Cite this article

Ren LW, Guo WD and Deng YB (2018)

Analysis of vertically loaded jet-grout-pile-strengthened piles of expanded cross-section
Proceedings of the Institution of Civil Engineers – Geotechnical Engineering **171**(3): 252–266,
<https://doi.org/10.1680/jgeen.17.00059>

Research Article

Paper 1700059

Received 31/03/2017;

Accepted 30/11/2017;

Published online 10/01/2018

Keywords: field testing & monitoring/
foundations/piles & piling

ICE Publishing: All rights reserved

Geotechnical Engineering

ice publishing

Analysis of vertically loaded jet-grout-pile-strengthened piles of expanded cross-section

Lian Wei Ren BEng, PhD

Associate Professor, School of Civil Engineering, Henan Polytechnic University, Jiaozuo, China (corresponding author: renhpu@163.com)

Wei Dong Guo BEng, PhD, MASCE

Associate Professor, School of Civil, Mining & Environmental Engineering, University of Wollongong, NSW, Australia

Yue Bao Deng BEng, PhD

Lecturer, Institute of Geotechnical Engineering, Ningbo University, Ningbo, China

Piles are often installed together with jet grouting – to form a jet-grout-pile-strengthened pile – in soft subsoil regions of China to increase bearing capacity and reduce project costs. To facilitate their design, this paper presents a load-transfer approach to model the non-linear behaviour of such piles with expanded cross-sections. Three interface models are introduced to describe the interactions between soil–cement, the core pile and natural soil. Force equilibrium and displacement compatibility expressions are established and implemented through a purposely designed spreadsheet. The approach was verified by loading tests on two well-instrumented piles. A parametric study shows that having one to three segments of thick soil–cement enables a 20–60% gain in bearing capacity and a 43–55% reduction in head settlement compared with the core pile itself, which is slightly affected by the soil–cement modulus and stiffness ratio. It is cost-effective in practice to adopt two to four segments of soil–cement with a thickness of 0.1 m to a radius of core pile, an ultimate compressive strength of the soil–cement of over 2 MPa and a stiffness ratio of over 100 to reduce settlement. Finally, a simple equation is proposed to estimate the ultimate bearing capacity of such piles, which was verified by loading tests on piles in three case histories.

Notation

A_c	cross-sectional area of core pile	m	m th segment of core pile or soil–cement
A_x	cross-sectional area of soil–cement annulus	N	levels of pile head load after ultimate bearing capacity (divided by $0.5\Delta P$)
c	cohesion of soil around pile	n	number of core pile segments
E_c	Young's modulus of core pile	P	pile head load
E_x	Young's modulus of soil–cement	P_b	pile base load
G	shear modulus of soil	P_c	ultimate bearing capacity of core pile
G_b	shear modulus just beneath level of pile base	Q_b	total base resistance
H	depth to underlying rigid layer	Q_s	total shaft resistance
i	step number of core pile head load	Q_{sc}	shaft resistance from PC interface
$\{K\}$	symmetric matrix of coefficients	Q_u	ultimate bearing capacity of jet-grout-pile-strengthened pile (JPP)
k_c	shearing rigidity of first (core pile and soil–cement (PC)) interface	Q_x	shaft resistance from PS interface
k_{cm}	shearing rigidity of segment m for the first (PC) interface	Q_1	calculated load
k_t	ratio of increased load to increased settlement at pile head	Q_2	total applied load
k_x	shearing rigidity of second (core pile and soil (PS)) interface	q_{cs}	ultimate shaft friction of precast pile
k_{xm}	shearing rigidity of segment m for second (PS) interface	q_p	ultimate base pressure of precast pile
k_1	compressive rigidity of core pile or soil–cement base soil in the first stage	q_u	unconfined compressive strength
k_2	compressive rigidity of core pile or soil–cement base soil in the second stage	R_c	core pile base resistance
L	pile length	R_x	soil–cement pile base resistance
L_s	length of soil–cement segment	r_c	radius of core pile
L_x	total length of jet grouting soil–cement	r_x	radius of soil–cement pile
l_c	length of core pile	r_o	pile radius
l_x	length of jet grouting soil–cement pile	S_{bu}	base settlement related to ultimate base resistance in the first stage
M	levels of pile head load (divided by ΔP)	t	thickness of soil–cement
		U_m	compressive displacement of segment m of core pile
		U_n	compressive displacement of core pile base
		U_o	compressive displacement of core pile head

u	shaft displacement on pile–soil interface
u_b	base settlement
u_c	perimeter of core pile
u_m	compressive displacement of segment m of soil–cement
u_n	compressive displacement of soil–cement base for lower and full length
u_x	perimeter of soil–cement pile
u_o	compressive displacement of soil–cement head for upper and full length
z	depth below ground surface
β	rigidity ratio of first (PC) interface and second (PS) interface ($=k_c/k_x$)
$\{\Delta F\}$	load increment matrix of core pile head
ΔL	length of segment m
ΔN_m	axial force increment of segment m for core pile
Δn_m	axial force increment of segment m for soil–cement
ΔP	load increment of core pile head
ΔP_c	load difference value of ultimate bearing capacity between JPP and core pile
$\{\Delta U\}$	displacement increment matrix of core pile and soil–cement
ΔU_m	displacement increment of segment m for core pile
Δu_m	displacement increment of segment m for soil–cement
Δu_t	pile head settlement increment
ζ	shaft load-transfer factor
η_s	expanded coefficient
θ	power of the depth for shaft limit stress distribution
τ	shaft resistance on pile–soil interface
τ_c	shaft resistance developed in first (PC) interface of JPP
τ_{cu}	ultimate shaft resistance of first (PC) interface
τ_x	shaft resistance developed in second (PS) interface of JPP
τ_{xu}	ultimate shaft resistance of second (PS) interface
τ_o	local shaft stress
ν_s	Poisson's ratio of soil
φ	friction angle of soil around pile
ω	pile base shape and depth factor

