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Keywords

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Field study on the ultimate bearing capacity of enlarged grout base of pre-bored grouted planted pile

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Abstract: Pre-bored grouted planted pile is a new type of eco-friendly pile foundation. The combination of the lower section of PHC nodular pile and the pile base expansion greatly improves the vertical bearing capacity of single pile. A lot of application practices have been achieved in Jiangsu, Zhejiang and Shanghai regions, but limited to the current research status, the bearing capacity of enlarged grout base is not clear. Based on the in-situ self-balanced loading test, the ultimate compressive bearing capacity of the enlarged grout base of the pre-bored grouted planted pile is investigated. The research results reveal that the measured ultimate bearing capacity of the enlarged grout base of the pile is 40% higher than that calculated by the specifications. The back analysis of the test results shows that the ultimate end resistance reduction coefficient of Shanghai ⑦ layer of silt is 0.72-0.81, which is significantly higher than the recommended value of 0.50-0.55 in the specifications. The bearing capacity of the enlarged grout base of the pile is mainly controlled by the end bearing capacity, and the required displacement value for its full bearing capacity is about 0.03 times the pile diameters. The enlarged grout base of the pile accounts for 64% to 67% of the bearing capacity of pre-bored grouted planted pile, and the structural integrity of the enlarged grout base plays a key role in the working performance of the pre-bored grouted planted pile.

Keywords: pre-bored grouted planted pile; enlarged grout base; self-balanced loading test; bearing capacity; end resistance of pile

1 Introduction

The implantation pile has been introduced by Japan since the late 1960s, and the cemented soil core-insert composite pile, such as reinforced mixing pile, cemented soil composite pipe pile, emerged successively in China in the 1990s. The cemented soil thickness of the implantation pile is generally greater than 150 mm, and it emphasizes the concept of composite foundation, and has limited construction depth and single pile bearing capacity. In order to adapt the different geological conditions and construction environment in China, a new type of pre-bored grouted planted pile has been developed in recent years[1–2]. It uses a dedicated single-axis mixer to drill, mix, and grout the soil, forming a cemented soil pile hole with an enlarged base. Precast pile is implanted into the hole by its own weight, and then the implantation pile forms with the rigid pile body wrapped by solidified cemented soil, the cemented soil thickness is less than 75 mm, and its pile depth can reach up to 80 m. Pre-bored grouted planted pile have been applied in nearly 300 projects in Zhejiang and Shanghai regions due to its advantages of green, low environmental impact, and high construction efficiency[3].

The enlarged grout base of the pre-bored grouted planted pile is replaced with equal volume cement paste, and its water-cement ratio and grouting volume are different from those along the shaft (beyond the scope of the belled pile). The strength of the solidified cement paste at the belled pile end can reach 7–30 MPa, which is significantly higher than that of the cemented soil along the shaft[4]. Nodular piles are often used at the enlarged gout base to enhance the bonding strength between the pile and the enlarged solidified body through the protruding part, then they work jointly, and the enlarged pile end resistance is transmitted, then the high-strength concrete of the precast pile is fully utilized[4]. The interface of soil-cemented soil-precast pile plays a controlling role in the bearing capacity of the pile, where the interface stiffness and shear strength are correlated with the pile diameter[5].

The unique construction process, complex material composition and structure lead to complex bearing capacity of pre-bored grouted planted pile, which is influenced by many factors. Some scholars have explored its load transfer behavior and verified its reliable bearing capacity based on in-situ static load test, model test, numerical analysis, and other methods. While the bearing capacity of the enlarged grout base was not illustrated sufficiently[6–8]. Gong et al.[9] proposed that the vertical bearing capacity of pre-bored grouted planted pile consists of two parts: skin friction and enlarged grout base resistance, and the pile end resistance is contributed by nodular pile and enlarged cemented soil base. Zhou et al.[10] conducted single pile model tests to verify the effectiveness of enlarged cemented soil base, and found that the

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increase of the cemented soil strength at the enlarged grout base can effectively improve the bearing capacity of a single pile. Additionally, the enlarged pile end size also has an impact on vertical bearing capacity. Ling et al.[11] found that increasing the expanding rate and the enlarged grout base height is beneficial for bearing capacity by numerical simulation, and the influence of expanding rate is more obvious, which was also verified by Gong et al.[12]. In order to facilitate the design and calculation of pre-bored grouted planted pile, Wu et al.[13] developed a computing method for the bearing capacity of pre-bored grouted planted pile, which took specific penetration resistance as the basic parameter in China single bridge cone penetration test, and the enlarged grout base resistance coefficient was introduced to calculate the pile end resistance.

