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Field load tests on plastic tube cast-in-place concrete piles

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An instrumented axial load test programme was conducted to study the load transfer behaviour of plastic tube cast-in-place concrete piles (TC piles), which are increasingly being used for support of embankments over soft ground in China. Additionally, in order to enhance the bearing properties of TC piles, the effects of shaft pre-grouting and increasing the diameter of the pile were investigated through load tests. Grouting was found to increase the capacity by 8–20%, while settlement decreased by 20–36%. Additionally, increasing the diameter from 16 to 20 cm resulted in a 10–17% decrease in capacity, due to the accompanying decrease in pile length to accommodate the capabilities of the available construction equipment. Also, increasing the diameter increased settlement by 14–33%. The effect of the pile set-up was investigated, and the capacity was increased by 20%, 8% and 11% for TC piles, gravity-grouted piles and enlarged-diameter piles for axial load tests conducted after 105 d relative to tests conducted after 24 d. In addition, three calculation models of single-pile settlement were evaluated with respect to predictions made of the bearing capacity and settlement.

Notation

c_h	horizontal coefficient of consolidation
c_v	vertical coefficient of consolidation
D_b	pile base diameter
D_s	pile shaft diameter
E	elastic modulus of the soil
E_b	average elastic modulus of the pile base soil
E_p	elastic modulus of a pile
E_s	average elastic modulus of the pile shaft soil
e_0	initial void ratio
f_s	cone sleeve friction
h_i	ith soil thickness
I_b	influence coefficient used in settlement calculation
I_P	plasticity index
I_s	influence coefficient used in settlement calculation
L	pile length
L_0	free or low-friction length of a pile
Q	pile top loading
Q_b	measured pile base resistance
q_c	cone bearing resistance
S	predicted settlement
S_m	measured settlement
s_u	undrained shear strength
w	water content
γ_{sat}	saturated unit weight
η	factor used in settlement calculation
λ	bias coefficient
v	Poisson ratio
ξ	factor used in settlement calculation
φ	friction angle

1. Introduction

In China, plastic tube cast-in-place concrete (TC) piles are increasingly being employed to support embankments on soft soils, particularly in the southeast coastal regions (Chen *et al.*, 2008, 2012, 2013; Wang *et al.*, 2011). TC piles consist of a post-grouted plastic corrugated tube attached to a pre-manufactured reinforced concrete base with a diameter larger than that of the tube. TC piles typically employ 3 mm thick, 160 mm outer diameter by 4 m long tubes that are joined together using glued tube joints. The TC pile is constructed as follows (Figure 1). First, the pre-manufactured base is attached to the corrugated plastic tube. Second, the plastic tube is inserted into a temporary steel casing by way of a hook, pulley and rope, and the base is attached to the casing. Third, the casing, plastic tube and base are raised and positioned above the location where the pile

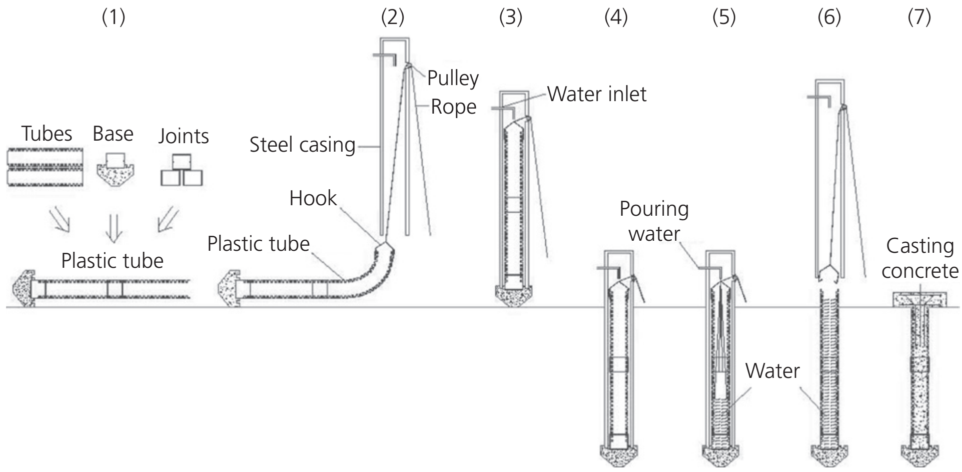

Figure 1. Construction process of a TC pile

is to be inserted. Fourth, the casing is jacked down to the desired depth or resistance using suitable equipment (e.g. an excavator). Sometimes, a vibrator is employed to aid the jacking. Fifth, the plastic tube is filled with water, to prevent it from collapsing due to earth stress upon subsequent removal of the casing. After many plastic tubes have been inserted into the ground, the water is pumped out of the tubes, one tube at a time, and immediately each tube is filled with plain concrete. A concrete pump truck with a long, flexible, 125 mm dia. hose is typically inserted into the plastic tube to guide the concrete. Finally, steel reinforcement is inserted in the top 3–5 m portion.

To improve the stiffness response to load of the TC pile installation, several approaches can be employed, such as (*a*) increasing the pile diameter (Fleming, 2009; Leung *et al.*, 2010); (*b*) enlarging the pile base (Fleming, 1993); (*c*) adding enlarged protrusions along the pile shaft, known in China as squeezed branches (Gao *et al.*, 2007); (*d*) employing drill displacement techniques during shaft installation (Park *et al.*, 2012); and (*e*) post-grouting of the pile (Mullins *et al.*, 2006). For slender piles, post-grouting is most widely used to increase the stiffness response. Post-grouting can be divided into base post-grouting, shaft post-grouting and base-and-shaft post-grouting. Base post-grouting was first used in the Maracaibo Bridge piers located in Venezuela in 1958, and was widely employed in Europe between 1960 and 1990 (Bruce, 1986a, 1986b). Gouvenot and Gabiax (1975) first employed shaft post-grouting to increase the bearing capacity of a jacked steel pile by about 200% compared with that of the ungrouted pile. The technology was subsequently used in Finland (Stocker, 1983), Hong Kong (Littlechild *et al.*, 2000; Lui *et al.*, 1993) and Australia (Joer and Randolph, 1998), among other places. Post-grouting is usually employed for piles used to support high-rise buildings and major bridges. However, for the piles used in embankment support, reports of the use of post-grouting are scarce.

Two of the above-mentioned improvement methods have been investigated by the authors: (*a*) enlarging the transverse geometry of the TC pile (from 160 to 200 mm for the pile shaft, and from 300 to 400 mm for the pile base) to form a larger-diameter TC pile (LDTC pile), and (*b*) gravity grouting the void between the soil with a cementitious slurry during extraction of the casing to form a shaft grouted TC pile (SGTC pile). Grouting is achieved using a single grouting pipe attached along the steel casing, as shown in Figure 2(a). Cement slurry in Figure 2(b) is cast into the annulus between the plastic tube and the steel casing during withdrawal of the grouting pipe while simultaneously filling the plastic tube with water. Both the improved piles and the original TC pile are referred to as plastic tube piles in this paper.

Plastic tube piles are commonly used for ground improvement, which is different from the conventional use of driven or cast-in-place piles. In this study, the bearing properties of TC piles, LDTC piles and SGTC piles are inferred from instrumented field tests. Data on the load–settlement response, the axial load transfer, and the shaft and base resistances are presented for all types of TC pile systems. Finally, simplified calculation models are introduced for modelling the load–settlement of individual plastic tube piles.