1. Introduction

High-pressure jet grouting is used to stabilise weak, soft subsoil before a conventional solid or pipe pile (simply referred to as a 'core pile' in this paper unless necessary) is 'pressed' into the soil (Ren *et al.*, 2008). This forms a jet-grout-pile-strengthened pile (JPP) – a composite of a core pile within a jet-grouted soil–cement pile. The bond between the core pile (e.g. prestressed concrete) and the soil–cement pile allows an ultimate bearing capacity twice that of the core pile itself and saves 30% total cost. As a result, JPPs are customarily installed in coastal, soft subsoil regions of China (e.g. Tianjin and Guangzhou) to underpin high-rise buildings, industrial plants and oil tanks.

Figure 1 shows soil–cement cores unearthed in Tianjin port and a stock of pipe piles for installing JPPs. JPPs are bonded with

soil–cements in clay, soft clay and silty clay. The cement bond (see Figure 2), generally speaking, is secured to full length, the upper portion, lower portion or two to four portions along the pile. The soil–cement thickness varies between 0.1 m and twice the radius of the core pile. Each of the soil–cement buttresses give additional 'end' capacity (along the JPP shaft) over the 'straight-shaft' core pile itself.

The response of a vertically loaded pile can be captured well by using, for instance, (a) analytical methods underpinned by theoretical load-transfer models (Guo and Randolph, 1999; Lee and Xiao, 2001; Randolph and Wroth, 1979; Sheil and McCabe, 2016), (b) the τ – z curve method (Chen *et al.*, 1994; Kraft *et al.*, 1981; Nanda and Patra, 2014; Zhang and Zhang, 2012), (c) finite-element methods (Comodromos *et al.*, 2009; Said *et al.*, 2009; Sheng *et al.*, 2005), (d) boundary-element methods (Ai and Han, 2009; Mandolini and Viggiani, 1997) and (e) a variational approach (Shen *et al.*, 1997). Among these and other methods (not all are mentioned here), the theoretical load-transfer method has been proven to be effective and efficient for single and group piles (Cao *et al.*, 2014; Liu *et al.*, 2004; Ren *et al.*, 2010; Zuo, 2008) and sufficiently flexible to accommodate soil–cement segment(s) of JPPs.

In this paper, the load-transfer model is modified to simulate a JPP by incorporating three types of interface models. New expressions for force equilibrium and displacement compatibility, and the overall stiffness matrix of the pile are generated, for which a specific program (operating in Excel) was developed to facilitate the simulation. The solution/program was compared with two well-instrumented loading tests and employed to optimise design parameters of JPPs.

2. Technical characteristics of JPPs

The enhanced capacity of JPPs was demonstrated in comparative full-scale loading tests conducted on a JPP, cast-in-place pile and jet-grouted soil–cement wall (with an embedment of 5 m and a diameter of 0.5 m) at a site in Hohai University, Nanjing, China (Liu *et al.*, 2010). The measured pile head load–settlement curves are plotted in Figure 3, which shows that the JPP attained 1.33 times the (ultimate) bearing capacity of the cast-in-place pile and 2.5 times that of the jet-grouted soil–cement pile. A JPP should have a larger (shaft) resistance (see Figure 1(b)) than a conventional cast-in-place pile. Its mobilisation is warranted by a good bond between the high-strength soil–cement and the core pile, which surpasses that of a cast-in-place pile of the same diameter.

It is sometimes difficult to drive a precast pile through deep-seated, stiff silty sand or silty clay layer to meet the desired depth(s). The common solution to this problem is to use high-pressure jet grouting to soften the barrier before proceeding with installation of the core pile. This pile–cement system (of JPPs) shows special features. Installation practice is

Figure 1. JPP head excavation and soil-cement corings in Tianjin port, China (Ren *et al.*, 2008): (a) unearthed (4000) JPP pile heads; (b) in situ diameter measurement; (c) enlarged diameter measurement; (d) core (PHC) piles; (e) soil-cement cores; (f) a typical JPP in soil

recognised by AB and/or BAB construction methods: A denotes the use of high-pressure jetting to form soil-cement and B represents statically pressing down a core pile through the grouting layer to the desired depth (e.g. silt in Tianjin). As shown in Figure 4, the AB method comprises six steps. The BAB method, on the other hand, starts with pressing down a pipe pile (B) into the upper surface of a stiff layer, then installing a grouting ('drill') rod through the pipe well into the 'deep' stiff layer (below the pipe base) and jet grouting (A) to soften the stiff layer, withdrawing the drill and finally pressing the pipe pile (B) well into the softened (desired) bearing stratum (see Figure 4). A precast or prestressed high-strength concrete (PHC) pipe pile is normally utilised as the core pile to ensure good corrosion resistance (in the concerned soil) and to allow the drill rod to pass through the pipe (BAB method only) into the underlying stiff layer.

