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STRUCTURAL MECHANICS OF CONSTRUCTIONS INTERACTING WITH FOUNDATION BEDS

ANALYSIS OF FEATURES OF LONG AND SHORT PILE COMPOSITE FOUNDATION IN HIGH-RISE BUILDINGS

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This study analyzed the mechanical mechanism of long-short-pile composite foundations under the interaction between the superstructure and foundation using the finite element method, field test data, and the standard formula calculation method. More specifically, the influences of the long-short-pile composite foundation on the axial force and side friction resistance of the long pile were analyzed, including the cushion thickness, pile length, and raft thickness. The results indicate that laying the cushion changes the stress mechanism of the pile, slows the stress concentration of the pile top, and adjusts the load-sharing ratio of long and short piles, which contributes to the total function of the pile stress and decreases the wear of the foundation. The bearing of the long-short-pile composite foundation is improved by increasing the long pile length. However, when the length of the long pile is increased to a certain limit, the bearing capacity of the foundation is not substantially improved. An excessive increase in pile length will cause material wastage and increase the engineering cost. The increase in the raft thickness slows the stress concentration at the long pile's top. In that design, the thickness of the raft can be increased to avoid damage to the pile top due to excessive stress. The results of this study serve as a reference for optimal designing of the cushion thickness, pile length, and raft thickness in this type of foundation.

Introduction

The long-short-pile composite foundation is a new type of foundation that is composed of long and short piles. This foundation not only provides an improved bearing capacity but also leads to a reduction in the engineering cost. Currently, this type of foundation is widely applied in the engineering field as a novel form for foundation treatment [1,2]. This novel composite foundation has significant development potential, and it is particularly suited for foundations with a thick compressed soil layer. Its upper load is further transferred to the deep soil owing to the existence of a reinforcement area. The change in strength and modulus along the depth of this foundation can help reduce settlement and decrease the foundation treatment cost. In the foundation analyzed in this study, both long and short piles are included in the shallow reinforcement area, which can improve the replacement rate of the composite foundation and subsequently improve the bearing capacity of the foundation.

Currently, much research is actively being conducted on pile and composite foundations, and several studies have been published. Myerhof [3] proposed a formula that estimates the equivalent stiffness of frame structures considering the interaction between the superstructure and foundation. Chamecki [4] considered the upper structure stiffness when calculating the settlement of a single foundation and analyzed it employing the load transfer coefficient method. Sommer [5] studied a simple frame structure with semi-infinite elastic soil, proposed a method for calculating the foundation settlement, bending moment, and contact stress, and considered the influence of superstructure stiffness. Cheung and Zinkiewicz [6] used the finite element method to analyze the foundation considering the interaction of the superstructure with the foundation. Lee and Harrison [7] and Haddadin [8] applied the substructure method to study the foundation considering the interaction of the superstructure. Christian [9] considered the interaction of foundation and superstructure in high-rise buildings. Based on as study by Mindin [10], Poulos and Daris [11] proposed the elastic theory method considering the in-

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teraction of pile and soil. Taking the superstructure interaction into consideration, Price and Wardle [12] designed the piled raft foundation of a high-rise building.

Bartolomey et al. [13] proposed the calculation method for pile foundation bearing capacity and settlement. They introduced a pile foundation projection method starting from the allowable settlement of buildings and structures.

Further, they summarized [14] the basic results of experimental and theoretical research on pile foundation interaction, calculation method development for limit conditions, and construction of pile foundations.

Chen et al. [15] carried out field test research on the realization of a long-short-pile composite foundation in high-rise buildings. They concluded that attention must be paid to the crucial influence of cushion thickness, compactness, and uniformity on the load-sharing ratio of long and short piles. Long piles may be prestressed concrete pipe piles, steel pipe piles, or bored piles, among others, whereas flexible piles may be sand gravel piles, gravel piles, cement-fly ash-gravel (CFG) piles, cement mixing piles, etc.

Zhang et al. [16] studied the application of long and short piles in deep soft soil. They also analyzed the design of the long pile, short pile, and cushion layer in the composite foundation.

Dzagov [17] presented the results of the static test on 6–24-m long driven piles and the soil static sounding of the test site. According to the soil static sounding data, the negative friction force of sinking soil and total resistance of the piles were evaluated.