Static load test at pile top is commonly used method to investigate the bearing capacity of pre-bored grouted planted pile in above researches. While this method cannot analyze the bearing capacity of the enlarged pile base due to some factors, such as the pile uncertain failure mode under the limit state, the estimation error of pile deformation, the detection accuracy of pile stress. In recent years, self-balanced loading test has been implemented increasingly, which can measure the bearing capacity at a specified pile zone[14], especially for pile under special conditions. Wu et al.[15], Zhou et al.[16] placed the load cell at the calculated equilibrium point of the pre-bored grouted planted pile by this testing method, and the end bearing capacity of the enlarged grout base was calculated according to the test results, while the ultimate bearing capacity of the enlarged grout base did not reach in the loading test.

As the traditional static load test at pile top has limitation in analyzing the bearing capacity of enlarged pile base of pre-bored grouted planted pile, and few self-balanced loading tests did not reach the failure state, the ultimate bearing capacity of enlarged pile base of pre-bored grouted planted pile is still ambiguous currently. Then a self-balanced loading test was conducted on a pre-bored grouted planted pile in a site in Shanghai to explore the ultimate bearing capacity of the enlarged pile base. The load cell was placed at the top of the enlarged pile base for quantitative analyzing of the overall bearing capacity of the enlarged pile base, as well as back analysis of the parameters of the pile end bearing capacity.

2 Design of self-balanced loading test

2.1 Site overview

The test pile field is located in a site in Fengxian District, Shanghai, China. The site is flat and covered with a thin plain concrete layer, and the elevation of the exploratory hole is 4.11–4.19 m. It can be classified as “coastal plain”. The soil layers, from the surface to a depth of 71.0 m, mainly consist of weak cohesive soil, silt, and sandy soil, and are stratified. The relevant parameters of the soil strata are shown in Table 1.

Table 1 Parameters of soil strata

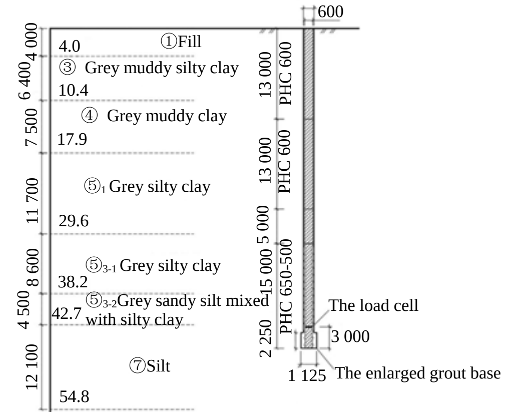
Soil number	Depth /m	W /%	γ /(kN • m^{-3})	c /kPa	φ /(°)	E_s /MPa	P_s /MPa	f_s /kPa	f_p /kPa
①Fill	4.0	25.0	18.0	10	20.0	4.00	—	15	—
③Grey muddy silty clay	4.8	39.8	18.0	13	19.0	3.41	0.53	20	—
④Grey muddy clay	7.3	48.7	16.9	11	11.5	2.46	0.64	25	—
⑤1 Grey silty clay	11.2	35.2	17.9	13	18.5	3.67	0.88	35	—
⑤3-1 Grey silty clay	9.1	33.5	18.1	16	18.5	4.20	1.74	60	1 500
⑤3-2 Grey sandy silt mixed with silty clay	4.9	28.4	18.7	9	29.5	7.76	3.44	65	2 000
⑦Silty sand	11.8	25.9	18.9	3	34.0	10.22	18.02	110	7 000
⑧2-1 Grey silty clay mixed with sandy silt	9.7	31.2	18.4	19	21.5	4.76	5.96	70	3 000
⑧2-2 Grey silty clay	3.4	31.9	18.2	19	20.5	4.49	2.86	60	2 000
⑨ Grey silty sand	—	27.0	18.8	3	33.5	9.30	16.65	—	—

Note: c and φ are the strength parameters of total stress in the consolidation quick direct test; f_s and f_p is the standard value of ultimate skin friction and ultimate end resistance of the precast pile, respectively; P_s is the specific penetration resistance of each soil layer; W is the water content in natural soil; γ is the unit weight of the natural soil; and E_s is the compressive modulus at a vertical pressure of 100–200 kPa.

