350, 600, 850 and 1000 respectively, the distance-diameter ratio is 7, the raft thickness is 1. 2m, and the pile length is 25m. For different values of k , the load-settlement curve of CPF is shown in Figure 1.

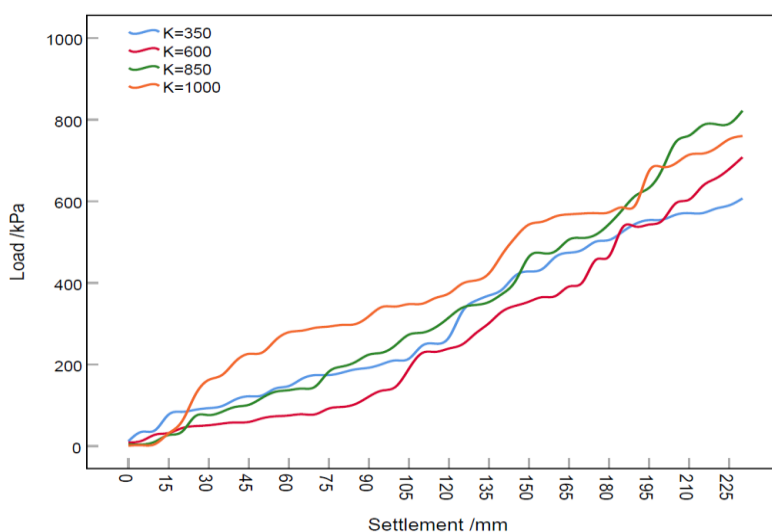


Figure 1. Load-settlement curve with different soil properties

The smaller the value of k , the flatter the load-settlement curve of CPF, and the larger the fixed value, the abrupt change of load-settlement curve. That is to say, the softer the soil is, the easier it is for the load-settlement relationship of CPF to change slowly, and the harder the soil is, the easier it is for the load-settlement relationship of CPF to change abruptly. The harder the soil is, the load-settlement relationship of CPF is close to that of single pile.

The bearing capacity of pile foundation is measured by MATLAB software, which is recorded as the experimental group. Then the traditional method is used to design the pile foundation for experiment, and the bearing capacity of the pile foundation is also measured by MATLAB software, which is recorded as the control group. Set the number of experiments to 15 times, and record the experimental results as shown in Figure 2.

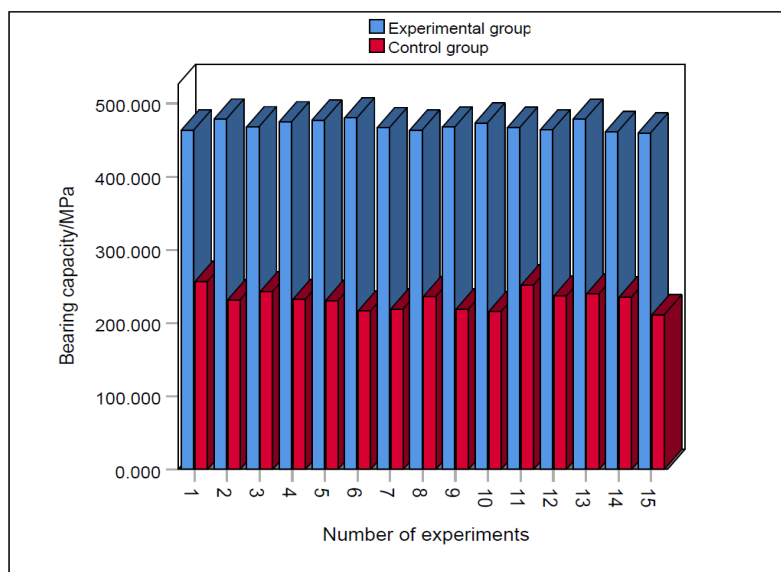


Figure 2. Comparison of pile foundation bearing capacity between two methods

It can be seen that the bearing capacity of the pile foundation designed in this paper is obviously higher than that of the control group, and it can realize the optimal design of the pile foundation, which has practical application value and deserves to be vigorously promoted.

4. Conclusions

Pile top settlement caused by elastic compression of pile body, pile end settlement caused by the transfer of pile side stress to pile end plane, and pile end additional settlement caused by pile interaction. The softer the soil is, the easier it is for the load-settlement relationship of CPF to change slowly, and the harder the soil is, the easier it is for the load-settlement relationship of CPF to change abruptly. The harder the soil is, the load-settlement relationship of CPF is close to that of single pile. The nonlinear optimization design of pile foundation based on the principle of settlement control in this paper can realize the optimization design of pile foundation, which has practical application value and deserves to be popularized.

References

- [1] Han, Y. , Xu, B. , Duan, Z. , & Huang, X. (2022). Stress-based bi-directional evolutionary structural topology optimization considering nonlinear continuum damage. *Computer Methods in Applied Mechanics and Engineering*, 2022(1), 396.
- [2] Huang, Y. , He, Z. , Yashima, A. , Chen, Z. , & Li, C. (2022). Multi-objective optimization design of pile-anchor structures for slopes based on reliability theory considering the spatial variability of soil properties. *Computers and geotechnics*, 2022(7), 147.
- [3] Kim, D. , Kwon, K. , Pham, K. , Oh, J. Y. , & Choi, H. (2022). Surface settlement prediction for urban tunneling using machine learning algorithms with bayesian optimization. *Automation in construction*, 2022(8), 140.
- [4] Xie Yunfei, Chi Shichun, & Zhou Xiongxiang. (2019). Research on optimization design method of large-scale pile-raft foundation in complex environment. *Geotechnical Mechanics*, 2019(1), 8.
- [5] Farlessyost, W. , & Singh, S. (2022). Reduced order dynamical models for complex dynamics in manufacturing and natural systems using machine learning. *Nonlinear Dynamics*, 110(2), 1613-1631.
- [6] Zhang Zhiguo, Zhang Rui, Huang Maosong, & Gong Jianfei. (2019). Optimization analysis of pile group foundation under vertical load based on differential settlement and axial stiffness control. *Geotechnical Mechanics*, 2019(6), 15.
- [7] Zhang Song, Liu Jinbo, Guo Jinxue, Raymond,&Liu Minyi. (2016). Experimental Research on Pile Foundation Based on Settlement Control. *Building Structure*, 2019(2), 5.

- [8] Wang Chenghua, Zeng Chaofeng,&Liu Weipeng. (2016). Optimal design method of pile foundation based on chaotic particle swarm optimization. *Building Structure*, 46(2), 6.
- [9] Krishna Kumari, Sun Hongwei, Shu Weinong, & Fang Yunfei. (2016). Design and Analysis of Pile-raft Foundation of Beijing New Airport Terminal Based on Differential Deformation Control. *Building Structure*, 46(17), 6.
- [10] Mo Pinqiang, Gao Xinwei, Huang Zifeng,&Ma Danyang. (2019). Analysis method of settlement control of squeezed soil pile caused by tunnel excavation. *Geotechnical Mechanics*, 2019(10), 11.