Numerical simulation of plug formation during casing installation of PCC piles

Mi Zhou¹, Hanlong Liu², Muhammad Shazzad Hossain³, Yuxia Hu⁴ and
Ting Zhang⁵

¹ Research Associate (PhD), Hohai University, 1 Xikang Rd, Nanjing, PR China, 210098; School of Civil, Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Tel: +61 8 6488 3071, Fax: +61 8 6488 1018, Email: mi.zhou@uwa.edu.au

² Professor (PhD), Key Laboratory of New Technology for Construction of Cities in Mountain Area, Chongqing University, Chongqing 40045, China; College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China, E-mail: hliuhhu@163.com

³ Corresponding Author, Associate Professor (BEng, MEng, PhD, MIEAust), ARC DECRA Fellow, Centre for Offshore Foundation Systems (COFS), The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Tel: +61 8 6488 7358, Fax: +61 8 6488 1044, Email: muhammad.hossain@uwa.edu.au

⁴ Professor (PhD, MIEAust), School of Civil, Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Tel: +61 8 6488 8182, Fax: +61 8 6488 1018, Email: yuxia.hu@uwa.edu.au

⁵ Director (PhD, MIEAust), Osen Group Pty Ltd, 7/2 Canning Highway, South Perth, WA 6151, Tel: +61 8 6161 9877, Email: ting.zhang@osen.com.au

• Number of Words: 6416 (text only)

• Number of Tables: 01

• Number of Figures: 14

Numerical simulation of plug formation during casing installation of PCC piles

Mi Zhou, Hanlong Liu, Muhammad Shazzad Hossain, Yuxia Hu and Ting
Zhang

Abstract: There is a historic lack of research examining inner soil plugging and outer lateral soil deformation during installation of pipe piles in clay. Furthermore, the influence of the pile tip geometry on soil deformation was not investigated. PCC concrete piles are a recent generation of pipe piles for soft ground improvement applications, and are casted-in-place by using an innovative double-walled steel casing with a tapered tip. This paper investigated the effect of the tip geometry on soil flow mechanisms inside and outside the PCC pile casing installing in clay. Large deformation finite element (LDFE) analysis was conducted simulating the continuous penetration process of the casing installation. The LDFE results were validated against (a) field monitoring data in terms of soil lateral displacement and heave outside the casing, and (b) centrifuge test data in terms of penetration resistance, with excellent agreement obtained. An extensive parametric study was then performed encompassing a practical range of parameters. The geometry of the casing tip was shown to have significant influence on the soil movements inside and outside of the casing, but minimal effect on the casing penetration resistance. The optimal tapered tip with a tip angle of 45° and minimal extended tip length beneath the tip angle allowed more soil to be pushed inside the casing and less lateral displacement outside the casing, which dictate the required concrete filling in the cavity inside the pile and the pile construction sequence. Design expressions were proposed for estimating soil movements inside and outside of the installing casing with optimal tip geometry.

55 **Key words:** pipe piles, casing installation, casing tip, clay, soil deformation, LDFE
56 analysis.

1. Introduction

1.1 PCC Pile and Construction Process

Recently, large diameter, cast-in-place concrete pipe (PCC) piles are increasingly used in soft ground improvement applications (improving the bearing capacity and reducing the settlement of soft ground) in particular as embankment piles for highway and railway construction and bridge abutments in China and Vietnam (Liu et al. 2007, 2009; Ding et al. 2011; Indraratna et al. 2015). The advantages of PCC piles over conventional piles used for soft ground improvement such as stone columns or cement mixing piles include (Liu et al. 2009; Indraratna et al. 2015):

- (a) Greater diameter, $D = 1\sim 1.5$ m (radius, $R = 0.5\sim 0.75$ m) compared to 0.5 m, and length, up to 25 m compared to 15 m;
- (b) Better quality with much more uniform cross section;
- (c) Easier quality checking either through excavation of the soil inside the pipe pile or by using nondestructive dynamic shear-wave methods;
- (d) Much better quality control with less uncertainties involved in the design and construction;
- (e) More economical with the cost of materials and installation of PCC pile per meter run about US\$22 and the cost per square meter of improvement about US\$25 compared to US\$50 and US\$27 respectively.

The wall thickness ratio of PCC piles of $t/R = 0.1\sim 0.3$ is one order of magnitude greater than that of commonly used steel pipe piles ($t/R = 0.02\sim 0.04$; API 2007). As the diameter of the pile is larger and the shaft friction develops along both inner and outer surfaces, the bearing capacity of PCC pile is generally much larger than other

types of pile. The PCC pile has a high shaft friction to concrete volume ratio (employing only 50% of the concrete of an equivalent solid concrete pile) and avoids the need for reinforcement to deal with handling and installation stresses; it therefore offers a cost-effective solution to resist compression loads (Xu et al. 2006). Note, however, PCC piles without any steel reinforcement are only applicable for compression loading.