Using a field test and numerical analysis, Zhu et al. [18] studied the features of the rigid flexible pile composite foundation. The influence of different cushion parameters and the replacement rate on foundation settlement, the ratio of pile–soil stress, and the sharing ratio of the pile–soil load were compared.

Xie et al. [19] analyzed the influence of different cushion moduli, cushion thickness, long pile length, and short pile modulus on the entire settlement and stress ratio of the studied composite foundation in this work by applying the finite element approach. They showed that the optimized parameter material can improve the mechanical behavior of the foundation and render its stress more reasonable.

Lin and Fang [20] asserted that in the presence of karst caves in the lower part of high-rise buildings, the use of the studied composite foundation would be economical and timesaving, and thus would be able to reduce construction difficulty. The high-strength composite foundation can also be used to reinforce the pile foundation in high-rise buildings.

Guo et al. [21] carried out experiments and numerical analyses on the aforementioned foundation. They found that the pile–soil stress ratio increases with the pile length and pile number. In this type of composite foundation, the stress concentration on the zest of the long pile is beneficial to reduce the foundation settlement.

Smolin et al. [22] analyzed the characteristics of equipment and measurement in bored pile testing according to Russian and American standards.

Gotman [23] proposed a method for calculating inclined pile foundation under the combined action of horizontal load and bending moment. Using the Winkler contact model, the nonlinearity of the pile-soil interaction was considered and the calculated data was compared with the experimental data.

Bokov et al. [24] studied the calculation methods of pile foundations with different pile lengths and diameters. Through theoretical analysis and calculation data, they obtained a calculation method for pile foundations to ensure the safety of buildings built on pile foundations.

Yang et al. [25] derived the consolidation equation of soil between piles in the composite foundation with multiple undrained long and short piles under instantaneous loading, and established a corresponding analytical solution based on the one-dimensional consolidation theory of double-layer foundation. The correctness of the analytical solution was verified via comparison with the corresponding finite element solution.

Lin et al. [26] conducted an on-the-spot investigation and foundation deformation monitoring based on the quality accident case of a cement mortar long-short-pile foundation, the foundation type examined in this study. According to the load transfer mechanism of the long-short-pile composite foundation with a flexible foundation, this study analyzed the main causes of engineering quality accidents and proposed preventive measures to avoid similar occurrences.

Ji et al. [27] carried out a static load physical model test of the composite foundation in the laboratory and analyzed the results of the load-sharing features of the composite foundation and the exertion degree of the end resistance and the pile side resistance.

To reveal the load transfer mechanism of the rigid flexible pile composite foundation in the collapsible loess area, Xiang et al. [28] conducted a field prototype test and analyzed the variation law of the stress of the pile body and soil between piles under different loads and depths.

Ter-Martirosyan et al. [29] studied the stress–strain state of the gravel pile surrounding the compacted soil-grid system under static and variable loads, considered the pile–soil interaction, and studied the influence of piles on the dynamic characteristics of the foundation.

Solovyev [30] studied a method of estimating the bearing capacity of end-bearing piles based on settlement criteria. Pile material and elastic modulus were the main factors affecting the failure of end-bearing piles and the allowable load of pile foundation was obtained.

Boyarintsev [31] analyzed Russia's experience in the application of polymer and composite pile structures, introduced the development history and types of piles, analyzed their advantages and disadvantages, and classified such piles.

Degtyar et al. [32] studied the seasonal frozen soil reinforcement method of the subgrade by double cone hollow piles and geotechnical materials in the northern region of the Russian Federation. A calculation method for roadbed in the form of double cone pile foundation reinforced with geotechnical materials was proposed.

Kornilov et al. [33] considered the possibility of using temperature-controlled under-floor spaces for low-rise buildings on pile foundations under frozen soil conditions. A predictive dynamic thermal model was proposed. By comparing with the obtained field observation data, the calculation model of the interaction between the building and the foundation with the space under the insulated floor was verified.

The mechanical analysis of the composite foundation with long and short piles, considering the interaction between the superstructure, pile, and soil, has consistently attracted interest in the fields of geotechnical engineering and architectural structure design; however, theoretical research on this type of foundation is far behind its practical engineering applications. The interaction between foundation and superstructure must be considered in structural design.

