

Numerical simulation study on bearing performance of artificial hard crust-flexible pile composite foundation in road soft soil subgrade

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Abstract: With the widespread application of artificial hard crust composite foundations in engineering, traditional pile-supported design methods can no longer effectively reflect their unique bearing performance. Due to the high strength and stiffness of the artificial hard crust, the interaction and deformation coordination modes between it and the embankment fill, pile bodies, and foundation soil during the load transfer process are significantly different. Therefore, there is an urgent need to optimize the existing design methods. In-depth research on the bearing characteristics and load transfer mechanism of the artificial hard crust-flexible pile composite foundation will help improve the stability and reliability of the foundation, and provide a scientific basis for the improvement of relevant design specifications.

Keywords: Road soft soil foundation; Artificial hard crust; Flexible pile; Composite foundation; Bearing performance.

1. Introduction

To address the challenges of soft soil foundations, traditional foundation treatment methods have various limitations. In this context, in-situ solidification technology has emerged due to its advantages such as environmental friendliness, cost-effectiveness, and convenient construction. With the deepening of its application, many scholars have conducted systematic studies on the performance of artificial hard crusts formed by in-situ solidification [1, 2, 3, 4].

Flexible pile composite foundation is a widely used foundation treatment technology in weak foundation reinforcement projects. Wang et al [5] studied the bearing characteristics of the gravel pile-cement-soil composite pile system and found that the use of a cement-soil solidified layer can effectively improve the pile-soil stress ratio. Xu Chao et al [6] conducted a comparative analysis of the working characteristics of cement mixing piles under rigid and semi-flexible loads through on-site load plate tests, and found that the load type and pile end bearing conditions are important factors affecting the bearing capacity of piles. Zhao et al [7] carried out field tests on the combined foundation of spiral piles and flexible piles in marine soft soil areas, and found that the bearing capacity of this composite system is about 35% higher than that of a single flexible pile, with a significantly reduced settlement rate. This indicates that the rigidity enhancement effect of spiral piles helps optimize the load transfer path. Song Xiuguang et al [8] obtained the curve of

the variation law of pile stress with depth based on field tests. Hu Xiuqing et al [9] studied the dynamic characteristics of soft soil foundations reinforced by cement-soil mixing piles through resonant column tests.

In terms of theoretical research, Hu Zhenhua et al [10] revealed that the artificial hard crust exhibits brittle failure characteristics under load through model tests and theoretical analysis. Chen Long et al [11] found through their research that appropriately increasing the thickness of the hard crust helps improve the bearing performance of the composite foundation, but when its modulus exceeds 50 MPa, the increase in the pile-soil stress ratio slows down. This suggests that in engineering design, a balance must be struck between economy and bearing effect. H. Chunxia et al [12] found through static load tests that there is a discrepancy between the test bearing capacity and the theoretical calculation value, indicating that the calculation model needs further optimization.

Based on experimental data, this study establishes a numerical analysis model using the finite element software ABAQUS to simulate the settlement and deformation evolution process of the artificial hard crust-flexible pile composite foundation under different working conditions, aiming to provide theoretical support and parameter basis for engineering design.

2. Model test

2.1. Model design

Table.1 Experimental plan of composite foundation with different structural forms.

Thickness of Silty Sand Layer (mm)	Thickness of Soft Soil Layer (mm)	Thickness of Artificial Hard Crust (mm)	Pile Length (mm)	Pile Spacing (mm)	Embankment Filling Height (mm)
150	750	150	750	130	300

The test equipment mainly includes a test model box and a test data acquisition system. During the test, BW-type micro soil pressure sensors were used to monitor the soil pressure on the embankment surface and pile top, with a measuring

range of 0.01~20 MPa; strain gauges of model 120-10AA were adopted for pile shaft axial force testing, and 5 measuring points were arranged at equal intervals along the pile length for each test pile. The Donghua Testing DH3816N

static stress-strain acquisition instrument was selected for test data collection. Among them, the soil pressure sensors were connected via a full-bridge wiring method, and the strain gauges were connected using a half-bridge method to ensure measurement accuracy and data reliability.