3. Load transfer for a single JPP

3.1 Interface model and assumptions

Figure 5(a) shows a vertically loaded JPP. To clarify the interfaces and interactions, the pile-cement-soil system is resolved into the core pile and the jet-grouted soil-cement wall (segment), with the pile head load (P), base resistances (R_c , R_x) and shaft shearing stresses along the pile (τ_c) and the wall (τ_x , τ_e) defined. The inside shaft stress on the cement wall is equal to the stress τ_c on the outside surface of the core pile but in opposite directions. The system is characterised by three types of interfaces (see Figure 5(b))

- a linear $\tau_c - u$ curve for the core pile and soil-cement (first or PC) interface
- an ideal elastoplastic $\tau_x - u$ curve for the core pile and soil (second or PS) interface and an ideal elastoplastic $\tau_x - u$

Figure 2. Common layouts and numbering rule in analysing JPPs: (a) full length; (b) upper portion; (c) lower portion; (d) segmented layout

Figure 3. Measured pile head load-settlement of three piles: (a) load settlement; (b) three-pile layout

curve for the soil-cement ‘wall’ and the soil (second or CS) interface

- a bilinear relationship (described by compressive stiffness k_1 and k_2 before and after base settlement (S_{bu}) between the base stress (τ_b) and displacement (S) at the tips of the core pile and the soil-cement.

The response of the JPP is captured by these models and the following hypotheses.

- The pile head load (P) is exerted on the top of the core pile only, as in loading tests.
- The core pile or soil-cement is elastic and with a constant cross-section along the depth.
- The load transfer observes the three interface models.
- The z -axis is measured from the top of core pile downward.

3.2 Load-transfer parameters of three interfaces

3.2.1 Shearing rigidities k_x and k_c

The shaft displacement u is correlated with the local shaft stress τ_x by (Randolph and Wroth, 1978)

$$1a. \quad u = \frac{\tau_x r_c}{G} \zeta \quad (\text{PS})$$

$$1b. \quad u = \frac{\tau_x r_x}{G} \zeta \quad (\text{CS})$$

where r_c is the radius of the core pile, r_x is the radius of the soil-cement pile, τ_x is the shear stress on the core pile and soil

Figure 4. JPP construction methods: (a) AB method; (b) BAB method

(PS) interface or the soil-cement 'wall' and soil (CS) interface, G is the soil shear modulus and ζ is a shaft load-transfer factor (Guo and Randolph, 1998) given by

$$2. \quad \zeta = \ln \left(1 + 1.1e^{-\sqrt{\theta}} \left(1 - e^{1-(H/L)} \right) \left(\frac{1 - \nu_s L}{1 + \theta r_x} \right) + 1 \right)$$

where ν_s is Poisson's ratio of the soil, L is the length of the core pile, θ is the non-homogeneity factor, H/L is the soil layer depth ratio and H is the depth to the underlying rigid layer.

The factor k_x is given by

$$3a. \quad k_x = \frac{\tau_{xu}}{u} = \frac{G}{r_c \zeta} \quad (\text{PS})$$

$$3b. \quad k_x = \frac{\tau_{xu}}{u} = \frac{G}{r_x \zeta} \quad (\text{CS})$$

The other factor, k_c , is equal to $0.5q_u$ (q_u is the unconfined compressive strength (UCS) of soil-cement) or $200k_x$ (Liu *et al.*, 2010; Voottipruex *et al.*, 2011).

3.2.2 Compressive stiffness factors k_1 and k_2

The gradients k_1 and k_2 for the bilinear correlation are determined between the base load (P_b) and base settlement (u_b). A linear relationship between base settlement and resistance (Randolph and Wroth, 1978) allows k_1 to be estimated as

$$4. \quad k_1 = \frac{P_b}{u_b \pi r_0^2} = \frac{4G_b}{\pi r_0 (1 - \nu_s) \omega}$$

in which ω is the base load-transfer factor and G_b is the shear modulus just beneath pile base level. The hardening factor k_2 is stipulated as (Chen *et al.*, 1994; Zhang and Zhang, 2012)

$$5. \quad k_2 = \frac{k_t}{1 - k_t (L/E_c A_c)}$$

where $k_t (= \Delta P / \Delta u_t)$ is the ratio of the load increment (ΔP) over the pile head settlement increment (Δu_t) and E_c and A_c are the Young's modulus and cross-sectional area of the core pile, respectively. Note that identical k_1 and k_2 values for the core pile base are adopted for each end of the soil-cement segment.

3.3 Load-transfer functions for a single JPP

3.3.1 Segment analysis of core pile and soil-cement

The JPP system is divided into n segments (see Figures 5(c) and 5(d)) and the following notation is adopted.

- r_c and r_x are the core pile radius and jet grouting soil-cement radius, respectively.
- A_c and A_x represent the section area of the core pile and the soil-cement wall, respectively.
- E_c and E_x represent the Young's modulus of the core pile and the soil-cement wall, respectively.
- u_m and U_m are the soil-cement displacement and the core pile displacement of segment m , respectively.
- u_0 and U_0 are the soil-cement head settlement and the core pile head settlement, respectively.

Figure 5. Load-transfer analysis of single JPP embedded in multi-layered soil: (a) core pile and soil-cement; (b) load-transfer models for three interfaces; (c) load transfer along JPP; (d) force equilibrium in typical segments

- u_n and U_n are the soil-cement base settlement and the core pile base settlement, respectively.
- k_x and k_c are the shearing rigidities between the soil-cement or core pile and soil around the JPP, and between the core pile and the soil-cement, respectively.
- k_1 and k_2 are the compressive rigidities of the soil below the core pile and the soil-cement base in the first and second stages of the load-displacement curve, respectively.

- S_{bu} is the core pile and soil-cement base settlement related to the ultimate base resistance in the first stage.

