Case Study on X-section Cast-in-place Pile-Supported Embankment over Soft Clay

Étude de cas pour un remblai renforcé par des pieux de section en X coulés en place dans de l'argile molle

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ABSTRACT: Pile-supported embankments are widely used for highway, railway, seawall, etc. over soft soils because of their effectiveness in minimizing deformation and accelerating construction. A new method of using X-section cast-in-situ concrete piles (referred to as XCC pile) which can improve bearing capacity, reduce settlement and costs effectively for foundations over soft clay is developed by Hohai University of China. In this paper, construction method, quality assurance (QA), and quality check (QC) involved in this method are described. A large-scale model test program on a XCC pile and a circular pile, both constructed with the same amount of concrete volume, was carried out to obtain the load transfer behavior of both piles under three different loading modes: compression, uplift, and lateral loads. One XCC pile-supported embankment application was presented. The large -scale load test indicated that load carrying capacity of XCC pile is slightly higher than that of circular pile, when the same amount of concrete volume was used. It is worth pointing out that this XCC pile type can be constructed rapidly, quality assurance (QA) and quality checked (QC) easily, and cost-effectively. The results of this study can provide reference for practical XCC pile-supported embankment design and construction.

RÉSUMÉ : Les remblais renforcés par pieux sont largement utilisés pour les autoroutes, les voies de chemin de fer, les digues, etc …construites sur des sols mous en raison de leur efficacité à minimiser les déformations et à accélérer la construction. Une nouvelle méthode développée par l'Université de Hohai en Chine consiste à utiliser des pieux en béton de section en X coulés in situ (appelés pieux XCC) qui peuvent améliorer la capacité portante, réduire efficacement le tassement et les coûts pour des fondations dans de l'argile molle. Dans cet article, méthode de construction, assurance qualité (AQ) et contrôle de qualité (QC) impliqués dans cette méthode sont présentés. Un programme d'essai sur des modèles à grande échelle avec un pieu XCC et un pieu circulaire, construits avec la même quantité de béton, a été réalisé pour obtenir le comportement de transfert de charge pour les deux pieux sous trois modes différents de chargement : compression, soulèvement et latéral. Une application pour un remblai renforcé par des pieux XCC est présentée. Le test de chargement à échelle réelle indique que la capacité portante du pieu XCC est légèrement supérieure à celle du pieu circulaire, pour la même quantité de volume de béton. Il est intéressant de souligner que ce type de pieu XCC peut être construit rapidement avec des assurances qualité (AQ) et contrôles de qualité (QC) faciles et à moindre coût. Les résultats de cette étude peuvent servir de référence dans la pratique pour la conception et la construction des remblais renforcés par les pieux XCC.

KEYWORDS: XCC pile, pile supported embankment, soft clay, case study.

1 INTRODUCTION.

Pile-supported composite foundation is one of useful soft soils treatment methods. It is widely used to construct highways, railways, and seawall on soft soils due to their rapid construction, small total and differential deformations, and low costs compared to other traditional soft soils improvement methods (such as, deep cement mixing (DCM) piles (Arulrajah *et al*. 2009), stone columns (Gniel *et al*. 2009), and precast prestressed piles (Han & Gab 2002; Dzhantimirovk *et al*. 2009; and Bakholdin *et al*. 2009)). Many cases using pile-supported embankments, such as, the railway widening projects (Jones et al. 1990; and Eekelen & Bezuijen 2008), the retaining wall projects (Alzamora et al. 2000), the vertical wall breakwaters (Suh *et al*. 2006), and the freeway embankment in USA and China (American Association of State Highway Officials/Federal Highway Administration 2002; Liu *et al*. 2009; and Chen *et al*. 2010*a*).

