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Study and application of pre-bored precast pile with enlarged base in China

Etude et application d'une pile préforée préforée avec une base agrandie en Chine

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ABSTRACT: The pre-bored precast pile with enlarged base (PPEB pile) is an innovative type of environmental pile foundation. It has the advantages of low noise, no soil squeezing, less mud discharge and has been increasingly used in China. However, the bearing characteristics, the distributions of the shaft and toe resistance and the cement soil characteristics in PPEB pile are still unclear. This paper presents the study and application of PPEB pile in China. Based on the static load test, the bearing and deformation characteristics of PPEB pile were preliminarily analyzed. The load test results showed that the PPEB pile could provide reliable vertical compression and uplift bearing capacity; About 75% of the compression bearing capacity was provided by shaft resistance when the ultimate load was applied and majority of shaft resistance was mobilized along the lower part of the test piles. To study the properties of cement soil around the pile shaft and at enlarged base, field test and laboratory test were carried out. These results indicated that the pre-bored precast piling method had good applicability in thick soft clay. Finally, engineering applications of PPEB pile technology were introduced.

RÉSUMÉ : Le pieu préfabriqué pré-foré à base élargie (pieu PPEB) est un type innovant de fondation sur pieux écologique. Il présente les avantages d'un faible bruit, pas de compression du sol, moins de décharge de boue et est de plus en plus utilisé en Chine. Cependant, les caractéristiques du roulement, les distributions de la résistance de l'arbre et du pied et les caractéristiques du sol de ciment dans les pieux PPEB ne sont pas encore claires. Cet article présente l'étude et l'application des pieux PPEB en Chine. Sur la base du test de charge statique, les caractéristiques de portance et de déformation du pieu PPEB ont été analysées au préalable. Les résultats des tests de charge ont montré que le pieu PPEB pouvait fournir une compression verticale fiable et une capacité portante de soulèvement; Environ 75% de la capacité portante en compression était fournie par la résistance de l'arbre lorsque la charge ultime était appliquée et que la majorité de la résistance de l'arbre était mobilisée le long de la partie inférieure des pieux d'essai. Pour étudier les propriétés du sol de ciment autour du puits de pieu et à la base élargie, des essais sur le terrain et des essais en laboratoire ont été réalisés. Ces résultats indiquent que la méthode d'empilage préfabriqué pré-percé a une bonne applicabilité dans l'argile molle épaisse. Enfin, des applications techniques de la technologie des pieux PPEB ont été introduites.

KEYWORDS: Pre-bored precast pile with enlarged base; Static load test; Bearing characteristic; Pile-forming effect; Cement soil.

1 INTRODUCTION

Bored piles and precast piles are widely used in pile foundation engineering. However, bored piles have the problems of large mud discharge and difficulty in controlling the quality of the pile shaft, while precast piles have some problems such as serious soil squeezing and noise pollution. In recent years, on the basis of pre-bored precast piling method widely used in Japan (Karkee et al. 1998; Yamato & Karkee 2004; Kobayashi & Ogura 2007), the pre-bored precast pile with enlarged base (PPEB pile) has been developed in China (Zhang et al. 2013). In this piling method, cement soil column with enlarged high strength base should be first formed using a special helical auger, then the precast concrete pile is inserted mainly by its self-weight. It is a new type

of green and environmentally friendly pile foundation.

Since 2010, the exploration work of PPEB pile has been carried out first in Zhejiang Province and Shanghai area of China. The high compression, uplift and horizontal bearing capacity of PPEB piles have been confirmed by previous applications and studies (Zhou et al., 2016, 2017; Qian & Wang, 2015). The load transfer mechanism of pile shaft and enlarged base were analyzed by field tests and laboratory tests (Ling et al., 2018; Wang et al., 2019a, 2019b). The design analysis method, construction technology and engineering application of PPEB pile have also been studied (Ling 2019).

