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Experimental study on the bearing property of the composite foundation with stiffened deep cement mixing pile based on the PHC pile

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Inserting a prestressed high-intensity concrete pipe pile into a cement–soil mixing pile can form a new composite pile named the composite foundation with stiffened deep cement mixing (SDCM) pile. The Huanghuai alluvial stratum in China is selected to carry out the *in situ* test for the SDCM pile, and the bearing capacity of the SDCM pile is tested by the slow-speed maintenance load method. The results show that for an SDCM pile with dense silt and fine sand as the bearing layer, the characteristic value of bearing capacity can reach 2,300 kN, which means an SDCM pile with a length of 8.0 m meets the load requirement of a general high-rise building. Further analysis shows that the SDCM pile saves more than 40% of the cost compared with the traditional CFG pile and has better quality control advantages at the same time. This research can provide basic data and design references for similar site foundation projects.

KEYWORDS

prestressed high-intensity concrete pipe pile, composite foundation with stiffened deep cement mixing pile, characteristic value of bearing capacity, construction cost, *in situ* test

1 Introduction

The composite foundation with stiffened deep cement mixing (SDCM) pile, as a new type of pile composed of a prestressed high-intensity concrete pipe (PHC) pile and a cement–soil mixing pile, bears most of the vertical load through the PHC pile with higher strength and rigidity and avoids cement–soil mixing pile loss of bearing capacity due to insufficient strength of the pile body, leading to premature bearing capacity loss. At the same time, the shear strength of the surrounding soil of the PHC pile can be increased by solidification of the cement–soil mixing pile so that the strength of the PHC pile can be fully exerted. The combination of the two pile types can maximize strengths and avoid weaknesses. Using the SDCM pile can obtain a higher bearing capacity with a cheaper construction cost (Bai et al., 2021; Zhu, 2021; Bai et al., 2023). Under the condition of vertical load, the axial force of the inner core at the same cross-section is much greater than that of the cement–soil mixing pile, and the PHC pile is the main undertaker of the vertical load. The SDCM pile was first proposed in Japan (Lu, 2016) and introduced in China in 1988 (Ding et al., 2005).

Jamsawang et al. (2010), Wonglert et al. (2018), and Phutthananon et al. (2018) performed field tests for the SDCM pile, finding that the bearing capacity of the SDCM pile will increase with the increment of the pile diameter and pile length under the same working condition. Among the influencing factors of pile bearing capacity, pile length is the most significant one. Voottipruex et al. (2010) studied the bearing mechanism of SDCM piles in the form of numerical simulation based on a field full-scale test. The research results also showed that increasing the "core length ratio" of SDCM piles can effectively improve their ultimate bearing capacity. Wonglert and Jongpradist (2015) and Voottipruex et al. (2011) also used numerical simulation to study the effect of stiffness of the PHC pile on the bearing capacity of the SDCM pile, pointing out that the stiffness will have a more significant impact on the vertical bearing capacity only when the PHC pile length is large enough.

In China, Gao et al. (2012), Yang (2019), Wang (2020) studied the load transfer characteristics of the SDCM pile through an *in situ* pile test and non-destructive inspection, finding that the influence range of the SDCM pile on the soil around the pile is larger, which is more conducive to the exertion of the bearing capacity of the soil around the pile, providing the technical applicability and economic feasibility of the SDCM pile in the southern region in China. Wang et al. (2013) and Wang et al. (2014) conducted a comprehensive study on the bearing property of the SDCM pile using numerical simulation on the basis of an *in situ* test. The research results show that the ring-layer structure of the SDCM pile can prevent the soft soil around the pile from being crushed under a large load and, at the same time, ensure that the upper load can be transmitted to the deeper soil. Compared with the cement–soil mixing pile, the "effective pile length" of the SDCM increases. Wang et al. (2018) and Cheng (2021) used laboratory tests and the theoretical analysis method to study the mechanical characteristics of the SDCM pile and obtain the influence law of pile body parameter on the bearing characteristics of the composite pile. Several scholars only carried out laboratory tests or numerical simulations. Ye et al. (2014) and Peng et al. (2007) used the finite-element analysis software to obtain the vertical bearing characteristics of the SDCM pile, including the axial force distribution characteristics of the SDCM pile, the load sharing ratio of the pile skin and the pile end, and the influence of stiffness on the load transfer of the SDCM pile.