There are some ways to optimization pile-supported composite foundation designs by coordinating load share ratio of pile-soil. Special shape piles can improve the contact areas of pile-soil interface and lateral stiffness in specific direction effectively, which means the friction of pile shaft, and lateral load capacity can be improved in the same concrete consumption. It can coordinating load share ratio of pile-soil more suitable. Barrette pile (Lei *et al*. 2001), H-pile (So *et al*. 2009), and steel pipe pile (Arulmoli *et al*. 2010) etc, are widely used for pile foundation. While these special concrete piles have low costs and are more suitable for soft soils treatment. Y-section cast-in-situ concrete pile use for pile-supported embankment is reported (Chen *et al*. 2010*b*), while the lateral stiffness of these piles is not easy to control.

Hence, this paper presents one new method of soft soils treatment: XCC pile-supported composite foundation method. The construction method, quality assurance, and quality check involved in this method are described. A large-scale model test program on a XCC pile and a circular pile, both constructed with the same amount of concrete volume, was carried out to obtain the load transfer behavior of both piles under three different loading modes: compression, uplift, and lateral loads. A case study that illustrates the application of this method in a pile-supported composite foundation over soft clay is presented. The pile shaft of XCC pile are measured and analyzed.

2 CONSTRUCTION METHOD

Cast-in-situ rather than precast concrete X-section piles are used. This is because it is difficult to transport and install X-section piles without affecting the integrity of the pile, particularly when the piles are not reinforced in the corner part of piles. For this purpose, a special pile driving machine and methods have been designed to install the XCC pile (Liu *et al*. 2007). Pictures of the piling machine in action and the flap pile shoe are shown in Fig. 1.

The construction procedures for XCC piles are as follows: First, the vibratory pile driver is connected to the X-section steel casing by flange. Next, the X-section steel casing is connected with the flap pile shoe. Then, the vibratory driver drives the X-cross section steel casing into the desired elevation. After reaching the required penetration depth, concrete is then fed through the X-section steel casing inlet mouth. Finally, use the vibrating driver to extract the casing to the ground. Thus, XCC pile is formed. Pile cap can be constructed after casing is removed.

Figure 1. Physical diagrams of pile-driving machine: (a) XCC pile-driving equipment and pile mould; and (b) Pile driver locating and flappable pile shoes.

3 QUALITY ASSURANCE AND QUALITY CHECK

In order to improve the quality of pile, the withdrawing rate should be controlled within 1.0 to 1.5 m/min under normal circumstances. The casing should vibrate for 10 s before withdrawal. Subsequently for every 1 m withdrawal, the pulling should be stopped temporarily to vibrate the casing for 5 to 10 s until the casing is completely withdrawn. The vibratory effect applied to the casing during withdrawing also helps the concrete to be compacted. The maximum depth of the XCC pile is controlled by the height of the XCC piling machine and is normally within 25 m, and too long pile casing will reduce the install speed. The maximum advantages of XCC pile is the contact areas of pile-soil interface improvement with special cross-section. The most difficult part of XCC pile construction is the shape of pile head, overflow concrete may change the shape as the lateral soil pressures near ground are low.

To check the quality of the pile after formation, the following four methods can be used: (1) excavate the surrounding soil of pile to check the shape of piles, (2) static pile load testing, (3) low-strain integrity testing, and (4) amount of concrete poured in during concreting. To excavate the surrounding soil of pile for visual inspection and for taking concrete samples from the XCC pile is a good way to check the quality of XCC pile. Obviously, static pile load testing, and low-strain integrity testing can be also used for XCC pile.

4 LARGE-SCALE MODEL TEST

4.1 Summary of Model Test Conditions

A large -scale test facility is composed of a fairly rigid model container, a loading system, and a data measuring system. The model container is measured as 5 m × 4 m × 7 m (length × width × height). The loading system consists of hydraulic jacks, beams, reaction walls, and hanging baskets and bolts, etc. The data measuring system consists of load cells, reinforcement bars, earth pressure cells, frequency instrument device, and LVDTs.