In this study, the construction technology and characteristics of PPEB pile were summarized. The bearing and deformation characteristics, actual pile forming effect and construction efficiency of PPEB pile were preliminarily analyzed. The

behavior of cement soil in PPEB pile was studied through field test and laboratory test. Finally, the engineering applications of PPEB pile technology in China were introduced.

2 CONSTRUCTION TECHNOLOGY OF PPEB PILE

2.1 Construction technology

The PPEB pile requires special installation process, which can be summarized into the following five steps, as shown in Figure 1.

2.1.1 Drilling

A borehole is first drilled with a special equipment combining an auger (Figure 2a) and a soil mixer (Figure 2b). According to the geological conditions, a water or bentonite slurry is injected simultaneously to form slurry with a specific gravity of about 1.5 to support the borehole.

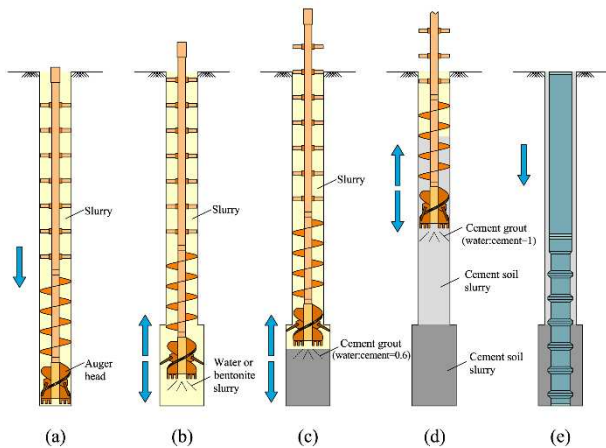


Figure 1. Typical construction sequence of a PPEB pile: (a) Drilling; (b) Expanding base; (c) Grouting at enlarged base; (d) Grouting along pile shaft; (e) Inserting precast pile.

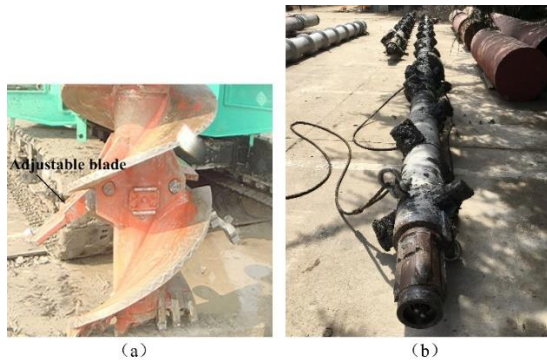


Figure 2. PPEB drilling equipment: (a) Adjustable auger head; (b) soil mixer.

2.1.2 Expanding base

After the drilling reaches a required depth, the adjustable blade of the drill bit is unfolded by a hydraulic system to enlarge excavation in the toe region (Figure 1b). According to the experience of applications and technical specification DB33/T 1134-2017 (RCCUGE 2017) in China, the diameter of the enlarged base should not be more than 1.6 times the diameter of the pre-bored hole, and the height of the enlarged base should not be less than 3 times the diameter of the pre-bored hole.

2.1.3 Grouting at enlarged base

After the completion of the pile hole, premade base-forming cement grout with a water cement ratio of 0.6 is injected into the enlarged base (Figure 1c), and the injection amount is 100% of the volume of the enlarged base. The cement grout is generated by an automatic mixing and monitoring system and is injected

through the drill pile under a pressure of 1.5 MPa throughout the grouting process. The auger has to travel up and down several times to make the cement grout mix with soil thoroughly. In this case, the mixed slurry can be referred to as cement soil slurry.

2.1.4 Grouting along pile shaft

Once the enlarged base is completed, the blade is folded, and the side-forming cement grout with a water cement ratio of 1.0 is injected into the borehole during withdrawal of the equipment (Figure 1d). In general, the injection amount of the side-forming cement grout is equal to 30% of the borehole volume.