3. Numerical simulation

3.1. Establishment of finite element model

A numerical simulation study was carried out using the finite element software ABAQUS to establish a three-dimensional model of the artificial hard crust-flexible pile composite foundation. The soil was divided into three layers from top to bottom: the artificial hard crust (150 mm thick), the waste sludge layer (550 mm thick), and the silty sand layer (150 mm thick). To improve the calculation accuracy, hexahedral structured meshes were used for the soil, and the element type C3D8 was selected. The cement-soil mixing piles were arranged in the same manner and size as in the indoor model test, with a square layout, a diameter of 35 mm, and a length of 750 mm. The cement mixing piles also used hexahedral structured meshes with the element type C3D8. The embankment fill height was 300 mm with a slope ratio of 1:1.5, and hexahedral structured meshes with the element type C3D8 were used. To realistically simulate the embankment filling conditions, the "model change" tool in the "Interaction Manager" of the ABAQUS software was used to fill the embankment in three stages. The model boundary conditions were set as fixed constraints on the bottom surface ($U_1=0, U_2=0, U_3=0$) and normal displacement constraints on the side surfaces ($U_1=0$ or $U_3=0$). The calculation model of the

artificial hard crust-flexible pile composite foundation is shown in fig. 1.

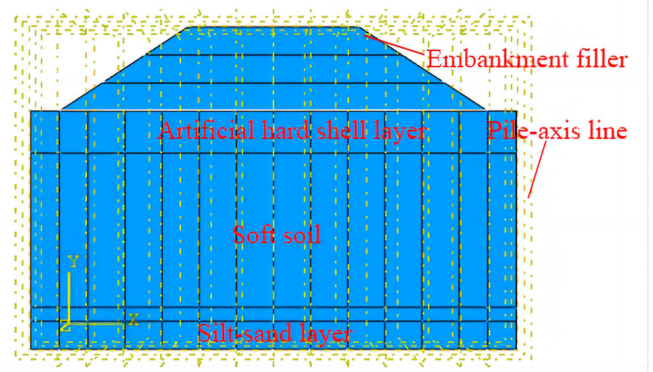


Fig.1 Computational model of artificial hard crust flexible pile composite foundation.

3.2. Model parameters and calculation conditions

The foundation soil, cement mixing piles, and embankment filling materials in the artificial hard crust-flexible pile composite foundation model all adopt the Mohr-Coulomb constitutive relation. The basic physical property indices of the soil, cement mixing piles, and embankment filling materials are measured through indoor tests, and reference is made to the selection of soil and cement mixing piles in relevant literature. The physical strength indices of each part of the artificial hard crust-flexible pile composite foundation are shown in Table 2 below.

Table .2 Model parameters

Material	Elastic Modulus (kPa)	Void Ratio	Cohesion (kPa)	Friction Angle (°)	Density ($g \cdot cm^{-3}$)	Constitutive Relation
Artificial hard crust	100000	0.28	346.18	51.47	1.88	Mohr-Coulomb
Waste mud	530	0.35	7.32	6.78	1.51	Mohr-Coulomb
Embankment filling material	25000	0.31	2.56	34.91	1.85	Mohr-Coulomb
Cement mixing pile	200000	-	150	-	2.11	Mohr-Coulomb

4. Analysis of test and numerical simulation results

4.1. Finite element model validation

Fig. 2 show the comparison of settlement curves at various measurement points (including the embankment center and shoulders on both sides of the embankment) under different embankment loads between the numerical simulation and the indoor model test. Through this comparison, the accuracy of the numerical simulation results was verified, thereby validating the effectiveness of the established numerical model. As can be seen from the figures, the settlement curves of the artificial hard crust-flexible pile composite foundation during the three embankment filling stages in the numerical simulation are basically consistent with those in the indoor test, which verifies the rationality of the selected soil parameters and indicates that the established numerical simulation model of the artificial hard crust-flexible pile composite foundation is correct.

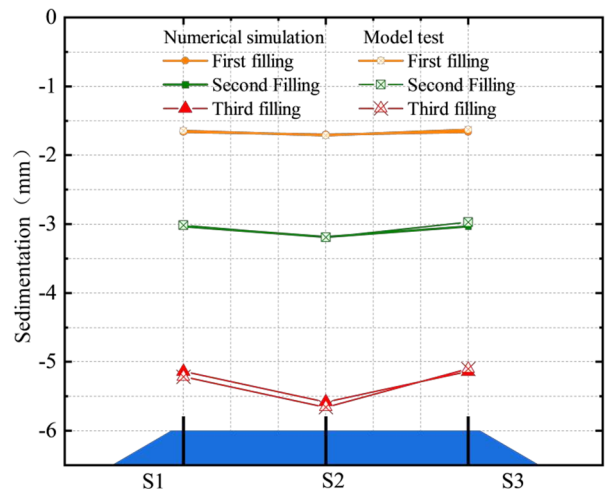
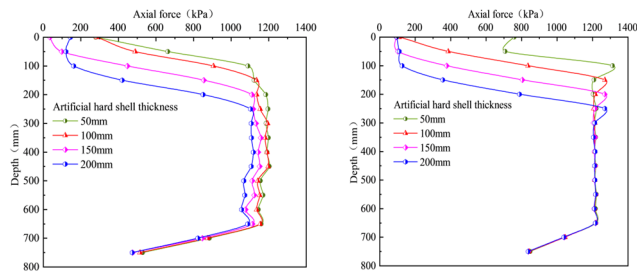


Fig.2 Settlement curve of numerical simulation and indoor model test.