Most of the abovementioned studies are aimed at a single layer of soil and mainly based on laboratory tests and numerical simulations. In actual engineering, the SDCM pile will pass through various soil layers, and the same soil layer is also of certain inhomogeneity. In addition, most of the research is conducted in the southern region of China, so it is necessary to carry out experimental research on the bearing characteristics of the SDCM pile on the hard soil layer in the northern region of China.

2 Characteristics of the test site

The research site is located in Zhoukou city, shown in Figure 1. The topography and geomorphology unit of the site is relatively simple, and the geomorphology unit is the alluvial plain of the Huanghuai River. The original terrain of the site is basically flat. The main strata in the field are covered by Quaternary soil layers. According to the drilling description, *in situ* test, and geotechnical test result, the foundation soil within the exploration depth of 50 m is divided into nine layers. The lithological characteristics of each layer are described from top to bottom as follows:

① Layer of mixed backfill: Mainly composed of construction waste, mixed with bricks, concrete blocks, and building foundations. This layer is not uniform, so it is not suitable for direct use.

② Layer of silt: Brownish yellow, wet, and slightly dense and contains snail shell fragments, with rapid shake response, matte response, low dry strength, low toughness, and moderate compressibility.

③ Layer of silty clay: Brownish yellow to brownish gray and soft plastic, with no shaking reaction, slightly glossy reaction, dry strength, medium toughness, and high compressibility.

④ Layer of silt: Grayish brown to brownish gray, mainly composed of quartz, feldspar, mica flakes, etc., saturated, and medium to dense, with average particle gradation, containing a small amount of snail shavings, etc., and partially mixed with fine sand and silt.

⑤ Layer of fine sand: Brownish yellow, saturated, and dense, with low compressibility, containing mineral components such as quartz, feldspar, and mica, with general particle gradation, iron oxides, a small amount of ginger stone, snail debris, etc., and a partially silty thin layer and medium and coarse sand.

⑥ Layer of silty clay: Taupe, yellowish brown, and plastic, with no shaking response, medium dry strength, and medium toughness, and yellowish gray, wet, and dense, with sandy silt and a large number of yellow–brown stripes, rust spots, and blue–gray stripes, occasionally containing snail shells, ginger stones, and calcareous nodules.

⑦ Layer of silty clay with silty soil: Yellowish brown and plastic to hard plastic, with medium dry strength, medium toughness, and bluish-gray stripes, more locally available, containing a large number of yellow–brown rust spots and occasionally calcareous nodules with a particle size of about 2 cm, with partially silty soil.

⑧ Layer of silty clay: Yellowish brown, plastic to hard plastic, with medium dry strength and medium toughness, containing a large number of yellow–brown rust spots and occasionally calcareous nodules with a particle size of about 2 cm, partially silty, wet, and dense.

⑨ Layer of silty clay with silty soil: Yellow to yellowish brown and plastic to hard plastic, with high dry strength and medium toughness, containing a lot of yellow–brown rust spots and occasional calcareous concretions with a particle size of about 2 cm.

The detailed distribution of each soil layer can be seen in Table 1, and the typical engineering geological profile of the site is shown in Figure 2.

3 Test method

3.1 Pile foundation parameters

The SDCM pile based on the PHC pile selected in this test is shown in Figure 3. The inner core PHC pile is PHC-400AB95, the

FIGURE 1
Location of the test.

TABLE 1 List of soil layer properties of the project site.