In this study, the mechanical mechanism of long-short-pile composite foundation was analyzed under the interaction between the superstructure and foundation. The variation law is summarized herein, and this study serves as theoretical guidance for the further design optimization of this type of foundation. A finite element model is also established to analyze the mechanical performance of the long-short-pile composite foundation. Two types of finite element software are used, and the developed models are compared for verification. At the same time, an in-situ test and standard formula calculation are performed. The effects of different cushion thickness, length of long pile, and raft thickness on the axial force and the side friction of the long pile are also discussed.

Engineering and Establishment of Finite Element Model

A typical commercial high-rise building [34] is rectangular in shape, with a length of approximately 81 m and width of 18 m. The survey building has 30 stories and a basement, which has a shear wall structure. The underground soil layer includes fill, silt, silty clay, medium sand, and pebbles. The raft is located on the silt layer. The groundwater level elevation is –1.00 m. Because the second layer of the soil is soft and the superstructure requirements with respect to the bearing capacity can never be met, the CFG pile and lime soil pile (deep lime and fly ash) combined with the long and short pile composite foundation are adopted in the whole foundation treatment after optimization. The CFG pile is employed as a long pile and the lime-fly ash pile is used as a short pile. The CFG pile di-

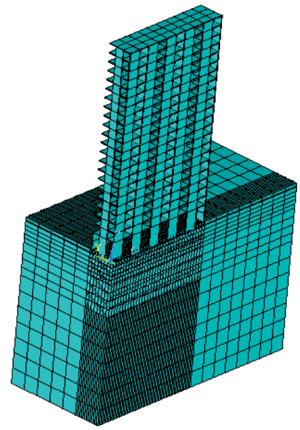

Fig. 1. Finite element analysis model with the upper part representing the shear wall structure, and the lower part representing the soil and pile.

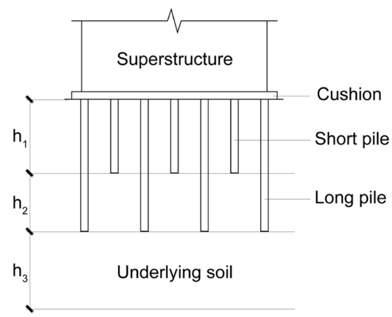

Fig. 2. Schematic of settlement calculation of long-short-pile composite foundation.

ameter is 400 mm, the pile length is 18 m, the diameter of the lime-fly ash pile is 400 mm, and the length of the pile is 7 m. The spacing between the long and short piles is 1200 mm, the cushion is gravel, and the composite foundation adopts a 300 mm thick gravel cushion.

The following assumptions were used when establishing the finite element model [35]. (1) The total stress method is used for analysis and calculation. (2) Soil, cushion, and short pile are continuous elastoplastic bodies, and the Drucker–Prager model is employed. (3) Other structures are linear elastomers.

A quarter of the model was used for finite element analysis and calculations as the building is symmetrical (Fig. 1); this also helps reduce the number of calculations. The spatial eight node coordination unit is appropriate for the model. Piles are made of cylindrical tube elements. The beam column adopts a three-dimensional beam element. Elastic shell elements are used for building the shear walls and floors. The vertical load is 20 kPa per layer, and it is applied to every floor. The length of the soil mass is 80 m, its width is 35 m, and its depth is 54 m, which is three times the length of the pile, determined via trial calculations [36]. The boundary conditions of the finite element model are as follows: the rotation angle and displacement of the soil bottom are limited, and those of the horizontal direction are likewise limited by the soil side. The symmetrical constraint is applied on the symmetry plane, and the upper boundary of the soil has no constraints. There are 39171 elements. More accurately, the model contains 32388 nodes, along with 272 long piles and 231 short piles.

The field test was carried out on an engineering site, and the settlement of the pile was observed using a settlement observation instrument. ANSYS and ABAQUS finite element models were established; the ABAQUS model was used to verify the accuracy of the ANSYS results.