The shaft resistances Q_{sc} (from the PC interface) and Q_x (from the PS interface) under $\tau_x < \tau_{xu}$ (limiting shearing stress of the PS interface) are estimated as

$$6. \quad Q_{sc} = 2\pi r_c \Delta L k_{cm} (U_m - u_m) \leq 2\pi r_c \Delta L \tau_{cu}$$

$$7. \quad Q_x = 2\pi r_x \Delta L k_{xm} u_m \leq 2\pi r_x \Delta L \tau_{xu}$$

where k_{cm} and k_{xm} are the shearing stiffnesses (of segment m) for the first (PC) and the second (PS) interfaces, respectively and ΔL is the length of pile segment m . The base resistance of the core pile (R_c) is linearly related to U_n (core) by Equation 8 with a different gradient from the turning point S_{bu} (ultimate base settlement) onwards. The soil–cement resistance (R_x) is linearly related to u_n by Equation 9.

$$8a. \quad R_c = A_c k_1 U_n \quad (U_n < S_{bu})$$

$$8b. \quad R_c = A_c k_2 U_n + A_c (k_1 - k_2) S_{bu} \quad (U_n \geq S_{bu})$$

$$9a. \quad R_x = A_x k_1 u_n \quad (u_n < S_{bu})$$

$$9b. \quad R_x = A_x k_2 u_n + A_x (k_1 - k_2) S_{bu} \quad (u_n \geq S_{bu})$$

Incremental axial forces on segment m of the core pile (ΔN_m) and the soil–cement (Δn_m) are given by

$$10. \quad \Delta N_m = B_m (\Delta U_{m-1} - \Delta U_m) \text{ with } B_m = A_c E_c / \Delta L$$

$$11. \quad \Delta n_m = b_m (\Delta u_{m-1} - \Delta u_m) \text{ with } b_m = A_x E_x / \Delta L$$

3.3.2 Load-transfer matrix for pile–soil system

The JPP consists of combined segments (soil–cement and core pile) and the core-pile-only segment. The current analysis adopts the numbering shown in Figure 2. The equilibrium of axial force and displacement compatibility allow development

of expressions (T1) to (T14) as summarised in Table 1. The expressions allow the load–settlement relationship for the JPP to be written as

$$12. \quad \{\mathbf{K}\}\{\Delta \mathbf{U}\} = \{\Delta \mathbf{F}\}$$

where $\{\Delta \mathbf{U}\}$ is the displacement increment matrix of the core pile and soil–cement, $\{\mathbf{K}\}$ is the symmetric coefficient matrix of $2(n+1) \times 2(n+1)$ for full length, $(n+n_1+2) \times (n+n_1+2)$ for upper or lower portion, $[n+1+N(n_2+1)] \times [n+1+N(n_2+1)]$ for a segmented layout, in which n is the segment number of the core pile, n_1 is the segment number of the soil–cement, N is the number of soil–cement wall for segment layout and n_2 is the segment number of each soil–cement wall for segment layout.

$$13. \quad \{\Delta \mathbf{Y}\}^T = \{\Delta U_0, \Delta u_0, \Delta U_1, \Delta u_1, \dots, \Delta U_n, \Delta u_n\}$$

$$14. \quad \{\Delta \mathbf{F}\}^T = \{\Delta P, 0, 0, \dots, 0\}$$

Soil–cement settlements Δu_m of the core-pile-only segment are removed from the matrix $\{\Delta \mathbf{U}\}$.

3.3.3 Algorithm for calculation of a single JPP in layered soils

A single JPP in a multi-layered soil is modelled in the following nine steps.

- Divide the core pile into n segments, each with length $\Delta L (= L/n)$, as is adopted for each segment of the soil–cement. The length ΔL thus needs to suit the thickness of each soil layer and the length of the soil–cement. The load P is divided into M levels ($\Delta P = P/M$), with a first step $i (= 1)$. Note, to improve accuracy, the loading rate is reduced into $0.5\Delta P$ (N levels) as the total load P approaches the ultimate

Table 1. Equations of the simplified method for JPPs

	Core pile	Soil–cement pile
Combined	$-(B_1 + D_0)\Delta U_0 + D_0\Delta u_0 + B_1\Delta U_1 = -\Delta P \quad (m=0) \text{ (T1)}$ $B_m\Delta U_{m-1} - (B_m + B_{m+1} + D_m)\Delta U_m + D_m\Delta u_m + B_{m+1}\Delta U_{m+1} = 0 \text{ (T2)}$ where $D_m = 2\pi r_c \Delta L k_{cm} \text{ (T3)}$ $B_n\Delta U_{n-1} - (B_n + D_n + D_c)\Delta U_n + D_n\Delta u_n = 0 \quad (m=n) \text{ (T4)}$ where $D_c = A_c k_1 \quad (U_n \leq S_{bu})$ or $D_c = A_c k_2 \quad (U_n > S_{bu}) \text{ (T5)}$	$D_0\Delta U_0 - (b_1 + d_0 + D_0)\Delta u_0 + b_1\Delta U_1 = 0 \quad (m=0)^a \text{ (T10)}$ $b_m\Delta u_{m-1} + D_m\Delta U_m - (b_m + b_{m+1} + d_m + D_m)\Delta u_m + b_{m+1}\Delta U_{m+1} = 0 \text{ (T11)}$ where $d_m = 2\pi r_x \Delta L k_{xm} \text{ (T12)}$ $b_n\Delta u_{n-1} + D_n\Delta U_n - (b_n + d_n + D_n + d_x)\Delta u_n = 0 \quad (m=n)^a \text{ (T13)}$ where $d_x = A_x k_1 \quad (u_n \leq S_{bu})$ or $d_x = A_x k_2 \quad (u_n > S_{bu}) \text{ (T14)}$
Core pile only	$-(B_1 + D_0)\Delta U_0 + B_1\Delta U_1 = -\Delta P \quad (m=n) \text{ (T6)}$ $B_m\Delta U_{m-1} - (B_m + B_{m+1} + D_m)\Delta U_m + B_{m+1}\Delta U_{m+1} = 0 \text{ (T7)}$ where $D_m = 2\pi r_c \Delta L k_{xm} \text{ (T8)}$ $B_n\Delta U_{n-1} - (B_n + D_n + D_c)\Delta U_n = 0 \quad (m=n) \text{ (T9)}$	