2.1.5 Inserting precast pile

Before the initial setting of the cement soil slurry, the precast concrete pile is inserted into the cement soil slurry mainly by its self-weight (Figure 1e). Finally, a kind of pre-bored precast pile wrapped with cement soil is formed after cement soil solidification.

The main equipment for the construction of PPEB pile includes a special mixing rig, a crane and the supply system of cement grout, as shown in Figure 3. Automatic monitoring device and intelligent management are used in the construction process to ensure that the whole construction process is traceable.

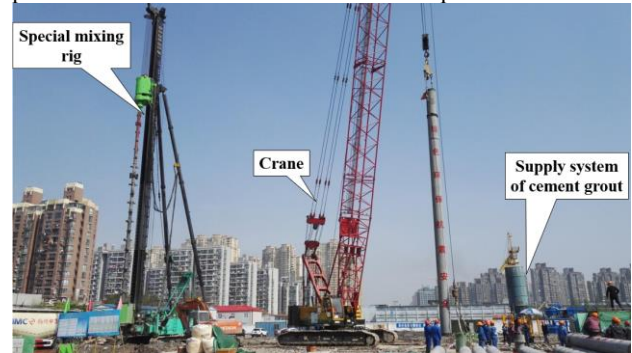


Figure 3. The main equipment for the construction.

2.2 Technical characteristics

The inner concrete precast piles can be made up of prestressed high-strength concrete (PHC) piles, PHC nodular piles, prestressed reinforced high-strength concrete (PRHC) piles and so on. The PHC nodular pile is a kind of precast pile with a node existing along the pile shaft every 1 m. As shown in Figure 4, the diameter of the 650(500) mm-PHC nodular pile shaft is 500mm, and the diameter of the node along the shaft is 650 mm.

The composition of inner precast piles can be altered to achieve different requirements of load performance. The PHC pile with equal cross-section is usually used in the upper part and the PHC nodular pile with variable cross-section is used in the lower part. When the horizontal resistance is high, PRHC pile can be used in the upper part.



Figure 4. Photograph of nodular pile and PHC pile.

PPEB pile integrates the advantages of bored pile, precast pile, deep mixing pile, and enlarged base pile, which can fully explore the performance of pile foundation. Its characteristics are summarized as follows:

(1) The thickness of the outer cement soil is less than 75mm, so the precast pile with larger diameter can be inserted to give full play to the bearing capacity of the high strength precast pile.

(2) The use of the PHC nodular pile in the lower part of the precast pile is beneficial to improve the bond between the precast pile and cement soil, and to exert higher shaft resistance.

(3) The enlarged base is used to strengthen the pile toe, which can effectively improve the end bearing capacity and control the settlement.

3 BEARING CHARACTERISTICS OF PPEB PILE

Base on the engineering projects, the load tests of compression and uplift capacity of PPEB piles were carried out. Through the measurement of axial force of pile shaft, the distribution and exertion characteristics of shaft resistance were analyzed.

3.1 Field testing program

The field tests were carried out in the intersection of Jiang Yang South Road and Hong Wan Road of Shanghai. A series of laboratory and in situ tests were performed at this site. The basic physical and mechanical properties of the soils are summarized in Table 1. The cohesion c and friction angle φ were determined from consolidated undrained tests, and modulus of compressibility E_s worked under 100-200 kPa. The ultimate unit shaft resistance q_{sik} are recommended for precast piles in technical code DGJ08-11-2018 (ECADI, 2019).