No. of layers	Thickness (m)	Cone tip resistance q_c (MPa)	SPT *N*	PHC pile			
				q_s (kPa)	Skin resistance adjustment coefficient ξ_{si}	q_p (kPa)	End resistance adjustment coefficient ξp
①	0.4~2.4	—	—	—	—	—	—
②	1.7~5.1	1.45	3.7	—	—	—	—
③	3.2~6.3	0.60	4.2	21	1.6	—	—
④	1.4~3.6	9.7	35.0	35	1.8	2,000	1.6
⑤	8.1~11.2	16.5	45.1	40	2.0	2,500	1.8
⑥	3.9~8.1	—	14.6	—	—	—	—
⑦	0.8~12.5	—	18.3	—	—	—	—
⑧	2.8~8.2	—	19.2	—	—	—	—
⑨	-	—	22.2	—	—	—	—

outer core is the Φ700 mixing pile, the effective pile length is 8.0 m, the bearing layer at the pile end is layer ⑤, the pile enters into the bearing layer at about 4.0 m, and the constructional requirement of the characteristic value of bearing capacity for one single pile is more than 1,300 kN.

3.2 Experimental design

Three groups of test piles are designed for this test in total, and the absolute elevation of the top of the test piles is 39.45 m. Since the characteristic value of the bearing capacity of a single pile is not less than 1,300 kN, the maximum loading capacity of the test pile is 2,600 kN. The test started on 25 June 2020 and ended on 10 August 2020, using static pressure equipment. The equipment parameters and main control indicators used in the site are shown in Table 2. Because the construction quality cannot be guaranteed due to the small construction torque of the mixing piles in the sand layer, the three-axis mixing is changed into single-axis mixing for the construction technology of the cement–soil mixing pile. The background grouting pump is between the high-pressure rotary grouting pile and the low-pressure ordinary mixing pile. The pile part is stirred evenly, and the amount of cement is in an appropriate amount in accordance with the research requirement.

Partial construction photos of the site are shown in Figure 4.