2. Field test programme

2.1 Site conditions

The soil layers, groundwater level and variation in the cone resistance q_c and sleeve friction f_s with depth are shown in Figure 3. The properties of each soil layer obtained from laboratory tests are summarised in Table 1. In general, the subsurface soils are normally to slightly over-consolidated clays (over-consolidation ratio = 1–1·8), having a water content of 56% in the top 8 m, reducing to 25–30% in deeper layers. The undrained shear strength ranged from 10 to 30 kPa (200–625 psf).

2.2 Construction

Two each of 19 m-long TC and SGTC piles and 18 m-long LDTC piles were installed at a test site located in the northern

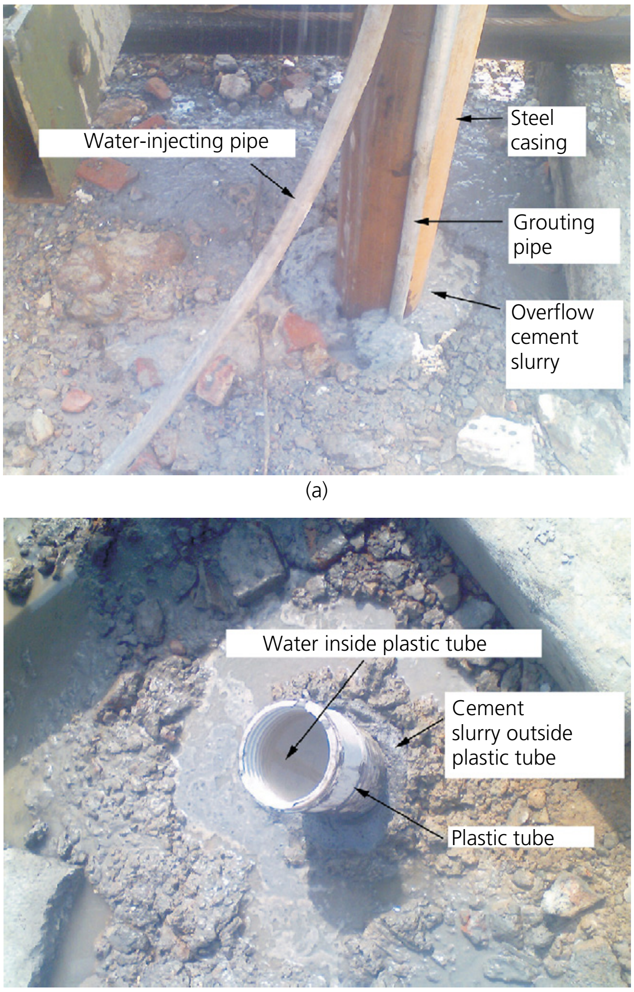

Figure 2. Pre-grouting of an SGTC pile: (a) grouting and water injecting; (b) completing the grouting and water injection

region of Zhejiang province in China. The dimensions and the construction details of all the tested piles are summarised in Table 2. The piles employed a 160 mm dia. plastic tube, resulting in a shaft diameter of 160 mm for the shaft and 300 mm for the base of TC piles. LDTC piles were 200 mm in diameter and 18 m long. The shorter length was required to accommodate the crowd capacity (downward thrust) of the available construction equipment. All pile bases were prefabricated using 30 MPa concrete, while pile shafts were poured using 25 MPa concrete. The water–cement ratio used for the shaft grouting of SGTC piles was 0·5. The arrangement of the tested piles is shown in Figure 4(a).

2.3 Instrumentation

Seven GXR-1010 vibrating-wire steel stress meters were installed in each of the six tested piles, as shown in Figure 4(b). The stress meters were installed at the centre of each pile. The stress meters were daisy-chained to each other with spacers made of rebar, welded in between successive stress meters, to achieve the required separation. Three steel centralisers were also attached to the spacers, to ensure that the stress meters were centred in the middle of the pile.

2.4 Static load test (SLT)

Each pile was load tested twice, in the axial direction, after 24 d and after 105 or 106 d (see Table 2). The 24 d SLT is referred to as the early-date SLT, and the 105 or 106 d SLT is referred to as the late-date bearing capacity. Tests were conducted according to the Chinese standard technical code (MOC, 2003) for the testing of building foundation piles (JGJ106-2003). In each SLT, the first increment of loading was 30 kN, followed by 15 kN increments. Under each increment of loading, the settlement of the pile head was recorded at least six times after 1, 5, 15, 30, 45 and 60 min of loading application. After a minimum 60 min load-holding, new increments were applied when the difference in settlement between the last two readings was less than 0·125 mm/15 min. The pile head settlements shown in Figure 5 are the settlements before the addition of a new load increment. Piles were unloaded in increments of 30 kN, with a 15 min wait between unloading increments. The readings from the stress meters inside each tested pile were taken simultaneously with the 15 min readings.

3. Analysis of the SLT results

3.1 Analysis of the load–settlement curves

The load–settlement curves of the three types of TC piles considered in this study are similar (see Figure 5). The curves exhibit linear deformation followed by plunging failure. The capacities corresponding to the method recommended by JGJ106-2003 for both early- and late-date SLTs are shown in Table 2 along with capacities computed according to Davisson (1972) and 10% of the pile diameter (Terzaghi, 1942). The ultimate bearing capacities of SGTC, TC and LDTC piles according to JGJ106-2003 were 180, 150 and 135 kN in the early-date SLT, and 195, 180 and 150 kN in the late-date SLT.

In the early-date SLT, the bearing capacities of SGTC piles were increased by 20% compared with those of TC piles. In the late-date SLT, SGTC piles exhibited approximately 8% more capacity than TC piles. Grouting widened the surface and enhanced the contact between the pile and the supporting length, but the increase in capacity is relatively small due to the low strength of the supporting soils, which are able to squeeze against the pile without the aid of grouting. This is consistent with using a low alpha value for the design of piles in weak clays (Peck *et al.*, 1974).

Grouting played a more important role in reducing pile settlement than for increasing capacity. When settlement is compared under the same applied load, SGTC piles typically exhibited approximately 20% less settlement than TC piles and 40% less settlement than LDTC piles for the early-date SLT and 36% less settlement than TC piles and 44% less settlement than LDTC piles for the late-date SLT (Table 3).