^aPile head and base number of each soil–cement segment equals the number of core piles at the same cross-section, so is not constant, as shown in Figure 2

Figure 6. Full-scale loading test on a JPP (case 1): (a) pile and soil system; (b) shaft resistance–displacement curves; (c) base resistance–settlement curve; (d) head load–settlement curves; (e) axial force distributions; (f) local shear stress–displacement curves

level (the second (PS) interface rigidity k_x of every layer soil are almost all zero).

- (b) Calculate the parameters B_m , b_m , D_m , d_m , D_c and d_x using Equations 10 and 11, and Equations (T3), (T8), (T12), (T5) and (T14) (in Table 1), respectively.

- (c) Calculating each element in the symmetric matrix using Equations (T1), (T2), (T4), (T6), (T7), (T9), (T10), (T11) and (T13) (in Table 1) and form the matrix $\{\mathbf{K}\}$.

- (d) Solve Equation 12 to gain elastic deformation increments of the core pile and soil–cement segments at the i th ΔP .

Table 2. Physical and mechanical parameters of soil in full-scale tests (Liu *et al.*, 2010)

Soil	Water content: %	Density: kN/m ³	Cohesion: kPa	Friction angle: degrees	Compression modulus, E_s : MPa
Clay	29.3	19.2	24.70	28.2	4.69
Sand	5.49	15.5	9.76	24.3	14.70

Table 3. Parameters for load-transfer model (case 1)

Soil	Thickness: m	k_c : MPa/m	k_x : MPa/m	k_1 : MPa/m	k_2 : MPa/m	τ_{xu} : kPa	S_{bu} : mm
Clay	3.0	778	3.89	—	—	17.51	—
Sand	3.5	1 434	7.17	72.53	7.15	24.00	2

Table 4. Comparison of calculated and measured parameters for load-transfer model

Soil	G : MPa	k_x : MPa/m		ζ		k_1 : MPa/m		k_2 : MPa/m	
		Measured	Equation 3	Measured	Equation 2	Measured	Equation 4	Measured	Equation 5
Case 1 ^a									
Clay	2.61	3.89	3.64	2.68	2.86	72.53	85.32	7.15	6.21
Sand	5.44	7.17	7.62	3.04					
Case 2 ^b									
Clay	5.78	—	4.01	—	4.12	—	144.74	—	66.41
Soft clay	3.89	—	2.70						
Silty	5.56	—	6.74						

^aCase 1: $\nu_s = 0.35$, $\theta = 0.5$, $G_b = 10.89$ MPa, $\omega = 1$

^bCase 2: $\nu_s = 0.35$, $\theta = 0.5$, $G_b = 14.78$ MPa, $\omega = 1$

- (e) Calculate the shearing stress of the first (PC) and second (PS) interface of each segment using Equations 6 and 7, respectively, and the axial force of the core pile and soil–cement using Equations 10 and 11, respectively.
- (f) Take shearing stiffness k_x (between soil–cement or core pile and soil) as zero if the shearing stress exceeds the upper limit.
- (g) Change the rigidity k_1 into k_2 at the next load step when the base settlement of the core pile or soil–cement reaches the ultimate deformation S_{bu} .
- (h) Calculate the load Q_1 ($= Q_s + Q_b$, Q_s is the total shaft force and Q_b is the total base resistance) and check whether $(Q_2 - Q_1)/Q_2 < 0.05$ (a specified tolerance) is valid, in which the total load is Q_2 ($= \Delta P + \Delta P + i \dots$). Use $(Q_2 - Q_1)$ as the new value of ΔP to repeat steps (a)–(g) until $(Q_2 - Q_1)/Q_2$ is within the assumed tolerance.
- (i) $i = i + 1$, if $i \leq M + N$, move to the next load step until the calculation process is complete.

The calculation results show that the proposed calculation method is simple and efficient, regardless of layered soils and variable cross-sections and layouts.

4. Case studies

The proposed method is exemplified by simulating single JPPs in two multi-layered soil profiles.

4.1 Case 1: Full-length JPP in a clay–sand layer

Liu *et al.* (2010) reported full-scale loading tests on a single JPP embedded in a 3 m clay layer underlain by a 3.5 m sand layer (Figure 6(a)). The physical and mechanical parameters of the subsoil are provided in Table 2. The clay/sand–cement (JPP) pile had an external radius of 0.25 m, a wall thickness of 0.1 m ($r_x = 0.25$ m) and Young's moduli of $E_{xc} = 0.90$ GPa for clay–cement and $E_{xs} = 2.19$ GPa for sand–cement. A PHC pipe pile (0.15 m in external radius and $E_c = 38$ GPa) was pressed 5 m down into the subsoil.

The loading tests provided the average shaft resistance (τ)–relative displacement curve (w), the base resistance–settlement curve, the pile head load–settlement curve of the JPP and the axial load distribution of the pipe pile; these are shown in Figures 6(b), 6(c), 6(d) and 6(e), respectively. The single JPP was divided into five segments ($m = 5$) with a segment length (ΔL) of 1.0 m. It was modelled using the parameters shown in Table 3. The calculated load–settlement curves and the load distribution are shown in Figures 6(d) and 6(e), respectively. The slight overestimation of the ultimate bearing capacity (of 200 kN) is due to a similar overestimation of the shearing stress τ against the field measurement (see Figure 6(f)). The parameters ζ , k_x , k_1 and k_2 describing the τ – u curves agree well with the measured results (see Table 4). Equations 2–5 are thus sufficiently accurate in terms of predictions against measured data. This conclusion is further validated in the following case.

