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Development and application of the large-diameter driven cast-in-place concrete thin-wall pipe pile

Développement et application du large-diamètre de la vibration du béton coulé sur place au paroi mince pour le tuyau du pile

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ABSTRACT
A new form of driven Cast-in-place Concrete thin-wall Pipe pile (referred as PCC pile) developed independently by GeoHohai has recently been patented in China. PCC piles are rapidly increasing in popularity as one of the most cost-effective soft ground improvement techniques in China since its first application. This paper tells the story of PCC pile development in the aspects of the technique principles, the soil improvement mechanisms, the proprietary construction equipment and technology, and integrity testing methods, and its field application in an expressway foundation improvement project in Shanghai, China. The field study has demonstrated that PCC pile composite foundation is a cost-effective way to enhance ground bearing capacity and reduce settlement. Compared with traditional piling practice, the paper concludes with the statement on the potential application value of PCC pile with regard to other traditional piling techniques as being high bearing capacity, easily controlled and reliable quality and low construction cost.

RÉSUMÉ
La vibration du béton coulé sur place au paroi mince pour le tuyau du pile (appelée PCC pile) est une nouvelle technique de la fondation sur pilotie, développée de manière indépendante par le Géo-Hohai, Chine. Les PCC piles sont utilisés de plus en plus dans les régions de terre molle. Cette résumé présente les principes techniques, les équipements et technologies de l'application, les méthodes de conception et le contrôle de qualité. On présente aussi en détail les essais des PCC piles du Projet de l'Auto Route Shanghai, selon le résultat des essais et en comparant le pile traditionel, cette sorte de pile possède une grande capacité de charge, une bonne qualité stable, et le prix de revient réduit etc. Ce pile est facile à contrôler et à réaliser.

1 INTRODUCTION

Piled foundation, cement grouted pile, vacuum preloading, overload surcharge preloading, and dynamic compaction are popular soft ground improvement techniques. Every improvement technique has its range of applicability and limitations. For instance, cement grouted pile has limitations in improvement depth, difficulties in controlling quality, low strength of pile body and high post construction inspection cost; overload surcharge preloading has difficulties in ensuring foundation stability during construction because of the initially very low strength of the soil, thus a long construction period is required, which consequently has adverse effect on the project economic evaluation; dynamic compaction is mainly applicable for soft soil with good permeability, thus it is not a suitable method for soft clay.

Piles are relatively long and slender members used to transmit foundation loads through soil strata of low bearing capacity to deeper soil or rock strata having a high bearing capacity. They are widely used in building and road engineering projects, because of their advantages in the following aspects: relatively fast construction speed, unlimited penetration depth, suitability for various geological conditions, improved foundation stability, high bearing capacity and reduced settlement. Precast solid concrete pile, cast-in-place solid concrete pile, and precast concrete pipe pile are the main types commonly used in practice. The cost of the precast solid concrete pile is higher than that of the cast-in-place solid concrete pile, which has a lower unit price for concrete, but not an efficient way for saving concrete. Basically, the cost of the cast-in-place solid concrete pile is not much reduced. Consequently, precast concrete pipe piles (PHC piles) have been developed, the load capacity per unit volume of concrete of which are obviously improved compared with cast-in-place solid concrete piles. However, uncertain factors existing in transportation and construction make reinforcement of the precast concrete pipe piles necessary to avoid any possible damages. This will again bring up the foundation improvement cost. Based on above considerations, the problem requesting an urgent solution for geotechnical engineers is to seek for some new form of piles, which consume less concrete for a lower construction cost, have high load capacity and are capable to improve foundation stability. In view of the disadvantages of cast-in-place solid concrete pile and precast concrete pipe pile and facing the need for a new form of pile, Liu et al. (2003) have developed a cost-effective piling technique for soft ground improvement, large diameter cast-in-place pipe pile, referred as PCC pile, which is patented in China with patent numbers as: ZL02219218.X (Liu et al. 2004) for PCC pile equipment and ZL02112538.4 (Liu et al. 2004a) for construction technology.