The soils used to fill the model container consist of both sand and clay, taken from Hexi District of Nanjing, China. The sand is uniformly graded with uniformity coefficient (C_u) and curvature coefficient (C_c) equal to 1.58 and 0.99, respectively. The soil layers are filled in the container by controlling the density of the in-place dry soils. The dry density for sand and clay is 1.54 ~ 1.57 g/cm^3 and 1.47 ~ 1.51 g/cm^3, respectively. The mechanical properties of the soils with the specified density are shown in Table 1. The soil layers in the model test container are as follows: sand of 2.4 m deep at the top, clay of 3.9 m deep in the middle, and crushed rock of 0.3 m at the bottom.

Two pile types (XCC pile and circular pile) were subjected to three different modes of loading (axial compression, uplift, and lateral load) at the top of the pile for deriving load transfer behavior. The experimental set up is summarized in Table 2.

Table 1. The mechanical indices of test soil with the specified density

Materials	Cohesion, c (kPa)	Internal friction angle, φ (°)	Compression modulus, E_s (MPa)	Moisture content, ω (%)	Control density, ρ (g.cm^{-3})
Sand	17.60	25.90	17.00	5.10	1.55
Clay	27.60	21.20	4.60	16.70	1.50

Table 2. Summary of model test conditions

Types	XCC pile		Circular pile	
Section size	Diameter, a (m)	0.530	Diameter, R (m)	0.426
	Distance of arc, b (m)	0.110		
	Open arc, θ (°)	90		
Pile length, L (m)	5.0		5.0	
Cross-section area, A (m^2)	0.1425		0.1425	
Pile perimeter, C (m)	1.759		1.338	
Pile modulus, E (GPa)	28.5		28.5	
Moment of inertia, I (cm^4)	186430.6		161580.0	
Loading types	Compressive		Compressive	
	Uplift		Uplift	
	Lateral		Lateral	

The dimension of XCC pile constructed in the test facility is as follows: 5.0 m in length (L), 0.53 m in the diameter of outsourcing (a), 0.11 m in the spacing of two open arcs (b), and 90° in angle of open arc (θ). The reinforcement cage of the XCC pile is made of four reinforcing bars, with 12 mm in diameter and 0.35 m in the distance between the opposite reinforcing bars. The 28-day compressive strength of model pile concrete is equal to 28.5 GPa (JGJ94). Reinforcement sister bars were attached to the reinforcing bars, earth pressure cells were laid on pile tip and the surrounding soils, respectively. During the load tests, the total load applied to the pile head was measured by a load cell placed on the pile head, while the axial force along pile depth was calculated from the attached sister bars. The soil pressures were measured by the earth pressure cells, while the settlement of the pile head was recorded by two LVDTs installed symmetrically at the pile head. Data from the load cells and LVDTs during the load test were captured by a data acquisition system.

In order to perform a comparative analysis between the XCC pile and the circular section pile, a typical circular pile was also constructed and tested in the test facility. The dimension of the circular section pile is as follows: 5.0 m in length (L) and 0.426 m in diameter (R). The cross section area of the circular pile is equal to 0.1425 m^2 which is the same as that of XCC pile.

However, the perimeter of the circular pile is 1.338 m, which is smaller than that of the XCC pile of 1.759 m. Thus, with the same cross section area, the pile-soil interface contact area of the XCC pile is 31.5 % more than that of the circular pile.