2.2 Test pile design

Two pre-bored grouted planted piles were used in this test, the upper section was PHC pipe pile and the end was PHDC nodular pile. The pile combination from bottom to top is: PHC600(130)AB C100-13+ PHC600(130)AB C100-13+PHC600(130)AB C100-5+ PHDC650-500(125)ABC100-15. The test pile is 46 m long, and it enters the ⑦ bearing layer of silty sand about 2.50 m, as shown in Fig. 1. Based on the core drilling test result, the ⑦ layer is grey dense silty sand, containing mica, organic matter, and thin silty sand layer, whose thickness is about 12.10 m, and it can be classified as medium compressibility soil.

The test pile had a drillhole diameter of 0.75 m. The construction of the enlarged grout base commenced after the drilling rig sank to the elevation of the pile end. The diameter, height, and volume of the enlarged grout base were 1.125 m, 2.25 m, and 2.24 m^3, respectively. The injected volume of cement paste at the pile end was the entire volume of the enlarged zone (i.e. 2.24 m^3), with a water-cement ratio of 0.6, and the grouting pressure was controlled between 0.8 and 1.3 MPa. The drilling rig raised and lowered repeatedly in the grouting process until all the cement paste was injected into the enlarged zone. Afterward, the drilling rig was lifted, and the cement paste was injected along the shaft. The injected volume of cement paste along the shaft was calculated as (the drillhole volume + the enlarged grout base volume + the precast pile volume) ×30%, resulting in 3.73 m^3, with a water-cement ratio of 1.0. The pre-imbedded hole pile connection technology was adopted in the planting process, which began within 2 hours after injecting the cement paste.



Note: The stratum depth is in m, and the pile size is in mm.

Fig. 1 Stratum distribution of pile test site and pile details

Based on the typical soil types of ⑤$_1$ silty clay and ⑦ silty sand in the Shanghai region, cemented soil samples were prepared by simulating the on-site construction process, the unconfined compressive strength test was carried out. The test detail and calculation basis have been elaborated in literature[4], which are not described in this paper. The cement ratio of the cemented soil along the shaft is approximately 18.7%, resulting in an unconfined compressive strength of about 1.4 MPa after 28 days, and a deformation modulus of about 150 MPa. Meanwhile, the cement ratio of the enlarged grout base is around 86.6%, leading to an unconfined compressive strength of about 13.4 MPa after 28 days, and a deformation modulus of about 1 500 MPa, as shown in Fig. 2.

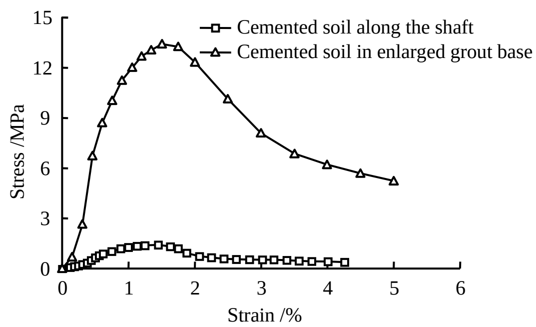


Fig. 2 Test results of cement soil strength of test piles

2.3 Load design

The self-balanced loading test method was adopted to directly measure the ultimate compressive bearing capacity of the enlarged grout base, where the load cell was placed over the enlarged grout base (3 m from the pile end), with a clearance of about 0.75 m from the top of the enlarged grout base. The load cell took the upper and lower sections of the pile as reaction fulcrums for each other, and it was filled with compressed oil by ground high-pressure oil pump, vertical load was then applied to the upper and lower pile sections, as shown in Fig.3. The model of load cell is CH-180009, and its ultimate loading capacity can reach 2×9 000 kN.