4.2 Case 2: Upper portion of JPP in clay–soft clay–silty clay layer

Ren *et al.* (2008) conducted loading tests on a JPP ‘wrapped’ with soil–cement to 75% of its length from ground level (see Figure 7(a)) and provided load–displacement curves. A PHC pile ($E_c = 38$ GPa, diameter of 0.4 m) was installed to a depth of 20 m. The jet-grouted soil–cement wall was 15 m long, 0.7 m in external diameter (0.15 m in wall thickness) and had an UCS of 2 MPa (mean value, due to sufficient cement

mixed with clay/soft clay, see Figure 7(a)). JPPs were installed in situ by the jet grouting method with a jet pressure of 23 MPa. The water/cement ratio of the cement slurry was 1.2 and the cement content employed for jet grouting construction was 160 kg/m³ of soil.

The parameters ζ , k_x , k_1 and k_2 were estimated and are shown in Table 4. S_{bu} was deduced from the loading test results. The subsoil was modelled as a four-layer soil system (i.e. clay, soft clay, silty clay and silt layers; see Table 5). The values of τ_{xu} (as deduced from the geotechnical investigation report) were 29 kPa, 23 kPa and 62 kPa for the upper soil layers. The predicted load–settlement curve (see Figure 7(b)) and ultimate bearing capacity (of 1.8 MN) compare well with the measured data for the JPP (upper portion), despite the slight underestimation (<1.2 MN) or overestimation (>1.2 MN) of the settlement.

5. Parametric study

The impact of layout of segments, soil–cement thickness, soil–cement modulus E_x and stiffness ratio k_c/k_x on the load–displacement response of a single JPP embedded in a homogenous soil is examined in this section. The hypothetical JPP is 20 m long and 0.6 m (soil–cement) and 0.4 m (core pile) in diameter (see Figure 8(a)). The Young’s moduli are 38 GPa for the core pile and 0.9 GPa for the soil–cement. The limiting shaft resistance of each segment, τ_{xu} (Guo and Randolph, 1997), is taken as $\tau_{xu} = 10z^{0.5}$ where z is the depth below the ground surface. The interface models are described by $k_c = 1000$ MPa/m, $k_x = 10$ MPa/m, $S_{bu} = 5.5$ mm, $k_1 = 50$ MPa/m, $k_2 = 5$ MPa/m.

5.1 Layout of segments

It is often critical to select the grouting layout for each site. As an example, a JPP in a homogenous soil were simulated concerning a full length, an upper portion, a lower portion, two segments and three segments of soil–cement (see Figure 8(a)). The total length of the soil–cement was maintained at 12 m in the form of either two 6 m length segments, three 4 m long segments and so on. The predicted load–settlement curves and pile head load–base load curves are shown in Figures 8(b) and 8(c), respectively. The figures indicate that three segments (also full length) of soil–cement offered the highest ultimate bearing capacity of the JPP. The capacity reduced gradually from layouts of three segments, two segments, lower portion to upper portion (the lowest). These reduction may originate from the base resistance, which exhibited a similar reduction. This

Figure 7. (a) Pile–soil system for case 2. (b) Predicted and measured pile head load–displacement curves for case 2

Table 5. Soil profile and parameters for load-transfer model (case 2)

Soil	Layer thickness: m	Density: kN/m ³	Modulus, E_s : MPa	k_c : MPa/m	k_x : MPa/m	τ_{xu} : kPa
Clay	5	18.9	5.2	980	4.9	29
Soft clay	10	17.7	3.5	660	3.3	23
Silty clay	5	19	5	1648	8.24	62
Silt	8	19.8	13.3	—	—	—
$S_{bu} = 6$ mm

Figure 8. Soil–cement layouts for capacity and settlement: (a) five layouts; (b) pile head load–settlement curves; (c) head load–base load curves; (d) L_s/L_x plotted against normalised gain in head capacity; (e) L_s/L_x plotted against normalised reduction in head settlement

analysis concurs with the practice of forming two to four soil–cement segments (by jet grouting) to increase bearing capacity and reduce settlement.

5.2 Soil–cement thickness

The soil–cement thickness ‘wrapping’ the core pile needs to be selected to ensure sufficient pile capacity. Taking a thickness

t ($= r_x - r_c$) of 0–0.2 m (or $t/r_c = 0$ –1.0, thickness normalised by the radius of the core pile), the head load–settlement and head load–base load curves were obtained for the three-segment JPP. As shown in Figures 9(a) and 9(b), an increase in thickness (and thus cross-section and shaft area) to an effective radius r_x ($< 10r_c$ theoretically) increased the ultimate bearing capacity. The force equilibrium of the soil–cement unit

Figure 9. Soil-cement thickness for capacity and settlement: (a) pile head load-settlement curves; (b) base load-head load curves; (c) t/r_c plotted against normalised gain in head capacity; (d) t/r_c plotted against normalised reduction in pile head settlement

(see Figure 5(a)) requires $r_x/r_c < \tau_{cu}/\tau_{xu}$ (through $2\pi r_c \tau_{cu} \Delta L > 2\pi r_x \tau_{xu} \Delta L$), which leads to an upper bound of $r_x/r_c < 10$ for $\tau_{cu} = 0.25q_u = 0.25 \times 2000 = 500$ kPa and $\tau_{xu} = 50$ kPa. This implies that the practice of using a soil-cement thickness of

Figure 10. Pile head settlement for typical soil-cement modulus E_x (predicted for single JPP at different head loads)

0.1 m to r_c is good for curbing settlement and conservative for mobilising capacity.