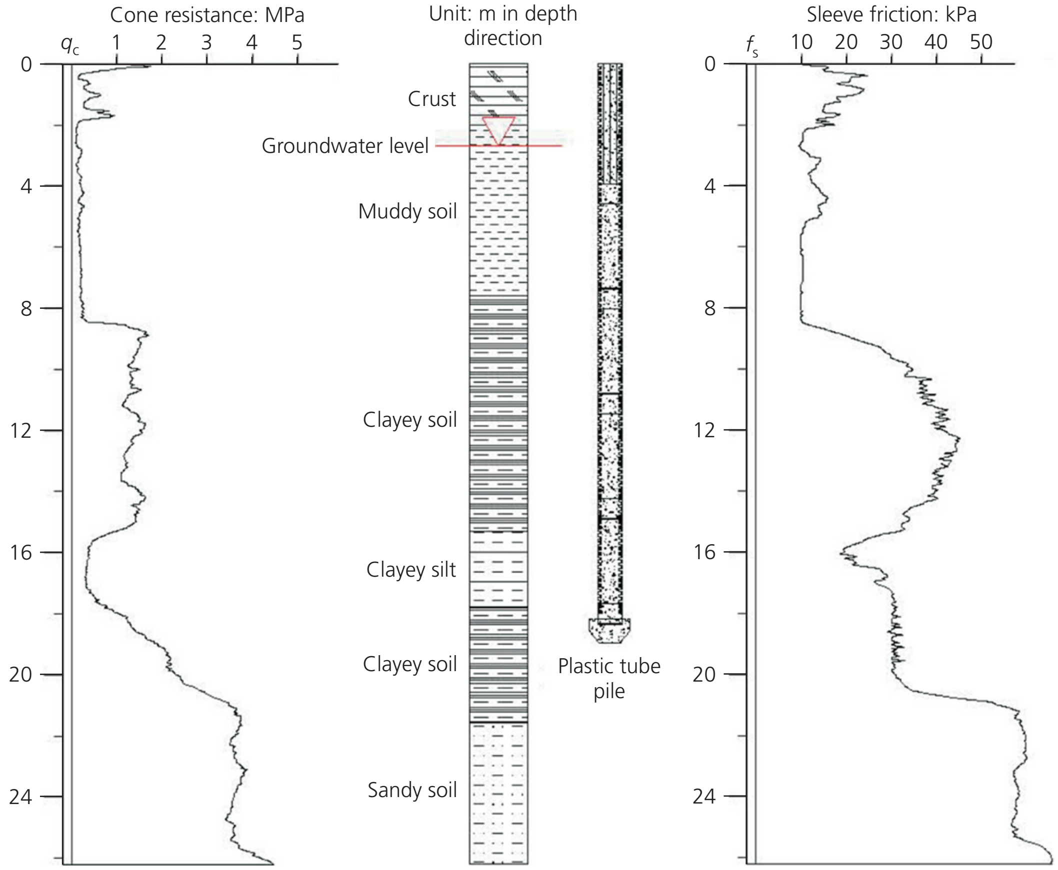

Figure 3. Cone penetration test results from a field test

	h_i: m	w: %	e_0	γ_{sat}: kN/m^3	I_P	E: MPa	s_u: kPa	c_v: m^2/d	c_h: m^2/d	φ: °
Crust	2·0	32·0	0·913	18·94	13·6	2·79	11·4	0·0183	0·0535	12·4
Soft clay	5·6	56·6	1·627	16·54	18·9	2·01	9·8	0·0100	0·0510	10·2
Clay 1	7·7	30·7	0·877	19·11	14·5	4·83	30·1	0·0013	0·0027	18·8
Clayey silt	2·5	29·4	0·826	19·36	13·2	3·03	18·2	0·0032	0·0029	16·2
Clay 2	3·8	24·8	0·708	20·01	10·1	6·18	24·3	0·0016	0·0023	15·1
Sand	5·2	24·6	0·666	20·01	—	8·34	—	—	—	—

Table 1. Soil properties in test site

As the transverse geometry of TC piles is enlarged, the bearing capacities of LDTC piles were reduced by 10% in the early-date SLT and 17% in the late-date SLT compared with those of TC piles. This is evidence that much of the capacity is derived from the final metre of the shaft length, because LDTC piles are 18 m long while TC piles are 19 m long.

All piles exhibited varying degrees of pile set-up. The bearing capacities of TC, SGTC and LDTC piles increased by approximately 20%, 8% and 11% in the 82 d period between the early- and late-date SLTs. The smaller increments for the SGTC pile set-up may be caused by acceleration of the pile–soil interaction by the shaft pre-grouting.

To sum up, the bearing capacity of a plastic tube pile was increased by approximately 8–20% and the settlement was reduced by 20–36% due to shaft pre-grouting. Enlarging the diameter was not effective in improving the pile performance because it was accompanied by a reduction in the pile length in order to accommodate the capabilities of the available construction equipment.

TC series	Shaft diameter: mm	Base diameter: mm	Pile length: m	Pile No.	Period between casting concrete and the SLT: d	Capacity (Davisson's criteria): kN	Incremental increase relative to the TC pile: %	Capacity (Terzaghi's method – 10% of the diameter): kN	Incremental increase relative to the TC pile: %	Capacity (China JGJ106-2003): kN	Incremental increase relative to the TC pile: %
SGTC	160/300	300	19·0	SGTC24	24	189	16	–	–	180	20
	160/300	300	19·0	SGTC105	105	206	10	–	–	195	8
TC	160	300	19·0	TC24	24	163	–	–	–	150	–
	160	300	19·0	TC105	105	188	–	191	–	180	–
LDTC	200	400	18·0	LDTC24	24	147	−10	–	–	135	−10
	200	400	18·0	LDTC106	106	164	−13	–	–	150	−17

Table 2. Pile properties, static load tests (SLTs) and total bearing capacities for each tested pile

3.2 Analysis of the axial load transfer

Load transfer along pile shafts under different loading stages for the plastic tube piles in the early-date and late-date SLTs is shown in Figure 6. It can be clearly seen that the axial loads along the pile shaft increase with increasing pile head loading, and decrease with the pile depth. The tendencies of the load transfer along the pile shafts for different plastic tube pile series are similar. All piles exhibit a region of little load transfer in the top one-quarter to one-third section. This region is followed by a region of rapid load transfer that extends to the bottom of the pile for the late-date SLT, but only to the three-quarters length point for the early-date SLT, with an inflection point emerging. However, there is typically no load transfer near the bottom of the pile for small load ranges. Finally, more load is transferred in end bearing than in skin friction in the late date SLT than in the early-date SLT. Also, tests on LDTC piles showed more load transfer in skin friction than tests on TC piles.

Load transfer is further explored in Figure 7, where the average rate of skin friction transfer is plotted against the pile head load for different stages of pile head loading. Each point on these six curves represents the average linear load transfer along the entire pile. The rates of average load transfers are similar for both the early-date SLT and the late-date SLT. Grouting resulted in an increase in the average rate of load transfer by approximately 20–30%, while increasing the diameter resulted in essentially no change in the average load transfer, with early-date tests exhibiting higher skin friction than late-date tests.

3.3 Analysis of the skin friction variation

Variations in the skin friction of the plastic tube piles with depth and pile head loading are shown in Figures 8(a) and 8(b) for the early-date SLT and the late-date SLT, respectively. Skin friction gradually mobilised as the pile head loading increased; and the maximum skin friction was located at approximately three-quarters of the pile length from the top. The distributions of the skin friction with depth for the three tested pile types can be summarised by the following observations.

- Grouting resulted in an increase in the average unit mobilised skin friction by approximately 35% and 30% in the early-date SLT and late-date SLT, respectively. In particular, skin friction in the clayey soil located at a depth of 7–16 m increased by 46% and 42% for the early-date SLT and the late date SLT, respectively. For the shallow weak clay layer located at a depth of 2–7 m, the skin friction increased by 81% and 55% for the early-date SLT and late-date SLT, respectively, due to grouting.
- The envelope areas resulting from the skin friction with depth curves are largest for SGTC piles and smallest for LDTC piles, with TC piles in between the two.
- The skin friction of SGTC and TC piles obtained in the late-date SLT was larger than that in the early-date SLT; however, this trend was not discernible for LDTC piles.

