A hybrid method of deep foundation construction in soft soils

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ABSTRACT
A new construction method for deep foundations in soft soils, which is termed as "cast-in-place tubular (pipe) pile" (denoted as CTP or PCC pile) is described in this paper. The vertical and lateral bearing capacity calculation method for CTP/PCC pile using the SHAFT *plus* 5.0 and LPILE *plus* 5.0 programs is proposed. Two case studies on CTP/PCC pile bearing capacity under vertical load or lateral load are described. Based on the comparisons between the measured and calculated results, it appears that the suggested calculation methods can be sued for design and analysis. It is also shown that CTP/PCC pile could be a cost-effective pile due to the reduced amount of concrete needed for casting the pile.

RÉSUMÉ
Este artículopresenta la descripción de unnuevométodo de construcciónparacimentacionesprofundas en suelosblandosdenominado "Moldeado in situ de pilote tubular (CTP o PCC porsussiglas en inglés)". El cálculo de la capacidadportante vertical y lateralparapilotes CTP/PCCmediante el usode los programas SHAFT *plus* 5.0 y LPILE *plus* 5.0 espropuesto. Dos casos de estudiosobrecapacidadportante de pilotesCTP/PCC bajocarga vertical o lateral son presentados. La comparación entre los resultadosmedidos y calculadossugiereque los métodos de cálculopresentadospuedenserusados con propósitos dediseño y análisis. El estudioigualmentemuestraque el piloteCTP/PCC podríarepresentarunaalterantivacostoefectivadebido a la reducción en la cantidad de concretonecesariaparasumoldeado.

1 INTRODUCTION

Current methods of deep foundation constructions are driven piles and drilled shafts. Driven piles are typically for piles size in the range of 30 to 40 cm (12 to 16 inches) in equivalent diameters, while drilled shafts are for larger diameters, typically ranging from 61 to 152 cm (24 to 60 inches). Each method offers advantages for certain applications, but also presents some construction induced problems. For example, driven piles may cause ground vibration, noise, and becomes expensive when the size of the pile becomes very large. Drilled shafts construction in soft soils may need to use casing, drilling slurry, and could create a large amount of spoils to be disposed of.

The deep foundation is constructed with a hybrid method utilizing a vibratory hammer to drive double steel casing, fitted with a ring shaped pile shoe, into the desired depth; the annulus space between the double steel casing is subsequently filled with concrete and steel cage while gradually extracting the casing. The foundation formed in such way is termed as "cast-in-place tubular (pipe) piles" (referred to as CTP or PCC pile), which can be as large as 90 to 140 cm (36 to 54 inches) in outside diameter and 20 to 25 cm (8 to 10 inches) in pile thickness. The CTP/PCC piles minimize the construction problems mentioned for driven piles or drilled shafts, while offering superior geotechnical resistance (both lateral and vertical) with the use of a small amount of concrete materials. The application of PCC pile supported embankment on soft clays (one of accelerated embankment construction methods on soft clays) is elucidated with a comparison with other types of piles. PCC pile-supported embankment is one of economical efficiency soft ground treatment methods with low area ratio (<10 %) was reported by Liu et al. (2007). The installation effects of PCC pile driving was carried out by Xu et al. (2006), and Liu et al. (2009). The reduced use of concrete materials in tubular piles, for achieving similar geotechnical resistances as from driven piles or drilled shafts, means that the hybrid method of deep foundation construction offers a more sustainable and greener solution than conventional deep foundation construction methods.

In this paper, a new construction method for deep foundations in soft soils will be described. The vertical and lateral bearing capacity calculation method for CTP/PCC pile complying with ASCE specification was built. Then, two cases studies on CTP/PCC pile bearing capacity under vertical load or lateral load were described, and calculation method basing on SHAFT plus 5.0 (Reese et al. 2001) or LPILE plus 5.0 (Reese et al. 2004) were analyzed and discussed.