5.3 Soil-cement modulus (E_x) and shear stiffness ratio (k_c/k_x)

Minimising the duration of construction is important and this may rely on the allowable degree of strength and stiffness (modulus) gain of the soil-cement. The pile head settlement of the three-segment JPP was obtained for a soil-cement modulus (E_x) of 0.6–1.5 GPa, at five typical load levels. As shown in Figure 10, the value of E_x had a negligible effect on the settlements at each load level and on the bearing capacity. This warrants proceeding with construction earlier, at a smaller modulus of E_x (0.6 GPa), and implies a negligible effect of E_x on the shearing stress between the soil-cement and the core pile.

It is difficult (if not costly) to determine exact values of the stiffness k_c (of the PC interface) and k_x (of the PS interface). The load-settlement curves (of a single three-segment JPP) were obtained for $\beta (= k_c/k_x) = 10, 100$ and 1000. As shown in Figure 11, the value of β barely affected the bearing capacity, and the low β (of 10) induced a slightly higher settlement. The negligible effect of β on the pile response is used as current practice requires $\beta > 100$.

5.4 Comments on JPP design

The numerical simulations indicate that enhanced pile capacity comes from three-segment and full-length soil-cement and a thick soil-cement (and is insensitive to the soil-cement modulus and interface stiffness ratio β).

Further analysis provided the impact of segment length over the total length of soil-cement (i.e. L_s/L_x) on the capacity gain (ΔP_c) over the ultimate bearing capacity of the core pile (P_c) and on the settlement reduction of the pile head (ΔU_0) from the settlement U_0 of the core pile at P_c . The load ratio $\Delta P_c/P_c$ and displacement ratio $\Delta U_0/U_0$ are plotted against the normalised length (L_s/L_x) in Figures 8(d) and 8(e). These figures

Figure 11. Load-settlement curves for different stiffness ratios β (predicted for single three-segmented JPP)

reveal that three short segments allowed up to 60% gain in the ultimate bearing capacity or 55% reduction in head settlement, while one or two long segment(s) enabled a 20–60% gain in capacity or a 43–52% reduction in head settlement. This further attests the benefits of using three segments over other layouts and one or two long segment(s) over conventional cast-in-place piles. The results also indicate that a thick soil–cement annulus (t) raises the normalised capacity of $\Delta P_c/P_c$ (see Figure 9(c)) and reduction in head settlement at P_c of $\Delta U_0/U_0$ (see Figure 9(d)) over the core pile. The settlement reduction in particular is four times more effective with $t/r_c = 0.25$ than otherwise.

The results of this study generally uphold the practice of using two to four segments around each JPP and a soil–cement thickness of $0.5r_c$ – $1.0r_c$ (or $r_x \leq 1.5r_c$ – $2.0r_c$) and $r_x - r_c \geq 0.1$ m.

Figure 12. JPPs installed in three projects: (a) Huazheng office building; (b) Wantong building; (c) Lanling apartment (provided by Yuhua Lei, Huazheng Geotechnical Co., Ltd, Tianjin, China)

Extra thickness beyond $0.25r_c$ facilitates only 25% settlement reduction of a thinner cement wall, but it couples the core pile and soil–cement well (by controlling $q_u \geq 2$ MPa and $\beta \geq 100$) and allows a continual increase in capacity.

The ultimate bearing capacity (Q_u) of a JPP may be pragmatically estimated using

$$15. \quad Q_u = u_x \eta_s \sum_{i=1}^m q_{csi} l_{xi} + u_c \sum_{j=1}^n q_{csj} l_{cj} + q_p A_p$$

in which u_x and u_c are the perimeters of the soil–cement and core pile, respectively, q_{csi} (q_{csj}) and q_p are the ultimate shaft friction and base pressure of the core pile in the i th (j th) soil layer (see JGJ 94-2008 (MOHURD, 2008)), respectively, m and n are total numbers of soil layers in the zone of the soil–cement and the core pile, respectively, η_s is the coefficient of shaft resistance, 1.3–1.7, and l_{xi} and l_{cj} are the lengths of soil–cement in the i th layer and the core pile in j th layer, respectively.

Equation 15 offers slightly conservative capacities against the measured values (taking $\eta_s = 1.35 - 1.50$) for three typical projects (see Figure 12).

6. Conclusions

A simplified load-transfer approach to model the non-linear behaviour of a single JPP with expanded cross-sections at desired depth(s) has been presented. The approach is underpinned by three interface models (for interactions between two of the soil–cement, core pile and natural soil). The approach was compiled into an Excel program and was shown to produce good comparisons with the results of loading tests on two well-instrumented JPPs. The proposed approach can readily accommodate layered soils and variable pile cross-sections. It captures the evolution of the pile response well, including distributions of axial force and displacement along pile and so on.

A parametric study revealed the following.

- One to three segments of thick soil–cement enable a 20–60% gain in bearing capacity and a 43–55% reduction in head settlement compared with a core pile without jet grouting; this was slightly affected by the modulus of the soil–cement wrapping and the stiffness ratio β (of PC pile–cement and PS pile–soil interfaces).
- It is cost-effective to adopt two to four segments of soil–cement with a thickness of 0.1 m to the radius of the core pile to produce an UCS for soil–cement of > 2 MPa and a stiffness ratio $\beta > 100$ to reduce settlement.