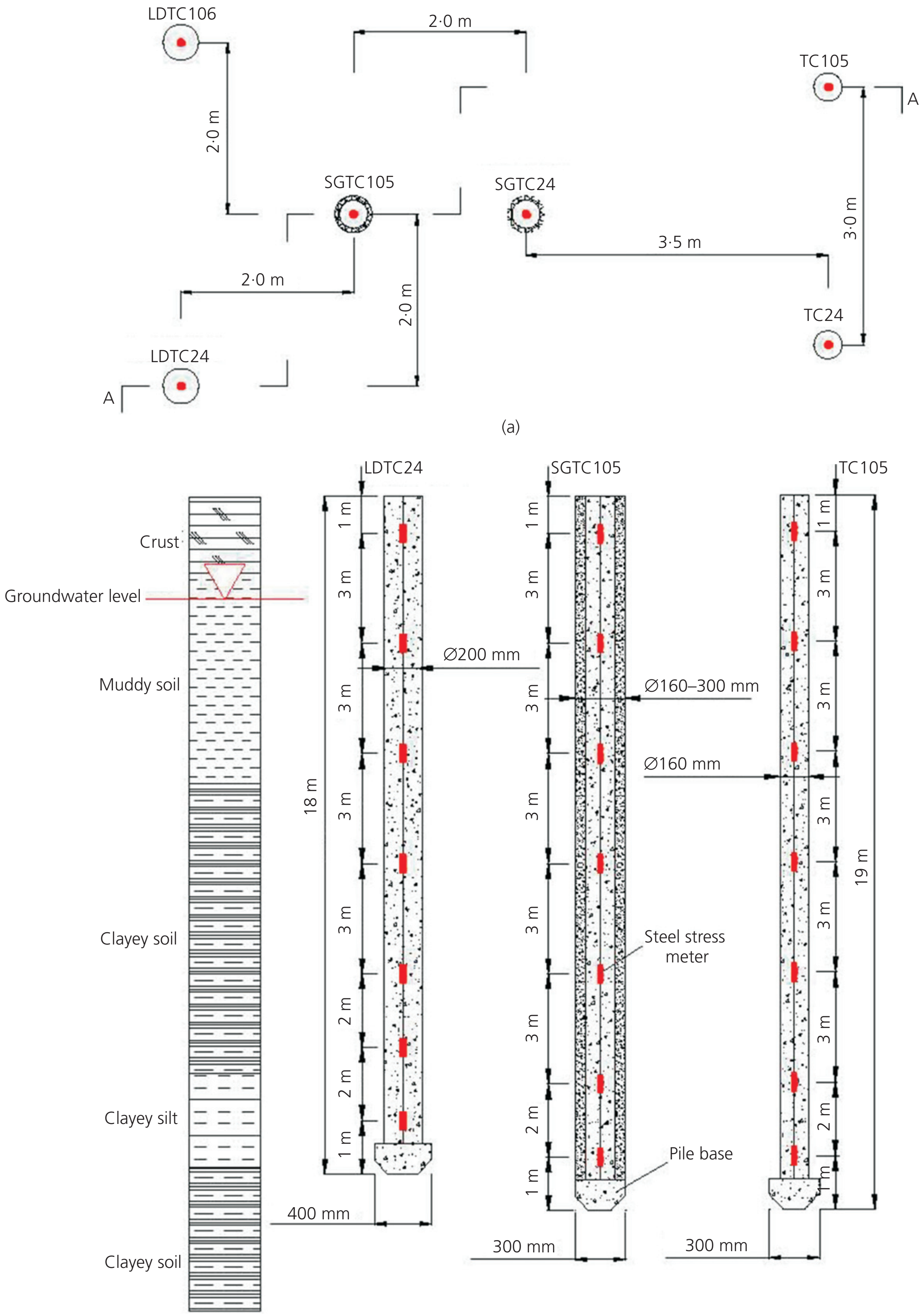

Figure 4. Installation position and instrumentation of each pile type: (a) layout of the piles; (b) arrangement of steel stress meters in the piles

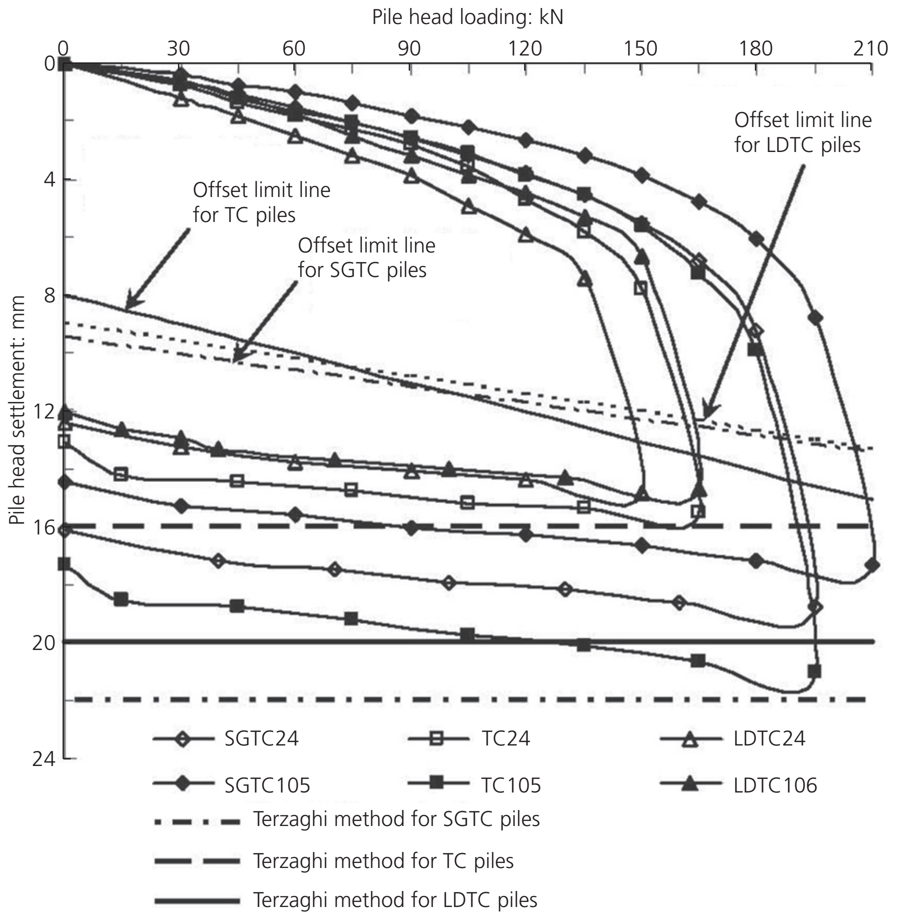

Figure 5. Load–settlement curves of each plastic tube pile type

		Pile head loadings: kN										Average
		30	45	60	75	90	105	120	135	150	165	
SGTC24 compared with	TC24	4	22	16	11	10	10	19	21	29	56	20
	LDTC24	41	43	38	36	34	35	36	38	63	—	40
SGTC105 compared with	TC105	35	40	40	33	30	30	31	30	31	35	36
	LDTC106	32	37	43	45	43	44	41	40	42	68	44

Table 3. Settlement reduction ratios (%) for the SGTC piles

- LDTC piles exhibited less unit skin friction than TC piles, which may have resulted from the increase in the excess pore water pressure due to pile jacking with pile diameter, as predicted by the cavity expansion theory. In addition, LDTC piles are expected to require more time to dissipate the installation pore pressure than conventional TC piles.