2 CONSTRUCTION METHODS FOR CTP AND PCC PILE

A twin-tube casting with precast pile shoe or valve pile tip is driven into the soft ground to the desired depth by the vibratory force from a hammer sitting on the top of casing. Circular steel reinforcement cage is placed, and concrete is poured into the annular borehole after the soil has been extracted from the casing. A tubular (pipe) pile is formed after the casing is totally extracted from the ground, steel reinforcement cage and concrete is placed inside the annular borehole. To facilitate installation, the inner and outer tubes are staggered to form a cutting edge of 30°; valve pile tip is closed when driving, and separated when excavating. CTP/PCC pile, which is belongs to low displacement pile, is continuously cast-in-situ and installed with high frequency vibration. The soils are mainly confined with CTP/PCC pile and with some saturated clay being squeezed out from the top of piles when tube driving. Thus the completeness and density of concrete and quality control is considerably good with high speed of construction. In the meantime, this overcomes the shortcomings of drilled shafts or precast driven piles soil pushing out effects, and thus reduce the foundation swelling or expansion effects. The CTP/PCC pile installation sequences are shown in Figure 1. The tubular (pipe) pile has a large contact surfaces with soil, shaft friction develops along both the inner and outer surfaces of CTP/PCC pile, which lends higher bearing capacity. In the other ways, when large-diameter piles with soils inside are used, larger pile spacing can also be used, the total number of piles and the usage of concrete can then be reduced.

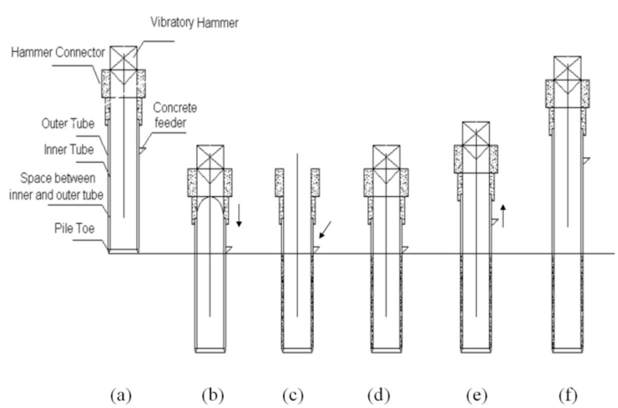

Figure 1. CTP/PCC pile installation sequences: (a) positioning casing; (b) driving casing; (c) placing steel gage and pouring concrete; (d) vibrating casing; (e) extracting casing; (f) completing of the pile

3 CALCULATION METHOD

3.1 CTP/PCC Piles under Vertical Load

The alpha (α) method is used to calculate the vertical bearing capacity of CTP/PCC piles in cohesion soils. The values of α was assumed to be zero from ground surface to depth along CTP/PCC pile of 1.5 m, and bottom one diameter of the CTP/PCC pile. For all other points along the sides of the CTP/PCC pile, the values of α were chosen as shown in Figure 2. The unit end bearing f_{sb} for CTP/PCC pile in saturated cohesion soils were also shown in Figure 2.

$$f_{sn} = \alpha (S_u)_s$$

α is shown in Figure.

$$f_{sb} = 0.83 N_c^* (S_u)_b$$

N_c^* is given by SHAFT ($N_c^* = 6.5 - 9.0$)

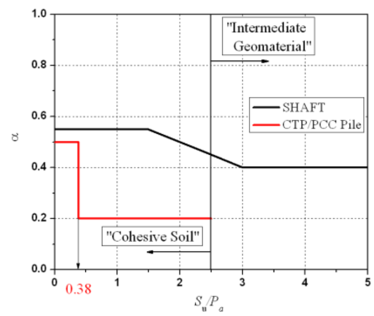

Figure 2. The unit side and end bearing of CTP/PCC pile in cohesion soils

3.2 CTP/PCC Piles under Lateral Load

The value of modified modulus of CTP/PCC pile is obtained by modulus of pile multiplied by cross-section area of pipe pile plus modulus of soils multiplied by cross-section area of pile core soils, then these divided by total areas of pipe pile and pile core soils, which were shown in Figure 3.

