Applicability of Research on Single-Pile Composite Foundation Load Test for High-Rise Buildings

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Abstract. Plain concrete pile composite foundations in loess areas predominantly rely on single-pile composite foundation load tests to determine bearing capacity. Despite high-rise buildings' composite foundations meeting the design criteria for bearing capacity through load testing, they still exhibit considerable settlements post-construction. This study aims to investigate the suitability of determining the bearing capacity of high-rise buildings' composite foundations through load testing. Employing the finite element method, the settlement development characteristics of single-pile and group-pile composite foundations under high-rise building conditions are calculated and compared. Results indicate that under high-rise building conditions, the settlement of the composite foundation is significantly greater than that of the single-pile composite foundation. Furthermore, the settlement difference between single-pile and group-pile composite foundations increases with more substantial pile separation and lower pile length and diameter. Based on settling discrepancies, a reliability index is established to describe the characteristic values of the bearing capacity of single-pile composite foundations. The analysis reveals a risk of unreliability in the load test of the single-pile composite foundation, and there is a high probability of experiencing significant settlement if the composite foundation of high-rise buildings adopts the bearing capacity characteristic value of that test.

Keywords: Plain concrete Composite foundation, Load test, Bearing capacity, Settlement.

1 Introduction

The plain concrete pile composite foundation offers advantages such as a brief construction period and low costs [1-2]. This foundation type finds extensive application in projects dealing with poor soil conditions and demanding post-construction settlement requirements in industrial and civil construction. Additionally, it is a common choice for Class A buildings exceeding 30 stories in height. At present, there are many results on the bearing characteristics of composite foundation [3-9], but in actual engineering, the single-pile composite foundation load test is still the most commonly used method to determine the bearing capacity. Liu et al. [10] investigated the influence of

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bearing plate size change on bearing performance in the composite foundation load test, revealing the size effect of rigid pile composite foundations. Yang et al. [11] proposed several problems in estimating the bearing capacity of foundations through pressure plate load tests. Zheng et al. [12] explored how composite foundation failure mechanism, bedding layer, and load plate width affect the evaluation of composite foundation bearing capacity through load testing, employing data from composite foundation field load tests. However, there needs to be more study on the reliability of assessing the carrying capacity of high-rise building composite foundations using load testing.

To investigate the reliability of the load test for single-pile composite foundations in high-rise buildings, this paper establishes a numerical model based on the working conditions of a high-rise building in Xi'an to simulate the settlement of composite foundations of single-pile and group-pile. It compares the load-bearing differences between single-pile and group-pile composite foundations and establishes reliability indicators to judge the reliability of applied load tests in high-rise buildings.

2 Analysing the difference in settlement between single-pile and group-pile composite foundations

2.1 Composite Foundation Finite Element Modelling

Using a high-rise rigid pile composite foundation in Xi'an as an example, the foundation soil comprises fill soil, loess, and ancient soil, with the geomorphological unit identified as a loess plateau. Soil parameters are detailed in Table 1. The building, classified as Class A, consists of 33 above-ground floors and 2 underground floors. The pile configuration includes a spacing of 1.3m, a diameter of 0.4m, a length of 22m, C35 concrete strength, and a mattress thickness of 0.2m. The requirement stipulates that the characteristic value of the bearing capacity for the composite foundation, involving shaped cloth piles and plain concrete piles, should not be less than 700kPa.

Table 1. Soil parameters

number	thickness/m	γ/kN/m	Es/Mpa	C/kPa	φ/°
①	0～2.5	16	13.5	15	15
②	2.5～6	16.7	16.6	16	22
③	6～9	17.8	26.2	18	23
④	9～18	21.8	24.6	26	21
⑤	18～22	21.7	23.8	21	23
⑥	22～30	18.5	26.2	23	22

Table 2. Design parameters of composite foundation

Number	Pile length/m	Pile diameter/m	Pile spacing/m
1	22	0.3	1.3
2	16	0.4	1.3
3	19	0.4	1.3
4	22	0.4	1.3
5	25	0.4	1.3
6	22	0.5	1.3
7	22	0.6	1.3
8	22	0.4	1.1
9	22	0.4	1.5
10	22	0.4	1.7