None of the piles were exhumed to check the actual location of the failure surface. The preceding analyses assumed that failure occurred at the plastic tube interface. For SGTC piles a non-uniform enlargement in the shaft diameter is plausible. Thus, shafts can vary between 160 mm (outer diameter of the plastic tube) and 180 mm (inner diameter of the steel casing). Considering mixing of the slurry with the subsoil, a diameter of 170 mm is possible, which would decrease the reported values of the skin friction by approximately 6% (170/160). This difference does not explain the marked increase in the skin friction observed due to gravity grouting.

3.4 Analysis of the base resistance ratio

The base resistance ratio, defined as the ratio of the tip resistance to the total applied load on the pile head (for each loading step in the SLT), is an important index in the

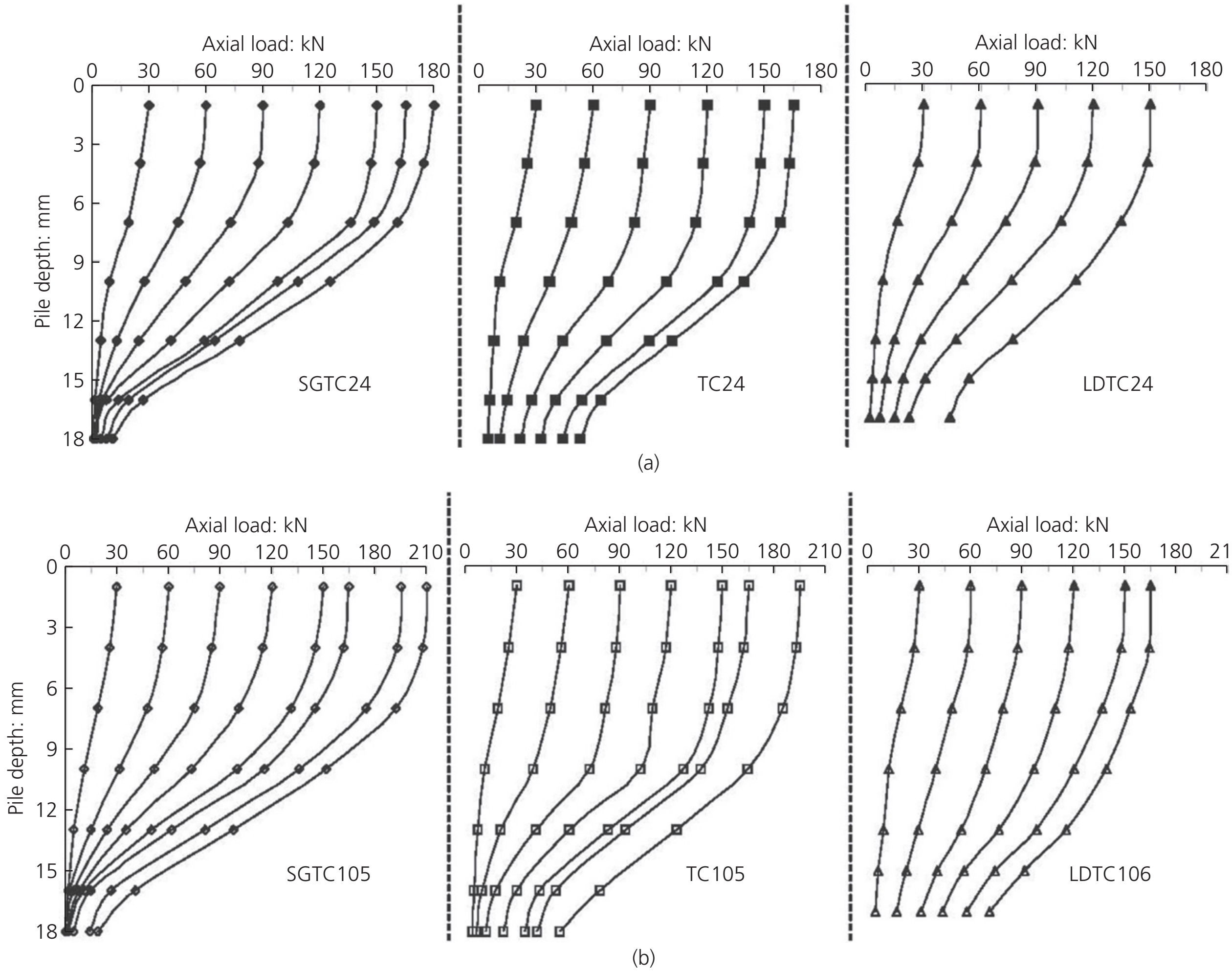

Figure 6. Variation in the axial load of each pile type with pile depth and load: (a) early-date SLT; (b) late-date SLT

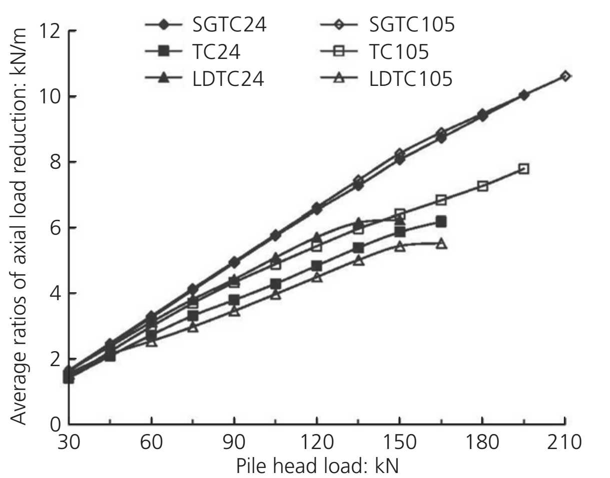

Figure 7. Variation in the average ratios of axial load reduction of each pile type with load

measurement of the mobilised degree of tip resistance in pile engineering (Fleming, 2009; Polous and Davis, 1980). The variation in the tip resistance ratios of the plastic tube piles with pile head loading are shown in Figure 9. The following trends can be discerned.

- LDTC piles exhibit the highest tip resistance ratio in both early-date and late-date SLTs. Under ultimate loading conditions, the maximum base resistance ratios obtained in the early-date and late-date SLTs for LDTC piles were 30% and 40%, respectively. In comparison, ratios of approximately 30% were observed for TC piles and 6–9% for SGTC piles.
- Typically, the base resistance ratio of the plastic tube piles increased with increasing pile head loading.
- The tip resistances of TC and LDTC piles were larger and mobilised earlier than those of SGTC piles. In fact, the tip resistance of SGTC piles represents less than 3% of the total bearing capacity at a pile head loading of less than 150 kN.