4.2 *Analysis of Test Results and Discussions*

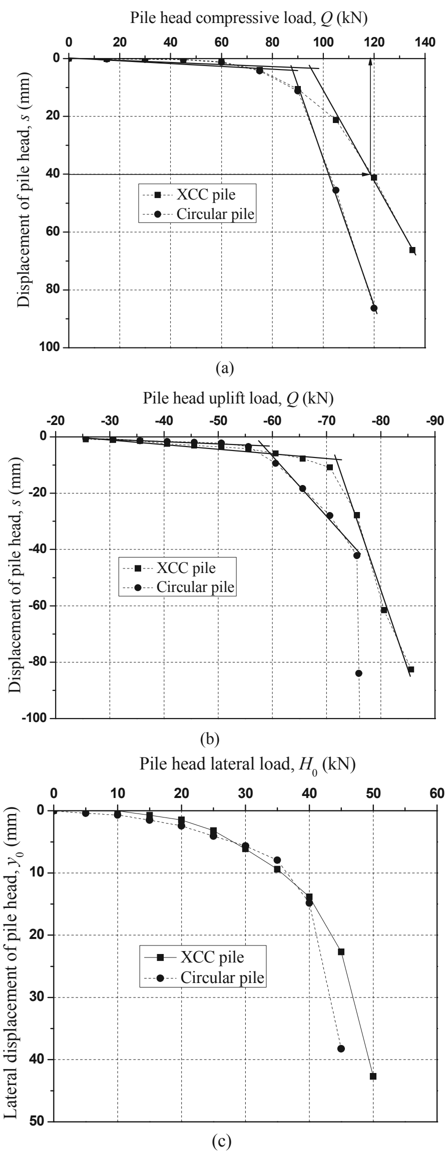

Figure 2. The curves of load versus displacement: (a) compressive load-displacement; (b) uplift load-displacement; (c) lateral load-displacement.

Fig. 2(a) shows load-displacement curves of the XCC pile and the circular section pile at the pile head. The ultimate compressive load-carrying capacity of the circular pile and XCC pile is equal to 90 kN, and 111 kN, respectively. The ultimate compressive capacity was improved nearly 24.0 % by changing the pile cross section from common circular section to X-section when the same amount of concrete volume was used. Fig. 2(b) shows the load-displacement curves under uplift load for the two different pile sections. The uplift capacity of XCC pile and circular pile was found to be -70.6 kN and -56.1 kN, respectively. The ultimate uplift capacity was improved nearly 25.8 % by changing the pile cross section from a circular section to an X-section for the same amount of concrete volume used. The test result of the lateral load versus lateral deflection at pile head is plotted in Fig. 2(c) for two different pile sections. The lateral H_0-y_0 curve of XCC pile is similar with that of circular pile. For the same lateral capacity, the amount of concrete volume used in a XCC pile is about 6.9 % less than in a circular pile.

5 FIELD TEST CASE STUDY

5.1 *Summary of Field Test Conditions*

The test site locates at north bridge of Nanjing city, where the landform is Yangtze River floodplain. By geological exploration, and laboratory soil test, the physical and mechanical parameters and distribution of soil layers are shown in Table 3.

Table 3. The soil layers and soil parameters in field test site

Soil symbol	Name	Depth *h* (m)	Water content *w* (%)	Unit weight *γ* (kN/m^3)	Modulus E_s (MPa)	Void ratio *e*
□	Filled back soil	0.20				
□$_2$	Mucky silty clay	1.30	38.60	17.60	3.50	1.11
□$_{2A}$	Silty sand	1.00	25.30	19.20	10.77	0.70
□$_2$	Mucky silty clay	1.50	38.60	17.60	3.50	1.11
□$_{2B}$	Silty sand	1.80	26.10	19.30	8.00	0.71
□$_2$	Mucky silty clay	2.30	38.60	17.60	3.50	1.11
□$_3$	Fine sand	9.40	26.30	18.90	11.83	0.76

The pile layout in Fig. 3 shows that the piles distribute as equilateral triangles, and the distances between two adjacent piles for single pile test and 2×2 pile groups test equal 1.85 m, and 1.80 m, respectively. In static loading tests of 2×2 pile group composite foundation, the loading plates are rhombic with side length of 3.6 m, which covers four piles. A layer of gravel cushion with the thickness of 30 cm is paved between pile top and loading plate. During the load tests, the total load applied to the loading plate was measured by a load cell placed on the loading plate, the axial force of pile shaft along pile depth was measured by reinforcement stress meters, the soil pressures and pile head pressures were measured by earth pressure cells, and settlement of the pile head was recorded by two LVDTs installed symmetrically at the loading plate. Data from the load cells and LVDTs during the load test were captured by a data acquisition system.