Table 1. Summary of soil parameters

Soil layer	w /%	γ /($\text{kN}\cdot\text{m}^{-3}$)	c /kPa	φ /($^{\circ}$)	E_s /MPa	q_{sik} /kPa
①Fill	27.0	18.9	5	32.0	10.0	15
②Silty clay with silt	27.0	18.9	5	32.0	10.0	15
③Muddy silty clay	40.4	17.6	12	17.5	3.3	15
④Muddy clay	50.4	16.7	10	11.5	2.0	25
⑤ ₁ Silty clay	33.1	18.2	15	19.5	4.3	40
⑤ ₃ Silty clay	32.9	18.2	16	21.0	5.0	55
⑤ ₄ Silty clay	23.1	19.7	40	20.0	7.2	65
⑦Clayey silt	24.3	19.3	6	31.5	10.5	65
⑧ ₁ Silty clay	31.0	18.4	19	20.5	5.5	60
⑧ ₂ Silt mixed silty clay	28.2	18.7	12	26.5	9.0	80
⑨Silty sand	25.9	19.0	3	35.0	12.8	110

Two groups of six load tests were carried out at the same site. Three piles (designated piles S1-1, S1-2 and S1-3) of S1 group were used for vertical compression static load test, and three piles (designated piles S2-1, S2-2 and S2-3) of S2 group were used for vertical uplift static load test. All of them were designed to be loaded to reach the ultimate capacity of plunging failure. The section of the test piles and soil layers are shown in Figure 5.

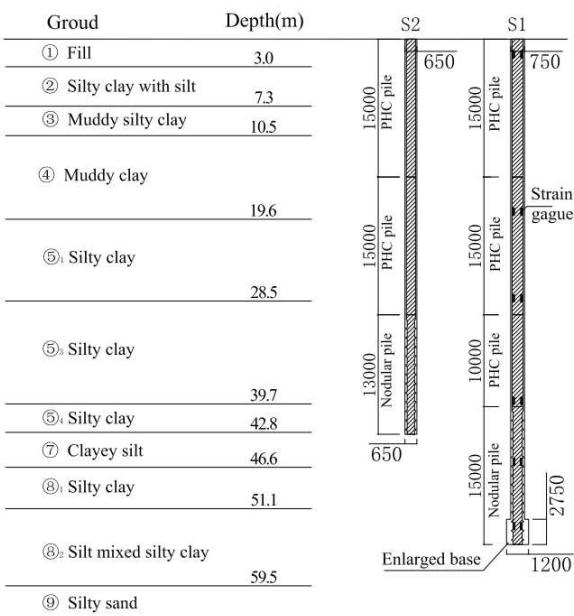


Figure 5. Profile of soil layers and test piles.

The length and shaft diameter of the test piles of S1 group were 55 m and 750 mm, respectively. The inner precast concrete piles were assembled by a 40 m long 600 mm diameter PHC pile in the upper part and a 15 m long 650 mm (500 mm) diameter nodular pile in the lower part (as shown in Figure 5). The enlarged bases were 2750 mm long with a diameter of 1200 mm. The length and shaft diameter of the test piles of S2 group were 43 m and 650 mm, respectively. The inner precast concrete piles were assembled by a 30 m long 500 mm diameter PHC pile and a 13 m long 550 mm (400 mm) diameter nodular pile. The test piles of S2 group were set as non-enlarged base.

3.2 Bearing performance

Static load tests were carried out 43-45 days after pile installation. The maintained load method was adopted in accordance with the Chinese code JGJ106-2014 (CABR, 2014).