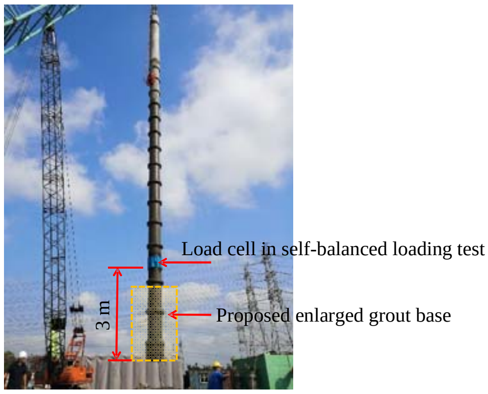


Fig. 3 Photo of test pile sinking site

According to "*Technical specification for pre-bored precast concrete pile foundation*" (DB33/T 1134-2017)[17], the downward friction of each layer is 0.7 times the upward friction, and the sharing load of each pile section was estimated, as shown in Table 2. It can be found that the standard value of skin friction of the upper pile section was about 2 271 kN, the dead-weight of the upper pile section was about 214 kN, and the sum of the end bearing capacity and skin friction standard value of the lower pile section equaled around 4 800 kN.

Considering that the current research has some deficiency yet on the ultimate bearing capacity of the enlarged grout base, self-balanced loading test was used to achieve the ultimate bearing capacity of the lower pile section (i.e. the enlarged grout base), and reach failure condition. Table 2 illustrates that the dead-weight and skin friction of the upper pile section were not sufficient to provide the reaction force for the lower pile section reaching the compressive limit state. Therefore, concrete blocks of 8 300 kN were loaded at the top of the test pile to provide supplementary reaction force, and the total reaction force provided by the upper pile section was not less than 1.2 times the maximum load of the load cell. Meanwhile, a jack was used to apply load between the stacking weight and the pile top before loading for pre-contact.

Table 2 Load distribution for self-balanced loading test

The sharing load of pile	Vertical load /kN
Dead-weight of the upper pile section	214
Standard value of skin friction of the upper pile section	2 257
Standard value of bearing capacity of the upper pile section	2 471
Standard value of skin friction of the lower pile section	950
Standard value of end resistance	3 850
Standard value of bearing capacity of the lower pile section	4 800

2.4 Test system layout

The self-balanced loading test system mainly consists of a self-balanced loading cell, displacement wire, pressurized oil pipe, loading system, data acquisition system, etc., as shown in Fig. 4.

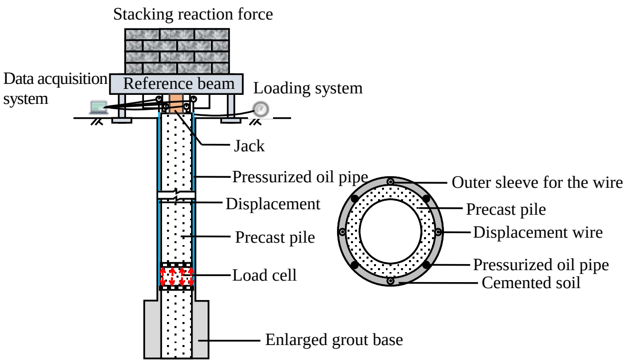


Fig. 4 Schematic diagram of the self-balanced loading test system

Six electronic displacement meters (model RS-JYD) were used for each test pile to measure pile displacement, which were fixed on the reference steel beam through a magnetic stand. Two of these displacement meters were used to measure the upward displacement at the top of precast pile, two for the upward displacement at the top of load cell, and the remaining two for the downward displacement at the bottom plate of the load cell. The displacement wire was welded at the end of the load cell, and an outer protective sleeve was installed, as shown in Fig. 5.

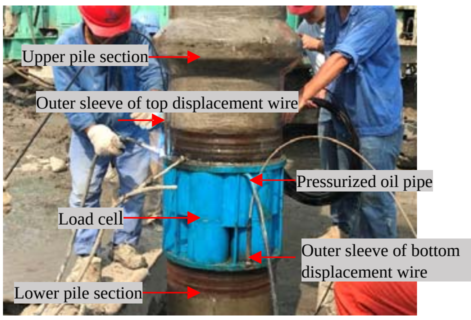


Fig. 5 Photo of displacement wire installation site

2.5 Loading scheme

The loading scheme referred to the "*Technical specification for static loading test of self-balanced method of building foundation piles*" (JGJ/T 403-2017)[18], and slow speeded load method was used for stepwise loading according to 2×300 kN. When the change rate of displacement reaches a relatively stable standard (with displacement increment not exceeding 0.1 mm per hour and occurring twice consecutively), the next load level was applied. When the displacement increment of the upper or lower pile sections was greater than 5 times that under the previous load level, and the total displacement exceeds 40 mm, the test was terminated.