Figure 2 shows a simplified diagram of the settlement calculation of the long-short-pile composite foundation. Calculated settlement area is along the vertical direction. The domain is divided into

TABLE 1

Number of layers	Soil layer name	Soil thick-ness, m	ω, %	ρ, kN·m^{-3}	E_s, MPa	f_{ak}, kPa	q_s, kPa
1	Silt	7	22.7	20.2	23.89	150	50
2	Silty clay	11	25.5	20.1	20.66	280	55
3	Silt	36	19.7	21	47.03	360	–
4	Pebble	10	Saturation	–	50.38	750	–

three parts: long and short pile area h_1, long pile area h_2, and underlying layer area h_3. The settlement of the long-short-pile composite foundation consists of the settlements of h_1, h_2, and h_3.

The index parameters of engineering foundation mechanics are shown in Table 1.

The formula for calculating the bearing capacity of the long-short-pile composite foundation is [37]:

$$f_{spk} = \lambda_1 m_1 \frac{R_{a1}}{A_{p1}} + \lambda_1 m_2 \frac{R_{a2}}{A_{p2}} + \beta(1 - m_1 - m_2) f_k, \tag{1}$$

where m_1 and m_2 are the area replacement ratios of the long and short piles, respectively; R_{a1} and R_{a2} are the characteristic values of the bearing capacity of the long and short piles, respectively, which can be determined according to the bearing capacity of the single pile determined by the static load test or the pile body strength; λ_1 and λ_2 are the coefficients of bearing capacity of single piles of long and short types, respectively; A_{p1} and A_{p2} are the cross-sectional areas of long and short piles, respectively; β is the coefficient of bearing capacity of soil between piles; f_{sk} is the bearing capacity of soil between piles of composite foundation after treatment; f_{spk} is the characteristic value of the bearing capacity of the composite foundation.

The replacement rate of the long and short piles in this project are $m_1 = m_2 = 0.101$, and the composite foundation compressive modulus is equal to ζ times the natural foundation compressive modulus of this layer. After calculation, the composite foundation compressive modulus within the range of long and short piles is 70 MPa. The compressive modulus of the composite foundation in the long pile range is 105 MPa.

As shown in Fig. 2, the settlement of the long-short-pile composite foundation consists of three parts: the long-short pile area, the long pile area, and the underlying layer area. In engineering practice, the settlement calculation of each part can be recommended by the current "Building Foundation Design Code." The method is used in [38]. The calculation formula for the settlement of the long-short-pile composite foundation is as follows:

$$S_c = \left(S_{h1} + S_{h2} + S_{h3}\right) = \sum_{i=1}^{n_1} \frac{P_0}{E_{spi}} \left(Z_i \bar{\alpha}_i - Z_{i-1} \bar{\alpha}_{i-1}\right) + \sum_{i=1}^{n_2} \frac{P_0}{E_{spi}} \left(Z_i \bar{\alpha}_i - Z_{i-1} \bar{\alpha}_{i-1}\right) + \sum_{i=1}^{n_3} \frac{P_0}{E_{spi}} \left(Z_i \bar{\alpha}_i - Z_{i-1} \bar{\alpha}_{i-1}\right), \tag{2}$$

where S_c is the total settlement, S_{h1} is the settlement within the scope of the long pile and short pile, S_{h2} is the settlement within the range of the long pile, and S_{h3} is the settlement of the soil layer within the calculation range of the long pile bottom; P_0 is the attachment pressure at the bottom of the foundation; E_{spi} is the composite modulus of the pile–soil or natural soil; Z_i and Z_{i-1} are the distances from the bottom of the foundation to the bottom of layer i and layer i-1; $\bar{\alpha}_i$ and $\bar{\alpha}_{i-1}$ are the average additional pressure coefficients within the calculation range from the calculation point of the bottom surface of the foundation to the bottom surface of layers i and i–1, respectively; and n_1, n_2, and n_3 are the numbers of soil layers within the calculation range.