$$E_{\text{combined}} = \frac{E_c A_c + E_s A_s}{A_c + A_s}$$

$$A_{\text{combined}} = A_c + A_s = \frac{\pi D_{\text{out}}^2}{4}$$

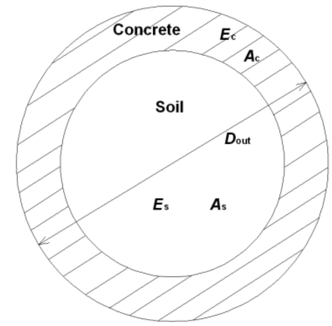

Figure 3. The modified modulus and cross-section areas of CTP/PCC pile

4 CASE STUDIES

Two cases with CTP/PCC pile static load tests under vertical load, and lateral load, respectively, are used for bearing capacities performance calculation and discussion.

4.1 Shanghai North Central Expressway Embankment Project

4.1.1 Field test and calculation parameters description

Shanghai north central expressway is located in the Western suburbs of Shanghai, China. The maximum depth of soft soils reaches 18 m along the expressway embankment. The backfill height is 5.0 m. CTP supported embankment was explored to improve the soft ground of bridgehead. CTP (1.0 m out-diameters, and 120 mm wall thickness) with 6 m～15 m lengths, 3.5 m pile spacing in horizontal (vertical road), and 3.0 m pile spacing in vertical (along road) were used in this filed. The concrete

Table 1. Soil physical and mechanical index properties at Shanghai north central expressway embankment.

No	Soil Name	Thickness (m)	Unit Weight (kN/m^3)	Void ratio	Compression Modulus (MPa)	UU Test	
						c_u (kPa)	φ_u (°)
2	Mud Clay	1.5	19.60	0.67	5.94	26.1	14.5
4	Mud Clay	10.0	16.46	1.50	1.96	11.6	10.7
6	Silty Clay	3.5	19.31	0.74	7.95	45.2	15.9
7	Silty Clay	4.9	18.03	0.96	10.4	28.5	28.5
8-1	Silty Clay	14.9	17.74	1.08	4.16	16.3	15.3
8-2	Silty Clay with Silty Sand	14.8	17.93	0.99	6.97	23.2	20.4

Table 2. The undrained shear strength results for each divided soil layers at Shanghai north central expressway embankment.

No	Soil Name	Thickness (m)	K_0	K_a	K_{choose}	Undrained confined strength, S_u (kPa)
2	Mud Clay	1.5	0.75	0.60	0.68	29.31
4	Mud Clay	3.3	0.81	0.69	0.75	20.44
		3.3	0.81	0.69	0.75	29.69
		3.4	0.81	0.69	0.75	39.09
6	Silty Clay	3.5	0.73	0.57	0.65	105.78
7	Silty Clay	2.4	0.52	0.35	0.44	147.54
		2.5	0.52	0.35	0.44	154.52
8-1	Silty Clay	2.9	0.74	0.58	0.66	94.21
		3.0	0.74	0.58	0.66	106.40
		3.0	0.74	0.58	0.66	118.80
		3.0	0.74	0.58	0.66	131.20
		3.0	0.74	0.58	0.66	143.60
8-2	Silty Clay with Silty Sand	2.8	0.65	0.48	0.57	205.18
		3.0	0.65	0.48	0.57	220.84
		3.0	0.65	0.48	0.57	237.04
		3.0	0.65	0.48	0.57	253.24
		3.0	0.65	0.48	0.57	269.44

grade of cast-in-place pile is C15, and 22 GPa elastic modulus of CTP was recommended for calculation. Based on Chinese code, the filed static load test were carried out for 15 m length CTP. The site physical and mechanical index properties are shown in Table 1. The calculated results of undrained shear strength are shown in Table 2.