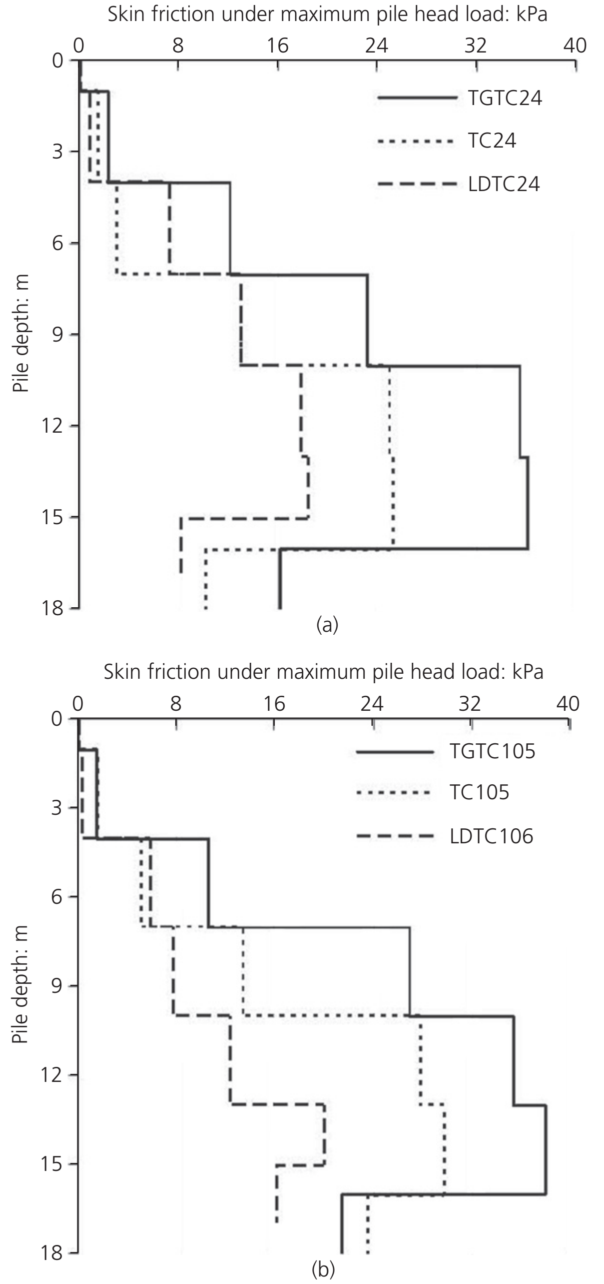

Figure 8. Variations in the skin friction of each pile type with pile depth under the maximum pile head load: (a) early-date SLT; (b) late-date SLT

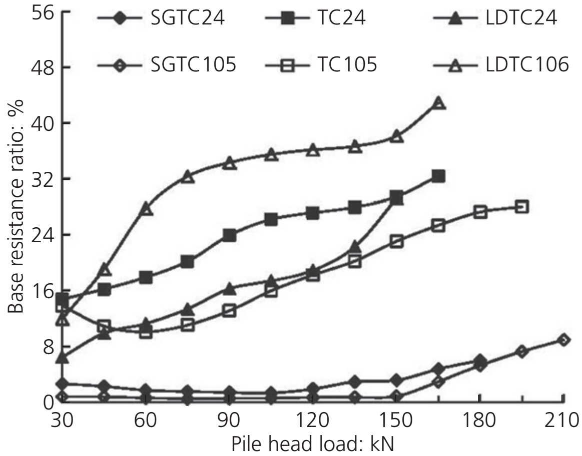

Figure 9. Variation in the end resistance ratio of each pile type with load

- The tip resistance ratios of SGTC and TC piles in the early-date SLT were greater than those in the late-date SLT, while the reverse tendency was observed for LDTC piles.

The theoretical base resistance ratio was computed using the elastic solution proposed by Randolph *et al.* (1994), and was found to range between 12% and 15% for the piles tested in this study. The instrumented load tests reported in this study suggest that the base resistance ratio depends on the TC pile diameter, the pile head loading and the shaft interface conditions. TC piles initially transferred more of the load in end bearing than anticipated according to Randolph *et al.* (1994); however, late-date TC piles exhibited behaviour consistent with the theoretical estimate, probably suggesting that the load transfer in skin friction improves with time, due to a variety of factors including concrete gaining more strength with time and dissipation of the pore pressure due to jacking of the casing. Grouted SGTC piles never reached the theoretical value over the entire loading range because grouting significantly improved the load transfer at the interface. Finally, LDTC piles exhibited a higher base resistance ratio, perhaps because more pore water pressure was generated due to pile jacking, as indicated by the cylindrical cavity expansion theory. Finally, Han and Ye (2006) measured a base resistance ratio of 8·7–12·5% for 0·15 m-dia., 8 m-long micropiles in Shanghai clays. The lower base resistance ratio is consistent with better quality control in micropiles (and SGTC piles) relative to conventional TC piles.

4. Settlement calculation models for a single plastic tube pile

The settlement of pile foundations in embankment engineering is often regarded as more critical compared with bearing capacity (Chen *et al.*, 2010; Han and Gabr, 2002; Liu *et al.*, 2007, 2012; Randolph, 1994). Therefore, it is vital to select the appropriate calculation models to predict single-pile settlement. Although the finite-element method has become an effective way to study pile–soil interaction, it is unlikely to be easily and conveniently applied in actual pile engineering practice due to its complexity and the requirement for numerous geotechnical parameters. Consequently, three simplified calculation models for estimating single-pile settlement were investigated in this paper.

In order to facilitate the settlement calculation for the three methods, the soil along the pile shaft and under the pile base was assumed to be uniform, homogeneous and isotropic; and the elastic moduli of soils along the pile shaft and under the pile base are represented by an average modulus. In order to quantify the prediction errors of each model, the bias coefficient λ, proposed by Shahin *et al.* (2005) and Zhang *et al.* (2008), was employed to assess the three models. The bias coefficient λ is expressed as

1. $$\lambda = S_{\mathrm{m}}/S$$

where S_{m} is the measured settlement and S is the predicted settlement. The calculation parameters required by the above three models are listed in Table 4. The settlement was computed for each loading step applied during the SLT. Undrained conditions were assumed during the SLT, and Poisson's ratio, υ, of the soil was taken as 0·5. The modulus of elasticity was defined as $E_{\mathrm{s}} = 1{\cdot}5q_{\mathrm{c}}$, where q_{c} is the tip resistance in the cone penetration test, according to the Chinese code (Engineering Geological Manual Editorial Committee, 2007). The average bias coefficients λ of each model for each pile are listed in Table 4. The three models employed are described below.