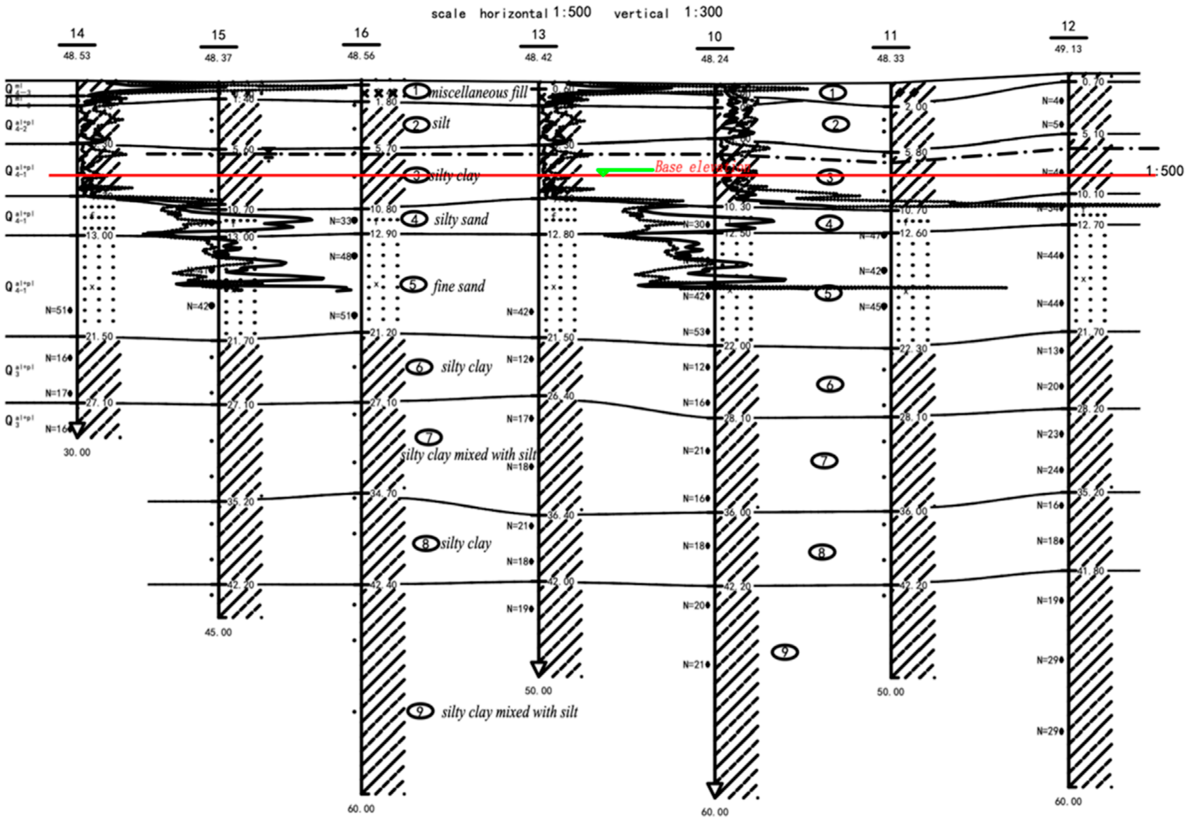

FIGURE 2
Typical engineering geological profile.

4 Test results

4.1 Basis for determining the characteristic value of bearing capacity

According to the "Technical Specifications for Building Foundation Pile Testing" (JGJ 106-2014), the vertical ultimate bearing capacity Q_u of a single pile can be comprehensively analyzed and determined according to the following methods.

(1) According to the characteristics of the changing of settlement with load, for the steep drop-type Q_s curve, the load value corresponding to the starting point of the obvious steep drop should be taken.
(2) According to the characteristics of the settlement over time, the load value of the previous level at which the tail of the s-lgt curve appears to bend downward should be taken.
(3) When under the action of a certain level of load, the settlement of the pile is greater than twice that under the action of the previous level of load and the relative stability standard has not been reached after 24 h, the value of the previous level of load is taken.
(4) For the slowly changing Q_s curve, it is better to take the load value corresponding to the total settlement of 40 mm from the pile top. When the pile diameter is more than 800 mm, the total settlement should be 0.05 D (pile diameter). When the pile length is greater than 40 m, the elastic compression of the pile body should be considered.
(5) When the vertical compressive bearing capacity of the pile is determined not to reach the limit according to the abovementioned four items, the maximum test load value should be taken as the vertical compressive ultimate bearing capacity of the pile.

Finally, the characteristic value R_d of the vertical bearing capacity of a single pile under the same conditions of the research should be weighted by 50% of the statistical value of the ultimate compressive capacity of the single pile.

4.2 Vertical static load test result of a single pile

The test results of the three groups of test piles are shown in Tables 3–5. The test adopts equal loading step by step, the step-by-step load is 1/10 of the design's ultimate bearing capacity, the first step takes twice the step-by-step load, and the maximum load is 2600 kN, classified as 0, 520, 780, 1,040, 1,300, 1,560, 1,820, 2,080, 2,340, and 2,600 kPa. Unloading is carried out in stages, the amount

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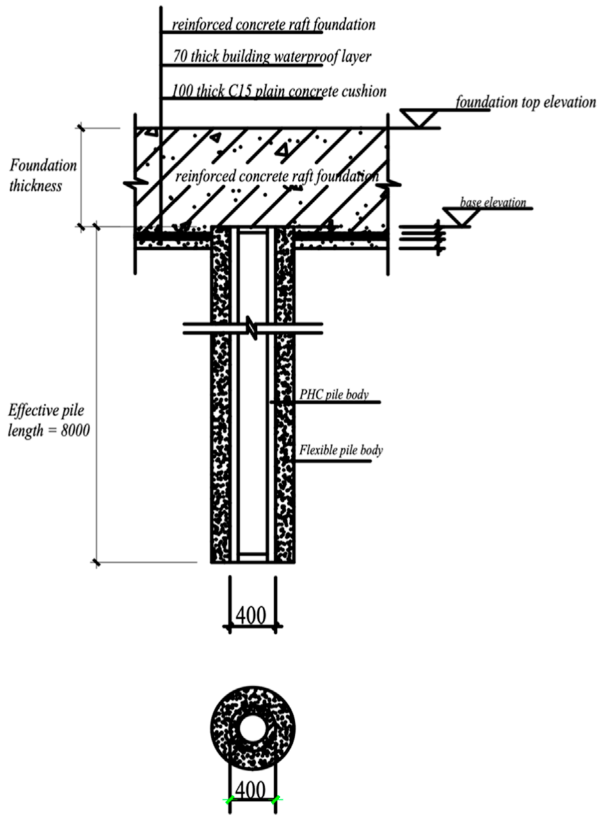

FIGURE 3
Schematic diagram of the SDCM pile.

of unloading at each stage is twice the load of the stage during loading, and the amount is equal step by step. They are 2,080, 1,560, 1,040, 520, and 0 kN, respectively.