2 PCC PILE TECHNIQUE PRINCIPLES

PCC pile technique mainly consists of driving an open-ended double walled steel casing by vibratory method, forming an annulus void, pouring concrete, and retrieving the steel casing. The double walled steel casing are formed by two pipe piles with different diameters, which are locked at the top and fitted at the tip by a moveable tapered driving shoe. The power supplier of PCC pile, vibratory hammer, is electrically powered, and consists of contra-rotating eccentric masses within a housing attached to the steel casing. While the eccentric masses rotating at the same speed, the horizontal eccentric force will be canceled out, while the vertical eccentric force will be doubled, resulting in high frequency up and down movements. The vibrator, which is heavy and with high velocity, could provide big dynamic force, driving the steel casing into the design depth at very fast speed. Sinking velocity of the steel casing is determined by the hammer frequency, vibrator mass, and soil properties. Mechanisms involved in PCC pile forming are stated as:

(1) Casing. After driven into the design depth, the steel casing is extracted under vibration; in the meantime, concrete is

poured from the concrete shunt. The annulus steel casing prevents the concrete wall from shrinkage and collapsing. The new technology allows a continuous accomplishment of void formation, temporary casing, concrete pouring, and wall expansion, which subsequently ensures the stability and fullness of the concrete in the void.

(2) Compaction of concrete. The concrete inside the annulus casing and the void is being fully compacted continuously while the casing being extracted under vibration. It is also being forced squeezing outside, which subsequently increases the concrete wall thickness.

(3) Compaction of soil. During driving of the steel casing under vibration, there is certain degree of compaction to the surrounding soil as well while the soil is displacement radially. The degree of compaction depends on the wall thickness and the soil properties.

3 CONSTRUCTION EQUIPMENTS AND TECHNOLOGY

Main technique requirements of the construction equipments are: (1) penetration depth up to 25m, (2) pile outer diameter 1000 to 1500mm, (3) wall thickness 100 to 150mm, (4) multiply concrete supplement, (4) pulling capacity up to 30t and pushing capacity (sum of overload and high frequency vibratory force) up to 100t.

Based on above requirements, the construction equipment is designed as shown in Figure 1. The basic components are: (1) base (including windlass), (2) gantry bracket, (3) vibratory head, (4) double-walled steel casing, (5) moveable tapered driving shoe, (6) concrete grout maker, and (7)concrete shunt.

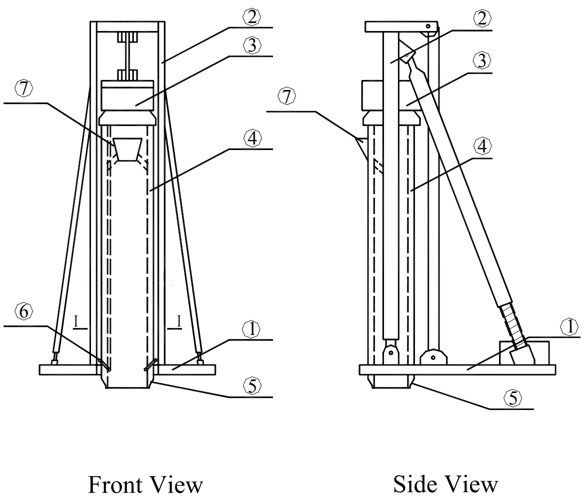


Fig.1 Schematic Drawing of Construction Equipment

The construction flow of PCC piles is: prepare for construction, assemble equipment in the field, locate equipment in place, drive steel casing, fill the annulus void space with concrete, withdraw steel casing, and locate another spot. The construction flow chart is depicted in Figure 2.

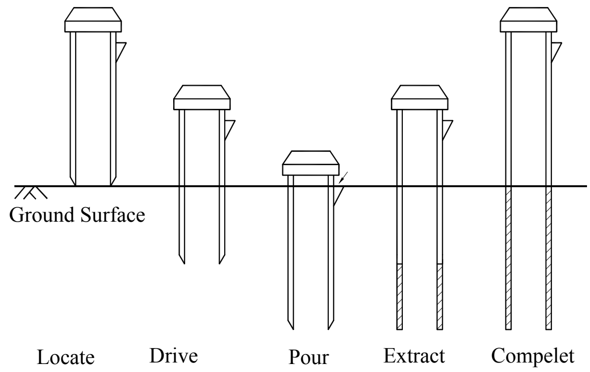


Fig.2 Construction Flow

4 ADVANTAGES OF THE PCC PILE TECHNIQUE

Application of PCC piles for soft ground improvements in road engineering will offer us a chance for good solutions to many practical problems as being low cost, short construction period, and high construction quality. The advantages of the PCC pile technique are illustrated based on a comparison with cement grouted pile.