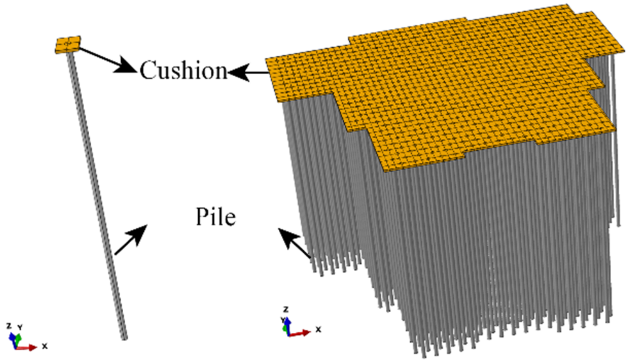
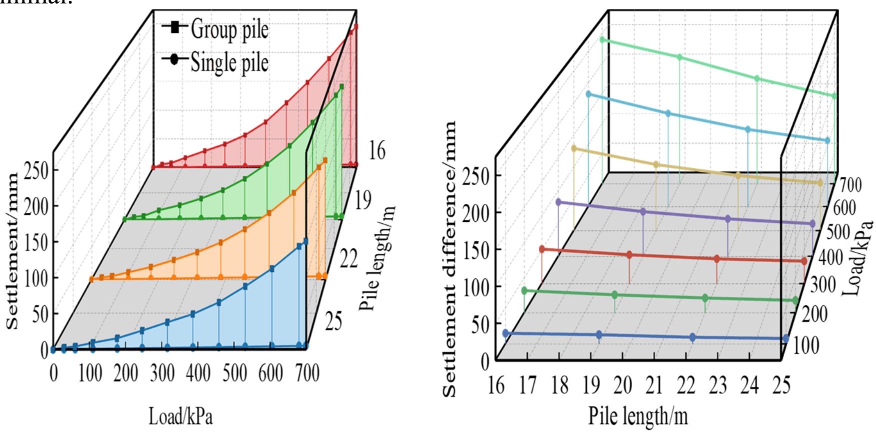


Fig. 1. Composite Foundation Model

This study examines the impact of varying pile lengths, diameters, and spacing on settlement differences. Ten single-pile composite foundations and group-pile composite foundations under different working conditions were established. Given the symmetrical plane characteristics of the composite foundation, 1/2 is utilized for analysis. The model's plane width (84m) is three times that of the composite foundation, with a depth (50m) not less than two times the pile length. The numerical model is created based on 1/2 of the axis in design diagram 1(a). The numerical model was constructed based on half of the actual raft. In Figure 1, three-dimensional models of both single-pile composite foundation and group-pile composite foundation are depicted. Detailed parameters for composite foundations are provided in Table 2.

2.2 Effect of variation in pile length on differential settlement

By maintaining the pile spacing at 1.3m, the pile diameter at 0.4m, and varying the pile length from 16m to 25m, the load-settlement curves for both single-pile composite foundations and group-pile composite foundations are depicted in Figure 2(a). With an increase in pile length, the vertical support function of the pile strengthens, leading to a reduction in the settlement of the composite foundation. While the settlement of a single-pile composite foundation decreases with increasing pile length, the change is minimal.



(a) Settlement of single-pile and group-pile composite foundation

(b)Settlement difference of single-pile and group-pile composite foundation

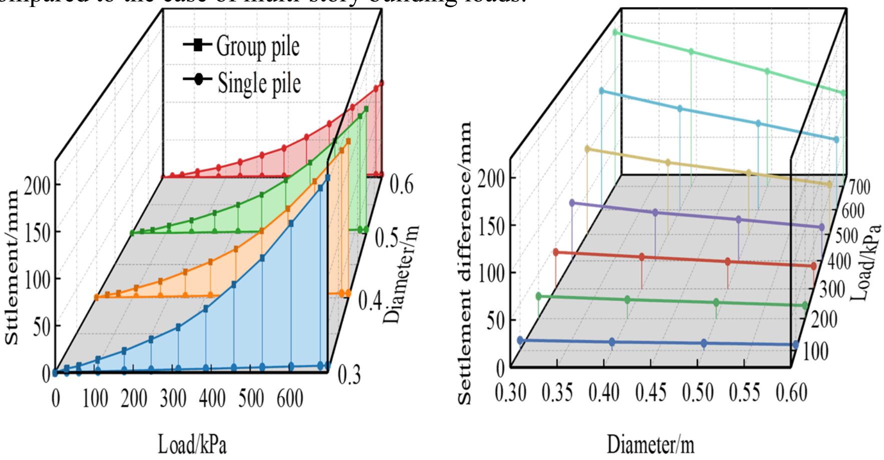
Fig. 2. Settlement in different pile lengths