3 Results

Figure 6 depicts the relationship curves between the loading capacity of the test pile load cell and the displacement of the upper and lower pile sections, with positive value indicating upward direction and negative value indicating downward direction. It can be observed that when the SZ1 test pile is loaded to 2×6 300 kN, the displacement of the upper pile section is 0.80 mm, and the displacement of the lower pile section is 68.20 mm, which meets the test termination condition. The previous load level of 6 000 kN is taken as the ultimate load of lower pile section. Similarly, when the SZ2 test pile is loaded to 2×6 900 kN, the displacement of the upper pile section is 1.73 mm, and the displacement of the lower pile section pile is 59.99 mm, meeting the test termination condition. The previous load level of 6 600 kN is taken as the ultimate load of the lower pile section.

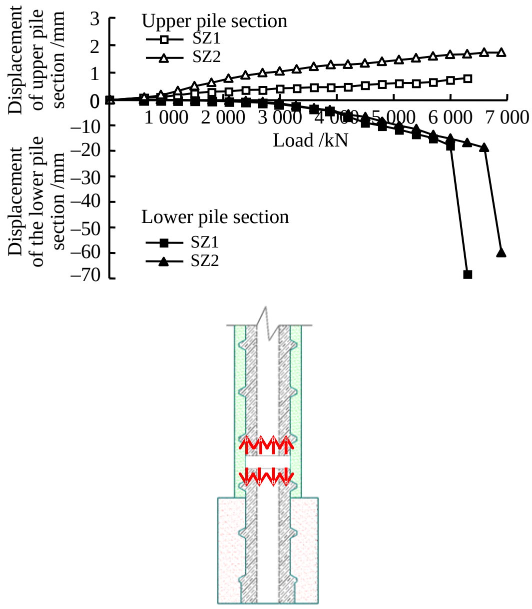


Fig. 6 Load–displacement curves of upper and lower sections of test pile

The load–displacement curves of the lower section of the two test piles show a significant steep decline, which can be considered as reaching the vertical bearing limit state of the lower pile section, and compression failure occurs. Meanwhile, the deviation of the ultimate bearing capacity of the lower section obtained from the two test piles is less than 10%, considering the complex construction process of the enlarged grout base and test errors, it is within a reasonable range.

Figure 7 shows the load–displacement curves at different positions of the upper pile section. It is evident that the displacements of the upper section of the two test piles are very small, and their upward displacements are less than 1.8 mm. The pile compression is about 0.2 mm. It can be considered that the upper pile section is in a stable state, and there is no significant shear slip at the interface between the precast pile and cemented soil, or between cemented soil and soil between piles. Sufficient reaction force and stable support are provided for the lower pile section.

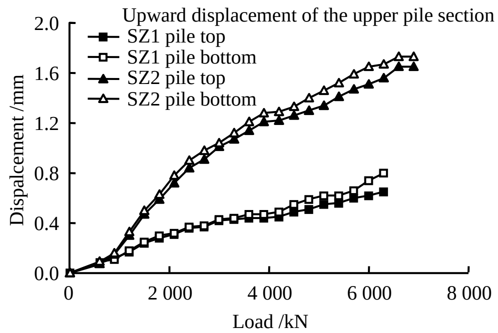


Fig. 7 Load–displacement curves at different positions of upper sections of test pile