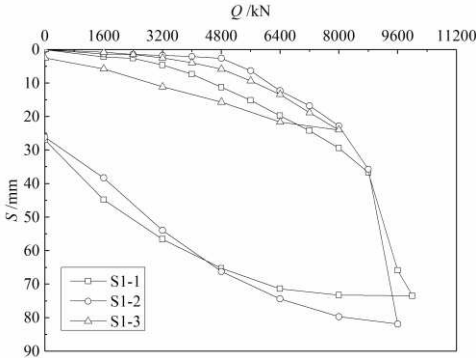


Figure 6. Q - s curves of compression piles

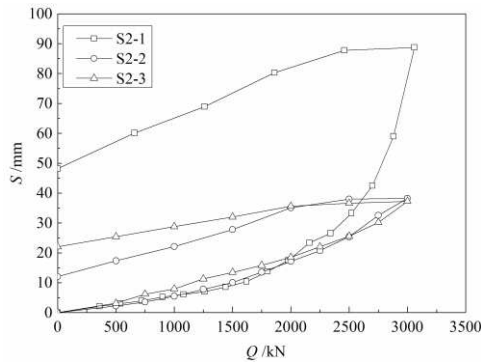


Figure 7. Q - s curves of uplift piles

Figure 6 shows the load-displacement (Q - s) curves of three compression test piles of S1 group. Obvious inflexion points can be observed on the Q - s curves of S1-1 and S2-2, so the ultimate bearing capacity of these two piles was 8800 kN. As the pile head of S1-3 inclined during the test, the loading process was terminated at applied load of 8000 kN. The ultimate bearing capacity of S1-3 was assumed as 8000 kN with pile head displacement of 24.0 mm. The Q - s curves of three uplift test piles of S2 group are presented in Figure 7. The ultimate uplift bearing capacity of test pile S2-1 was 2880 kN, and the uplift capacity of S2-2 and S2-3 test piles was higher than 3000 kN. The test results show that the PPEB pile is suitable for the stratum conditions in Shanghai area and can provide reliable vertical compression and uplift bearing capacity.

3.3 Axial force

The three test piles of S1 group were instrumented with strain gauges at six different depths, so the axial force distribution of the pile shaft under different loads could be obtained. The axial force distributions of the three test piles are basically consistent, and the typical distribution curve of S1-1 is illustrated in Figure 8.

Due to the high stiffness of the precast concrete pile and reinforcement of enlarged base, the axial force of the pile could be transferred directly from pile head to pile toe at the initial loading stage. The toe resistance obtained from the readings of the strain gauges near the pile toe could be roughly considered to represent the bearing capacity of the entire enlarged base. The toe resistance increased nonlinearly and accounted for 23.5-26.6% of the applied load under the ultimate condition.

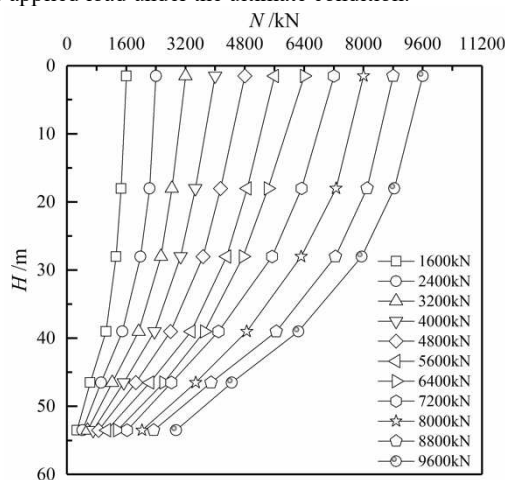


Figure 8. Axial force distribution on S1-1

3.4 Shaft resistance

The shaft resistance can be calculated from the measured axial

forces at different depths. Considering the cement soil around the pile as the reinforcement of the soil, the contact area around the precast pile was used to calculate the shaft resistance. The typical shaft resistance is shown in Figure 9.

At the initial stage of loading, the shaft resistance of upper and lower part of the test piles increased simultaneously. With the increase of applied load, the upper shaft resistance between the depth of 1.5 m to 28.0 m decreased to residual value, with residual adhesion ratios ranging from 0.80 to 0.92 after reaching the peak value. The shaft resistance of the lower part between the depth of 28.0 m to 53.5 m continued to increase until the end of the test.