4.2. Influence of hard crust thickness on pile shaft axial force

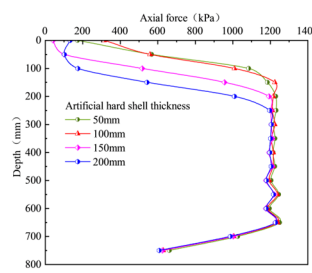
The analysis of Figs. 3 (a), (b), (c), (d) reveals the complex

law of axial force variation with depth in piles of the artificial hard crust-cement mixing pile composite foundation under embankment load, with the same pile spacing and different hard crust thicknesses (50mm, 100mm, 150mm, and 200mm respectively). In the soft soil, the axial force of the pile shaft shows a slight fluctuating characteristic, but the fluctuation is



(a) Pile spacing 111 mm

(b) Pile spacing 130 mm



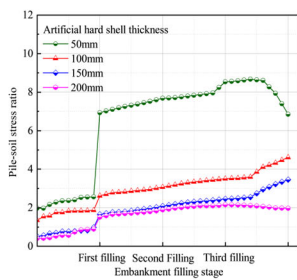
(c) Pile spacing 148 mm

(d) Pile spacing 166 mm

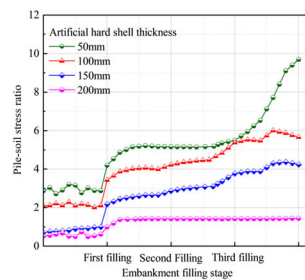
Fig.3 Variation curve of pile axial force with depth.

4.3. Analysis of pile-soil stress ratio

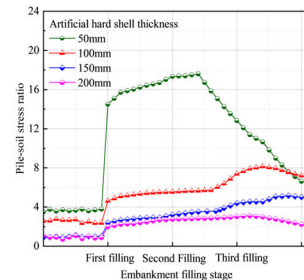
Figs 4 (a)-(d) show the pile-soil stress ratio changes during three embankment fillings with the same pile spacing. As the hard crust thickens, the ratio decreases relatively, with the 50mm-thick one significantly higher—indicating this thickness may be unreasonable, easily causing excessive pile stress and affecting foundation stability and bearing capacity.



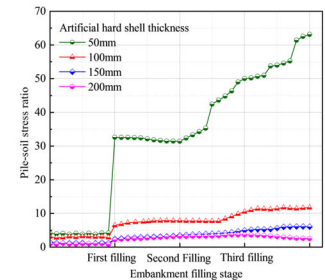
(a) Pile spacing 111 mm



(b) Pile spacing 130 mm



(c) Pile spacing 148 mm



(d) Pile spacing 166 mm

Fig.4 Variation curve of pile-soil stress ratio.

5. Conclusions

In the composite foundation of artificial hard crust and flexible piles, the pile axial force rises rapidly within the hard crust, showing that the hard crust can quickly transfer loads to the piles. As the hard crust thickens, the axial force growth slows, avoiding excessive stress difference between piles and the crust and reducing uneven embankment settlement. Under the same load, reduced pile spacing relatively lowers the stress on piles.

In the artificial hard crust-flexible pile composite foundation under embankment load, the stiffness of the artificial hard crust is similar to that of the cement mixing pile, and the hard crust can more effectively share the upper load in a coordinated manner. Therefore, with the increase of the hard crust thickness, the pile-soil stress ratio increases relatively.

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not obvious. When the depth reaches 650mm, the axial force of the pile increases slightly; from 650mm to 750mm in depth, the pile transfers the load to the bearing layer, and the axial force gradually decreases. In addition, as the thickness of the hard crust increases, the axial force-displacement curve of the pile gradually shifts downward.

The hard crust thickness significantly impacts the ratio: a thicker one effectively shares loads, reduces pile top stress and improves composite foundation performance; an overly thin one may overload piles, harming safety and durability. Thus, the thickness should be reasonably selected in design to ensure an appropriate ratio, achieving effective foundation reinforcement and rational load distribution.

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