Figure 2(b) depicts the variation curve of settlement difference with increasing pile length for different loads. A decreasing trend in settlement difference with increasing pile length is observed. At small loads, the impact of increasing pile length on settlement difference is minimal, and the decrease in settlement difference with increasing pile length is not pronounced. As the load increases, the reduction in settlement difference with increasing pile length becomes gradually significant. Notably, at a load of 700kPa, the decrease in settlement difference with increasing pile length is most prominent. This suggests that the higher the building load (number of floors), the more significant the settlement difference between the single-pile composite foundation load test and the group-pile composite foundation, and the more pronounced the effect of pile length change on settlement difference.

2.3 Effect of variation in pile diameters on differential settlement

With the pile length fixed at 22m and the pile spacing at 1.3m, the pile diameter is increased from 0.3m to 0.6m. The resulting load-settlement curves for both single-pile composite foundation and group-pile composite foundation are depicted in Figure 3(a). The augmentation in pile diameter significantly impacts the distribution of load between piles and soil, as well as the stress and settlement of the composite foundation. This increase not only enhances the bearing capacity of the piles but also improves the efficiency of pile side friction. Maintaining an equivalent side friction necessitates a reduced amount of pile settlement. Consequently, under the same load, the settlement of a composite foundation with a larger pile diameter is comparatively smaller, reducing overall settlement.

Figure 3(b) displays the settlement difference curve changing with the pile diameter increase. The settlement difference between single-pile and group-pile composite foundations diminishes with the increase in pile diameter. At small loads, the reduction in settlement difference with increasing pile diameter is less influenced by the pile diameter. With increased load, the settlement difference decreases to a greater extent as the pile diameter increases. This indicates that the higher the building load (number of floors), the more sensitive the settlement difference is to the increase in pile diameter compared to the case of multi-story building loads.



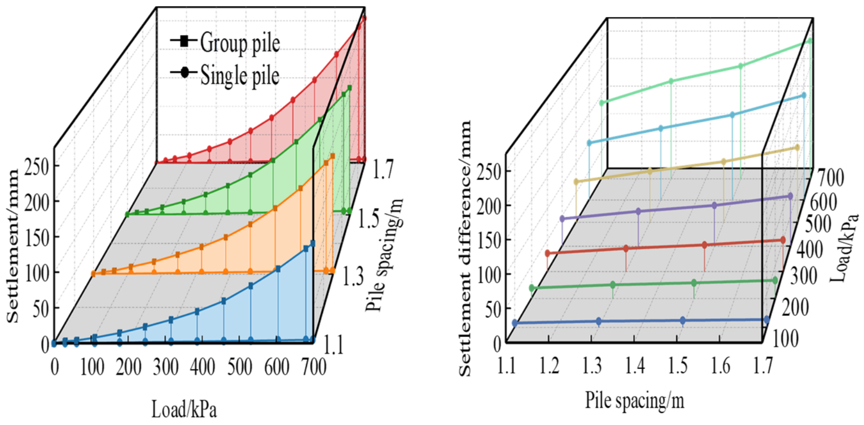
(a) Settlement of single-pile and group-pile composite foundation

(b)Settlement difference of single-pile and group-pile composite foundation

Fig. 3. Settlement in different pile diameter

2.4 Effect of variation in pile spacing on differential settlement

In this segment, maintaining the pile length at 22m and the pile diameter at 0.4m, the pile spacing is increased from 1.1m to 1.7m. Figure 4(a) illustrates the load-settlement curves for both single-pile composite foundation and group-pile composite foundation with varying pile spacing. The primary advantage of increasing the distance between piles is to enhance the bearing capacity of the soil between piles and reduce overall economic costs. However, this comes at the cost of increased load sharing among the soil between piles, leading to heightened vertical deformation. This, in turn, weakens pile side friction and may even result in negative friction. To ensure adequate bearing capacity, the pile body will further sink, enhancing the load-bearing performance of lateral resistance and end resistance. Consequently, as the distance between piles increases, the settlement of the composite foundation also increases.