4.1.2 Comparative analysis on SHAFT calculation and field test results

The predicted load-displacement (Q-s) curves results at the CTP/PCC pile head are compared with the measured results in Figure 4. In general, a relatively good agreement between the measured and the predicted can be observed. Although there is a small discrepancy between the two curves at the same load levels, the predicted displacement are nearly with the measured values.

4.2 Hangzhou～Qiandaohu Highway Embankment Project

4.2.1 Field test and calucation parameters description

Hangzhou～Qiandaohu highway project is one of Key projects in Zhejiang Province, which is located in the north of Zhejiang province, China. The total length of the highway is about 120 km, and the width of embankment is about 26 m. The designed driving speed is 100 km/h.

Table 3. Soil physical and mechanical index properties at Hangzhou～Qiandaohu road, Zhejiang Province, China.

Materials	Thickness (m)	Water Content (%)	Unit Weight (kN/m^3)	Compression Modulus (MPa)	UU Test	
					c_u (kPa)	φ_u (°)
Silty Clay	1.60	32.70	18.90	8.89	9.00	28.50
Mud Clay	3.85	27.60	19.30	11.62	5.00	30.50
Clay	4.80	28.50	19.50	10.80	3.50	31.50
Silty Sand	1.30	34.20	18.90	7.67	5.00	23.50
Silty Clay	8.70	45.20	17.60	2.60	16.80	12.00
Silty Clay	6.00	29.60	17.70	3.32	24.70	13.50
Clay	2.50	26.20	20.10	5.79	38.80	18.20

Table 4. Input data of soil physical and mechanical index properties for Hangzhou～Qiandaohu road embankment case.

Materials	Thickness (m)	Depth (m)	Effective unit Weight (kN/m^3)	Lateral earth pressure coefficient at rest	Horizontal effective stress (kPa)	Horizontal total stress (kPa)	UU test Undrained confined strength (kPa)
Silty Clay	1.60	0.80	8.90	0.52	3.70	11.70	15.35
Mud Clay	1.92	1.76	9.30	0.49	8.02	25.62	26.95
	1.93	3.69	9.30	0.49	16.79	53.64	43.46
Clay	2.40	5.85	9.50	0.48	26.68	85.18	62.83
	2.40	8.25	9.50	0.48	37.62	120.12	84.25
Silty Sand	1.30	10.10	8.90	0.6	53.93	154.93	77.70
Silty Clay	2.10	11.80	7.60	0.79	70.85	188.85	59.66
	2.20	13.95	7.60	0.79	83.76	223.26	66.98
	2.20	16.15	7.60	0.79	96.96	258.46	74.46
	2.20	18.35	7.60	0.79	110.17	293.67	81.94
Silty Clay	2.00	20.45	7.70	0.77	121.25	325.75	105.96
	2.00	22.45	7.70	0.77	133.11	357.61	113.61
	2.00	24.45	7.70	0.77	144.96	389.46	121.26
Clay	2.50	26.70	10.10	0.69	186.07	453.07	192.23

Most of the embankments were constructed over deep soft soils with high underground water table. Most of soft soils are saturated mud clay mixed with silt sand. PCC pile-supported embankment was explored to improve the soft ground beside bridgehead (Westlake section, F section on C ramp). PCC piles with 11 m – 20 m of length, 1.0 m of out-diameter, and 120 mm of wall thickness were used for soft ground treatment, in which 20 m length piles are used on the central of embankment, and 11 m length piles are used on the edge of embankment. The pile spacing is between 3.5 m and 4.0 m. The concrete grade of cast-in-place pile is C20, upper 6 m length are reinforced by steel gages. The reinforcement cage is made of 8Φ16 main steels, and Φ6 @ 250 stirrups. Based on China pile foundation code (JGJ94-2008) test criteria, one filed cyclic lateral load test, and one static lateral load test for 11 m length PCC pile were carried out. For cyclic loading, on each step, 4 mins constant load keeping after loading, the deflections and soil pressures are observed and recorded; then unload to zero, and read the residual displacement after 2 mins unloading; one cycle is finished till now; observations for 5 times cycles are taken for each load grade. The site physical and mechanical index properties are shown in Table 3. The calculated results of undrained shear strength are shown in Table 4.