Taking 30 layers as an example, the settlement of the long-short-pile composite foundation is calculated as follows: P_0 = 750 kPa, E_{sp1} = 75 MPa, E_{sp2} = 105 MPa, E_{sp3} = 180 MPa, Z_{i1} = 0 m, Z_{i2} = 7 m, Z_{i3} = 18 m, Z_{i4} = 54 m, $\bar{\alpha}_1$ = 0.25, $\bar{\alpha}_2$ = 0.241, $\bar{\alpha}_3$ = 0.2014, $\bar{\alpha}_4$ = 0.1173, ψ = 0.2, and

TABLE 2

Analysis method	Settlement within calculation depth, mm				
	4 layers	8 layers	15 layers	22 layers	30 layers
ANSYS	10	13	21	26	35
ABAQUS	11	14	20	27	34
In situ test	9.5	14.3	19.3	27.9	34.1
Formula calculation	10	14	20	27	34

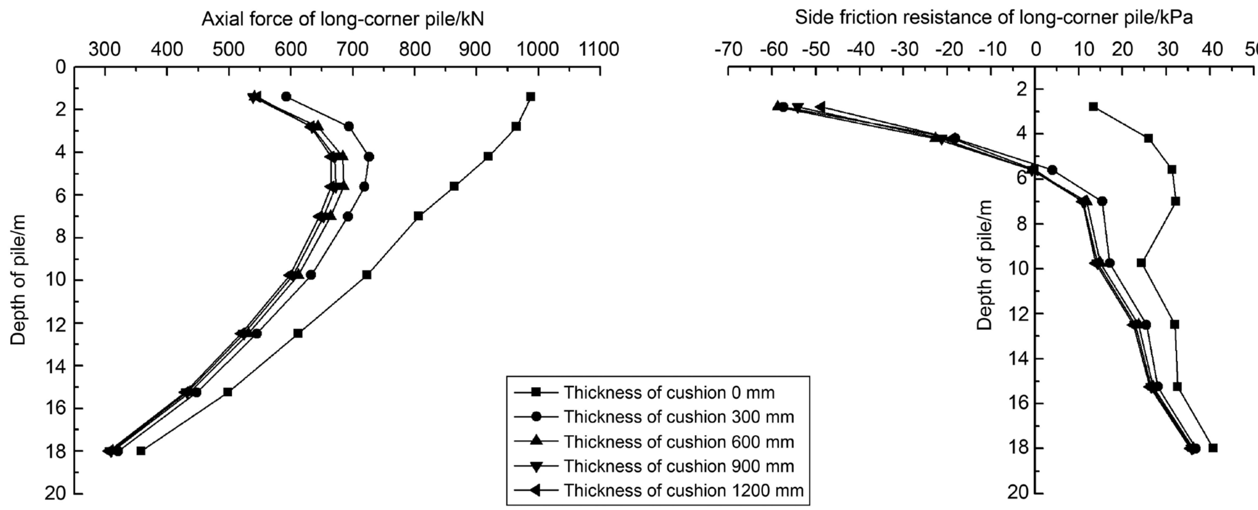

Fig. 3. Influence curve of cushion thickness on axial force and side friction of long pile.

$$S_{c30} = (S_{h1} + S_{h2} + S_{h3}) = \\ = \sum_{i=1}^{n_1} \frac{P_0}{E_{spi}} \left(Z_i \overline{\alpha}_i - Z_{i-1} \overline{\alpha}_{i-1} \right) + \sum_{i=1}^{n_2} \frac{P_0}{E_{spi}} \left(Z_i \overline{\alpha}_i - Z_{i-1} \overline{\alpha}_{i-1} \right) + \sum_{i=1}^{n_3} \frac{P_0}{E_{spi}} \left(Z_i \overline{\alpha}_i - Z_{i-1} \overline{\alpha}_{i-1} \right) = 34 \text{ mm}. \quad (3)$$

The same method can be used to calculate the settlement of 4, 8, 15, and 22 layers:

$$S_{c4} = 10 \text{ mm}, S_{c8} = 14 \text{ mm}, S_{c15} = 20 \text{ mm}, S_{c22} = 27 \text{ mm}. \quad (4)$$

The settlement within the calculation depth of the soil layer, calculated by various analysis methods, is shown in Table 2.