(1) Construction Applicability

PCC pile is rigid pile with body concrete grade up to C20~C25, diameter up to 1.5m and penetration depth up to more than 25m; Cement grouted pile has small diameter around 0.5m and limited penetration depth maximum up to 15m and at penetration depth greater than 10m, there are difficulties in controlling pile quality due to high grout pressure required.

(2) Construction Quality Control

PCC pile employs a very simple construction technology, which is easy to handle and in good control of the concrete quality; for cement grouted pile, cement is only conveyed under high pressure. In practical construction, the grout pressure is not uniform due to variation of ground conditions, thus easily resulting in faults in the pile body. Shadowed construction makes the supervision of cement grouted pile more difficult.

(3) Pile Inspection

PCC pile employs low strain dynamic testing or hand excavation inspection methods, which are cheap, only 1 to 2% of the total cost, non destroyable, extensive, and short inspection period; for cement grouted pile, quality inspection normally requires sample boring and static load test, which are expensive, 3~5% of the total cost, long inspection period, and small range of inspection, 2% of total number of pile which are normally not representative of the whole project quality.

(4) Improvement Effects

PCC piles could significantly improve the bearing capacity of the road foundation, which could be 10 times greater than that treated by cement grouted piles. PCC piles together with the top geogrid gravel cushion, act as a rigid pile group, which could remarkably reduce the settlement; Cement grouted pile has a low body strength and big settlement due to shallow penetration depth.

(5) Economics Comparison

Assuming PCC pile of 12m length, 1000mm diameter, 120mm wall thickness, and 3.3m pile spacing, the cost per meter is about 180 RMB/m, and the cost per unit improvement area is about 198 RMB/m^2; Assuming cement grouted pile of 12m length, 500mm diameter, and 1.4m spacing, the cost per meter is about 35 RMB/m, and the cost per unit improvement area is about 214RMB/^{2}. Based on above comparisons, although there is no significant difference in terms of construction cost, PCC pile has advantages of easily controlled construction quality, not requesting for preloading, and good behaviour at bridge road connections over the cement grouted pile. So it is more economic and reasonable to choose PCC pile, which is good substitute for cement grouted pile in view of the safety, economics and effectiveness issues.

5 DESIGN AND QUALITY INSPECTION OF PCC COMPOSITE FOUNDATION

The design of the PCC pile composite foundation is based on the rigid pile composite foundation design theory since PCC piles, top geogrid gravel cushion, and the soil behave like a rigid composite foundation (Liu et al. 2003a). The most reliable method to determine the foundation bearing capacity is by static load tests. Theoretical solutions are also proposed to predict the foundation bearing capacity. The settlement of the rigid composite foundation consists of two parts, the compression of the improvement area and the compression of the soil below the improvement area.

(1) Design Procedure

(a) Determine the bearing layer and pile length based on geological report;

(b) Determine the pile diameter d (1000~1500mm) and wall thickness w (100~150mm);

(c) Determine the spacing (normally 3~5d) and layout based on design bearing capacity and allowable settlement;

(d) Determine the concrete grade (normally C10~C25) based on design bearing capacity;

(e) Determine the cushion thickness (normally 10~40cm) and material (coarse gravel or small stone with geogrid in between);

(2) Quality Inspection

The quality inspection of PCC pile is normally carried out in following three ways:

(a) In situ excavation: to check the appearance of the pile around 14 days after pile formation.

(b) Low strain and high strain testing methods: to check the pile integrity by echo waves.

(c) Static load tests of single pile and composite foundation: to estimate the bearing capacities of single pile and composite foundation.