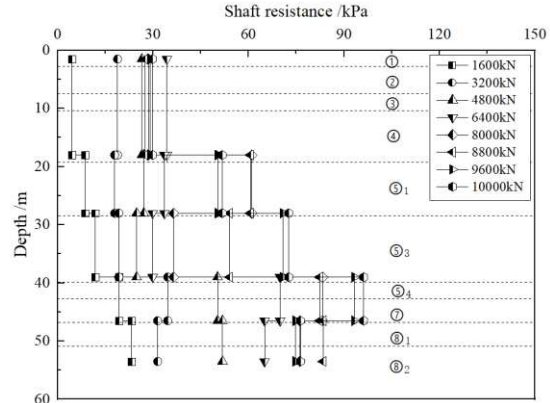


Figure 9. Shaft resistance distribution on S1-1

On the whole, the shaft resistance of the test piles had played a higher level. The ultimate shaft resistance of the upper soil layers (②, ③, ④, ⑤₁) was close to the upper limit value of the precast pile recommended by the technical code DGJ08-11-2018 (ECADI, 2019), while the ultimate shaft resistance of the lower soil layers (⑤₃, ⑤₄, ⑦, ⑧₁, ⑧₂) was 14% to 28% higher than the upper limit value of the code.

4 PILE-FORMING EFFECT AND CONSTRUCTION EFFICIENCY

4.1 Actual pile-forming effect

To investigate the quality and structure of the pile shafts of PPEB piles, the soils around the piles were excavated, approximately one year after pile installation. The cutting section of the test pile (Figure 10) clearly shows the characteristics of the pile shaft material of PPEB pile. The pile-soil system of PPEB pile is composed of concrete precast pile, cement soil and soil around the pile, which is the structural basis for forming the double-layer stress diffusion model of load.

At the excavation depth of 15 m, the measured diameter of the test piles ranged from 758 mm to 780 mm and the thickness of the cement soil annulus ranged from 45 mm to 130 mm. In general, the cement soil around the upper pile was thin, which may be related to the construction technology. Good binding of cement soil and inner precast pile indicated that slippage was most likely to occur at the interface between the cement soil and the surrounding soil after the displacement on the pile side exceeded the threshold value. In addition, the shape of the pile shaft was nearly cylindrical and symmetrical. Thus, the pre-bored precast piling was reliable in thick soft clay.

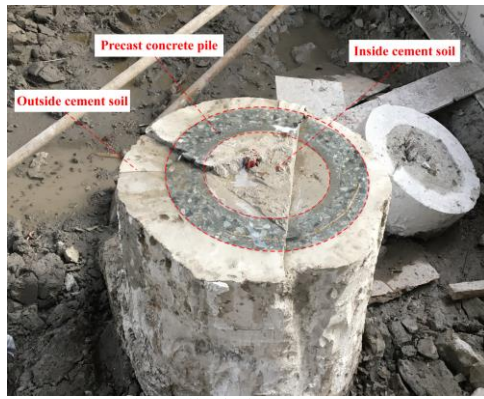


Figure 10. A section of test pile shaft

4.2 Construction efficiency

The total construction time of a single PPEB pile mainly includes the time of pre-drilling, grouting and inserting precast pile. According to the records, the construction time of compression test piles in group S1 and uplift test piles in group S2 are summarized in Table 2. Compared with the traditional bored pile, the construction speed of PPEB pile is faster and the work efficiency is higher. Assuming that the construction time is 16 hours a day, 3.5 compression piles (190 m/d) of S1 group can be constructed, and 6.5 uplift piles (275 m/d) of S2 group.

Table 2. Construction time of PPEB piles

Test pile	Borehole diameter /mm	pre-drilling /min	grouting /min	inserting precast pile /min	total construction time /min
S1-1	750	138	76	76	290
S1-2	750	102	80	68	250
S1-3	750	134	94	62	290
S2-1	650	61	27	33	121
S2-2	650	60	37	49	146
S2-3	650	88	28	61	177

Due to the lack of engineering experience, the pre-hole drilling speed of typical strata in Shanghai is relatively conservative, which is lower than that of similar strata in Zhejiang area. With the accumulation of engineering experience in Shanghai, the construction efficiency of PPEB pile will be further improved.

5 PROPERTIES OF CEMENT SOIL IN PPEB PILE

Cement soil is a part of the structure of PPEB pile, and its behavior has an important influence on the bearing performance. The cement soil characteristics in PPEB pile were discussed through field test and laboratory test.