According to the building foundation design code [38], the average settlement allowance of the high-rise building foundation must not exceed 200 mm. The final settlement value obtained by the standard formula method, in situ test, and numerical analysis is approximately 34 mm, which is less than 200 mm, thus meeting the requirements of the specification. Two finite element software and formula calculation methods were used to obtain the settlement of the building on the 4th, 8th, 15th, 22nd, and 30th floors, and in-situ tests were performed. The theoretical formula calculation, numerical simulation, and in situ test were used to obtain the various stages. All settlement values converge, the change trend is consistent, and the difference is less than 5%, which meets the engineering accuracy requirements. The four methods are mutually consistent, indicating that the establishment of the finite element model is correct and can be used to analyze the stress variation law of long and short pile composite foundations.

Finite Element Result Analysis

Figure 3 shows the influence curve of cushion thickness on the axial force and side friction of the long pile. When no cushion is found, the long pile's maximum axial force is at its top. This force decreases gradually with increasing depth. Owing to the absence of the cushion, the settlement of the pile top and raft is larger than that of the soil between piles, which results in positive friction of the pile

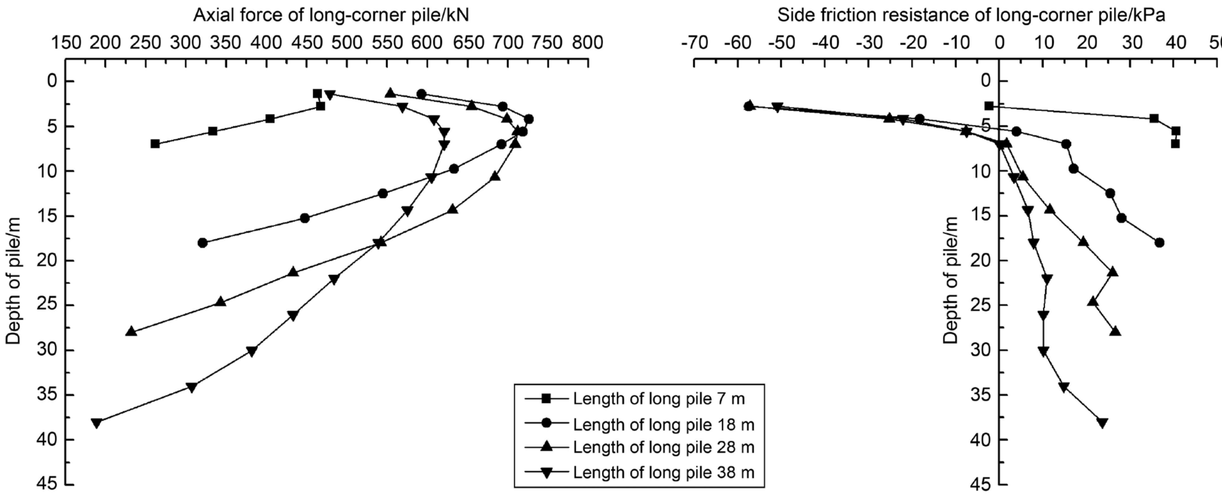

Fig. 4. Influence curves of long pile length on axial force and side friction of long pile.

body, leading to the maximum of the pile top's axial force and the gradual decrease along the depth. Its mechanism is similar to that of the pile foundation.

If a cushion is provided, the long pile's axial force will increase first and then decrease. Because of the existence of the cushion layer, negative friction is generated in a certain range above the pile body, which leads to the increase in that force along the pile body's depth at first, followed by a decrease.

When no cushion is provided, the force in front of the long pile body changes significantly along the depth. When the cushion is present, the change of that force of the long pile retards. This indicates that an increase in the cushioning alleviates the forces on the different parts of the log piles.

In the construction of the foundation examined in this study, the stress concentration on the pile top can be reduced by adding the thickness of the cushion layer to change the stress mechanism of the pile. By establishing the bedding, the load-sharing ratio of long and short piles can be allocated, and the load of the pile can be exerted more fully, thus reducing the cost of the foundation.

When the cushion is absent, the long pile's side friction is active in its body. Because of the absence of the cushion, the settlement of the body is larger than that of the soil around the pile, which results in positive side friction.