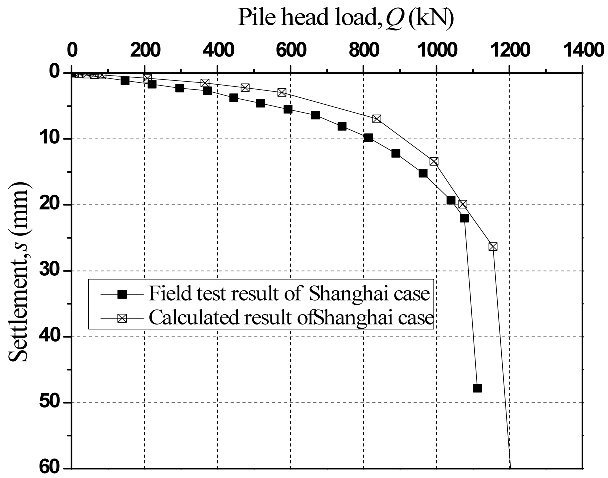

Figure 4. *Q-s* curves comparison of proposed calculation and field test results

4.2.2 Comparative analysis on LPILE calculation and field test results

The calculations with LPILE software on the lateral load versus pile top deflection (H_0-y_0 curves) results are compared with those of measured results in Figure 5. In general, a relatively good agreement between the calculated and the measured can be observed, especially for the cyclic load test case. It shows the comparative curves of static lateral load versus pile top deflection. Although there is a small discrepancy between the two curves at the same load levels, the calculated deflections are nearly with the measured values. In particular, the results of pile top deflection of field test and LPILE calculated under 130 kN static lateral load equal 8.22 mm, and 8.07 mm, respectively, which difference ratio is about 1.87 %.

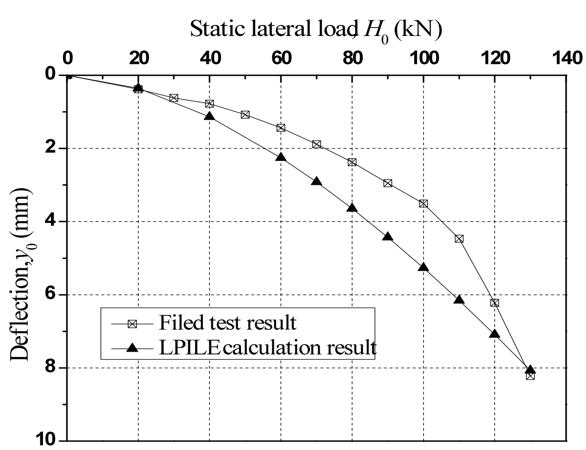

Figure 5. H_0-y_0 curves comparison of proposed calculation and field test results

5 SUMMARY AND CONCLUSIONS

In this paper, a brief introduction of CTP and PCC pile construction methods is described. A calculation method for CTP/PCC pile is developed in this paper that can be used in conjunction with SHAFT and LPILE computer analysis program to predict bearing capacities of the CTP/PCC pile in cohesive soils under the applied vertical loads, and lateral loads, respectively. Evaluations based on comparisons between the predicted and measured responses of several full-scale static load tests have shown the proposed approach for determining the ultimate bearing capacity of CTP/PCC pile. The results of this paper can provide design and calculation guide for practical CTP/PCC pile under vertical load in United States.

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