Finally, a simple expression was proposed to estimate the ultimate bearing capacity of a JPP. This equation was verified by comparing predictions from the equation with measured data of loading tests on JPPs in three case histories.

Acknowledgements

The authors would like to acknowledge the financial support of the National Natural Science Foundation of China (no. 51508166), the China Scholarship Foundation and the Key University Teacher Foundation of Henan Province (2015GGJS-243), the supply of loading test data from Tianjing Huazheng Geotechnical Engineering Co., Ltd and the inspirational collaborative support from the Centre for Geomechanics & Railway Engineering, University of Wollongong, Australia.

REFERENCES

- Ai ZY and Han J (2009) Boundary element analysis of axially loaded piles embedded in a multi-layered soil. *Computers and Geotechnics* **36**(3): 427–434.
- Cao W, Chen Y and Wolfe WE (2014) New load transfer hyperbolic model for pile–soil interface and negative skin friction on single piles embedded in soft soils. *International Journal of Geomechanics* **14**(1): 92–100.
- Chen LZ, Liang GQ, Zhu JY and Ge W (1994) Analytical calculation of axial loading–settlement curve of piles. *Chinese Journal of Geotechnical Engineering* **16**(6): 30–38 (in Chinese).
- Comodromos EM, Papadopolou MC and Rentzeperis IK (2009) Pile foundation analysis and design using experimental data and 3-D numerical analysis. *Computers and Geotechnics* **36**(5): 819–836.
- Guo WD and Randolph MF (1997) Vertically loaded piles in non-homogeneous media. *International Journal for Numerical and Analytical Methods in Geomechanics* **21**(8): 507–532.
- Guo WD and Randolph MF (1998) Rationality of load transfer approach for pile analysis. *Computers and Geotechnics* **23**(1): 85–112.
- Guo WD and Randolph MF (1999) An efficient approach for settlement prediction of pile groups. *Géotechnique* **49**(2): 161–179, <http://dx.doi.org/10.1680/geot.1999.49.2.161>.
- Kraft LM Jr, Richard PR and Takaaki K (1981) Theoretical τ – z curves. *Journal of Geotechnical Engineering* **107**(11): 1543–1561.
- Lee KM and Xiao ZR (2001) A simplified method for nonlinear analysis of single piles in multilayered soils. *Canadian Geotechnical Journal* **38**(5): 1063–1080.
- Liu HL, Ren LW, Zheng H and Xiao YZ (2010) Full-scale model test on load transfer mechanism for jet grouting soil–cement–pile strengthened pile. *Rock and Soil Mechanics* **31**(5): 1395–1401 (in Chinese).
- Liu J, Xiao HB, Tang J and Li QS (2004) Analysis of load-transfer of single pile in layered soil. *Computers and Geotechnics* **31**(2): 127–135.
- Mandolini A and Viggiani C (1997) Settlement of piled foundations. *Géotechnique* **47**(4): 791–816, <http://dx.doi.org/10.1680/geot.1997.47.4.791>.
- MOHURD (Ministry of Housing and Urban-Rural Development) (2008) JGJ 94-2008: Technical code for building pile foundations. MOHURD, Beijing, China.
- Nanda S and Patra NR (2014) Theoretical load-transfer curves along piles considering soil nonlinearity. *Journal of Geotechnical and Geoenvironmental Engineering* **140**(1): 91–101.
- Randolph MF and Wroth CP (1978) Analysis of deformation of vertically loaded piles. *Journal of Geotechnical Engineering* **104**(12): 1465–1488.
- Randolph MF and Wroth CP (1979) An analysis of the vertical deformation of pile groups. *Géotechnique* **29**(4): 423–439, <http://dx.doi.org/10.1680/geot.1979.29.4.423>.
- Ren LW, Liu HL and Lei YH (2008) Technology and application of JG soil–cement pile strengthened pile. *Chinese Journal of Geotechnical Engineering* **30**(s1): 518–522 (in Chinese).

- Ren LW, Liu XL and Wang GY (2010) Simplified calculation and analysis of load transfer behavior for single JPP. *Chinese Journal of Rock Mechanics and Engineering* **29**(6): 1279–1287 (in Chinese).
- Said I, Gennaro V D and Frank R (2009) Axisymmetric finite element analysis of pile loading tests. *Computers and Geotechnics* **36**(1): 6–19.
- Sheil BB and McCabe BA (2016) An analytical approach for the prediction of single pile and pile group behavior in clay. *Computers and Geotechnics* **75**(5): 145–158.
- Shen WY, Chow YK and Yong KY (1997) A variational approach for vertical deformation analysis of pile group. *International Journal for Numerical and Analytical Methods in Geomechanics* **21**(11): 741–752.
- Sheng D, Eigenbrod KD and Wriggers P (2005) Finite element analysis of pile installation using large-slip frictional contact. *Computers and Geotechnics* **32**(1): 17–26.
- Voottipruex P, Bergado DT, Suksawat T, Jamsawang P and Cheang W (2011) Behavior and simulation of deep cement mixing (DCM) and stiffened deep cement mixing (SDCM) piles under full scale loading. *Soils and Foundations* **51**(2): 307–320.
- Zhang QQ and Zhang ZM (2012) A simplified nonlinear approach for single pile settlement analysis. *Canadian Geotechnical Journal* **49**(11): 1256–1266.
- Zuo WL (2008) *Test Study and Analysis of Bearing Behavior of Grouted Gravel Pile*. PhD thesis, Hohai University, Nanjing, China (in Chinese).

How can you contribute?

To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions from the civil engineering profession (and allied disciplines). Information about how to submit your paper online is available at www.icevirtuallibrary.com/page/authors, where you will also find detailed author guidelines.