4.1 Vesic settlement model

The elastic method proposed by Vesic (1977), was employed, where the total settlement S under vertical loading is given as

2. $$S = \frac{4[Q_{\mathrm{b}} + 0{\cdot}5(Q - Q_{\mathrm{b}})]L}{\pi D_{\mathrm{s}}^2 E_{\mathrm{p}}} + \frac{4Q_{\mathrm{b}}}{\pi D_{\mathrm{b}} E_{\mathrm{b}}}(1-\upsilon^2)I_{\mathrm{b}} + \frac{4(Q - Q_{\mathrm{b}})}{\pi D_{\mathrm{s}} L}\frac{(1-\upsilon^2)]I_{\mathrm{s}}}{E_{\mathrm{s}}}$$

where Q_{b} is the measured pile base resistance, Q is the pile top loading, L is the pile length, D_{s} is the diameter of pile shaft, E_{p} is the elastic modulus of pile (taken as $2{\cdot}8 \times 10^7$ kPa), D_{b} is the pile base diameter, E_{b} is the elastic modulus of the soil under the pile base (see Table 4), v is Poisson's ratio, I_{b} is an influence factor (taken as 0·85), E_{s} is the average elastic modulus of the soil along the pile shaft (see Table 4) and I_{s} is an influence factor calculated by

3. $$I_{\mathrm{s}} = 2 + 0{\cdot}35\sqrt{L/D_{\mathrm{s}}}$$

The predicted settlements using Vesic (1977) for SGTC piles are consistent with the measured values, and its bias coefficients are relatively stable with the changing of loading stages and close to 1·0. However, the Vesic model overestimates the settlements of TC and LDTC piles, with bias coefficients ranging between 0·29 and 0·64.

4.2 Randolph and Wroth settlement model

The model based on pile–soil load transfer proposed by Randolph and Wroth (1978) is usually more appropriate for straight piles. However, Randolph and Wroth (1978) stated in their conclusion that 'special types of pile, such as partially sleeved or underreamed piles, may be analysed by appropriate modification of the relevant equations'; therefore, in this study the Randolph and Wroth settlement model was employed. The model is expressed as

4. $$S = \frac{4(1+\upsilon)Q}{E_{\mathrm{s}} D_{\mathrm{s}}} \times \frac{1 + \dfrac{4}{1-\upsilon}\dfrac{1}{\pi\eta}\dfrac{2L}{D_{\mathrm{s}}}\dfrac{\tanh\left[(2L/D_{\mathrm{s}})\sqrt{2/(\xi\eta)}\right]}{(2L/D_{\mathrm{s}})\sqrt{2/(\xi\eta)}}}{\dfrac{4}{1-\upsilon} + \dfrac{2\pi}{\xi}\dfrac{2L}{D_{\mathrm{s}}}\dfrac{\tanh\left[(2L/D_{\mathrm{s}})\sqrt{2/(\xi\eta)}\right]}{(2L/D_{\mathrm{s}})\sqrt{2/(\xi\eta)}}}$$

Pile No.	Pile shaft diameter, D_{s}: m	Pile base diameter, D_{b}: m	Pile length, L: m	Free or low friction length of the pile, L_0: m	Influence coefficients, I_{s}	Influence coefficients, I_{b}	Average bias coefficients		
							Fleming model	Randolph and Wroth model	Vesic model
SGTC24	0·30	0·30	19	4	4·8	0·85	2·88	1·06	1·07
TC24	0·16	0·30	19	4	5·8	0·85	2·26	0·86	0·29
LDTC24	0·20	0·40	18	4	5·3	0·85	2·69	1·17	0·64
SGTC105	0·30	0·30	19	4	4·8	0·85	2·08	0·80	0·88
TC105	0·16	0·30	19	4	5·8	0·85	2·91	0·82	0·33
LDTC106	0·20	0·40	18	4	5·3	0·85	1·24	0·90	0·30

$E_{\mathrm{p}} = 2{\cdot}8 \times 10^7$ kPa; $E_{\mathrm{b}} = 6{\cdot}18 \times 10^3$ kPa; $E_{\mathrm{s}} = 3{\cdot}77 \times 10^3$ kPa.

Table 4. Input parameters used for computing the single-pile settlement and the average bias coefficients for the three settlement models

where all terms are as defined previously, and the factors ξ and η are calculated by

$$\xi = \text{In}[5L/(1-v)/D_s] \quad (5)$$

$$\eta = 2(1+v)E_p/E_s \quad (6)$$

The Randolph and Wroth model predicted settlements that were comparable to the measured values (see Table 4). The predictions were best for SGTC and LDTC piles, while being slightly higher than those of TC piles. In addition, the bias coefficients of the Randolph and Wroth model remain relatively stable as pile head loading increases, averaging $\lambda = 0{\cdot}94$.

4.3 Fleming settlement model

Zhang *et al.* (2008) simplified the hyperbolic function originally proposed by Fleming (1992), where the settlement is expressed as

$$S = \frac{4(1+\upsilon)Q}{E_s D_s} / \left(\frac{4D_b E_b}{D_s(1-\upsilon)E_s} + \frac{4\pi(L-L_0)}{D_s} \right) \quad (7)$$

where L_0 is the free or low-friction length of pile. In the elastic stage, the measured settlements were approximately 2–6 times the predicted values. However, as the load–settlement approaches the plunging stage, the predicted values are more than 1·2 times the measured ones, and, correspondingly, the bias coefficients of the Fleming model are between 1·24 and 2·91, which shows that the estimated settlements of the Fleming model underestimate the settlement of plastic tube piles.

5. Practical relevance of the work

Plastic tube piles are employed when large numbers of inexpensive piles are required, such as for the ground improvement of weak soils. In this environment, TC piles are more economical compared with prefabricated or cast-in-place piles under comparable conditions: for example, assuming that the embankment height and pile penetration are constant. For TC piles, the usual spacing for 0·16 m-dia., 19 m-long TC piles is 1·5 m on centre, and the price of materials and installation is about \$5·5 per metre; therefore, the total cost of reinforcing a 1 m^2 zone is about \$46. In comparison, conventional 0·5 m-dia., 19 m-long cast-in-place piles are typically spaced 2·5 m on centre, and the price of materials and labour is about \$21 per metre; therefore, the total cost of reinforcing a 1 m^2 zone is about \$64. In addition to the cost savings, the smaller spacing is preferable for short embankments (height ≤ 2·5 m). Furthermore, the use of plastic tubes results in better control of the quality and the consumption of concrete. However, the use of an expanded pile toe can cause some loss of skin friction. Similarly, negative skin friction along the pile shaft is also reduced.

This study demonstrates that TC piles are viable for the support of working loads of the order of approximately 75–95 kN (8–10 ton). The study also demonstrates that pre-grouting is an efficient mechanism to increase the capacity and reduce settlement. On the other hand, increasing the diameter was not found to be an attractive alternative. Additionally, the settlement of plastic tube piles is underestimated by the Fleming model, and overestimated by the Vesic model. However, the Randolph and Wroth model agrees well with the measured settlement of plastic tube piles.

6. Conclusions

Instrumented load tests on plastic tube piles demonstrated that these piles are a viable option for the support of embankments, with ultimate load capacities in the range of 135–195 kN. The following conclusions can be drawn by examining the test results.

- All piles derive a majority of their capacity through skin friction, despite the construction methodology that involves extraction of a casing without filling the resulting gap, which may result in a poor bond between the pile and soil. This is believed to be possible due to the weak nature of the supporting clays, and is not necessarily a universal conclusion.
- Grouting resulted in an increase in the average unit mobilised skin friction by approximately 30–35%. Grouting also reduced the pile settlement by approximately 20% and 36% for the early-date SLT and the late-date SLT, respectively.
- Increasing the TC pile diameter was found to be impractical, because the increase resulted in the inability of the available construction equipment to jack the pile to the same depth as the unenlarged piles, resulting in piles with a somewhat lower capacity.
- All piles increased in strength as a result of pile set-up. However, the rate of increase was less for the grouted piles, with ungrouted piles gaining 20% in approximately 82 d, while grouted piles increased in capacity by 8% in the same period.
- Calibration of three simplified analytical model for single-pile settlement revealed that the predicted settlements using the Randolph and Wroth model agree well with the measured values for the plastic tube pile series.