5.1 Properties of cement soil on site

To examine the properties of cement soil in PPEB pile in Shanghai clay, one deep cement mixing pile K1 without inner precast piles and enlarged base was constructed according to the pre-bored technique of test piles of S1 group. So, the properties of cement soil of K1 should be in accordance with that of pile shaft of the test piles. The cement soil strength of the pile K1 with an age of 48 days is shown in Figure 11, in which the solid line is the measured result and the dotted line is the mean value.

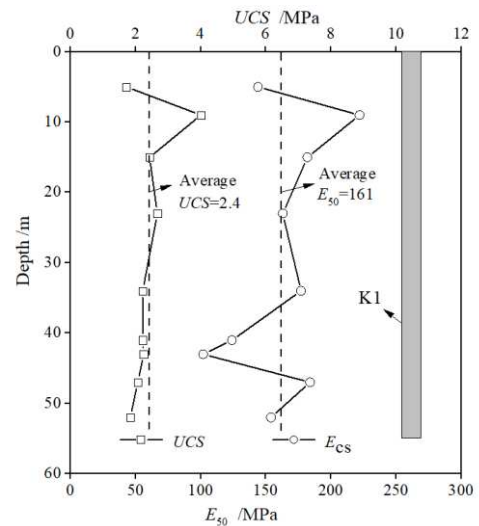


Figure 11. Strength of cement soil along the pile shaft of K1.

The unconfined compressive strength (UCS) varied from 1.7 MPa to 4.0 MPa, with an average of 2.4 MPa. The cohesion of cement soil ranged from 350 kPa to 700 kPa, while the internal friction angle ranged from 37 degrees to 45 degrees. As shown in Figure 11, the unconfined compressive strength of cement soil is stable along the pile shaft. It reflected that the cement soil in PPEB pile was fully stirred by the pre-drilling and grouting construction technology, and the cement soil property was relatively uniform. The Young's modulus (E_s) varied from 102 MPa to 222 MPa, with an average of 161 MPa. It was considered as the secant modulus value, which was calculated by dividing the peak UCS by the associated axial strain.

5.2 Laboratory test of cement soil

As the reasons of on-site construction, the cement soil at the enlarged base could not be sampled and tested in the past. Therefore, through the laboratory test of simulating the construction process, the mechanical properties of the cement soil with high cement content at the enlarged base and the cement soil with low cement content around the pile shaft were further studied.

The typical silty clay and silty sand in Shanghai area were selected as soil materials. P·O 42.5 ordinary Portland cement was selected for cement. According to the actual engineering experience, the specific gravity of slurry was controlled to 1.5 in laboratory test. In order to prepare cement soil with high cement content, the water cement ratio of cement grout was 0.6, and the volume ratio of cement grout to slurry was set to 1, 1.5 and 2. Similarly, to prepare cement soil with low cement content, the water cement ratio of cement grout was 1.0, and the volume ratio of cement grout to slurry was set to 0.15, 0.3 and 0.6. The cylindrical specimens of cement soil were made by hanging bag method, as shown in Figure 12.



Figure 12. Sampling by hanging bag method.

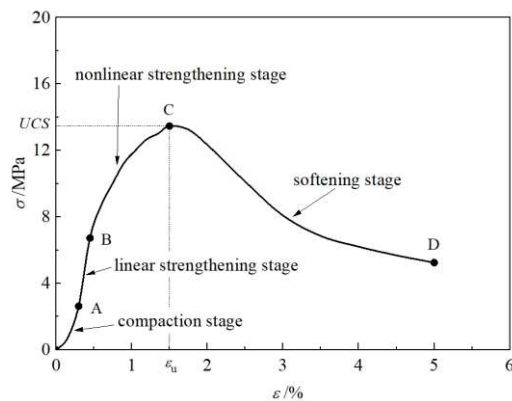


Figure 13. Typical compressive stress-strain curve of cement soil.