4 Analysis of the bearing capacity of enlarged grout base

4.1 The bearing capacity mode of enlarged pile base

Fleming et al.[19] reported that the traditional pile top displacement for its full skin friction was about 0.005–0.02 times the pile diameter, while the required displacement for the full pile end resistance was about 0.05–0.10 times the pile diameter, and the pile top load corresponding to the pile top displacement of 0.10 times the pile diameter was the ultimate bearing capacity of the pile foundation. When a load of 6 000 kN or 6 600 kN was applied to the lower pile section of SZ1 and SZ2, the downward displacements of the load cell bottom were 17.9 mm and 18.7 mm, respectively, which was about 0.03 times the pile diameter (the outer diameter of the precast pile is 600 mm). It can be considered that the skin friction of the lower pile section has been fully exerted. Considering the limited height of the enlarged grout base, little impact on end resistance analysis, and the overall stress characteristics of the enlarged grout base[11], further analysis were expanded in the later section. Here, we used the interface between the enlarged grout base and the soil between the piles (the diameter of the enlarged grout base is the outer diameter within 2.25 m of the pile end, and the ultimate skin friction is 110 kPa) and the 0.75 m section of the nodular pile interface. It can be estimated that the ultimate skin friction of the lower pile section was about 950 kN. The ultimate pile end resistance was 5 050–5 650 kN approximately by deducting the ultimate skin friction. Thus, the end bearing capacity accounts for 85% in the enlarged grout base, which plays a controlling role.

The loading process of the lower pile section in this self-balanced loading test can be regarded as a deep plate loading test, the pile end resistance was analyzed by in-situ testing method, and the enlarged pile base was the load plate. Based on the load–displacement curve of the lower pile section in Fig. 6, it was assumed that the skin friction development of the lower pile section was linearly proportional to its displacement. After deducting the skin friction of the enlarged base under each load level, the end resistance–displacement curve was obtained in Fig. 8. According to the deep plate loading test[20], the end bearing capacity should take the minimum value of the proportional limit load (2 550 kPa), 0.5 times the ultimate load (2 668 kPa), and the load (4 335–5 100 kPa) corresponding to the settlement of 0.01–0.015 times the plate diameter *D* as the characteristic value of bearing capacity. Therefore, 2 550 kPa was determined as the characteristic value of the bearing capacity, corresponding to the pile end settlement of 1.5 mm. The pile end resistance was within the proportional limit load under normal working conditions, and the pile end deformation was relatively small.

The standard value of the precast pile end ultimate resistance, provided by the geological survey, is 7 000 kPa at ⑦ silty sand layer from Table 1, (i.e. the characteristic value is 3 500 kPa). According to "*Technical code for building pile foundations*" (JGJ 94-2008)[21], the size effect coefficient of end resistance can be calculated as $(0.8/1.125)^{1/3} = 0.89$. The characteristic value of the end resistance of the ⑦ silty sand layer is adjusted to 3 115 kPa by considering the size effect. One can see that this value is significantly greater than the measured one (2 550 kPa), indicating that special structure and construction technology of the pile also have a certain impact on the end resistance except the size effect of the enlarged base.

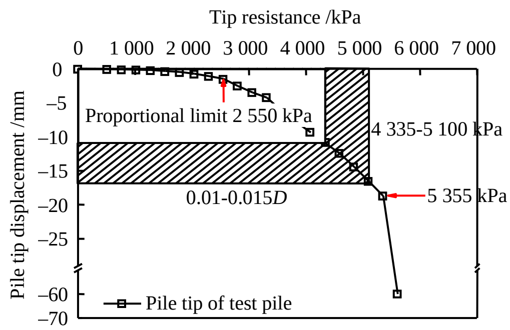
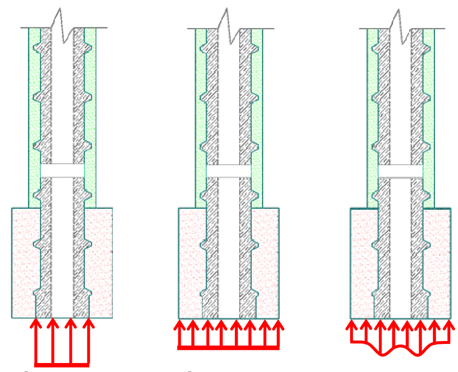


Fig. 8 End resistance–displacement curve of lower sections of test pile

Assuming that the precast pile end section is used as the acting surface of pile end resistance (i.e. the diameter of the pile end section is taken as 0.6 m). The average stress of the precast pile end section can be calculated to be 17 870–19 993 kPa according to the measured ultimate pile end resistance (6 000–6 600 kN), which is much greater than the standard value of the ultimate end resistance of ⑦ silty sand layer (7 000 kPa), as shown in Fig. 9(a). If the enlarged pile base only takes the precast pile end as the end bearing acting surface, it is limited by the bearing capacity of ⑦ silty sand layer and cannot provide the measured pile end resistance. Therefore, it can be inferred that the cemented soil in enlarged base also plays an end bearing role.