When the cushion layer is laid, the negative friction will gradually decrease with increasing depth until it reaches zero, after which the positive friction will gradually increase along the increasing depth. Because of the existence of a cushion layer, owing to the effectiveness of an upper load, the top of the pile is pierced upward, which makes the settlement of the pile top less than the settlement of the soil on the pile side, thus generating negative friction resistance. With increasing depth, the settlement of the body increases gradually, and the settlement of the soil body decreases gradually, which makes the negative friction resistance on the pile side decrease gradually. When the pile reaches a certain depth, the settlement of the pile body will decrease gradually. This is equivalent to the soil settlement on the side of the pile, such that the negative friction is reduced to zero. Consequently, the pile body's settlement is larger than that of the soil on the side of the pile, which results in positive friction and increases gradually.

The negative skin friction on the upper side of the pile increases the axial force of its body, which may cause damage to the pile body and cause a large settlement of the soil layer above the pile. By analyzing the variation law of the pile side friction resistance of the long-short-pile composite foundation after laying the cushion, engineering accidents caused by the negative friction resistance of the long-short-pile composite foundation in the design can be avoided.

Figure 4 shows the influence curves of the long pile length on the axial force and side friction of the long pile.

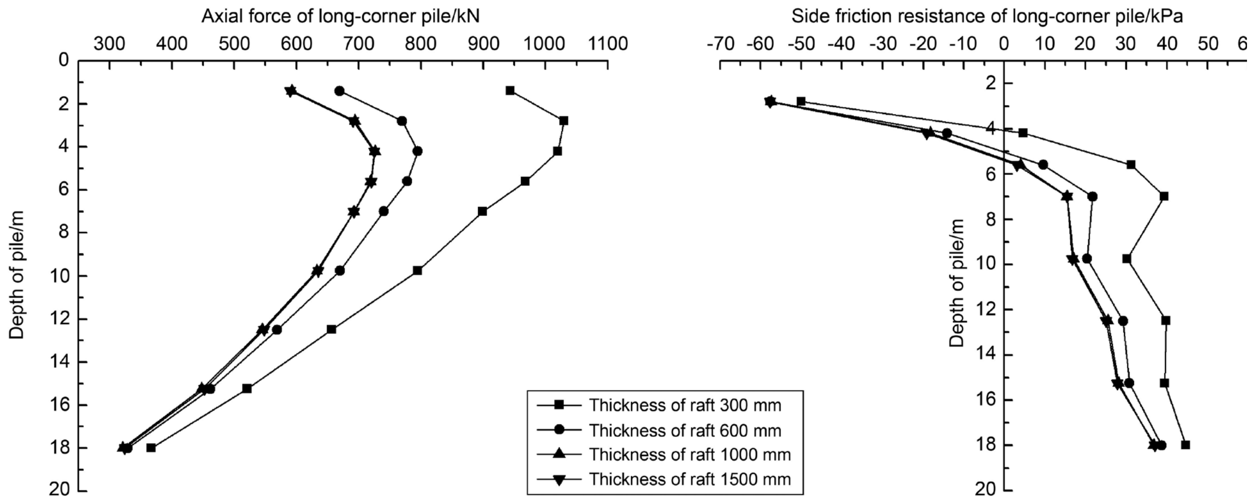

Fig. 5. Influence curve of raft thickness on axial force and side friction of long pile.

The long pile body's axial force increases and then decreases with increasing depth. When the depth with the length increases, the axial force at the top of the long pile is enhanced. When the length increases, the axial force tip will first increase and subsequently decrease.

By increasing the long pile length, the force of the long pile is increased, and the bearing capacity of the long-short-pile composite foundation is improved. However, if the length of the long pile increases to a certain limit, the force mentioned at the end of the pile decreases, which indicates that the lower pile cannot fully play its role, which will cause wastage of the lower pile and increase the engineering cost. By analyzing the variation of the axial force of its body with the length of the long pile, it is helpful to determine the pile length reasonably in the design of the foundation studied in this work, in order to reduce the engineering cost.

The upper side of the long pile exhibits negative skin friction, and when the length is increased, the maximum friction increases. When the pile length increases, the negative side friction along the long pile depth decreases. When the length is 7 m, the distance between the point where the frictional resistance is zero and the top of the pile is 2.5 m, and when the pile length is 38 m, the aforementioned distance is 7.5 m, which is an increase by approximately a factor of three.