6 FIELD STUDY ON THE APPLICATION OF PCC PILE

6.1 *Overview of the Project*

This project is located in the west suburb of ShangHai, China. Along the proposed highway, the depth of the underlay soft soil is up to 18m. The designed lower and upper widths of the embankment are 45.5m and 32m respectively. The maximum filling height is 4.5m. The section between K12+570 and K12+630 where the expressway meets a bridge is treated by PCC pile with geogrid embedded gravel cushion on the top. Design parameters of PCC pile are 1000mm in diameter, wall thickness 120mm, and concrete grade C15. The other sections are treated by overload preloading and prefabricated vertical drains (PVDs) with treatment depth up to 17.5m. The settlement induced in the PVDs treated area is much greater than that in the PCC pile treated area. To avoid differential settlement, a transition zone is set up by means of varying PCC pile lengths to adjust the differential settlement. Layout of PCC pile is illustrated in Table 1.

Table 1 Layout of PCC pile

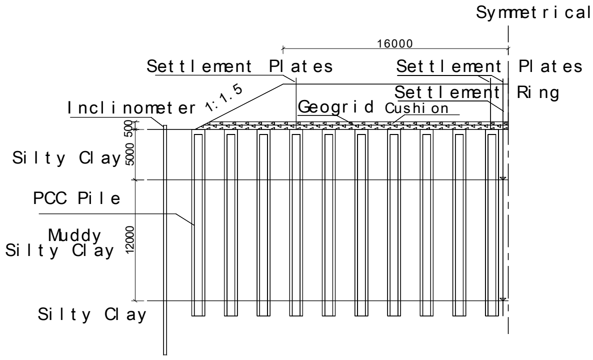
Kilometer Marker	K12+570 ～600	K12+600 ～610	K12+610 ～620	K12+620 ～630
Pile length (m)	18.0	17.0	16.0	15.0
Layout Spacing (m)	Triangular 2.5	Triangular 2.5	Triangular 2.5	Triangular 2.5

The soil condition at the testing site is alluvial lake deposition. The soil properties in the layered soil stratums are tabulated in Table 2.

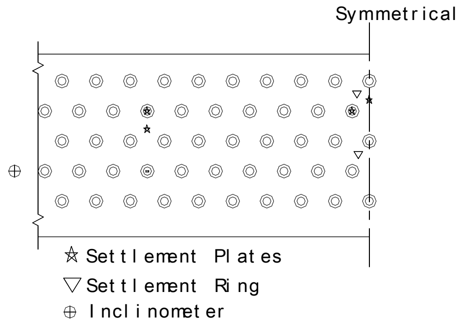
6.2 *Field Tests*

To demonstrate the ground improvement effects by PCC piles, one cross section was selected at K12+592. Instrumentation layout is illustrated in Figure 3.

Instruments employed in this study are as listed below:



(a) Cross section



（b） Plane section

Fig.3 Instrumentation Layout at section K12+592

Table 2 Soil properties

No	Soil layer	Thickness m	W %	γ g/m^3	e	IP	E MPa	Strength C kPa	φ°
1	Clay	1.3	35.4	1.8	1.061	15.2	3.26	35.6	13.2
2	Silty sand	2.7	34.7	1.86	0.956	8.20	7.81	21.0	6.0
3	Muddy silty clay	12.0	46.1	1.75	1.274	13.57	1.94	16.8	4.38
4	Silty clay	2.2	23.0	2.04	0.631	10.95	5.85	42.0	16.7
5	Silty clay	3.1	21.5	2.04	0.614	12.66	8.13	38.3	17.6
6	Silty sand	10.6	33.8	1.98	0.736	6.96	7.65	18.3	20.3
7	Silty clay	10.5	30.3	1.92	0.855	13.20	6.52	33.1	12.9
8	Clay	7.2	32.4	1.89	0.929	18.50	7.93	39.1	16.2
9	Silty clay	2.6	28.4	1.96	0.793	15.30	8.78	48.0	15.0
10	Medium dense sand	-	20.3	1.99	0.624	6.54	11.6	17.0	30.8

(1) Settlement plates: to investigate the displacement of PCC pile head and surface settlement of the surrounding soil during loading
(2) Settlement ring, to learn the deformation pattern of layered soil stratum;
(3) Inclinometer: to investigate the horizontal displacements at various depths.

6.3 *Analysis of Testing Results*

6.3.1 *Settlements at pile head and ground surface*

Figure 4 illustrate the variation of settlement at ground surface and pile head with time at K12+592. At the beginning of soil fill-ing, the ground settlement is increasing with soil filling height and there are several obvious inflexion points on the settlement curves. It indicates that at the beginning of road embankment filing, the soil between PCC piles is taking certain amount of load. At august 11 2001, the total settlement at K12+592 is 92mm with embank-ment filling height 4.5m. This demonstrates that the foundation is more stable with little settlement for the PCC pile composite foundation.