Three parallel samples were made under the condition of each mix proportion. After 28 days of standard curing, the average values of three parallel samples were taken as the test results. The test results indicated that the UCS of cement soil increased with the increase of cement content. Under the same cement content, the UCS of cement soil with silty sand was generally higher than that with silty clay. For the cement soil with high cement content, the UCS ranged from 6.2 MPa to 12.7 MPa when the soil was silty clay, and 11.8 MPa to 17.0 MPa when the soil was silty sand. For the cement soil with low cement content, the UCS ranged from 0.5 MPa to 2.7 MPa when the soil was silty clay, and 0.9 MPa to 4.6 MPa when the soil was silty sand.

With the increase of cement content, the failure strain (ϵ_u) of cement soil decreased gradually, and the properties of cement soil developed to brittleness. The failure strain of cement soil was about 1.0-3.0%, which was obviously higher than that of ordinary concrete. Therefore, the stress-strain property of cement soil was between soil and concrete. As shown in Figure 13, the typical compressive stress-strain curve of cement soil can be divided into compaction stage, linear strengthening stage, nonlinear strengthening stage and softening stage, in which the compaction stage is generally less than 30% of the failure strain.

6 ENGINEERING APPLICATIONS

PPEB pile was first applied in Zhejiang area, and gradually popularized in Shanghai and other areas in China. It has been used in about 70 projects in Zhejiang area, with a total workload of about 1.5 million meters. The maximum pre-drilling depth of PPEB pile was 82 m and the maximum effective pile length was 67m. The maximum diameter of precast pile used in PPEB pile was 800mm with the drill diameter 900mm, and the maximum diameter of enlarged base was 1440mm. In Zhejiang area, under the condition that the length of pile was 64m and the diameter of precast pile was 800mm, the maximum ultimate compression bearing capacity of PPEB pile was 16773kN.

PPEB pile has been used in more than 10 projects in Shanghai area. The typical engineering applications are summarized in Table 3. At present, the maximum effective length of PPEB pile in Shanghai was 56 m, and the maximum ultimate compression bearing capacity of a single pile was 11600kN. The PPEB pile could penetrate the thick layer of dense silt and silty sand, and the maximum thickness of the penetrated dense silty sand layer was about 25m.

Table 3. Typical engineering applications in Shanghai.

Project No.	L /m	B /mm	D /mm	Bearing stratum	Project overview	Q_u /kN
No.1	27	650	550	Silty clay	905 uplift piles; the geological conditions were mainly weak clayey soils.	>2820

No.2	30	650	550	Silty clay	140 compression piles; the teaching building of the school had high requirements for environmental protection.	2500
No.3	45	750	650	Silty sand	518 compression piles; precision instrument foundation required high settlement control; pile tip passed through the sand layer greater than 20m.	>6500

Note: L =pile depth; B =Borehole diameter; D =Diameter of precast pile; Q_u = Ultimate bearing capacity of test pile.

7 CONCLUSIONS

This paper presents the study and application of PPEB pile in China. The main findings include:

- PPEB pile was suitable for soft soil stratum and could penetrate thick, dense silty sand layer, which could provide reliable vertical compression and uplift bearing capacity. The setting of the enlarged base improved the end bearing capacity. Under the ultimate load, the end bearing capacity of the PPEB pile accounted for about 25% of the total load; the shaft resistance was mainly affected by soil properties and buried depth, and the shaft resistance at the lower part of the pile shaft played a higher level.
- In the PPEB pile, the shape of the cement soil was intact, and cement soil and inner precast pile had good binding. The properties of cement soil were related to soil properties and cement content. The UCS of the cement soil with low cement content around the pile shaft ranged from 0.5 MPa to 4.6 MPa, while the UCS of the cement soil with high cement content at the enlarged base ranged from 6.2 MPa to 17.0 MPa.
- The study and application of the PPEB pile in China has just started, and it is still necessary to further accumulate experience through a great deal of engineering practice and carry out theoretical research to promote the development and application of this new type of pile.

8 ACKNOWLEDGEMENTS

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