According to the "Technical Specifications for Building Foundation Pile Monitoring," the test load has reached the maximum load required by the design, and the settlement of the pile top has reached the relatively stable level, so the test is terminated. The load-settlement (Q_s) curve of the test pile is shown in Figure 5. It can be seen that the vertical load of the pile, 2,600 kPa, has not reached the ultimate bearing capacity. Therefore, the vertical compressive ultimate bearing capacity of the pile should be the maximum test load value. It is concluded in Table 6.

5 Discussion

5.1 Comparison of the test result and the code method result

When the pile skin failure surface of the SDCM pile is located at the interface between the inner and outer cores, the characteristic value of the ultimate bearing capacity of the foundation pile is calculated according to the "Technical Regulations for Stiffened Composite Pile" (JGJT327-2014) as follows:

$$R_a = u^c q_{sa}^c l^c + q_{pa}^c A_p c = 0.5 \times 3.14 \times 0.07 \times 2000 \times 9.0 + 2500 \times 0.196,$$
$$= 2460\,\text{kN}$$

u^c—Perimeter of the PHC pile of the SDCM pile (mm)

l^c—The thickness of soil layer of the length of the composite section of the SDCM pile (m)

A_p^c—The cross – sectional area of the PHC pile in the SDCM pile (m^2)

q_{sa}^c—Skin resistance of the PHC pile in the SDCM pile (kPa)

q_{pa}^c—End resistance of the PHC pile in the SDCM pile (kPa)

When the pile skin failure surface of the SDCM pile is located at the interface between the outer core and the soil around the pile, the ultimate bearing capacity of the foundation pile is calculated according to "Technical Regulations for Stiffened Composite Pile" for the SDCM pile as follows:

$$R_a = u \sum \xi_{si} q_{sia} l_i + \alpha \xi_p q_{pa} A_p = 0.7 \times 3.14 \times (35 \times 9.0 \times 1.8) + 0.8$$
$$\times 1.8 \times 2500 \times 3.14 \times 0.7 \times 0.7/4 = 2628\,\text{kN}$$

ξ_{si}—Adjustment coefficient of lateral resistance of the i – th soil layer of the outer core of the composite section of the SDCM pile

ξ_p—Adjustment coefficient of end resistance of the i – th soil layer of the outer core of the composite section of the SDCM pile

q_{sia}—The lateral resistance characteristic value of the i – th soil layer of the outer core of the composite section of the SDCM pile (kPa)

l_i—Thickness of the i – th soil layer in the composite section of th eSDCM pile (m)

TABLE 2 Construction equipment parameter list.

Pile type	Device parameters	Construction main control indicators
Static pile driver, ZYG680-type	Static pile driver, ZYG680	The pressure pile pressure should not be less than 3,000 kN, the pressure pile is repressed three times under the maximum pile pressure force, the cumulative settlement of the three repressed piles should not be greater than 30 mm, and the effective pile length is not less than 8.0 m
Φ700 cement–soil mixing pile	Single-shaft double-tube mixing pile driver, DZSJ28-type	The cement uses class P.O32.5 cement, the amount of cement added is not less than 200 kg per meter, the water–cement ratio of the cement slurry is 1:1, and the cement mixing time is not less than 2–3 min

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TABLE 3 Test results of the No. 1 pile.