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REFERENCES

Bruce DA (1986a) Enhancing the performance of large diameter piles by grouting (I). *Proceedings of the Institution of Civil Engineers – Ground Engineering* **19(4)**: 9–15.

Bruce DA (1986b) Enhancing the performance of large diameter piles by grouting (II). *Proceedings of the Institution of Civil Engineers – Ground Engineering* **19(5)**: 11–18.

Chen R, Xu Z, Chen Y, Ling D and Zhu B (2010) Field tests on pile-supported embankments over soft ground. *Journal of Geotechnical and Geoenvironmental Engineering* **136(6)**: 777–785.

Chen Y, Cao D, Wang X, Du H and Zhang T (2008) Field study of plastic tube cast-in-place concrete pile. *Journal of Central South University (Science and Technology)* **15(s2)**: 195–202.

Chen Y, Qi C, Wang X and Chen L (2012) Research on bearing performance of plastic tube cast-in-place single pile. *China Journal of Highway and Transport* **25(3)**: 51–59 (in Chinese).

Chen Y, Qi C, Xu H and Ng CWW (2013) Field test research on embankment supported by plastic tube cast-in-place concrete piles. *Geotechnical and Geological Engineering* **31(4)**: 1359–1368.

Davisson MT (1972) High capacity piles. *Proceedings of a Lecture Series on Innovations in Foundation Construction*. American Society of Civil Engineers, Chicago, IL, pp. 81–112.

Engineering Geological Manual Editorial Committee (2007) *Engineering Geology Manual*, 4th edn. China Architecture and Building Press, Beijing, China.

Fleming WGK (1992) A new method for single pile settlement prediction and analysis. *Géotechnique* **42(3)**: 411–425.

Fleming WGK (1993) The improvement of pile performance by base grouting. *Proceedings of the Institution of Civil Engineers – Civil Engineering* **97(2)**: 88–93.

Fleming WGK (2009) *Pile Engineering*, 3rd edn. Taylor and Francis, New York, NY, USA.

Gao X, Wang J and Zhu X (2007) Static load test and load transfer mechanism study of squeezed branch and plate pile in collapsible loess foundation. *Journal of Zhejiang University (Science)* **8(7)**: 1110–1117.

Gouvenot D and Gabiax FD (1975) A new foundation technique using piles sealed by concrete under high pressure. *Proceedings of the 7th Annual Offshore Technical Conference, Houston, TX, USA*, pp. 641–656.

Han J and Gabr M (2002) Numerical analysis of geosynthetic-reinforced and pile-supported earth platforms over soft soil. *Journal of Geotechnical and Geoenvironmental Engineering* **128(1)**: 44–53.

Han J and Ye SL (2006) A field study on behavior of micropiles under compression or tension. *Canadian Geotechnical Journal* **43(1)**: 19–29.

Joer HA and Randolph MF (1998) Capacity and model grouted piles in calcareous sediments. *Proceedings of 7th International Conference and Exhibition on Piling and Deep foundations, Vienna, Austria*.

Leung Y, Klar A and Soga K (2010) Theoretical study on pile length optimization of pile groups and piled rafts. *Journal of Geotechnical and Geoenvironmental Engineering* **136(2)**: 319–330.

Littlechild B, Plumbridge G, Hill S and Lee S (2000) Shaft grouting of deep foundations in Hong Kong. *New Procceedings of GeoDenver 2000: Technological and Design Developments in Deep Foundations, Denver, CO*. American Society of Civil Engineers, Chicago, IL, pp. 33–45.

Liu H, Ng C and Fei K (2007) Performance of a geogrid-reinforced and pile-supported highway embankment over soft clay: case study. *Journal of Geotechnical and Geoenvironmental Engineering* **133(12)**: 1483–1493.

Liu SY, Du YJ, Yi YL and Puppla A (2012) Investigations on performance of T-shaped deep mixed (TDM) soil-cement columns supported embankment over soft ground. *Journal of Geotechnical and Geoenvironmental Engineering* **138(6)**: 718–727.

Lui SPY, Cheung SPY and Chan AKC (1993) Pressure grouted minipiles for a 12-storey residential building at the mid-levels scheduled area in Hong Kong. *Proceedings of the Second International Conference on Soft Soil Engineering, Guangzhou, China*, pp. 419–424.

MOC (Ministry of Construction of the People's Republic of China) (2003) JGJ106-2003: Technical code for testing of building foundation piles. China Building Industry Press, Beijing, China (in Chinese).

Mullins G, Winters D and Dapp S (2006) Predicting end bearing capacity of post-grouted drilled shaft in cohesionless soils. *Journal of Geotechnical and Geoenvironmental Engineering* **132(4)**: 478–487.

Park S, Roberts L and Misra A (2012) Design methodology for axially loaded auger cast-in-place and drilled displacement piles. *Journal of Geotechnical and Geoenvironmental Engineering* **138(12)**: 1431–1441.

Peck RB, Hanson WE and Thornburn TH (1974) *Foundation Engineering*, 2nd edn. Wiley, New York, NY, USA.

Polous HG and Davis EH (1980) *Pile Foundation Analysis and Design*. Wiley, New York, NY, USA.

Randolph MF (1994) Design methods for pile groups and piled rafts. *Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering (ICSMFE), New Delhi, India*. Balkema, Rotterdam, the Netherlands, vol. 5, pp. 61–82.

Randolph MF, Dolwin J and Beck RD (1994) Design of driven piles in sand. *Géotechnique* **44(3)**: 427–448.

Randolph MF and Wroth CP (1978) Analysis of deformation of vertically loaded piles. *Journal of the Geotechnical Engineering Division, ASCE* **104(12)**: 1465–1488.

Shahin MA, Jaksa MB and Maier HR (2005) Neural network based stochastic design charts for settlement prediction. *Canadian Geotechnical Journal* **42(1)**: 110–120.

Stocker M (1983) The influence of post-grouting on the load-bearing capacity of bored piles. *Proceedings of 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki, Finland*.

Terzaghi K (1942) Discussion of the progress report of the committee on the bearing capacity value of pile foundations. *Proceedings of the American Society of Civil Engineering* **68**: 311–323.

Vesic AS (1977) *Design of Pile Foundation: Synthesis of Highway Practice 42*. Transportation Research Board, National Research Council, Washington, DC, USA.

Wang X, Chen Y, An Y, Qi C and Chen L (2011) Model test study of effect of inclination on bearing behavior of plastic tube cast-in-place concrete pile. *Chinese Journal of Rock Mechanics and Engineering* **30(4)**: 834–842 (in Chinese).

Zhang LM, Xu Y and Tang WH (2008) Calibration of models for pile settlement analysis using 64 field load tests. *Canadian Geotechnical Journal* **45(1)**: 59–73.

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