(a)Settlement of single-pile and group-pile composite foundation

(b)Settlement difference of single-pile and group-pile composite foundation

Fig. 4. Settlement in different pile spacing

The variation curves of settlement difference with increasing pile spacing are depicted in Figure 4(b). The larger the pile spacing, the more significant the settlement difference between single-pile and group-pile composite foundations under the same load. At small loads, the settlement difference gradually increases gradually as the pile spacing increases from 1.1m to 1.7m. With an increase in the upper load, the larger the pile spacing, the more rapid the growth of settlement difference. This illustrates that with an enormous load (number of layers), the increase in settlement difference due to the increase in pile spacing is more significant.

3 Reliability Analysis of Single-Pile Composite Foundation Load Test for High-Rise Buildings

Because of the substantial difference in dimensions between the bearing area of single-pile composite foundations and group-pile composite foundations for high-rise buildings, there exists a significant disparity between the load test and the actual settlement of the building due to dimensional effects. Consequently, there is a certain degree of error in determining the bearing capacity of composite foundations for high-rise buildings based on the load test, constituting the primary source of unreliability in the load test. The reliability of the load test of a single-pile composite foundation refers to the description that, under specified conditions, the corresponding settlement of its bearing capacity characteristic value is relatively small and within the allowable range of the actual settlement of the group-pile composite foundation. It is a quantitative evaluation of the reliability of the load test of a single-pile composite foundation.

The load test of a single-pile composite foundation can accommodate a specific range of settlement differences and is considered reliable within this allowable range. The reliability measurement method, grounded in interval analysis, enables the examination of system reliability within a defined interval.

The reliability index η is established using the settlement difference, as depicted in Equation (1).

$$\eta = 1 - \frac{s_c - s_s}{s_u - s_s} \tag{1}$$

In the formula, s_c represents the settlement of the group-pile composite foundation, s_s represents the settlement of the single-pile composite foundation, and s_u is the standard settlement limit. When η=0, it defines the failure surface, dividing the basic parameter space into two parts: the failure domain and the safety domain. A negative η indicates unreliability in the load test of a single-pile composite foundation, while a positive η indicates reliability. The proximity of η to 0 suggests a higher likelihood of unreliability, whereas a closer proximity to 1 signifies a more reliable application of load testing.

The reliability index curve in Figure 5 illustrates that the bearing capacity of high-rise building composite foundations, as determined by single-pile composite foundation load tests, exhibits good reliability under conditions of longer pile lengths, larger pile diameters, and smaller pile spacing. However, significant unreliability is observed when the pile length and diameter are small and the distance between piles is substantial.

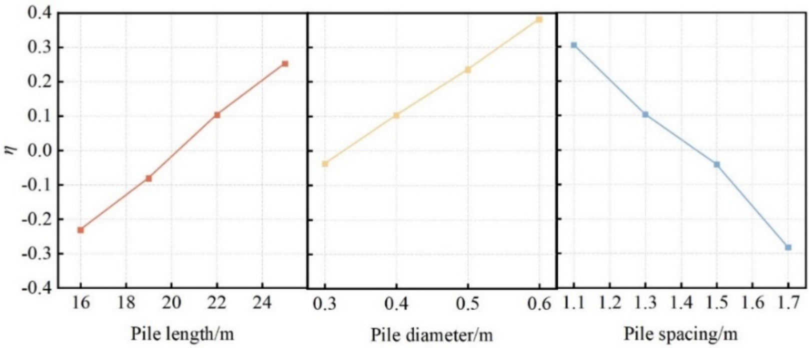


Fig. 5. Reliable index curves in different composite foundation parameters

4 Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) Utilizing the three-dimensional finite element numerical method, load-settlement curves for single-pile composite foundation and group-pile composite foundation under various working conditions were derived. It was observed that common settlement differences exist between single-pile composite foundation and group-pile composite foundation across diverse working conditions, and the settlement difference notably escalates with an increase in upper load (number of building layers). In this study, the settlement difference reaches its peak when the load is 700kPa.

(2) Building upon the settlement difference distribution and the reliability index, it is evident that the single-pile composite foundation load test is reliable under smaller loads. However, as the upper load (number of building layers) increases, the reliability diminishes in high-rise buildings. Notably, in this study, it becomes particularly unreliable at the maximum load of 700kPa.

(3) The reliability of the bearing capacity characteristic values in high-rise buildings, as determined by single-pile composite foundation load tests, increases with the length and diameter of the pile. At the same time, it decreases with the increase of pile spacing.

Acknowledgments

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