No.	Load (kN)	Duration (min)		Settlement (mm)	
		Current	Total	Current	Total
0	0	0	0	0	0
1	520	120	120	0.45	0.45
2	780	120	240	0.68	1.13
3	1,040	120	360	0.62	1.75
4	1,300	120	480	0.86	2.61
5	1,560	120	600	0.9	3.51
6	1,820	120	720	1.1	4.61
7	2,080	120	840	1.09	5.7
8	2,340	120	960	1.46	7.16
9	2,600	120	1,080	1.8	8.96
10	2,080	60	1,140	−0.31	8.65
11	1,560	60	1,200	−0.46	8.19
12	1,040	60	1,260	−0.87	7.32
13	520	60	1,320	−1.19	6.13
14	0	180	1,500	−2.22	3.91

TABLE 4 Test results of the No. 3 pile.

No.	Load (kN)	Duration (min)		Settlement (mm)	
		Current	Total	Current	Total
0	0	0	0	0	0
1	520	120	120	0.3	0.3
2	780	120	240	0.25	0.55
3	1,040	120	360	0.43	0.98
4	1,300	120	480	0.68	1.66
5	1,560	150	630	1.13	2.79
6	1,820	120	750	1.86	4.65
7	2,080	150	900	2.79	7.44
8	2,340	120	1,020	4.74	12.18
9	2,600	150	1,170	6.99	19.17
10	2,080	60	1,230	−0.25	18.92
11	1,560	60	1,290	−0.97	17.95
12	1,040	60	1,350	−1.03	16.92
13	520	60	1,410	−1.22	15.7
14	0	180	1,590	−2.18	13.52

α—Reduction factor of bearing capacity of natural foundation soil at the pile end of the SDCM pile

q_{pa}—End resistance of the SDCM pile (kPa)

A_p—The cross – sectional area of the SDCM pile (m^2)

TABLE 5 Test results of the No. 8 pile.

No.	Load (kN)	Duration (min)		Settlement (mm)	
		Current	Total	Current	Total
0	0	0	0	0	0
1	520	120	120	1.12	1.12
2	780	120	240	1.21	2.33
3	1,040	120	360	1.49	3.82
4	1,300	120	480	1.74	5.56
5	1,560	120	600	1.98	7.54
6	1,820	120	720	1.8	9.34
7	2,080	120	840	1.67	11.01
8	2,340	120	960	1.77	12.78
9	2,600	150	1,110	2.44	15.22
10	2,080	60	1,170	−0.15	15.07
11	1,560	60	1,230	−0.26	14.81
12	1,040	60	1,290	−0.48	14.33
13	520	60	1,350	−0.7	13.63
14	0	180	1,530	−1.36	12.27

We take the smaller value of the abovementioned two; that is, the characteristic value of the bearing capacity of the test pile calculated by the code method is 2,460 kN, which is greater than 2,300 kN. This test also directly verified that the piles do not fail when the characteristic value is 2,300 kN, which indirectly explained the rationality of 2,460 kN. For the sake of safety in actual engineering, the characteristic value of the bearing capacity of the SDCM pile foundation pile can be taken as 2,300 kN.

5.2 Economic comparison

Compared with the traditional CFG pile, the SDCM pile is used. Combined with the actual project on which this test is based, the base pressure of the SDCM pile is 490 kPa/m^2, and the basement area is temporarily 1,200 m^2. The upper load is 588,000 kN, the characteristic bearing capacity value of a single pile is 2,300 kN, and the actual pile layout is 588,000/2,300 = 256. The actual number of piles should be more than 256 according to the floor area and pile spacing, the pile spacing is 2.1 m by 2.1 m, the single pile treatment area is 4.41 m^2, and the foundation bottom area is 1,200 m^2, 1,200/4.41 = 272. The length of the strength composite pile is 9 m, totally 2,448 m, and the comprehensive price per meter is 560 yuan (including all material costs, labor and machinery costs, empty pile fees, electricity costs, value-added tax, pile inspection fees, and pile head cutting costs). The final cost of the SDCM pile is 560 by 2,448, that is, 1.3708 million Yuan.

If CFG piles were used, the base area is 1,200 m^2, the pile spacing is 1.2 by 1.2 = 1.44 m^2, 1,200/1.44 = 833 (roots), the single pile length is 19 + 0.5 = 19.5 m, the total pile length is 19.5 by 833 = 16,243 m, the unit price is 139 Yuan/m (including C25 concrete, labor, machinery,

FIGURE 4
Construction photos of the *in situ* test.