Assuming that the entire section of the enlarged grout base is used as the acting surface of the end resistance (the diameter of the pile end section is 1.125 m), its average stress can be calculated to be 5 083–5 687 kPa according to the measured ultimate pile end resistance (6 000–6 600 kN), as shown in Fig. 9(b). According to the geological survey recommendations, the standard value of ultimate end resistance for layer ⑦ of silty sand was adjusted by size effect to about 6 230 kPa. It can be seen that the actual end resistance was relatively small, indicating that although the enlarged base exhibits an overall force mode, the calculation of end resistance cannot directly refer to the standard value of bearing layer end resistance for precast piles. Compared with traditional precast pile, there is no squeezing effect during the construction process of pre-bored grouted planted pile, and the soil layer at the pile end will not be compacted. Additionally, based on the laboratory test results of cement-soil at the pile end in Fig. 2, the ratio of elastic modulus between the precast pile and cemented soil in the enlarged grout base can be estimated to be about 27, indicating a significant difference in stiffness on the pile end section and uneven stress distribution at the pile end. Fig. 9(c) illustrates that stress concentration occurs at the precast pile end in the actual application of pile end resistance, while the end resistance of the cemented soil decreases, and its stress is significantly lower than the unconfined compressive strength of the cemented soil at the pile end.



(a) Circular section of precast pile (b) Circular section of the enlarged grout base (c) Actual mode

Fig. 9 Simplified model diagram of enlarged grout base end resistance

4.2 Parameter analysis of pile end bearing capacity

The design standards for pre-bored grouted planted pile mainly include the local standard of Zhejiang province "*Technical specification for pre-bored precast concrete pile foundation*" [17] and the group standard "*Technical specification for pre-bored precast concrete pile*" (T/CECS 738-2020)[22], both of them assume that the enlarged pile base is under entire stress conditions, and there is no internal structural damage. The estimation method for vertical compressive bearing capacity is:

$$Q_{\mathrm{uk}} = \sum u_i q_{\mathrm{sik}} l_i + A_{\mathrm{p}} q_{\mathrm{pk}} \tag{1}$$

where Q_{uk} is the vertical compressive ultimate bearing capacity of a single pile; u_i is the pile perimeter, the outer diameter is taken for the nodular pile, and the pile diameter for other precast piles without considering the influence of the enlarged grout base diameter; q_{sik} is the ultimate skin resistance of the *i*-th soil, which take the recommended value in survey report; A_{p} is the pile end area, which is the enlarged grout base area; q_{pk} is the ultimate end resistance, which should reduce based on the ultimate end resistance of precast piles in the geological survey report; l_i is the thickness of the *i*-th soil layer.

It can be observed from Eq. (1) that reasonable value of the ultimate pile end resistance is the key to calculate the bearing capacity of the pile end. There are different provisions for the reduction value of ultimate end resistance in the above two specifications, as shown in Table 3. It can be found that the ultimate end resistance reduction coefficient given in "*Technical specification for pre-bored precast concrete pile*"[22] is larger than that in "*Technical specification for pre-bored precast concrete pile foundation*"[17], indicating that the estimated bearing capacity of the enlarged pile base is greater.

Table 3 Parameter values for calculating the ultimate end resistance of the enlarged grout base

Specification	End resistance reduction coefficient of the pile end soil under the enlarged base conditions				Not expanding the base
	Clay, silt, completely weathered rock	Silty sand, fine sand, medium sand	Coarse sand, gravelly sand, highly weathered rock	Gravel, pebble, moderately weathered rock	
"*Technical specification for pre-bored precast concrete pile foundation*"[17]	0.45–0.50	0.50	0.55	0.60	0.60
"*Technical specification for pre- bored precast concrete pile*"[22]	0.45–0.50	0.50–0.55	0.55–0.65	0.60–0.70	0.70

Table 4 shows the comparison between the calculated and measured bearing capacity of the enlarged grout base. When the ultimate end resistance reduction coefficient is taken as 0.50, 0.55, and 1.00, the calculated pile end resistance is 3 500, 3 850, and 7 000 kN, respectively. The measured value is about 38% to 42% higher than that calculated by specification[17, 22]. The back analysis of the test pile results show the ultimate end resistance reduction coefficient of ⑦ silty sand layer is 0.72–0.81, while the recommended value is 0.50–0.55 in the specification[22], which has a certain security reservation.