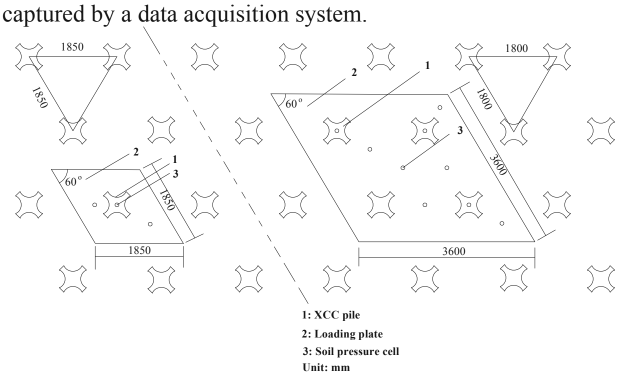

Figure 3. The instrument arrangements of XCC pile composite foundation.

5.2 *Analysis of Test Results and Discussions*

Fig. 4 shows the changes of axial forces result in the variations of side friction. When the load is relatively large, the side friction from the depth of -1 m to -2 m is negative, which is the typical characteristic of composite foundation. The load applied on loading plate causes the non-uniform settlement between the soil and piles. When the load is not very large, the differential settlement is in apparent, so the negative friction is extremely small. As the increase of the load step, the load shared by the piles also increases, and then the pile top tends to penetrate into the cushion, at the same time the soil subsidence occurs under the load shared by the soil, so the differential settlement is increscent. Because the compressibility of the soil is far greater than the pile, the settlement of the soil is far larger than the pile, as a result, the displacement of the soil is downward with respect to the pile and the downdrag is generated, that is the negative friction. The larger the load pressure, the greater the negative friction. The results in Fig. 4 also show that the location of neutral points is about -2 m, which is almost unchanged as the increase of the load.

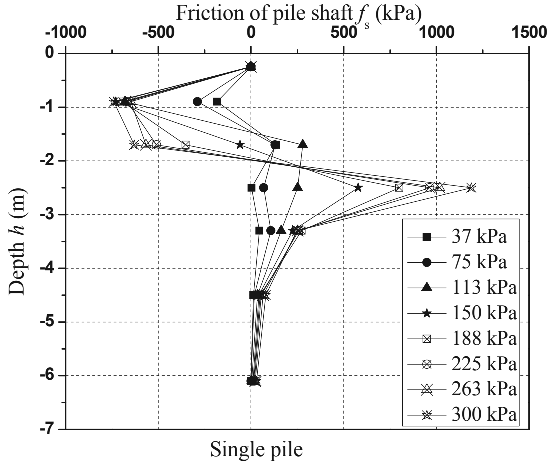

Figure 4. The distributions of friction of pile shaft along pile depth under different vertical load.

6 SUMMARY AND CONCLUSIONS

Based on large-scale load tests and field test of a XCC pile carried out in this paper, the following conclusions may be drawn.

(1) Regarding the contact area of pile-soil interface and EI of piles, XCC piles can increase these values in comparison to circular piles for the same amount of concrete volume used. The large-scale test in a load testing facility indicated that load carrying capacity of XCC pile exhibit a slightly higher capacity than circular pile when the same amount of concrete volume was used. Under the same working load level, XCC pile can be constructed with less concrete volume and exhibits smaller settlement when compared to the circular piles.

(2) The X cross section type offers a more reasonable section form as compared with other traditional pile sections from on the standpoint of offering contact areas of pile-soil interface and lateral stiffness. The contact areas of pile-soil interface can be improved obviously without the increasing of concrete consumption. XCC pile is also an economic environment new pile type. With less concrete usage can get the same treatment effect. In this case study, the maximum values of axial force of pile shaft is located on the -2 m deep, the location of neutral points is about -2 m of pile depth.

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