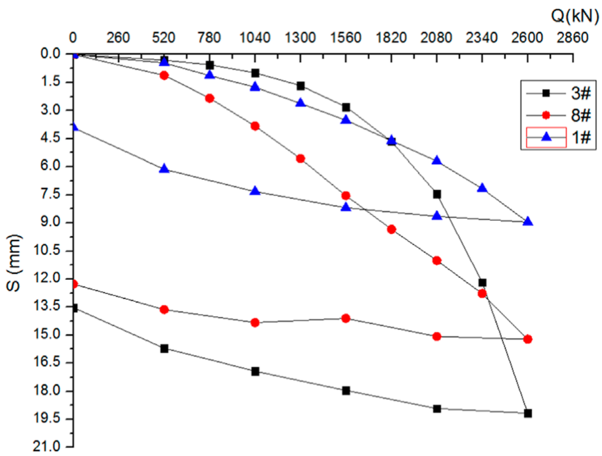

FIGURE 5
Q_s curves of test piles 1#, 3#, and 8#.

TABLE 6 **Statistical table of vertical compressive static load test.**

No.	Time (days)	Max. load (kN)	Max. settlement (mm)	Rebound amount (mm)	Rebound rate (%)	Characteristic value of bearing capacity (kN)
1#	21	2,600	8.96	5.05	56.36	≥1,300
3#	21		19.17	5.65	29.47	
8#	21		15.22	2.95	19.38	

electricity, value-added tax, pile inspection fee, and pile head cutting costs), the construction cost is 16,243 by 139 = 2.2577 million Yuan, and cancel cushion is 1,200 by 0.2 = 240 cubic meters (sand and gravel), 350 Yuan/m^3, which is 84,000 Yuan in total. The final cost of CFG piles is 2.2577 + 8.4 = 2.3417 million Yuan.

In summary, the core composite pile is 1.378 million Yuan, the CFG pile is 2.3417 million Yuan, and the pile foundation can save 960,000 Yuan in cost; that is, the SDCM pile saves 41% of cost.

In addition, for CFG piles, because the upper part of the pile length is in the fine sand layer and the lower part is in the clay layer during construction, the quality of the pile body is not easy to control, and the pile may have shrinkage and mud inclusions. Since the pile distance is only 1.2 m, it is necessary to take jump driving, it is difficult to remove the soil at the pile position for the second time, and the pile position is not easy to control. During the construction of the CFG pile, a large amount of sediment is displaced, limited by the control of dust, and it is difficult to transport outside, which affects the construction period, especially in the rainy season, and construction in the foundation pit, as the supply of concrete is not timely. Due to air pollution, the mixing station cannot guarantee the continuous supply of concrete, resulting in repeated stoppage of drilling, broken piles, and waste of concrete. We can easily control the quality using the SDCM pile, and the quality of the finished PHC pipe piles is guaranteed. The construction period is short, no soil is unearthed, and it is not restricted by the environment. After the strength of composite piles is processed, the length of the piles can be guaranteed to enter the fine sand layer.

6 Conclusion

Taking the silt and sandy soil of Huanghuai alluvial strata as the research background, this study carried out an *in situ* test on the SDCM pile based on the PHC pile, and the results are as follows:

(1) The SDCM pile based on the PHC pile with a length of 8.0 m can provide the characteristic value of bearing capacity of 2,300 kN, which can meet the vertical load requirements of general high-rise buildings.
(2) The SDCM pile has high promotion value in similar sites. The construction quality of the outer core has a significant effect on the bearing capacity of the SDCM pile. The construction quality should be strictly controlled.
(3) Compared with the CFG pile, the SDCM pile has the advantages of high strength, guaranteed construction quality, large bearing capacity, and good economy.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

ZM contributed to the conception of the study; TF, ZH, and DF performed the experiment; and CS and LF contributed significantly to analysis and manuscript preparation. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Authors TF, DF, CS, and LF were employed by The Seventh Engineering Co., Ltd., of CFHEC; ZH was employed by the Zhongyun International Engineering Co., Ltd.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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