Due to the complex load transfer mechanism of nodular pile-cement slurry-soil between piles at the enlarged pile base and the difference in cross-section stiffness, size effect and construction process, the direct calculation of pile end resistance using the cross-sectional area of the enlarged base and the ultimate end resistance of the precast piles (i.e., the reduction coefficient is taken to be 1) will overestimate the bearing capacity of the bearing capacity of the enlarged pile base.

Table 4 Calculation results of bearing capacity of enlarged grout base

Ultimate bearing capacity of lower pile section	Skin friction /kN	End resistance /kN	Summation /kN
Self-balanced loading test	950	5 050–5 650	6 000–6 600
"*Technical specification for pre-bored precast concrete pile foundation*"[17] takes 0.50	950	3 500	4 450
"*Technical specification for pre-bored precast concrete pile*"[22] takes 0.55	950	3 850	4 800
End resistance reduction coefficient is 1	950	7 000	7 950

Under the loading conditions of the pre-bored grouted planted pile top, the ultimate skin friction of the upper pile section can be calculated to be about 3 225 kN according to the specification[22], and the ultimate compressive bearing capacity of a single pile is about 8 025 kN. Based on the measured bearing capacity of the enlarged grout base, the ultimate compressive bearing capacity of a single pile is estimated to be about 9 225–9 825 kN, which is 15%–22% higher than that calculated using the specification. The bearing capacity of the enlarged grout base accounts for 64%–67%, and the pile end resistance for 55%–58%. The bearing capacity of the enlarged grout base plays a key role in the bearing capacity of pre-bored grouted planted pile, as shown in Fig. 10.

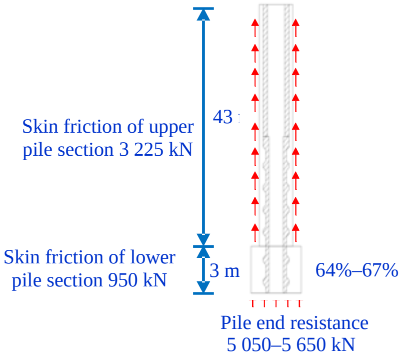


Fig. 10 Schematic diagram of pile bearing capacity distribution

5 Conclusions

To investigate the ultimate bearing capacity of the enlarged pile base in pre-bored grouted planted pile, self-balanced loading tests were conducted on two test piles. The vertical bearing deformation law of the enlarged pile base was analyzed according to the test results, and the calculation parameters of the pile end bearing capacity were discussed. The main conclusions drawn from the study were as follows:

(1) A load cell was placed at the top of the enlarged grout base of the pre-bored grouted planted pile by using the self-balanced loading test method, the influence of factors such as back analysis of pile top load–displacement and test errors of pile stress, were avoided, then the ultimate bearing capacity of the enlarged pile base can be measured and analyzed directly.

(2) The ultimate bearing capacity of the enlarged grout base of the pre-bored grouted planted pile was found to be approximately 6 000–6 600 kN, which was about 40% higher than the calculation results by relevant specifications. The back analysis results revealed that the ultimate end resistance reduction coefficient of Shanghai ⑦ layer of silty sand was 0.72–0.81, significantly higher than the recommended value of 0.50–0.55 in the specifications.

(3) The vertical displacement required for the full ultimate bearing capacity of the enlarged pile base was about 0.03 times the diameter of the precast pile, its end bearing capacity accounts for about 85%, with its end bearing capacity accounting for approximately 85%, significantly greater than the skin friction.

(4) The contribution of the bearing capacity of the enlarged pile base reached 64% to 67% under the pile top loading conditions. The structural integrity of the enlarged grout base played a key role in the bearing capacity of the pre-bored grouted planted pile. It was emphasized that the design parameters and construction process of cement paste injection at the pile end should receive more attention.

(5) The study identified certain limitations, including the lack of stress measurement for the enlarged pile base, the impact of skin friction along the shaft on actual pile end resistance, the small number of test piles, and the neglect of factors such as the size of the enlarged grout base and the bearing layer condition. Further research combining numerical methods was suggested to address these limitations.

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