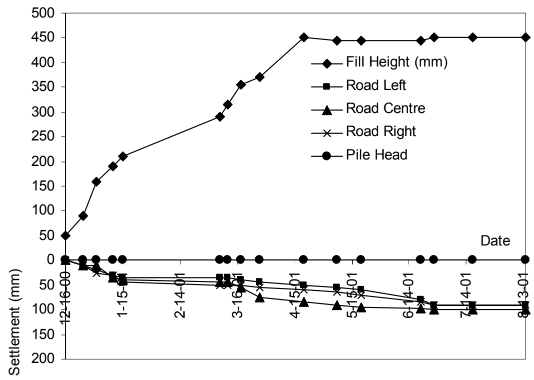


Fig. 4 Variation of Pile Head and Ground Surface Settlement with Time at K12+592

6.3.2 *Settlement at various depths*

The settlement at different depths at K12+592 is shown in Figure 6. It is obvious from Figure 5 that at K12+592, the settlement occurring mostly within 4m depth, particularly at 3.5m depth, the maximum settlement occurred as 92 mm; the settlement at depth greater than 6m basically has no variation. So settlement mostly occurred at the shallow depth of soil between piles. The measurement from the settlement ring at the surface of ground re-sulted in good agreement with the settlement plates. It proves that these measurements are reliable.

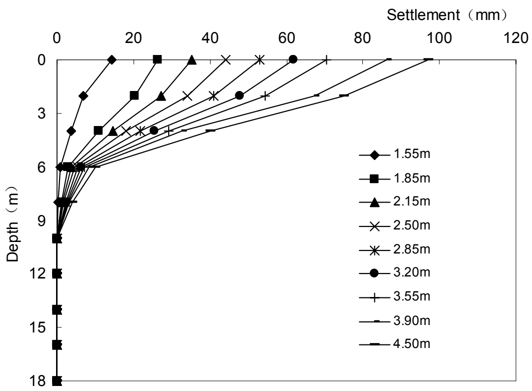


Fig.5 Settlement at Various Depths at K12+592

6.3.3 *Horizontal displacement*

Horizontal displacements measured by inclinometer at K12+592 are shown in Figure 6. The maximum horizontal displacement at K12+592 is less than 5mm, indicating small lateral deformation for the soils between piles, ensuing a stable founda-tion and avoiding foundation sliding.

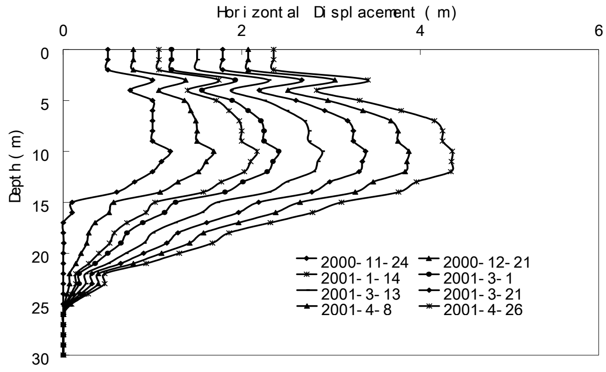


Fig.6 Horizontal Displacement at Various Depths at K12+592

7 CONCLUDING REMARKS

This new PCC pile technique combines the advantages from the precast pipe pile and the driven pile under vibration. PCC pile has high bearing capacity, large diameter, and deep penetration depth. The simple construction technology makes quality control and supervision easier. The study on the effect and mechanism of PCC pile improvement has been carried out based on a case of highway project. The field results demonstrated that: in PCC pile composite foundation, PCC piles are carrying most of the load, up to 70%~85% of the total load; the ratio of load carried by piles and soils are increasing with more loading; most of the settlement occurred in the soils, with little settlement from pile head; and the horizontal displacement is small thus increasing the sliding stability. The PCC pile composite foundation has more flexibility in terms of adjustable bearing capacity, high overall stiffness, reliable time sustained quality, low ground improvement cost, high bearing capacity, and low settlement, which make it an effective way for foundation improvement.

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