When the long pile length increases, the range of increase of its positive friction resistance gradually decreases. Accordingly, the reduction in the axial force of the body is retarded such that the long pile can further transmit the upper load to the deep soil layer, thus reducing settlement.

The increase in the long pile's length will increase its negative friction resistance. The increase in the length of this type of pile is conducive to transferring the axial force of its body to the soil layer. In the design, the bearing capacity of the composite foundation can be optimized in accordance with its increasing length.

Figure 5 shows the influence curves of raft thickness on the axial force and side friction of the long pile. When the raft thickness is 300 mm, the long pile top stress is 943 kPa; when the thickness is 600 mm, this stress is 668 kPa, which represents a reduction of 29%. However, when its thickness is greater than 600 mm, the influence of raft thickness on the axial force of the long pile decreases.

The increase in raft thickness can slow the stress concentration at the long pile's top. In the design, the thickness of the raft can be increased to avoid damage to the pile top due to excessive stress. When the thickness increases to a specific limit, the range of influence of the pile top stress will be reduced. In the design, a raft that is too thick must be avoided as this will lead to an increase in the engineering cost.

When the raft thickness increases, the friction of the long pile decreases in the positive and negative directions. If the raft thickness is above 600 mm, the influence of that on the long pile's side friction decreases. When the raft thickness increases, the depth of the point where the frictional resistance is increases along the long pile. In the design of this new composite foundation, the thickness of the raft can be increased to reduce its side friction and make the stress distribution of the long pile more uniform. Analyzing the influence of the increase in raft thickness on the stress of the composite foundation helps in determining the raft thickness in the design.

Implications of the Results

(1) In the design of the long-short-pile composite foundation, the stress mechanism of the pile is altered by laying a cushion, slowing the stress concentration of the pile top, and adjusting the load-sharing ratio of long and short piles, which can reduce the stress on the pile in the foundation and the cost of the foundation. The design of this foundation can serve as the basis for the design optimization of the cushion layer.

(2) Increasing the length of the long pile can improve the bearing capacity of the long-short-pile composite foundation. However, when the length of the long pile is increased to a certain limit, the bearing capacity of the foundation is not substantially optimized. An excessive increase in the pile length will thus lead to wastage and increase the engineering cost. To avoid this, the design optimization can provide a reference for determining a reasonable pile length, thus reducing the engineering cost.

(3) The increase in raft thickness can lower the stress concentration at the top of the long pile. In this design, the thickness of the raft is increased to avoid damage to the pile top from excessive stress. When the raft thickness rises to a specific limit, the influence range of the pile top stress will be reduced. In the design, one must avoid establishing a raft with a large thickness, as this will increase the engineering cost. The analysis results can serve as a reference for developing improved raft designs for the composite foundation analyzed in this study.

(4) Laying the cushion and changing the length of the long pile and raft thickness will affect the magnitude and depth range of the negative friction resistance of the long pile. The analysis results can help to avoid engineering accidents caused by the negative friction of the long-short-pile composite foundation. This design may serve as a reference for optimizing the long pile shaft strength.

Conclusions

In this study, the mechanical properties of a long-short-pile composite foundation were analyzed by establishing a finite element model and calculating and verifying the results via two types of finite element software packages. Simultaneously, an in-situ test and standard formula calculation were conducted. The results of the analysis and calculations were consistent with those of the field measurements.

The analysis results indicate that the cushion layer can lower the stress concentration on the pile top and adjust the load-sharing ratio of the pile and soil. Increasing the length of the long pile can improve the bearing capacity of the composite foundation. An increase in the raft thickness can reduce the stress concentration at the top of the long pile. By changing the thickness of the cushion, the length of the long pile, and the thickness of the raft, the design of the long-short-pile composite foundation can be further optimized. Such foundations can be used in the foundation design of high-rise buildings as they not only meet the requirements of building stress, but also significantly reduce the project cost. The analysis results can provide guidance for the wide application of this type of foundation.

The cushion in the long-short-pile composite foundation can be used as a seismic isolator and shock absorber. Therefore, the mechanical properties of this type of foundation must be studied under static loading in the future. It is necessary to further study the seismic performance of such foundations under the interaction of the superstructure and foundation for greater clarity regarding their behavior.

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