For constructing PCC piles, an innovative steel casing was introduced featuring an outer pipe, an inner pipe, and a tapered tip (see Figure 1a). The tapered tip, equipped with hinged plates and an iron wire, forms a conical shape during installation of the casing, preventing soil entering the annulus of the casing. Subsequent opening of the hinged plates upon pouring concrete through the annulus allows for reaching the concrete down to the base of the casing, and hence achieving the designed pile length. The details of the construction procedures for a PCC pile, including installation of the casing, can be found in Liu et al. (2009). A brief summary is given below:

(1) Casing installation stage: the annular casing is installed into soft ground initially by jacking, followed by vibro-driving. The iron wire is broken by the friction from the adjacent soils. However, the ambient pressure from soil keeps the hinged plates remained close (i.e. forming a cone).

(2) Concrete pouring stage: Once the casing is installed to the designed depth, concrete is poured into the annulus of the casing. A concrete pressure head leads to break the wire (if it hasn't broken during installation) and open up the hinged plates.

(3) Casing withdrawing stage: When the casing annulus is filled with concrete, the casing is withdrawn from the ground using vibro-driving. The opened up

104 hinged plates facilitates easy withdrawing of the casing leaving the concrete
105 pipe pile in the ground. The vibro-driving action during withdrawing has the
106 additional benefit of concrete compaction.

107 (4) Any formed cavity inside the pile is filled with concrete while withdrawing the
108 shaft.

109 The procedures are illustrated in Figure 1b, with a photo of a PCC pile after the
110 completion of construction shown in Figure 1c. A standard PCC pile installation time
111 is about 15 minutes (Liu et al. 2009). The casing is reused for subsequent installation.
112 Note, the application of this installation method is limited to very weak soil deposits
113 or landfills.

114 The major concern during the casing installation is the soil plugging inside the casing,
115 hence the formation of a cavity near the top of the pile. Upon withdrawing the casing,
116 this cavity may allow the poured concrete flowing inside the pile prior to curing.
117 Importantly, the degree of soil plugging directly influences the pile capacity (i.e.
118 contributions from both end bearing and inner and outer frictional resistances),
119 installation radial total stress, and generation and distribution of excess pore pressure
120 (and hence the degree of strength regain of clay deposit within the set-up period). This
121 study focuses on the effect of the casing tip geometry on the soil plugging inside the
122 casing during installation. The tip geometric definitions are given in Figure 1d.
123 During casing installation, positive excess pore pressures are generated in the
124 surrounding clay. After construction of the PCC pile, consolidation or set-up occurs,
125 leading to increase in the shear strength of the clay and local effective stresses. The
126 amount of strength regain, the final radial effective stress acting on the PCC pile wall
127 and the timescale for consolidation all depend on the pore pressures generated, which

in turn are affected by the magnitude of outward soil movement during casing installation. The extent of lateral soil displacement also dictates pile spacing. After installation of a casing, the soil inside the casing gives an indication of inner friction and the additional concrete required to fill in the cavity.

1.2 Previous Work

For PCC pile casing installation, the topography of the ground heave, soil lateral displacement, and net increase in lateral earth pressure outside of the casing were addressed by Xu et al. (2006) and Liu et al. (2009) through field data, on instrumented casings, and analytical solutions. The soil lateral displacements were presented as a function of lateral distance from the casing centre and depth below the ground surface. It was noted that the PCC pile casing installation induced less ground heave than that of a solid pile, and the lateral soil distortion was limited to 10 mm at a distance of 3.5 m from the centre of the PCC pile (i.e. at $r = 7R$). However, all these observations were based on the designed geometry of the casing tip ($\beta = 60^\circ$ and $w = 0.108$ m) without exploring other tip geometries and soil properties.

A number of investigations have been carried out on relevant double-wall pipe pile installation through experimental and analytical work, mostly focusing on soil plugging and corresponding influence on end bearing and frictional resistances, radial stress and generation of excess pore pressure (Paikowsky et al. 1989; Paikowsky and Whitman 1990; Paik and Lee 1993; Choi and O'Neil 1997, Lehane and Gavin 2001; Gavin and Lehane 2003, Randolph 2003; Paik and Salgado 2003; Paik et al. 2003; Igoe et al. 2010, 2011; Iskander 2010, 2011; Doherty and Gavin 2011). Soil plugging was expressed by plug length ratio (PLR) and incremental filling ratio (IFR) defined respectively according to

152 [1]
$$PLR = \frac{L}{d_t}$$

153 [2]
$$IFR = \frac{\Delta L}{\Delta d_t}$$

154 where L is the length of the soil plug inside the installing pile or casing of length d_t ,
 155 ΔL is the increment of L due to increment of installation Δd_t . By definition, IFR is a
 156 first derivative of PLR , meaning that IFR is a slope of the L vs d_t curve. Most of the
 157 investigations are limited to pile installation in sand except Paikowsky et al. (1989)
 158 and Doherty and Gavin (2011). This historic lack of research examining the effects of
 159 plugging on the resistance of piles in clay is largely due to as, for general applications,
 160 piles are based in sand (contribution of end bearing in clay is a much smaller portion
 161 of the total capacity). Furthermore, the influence of the pile tip geometry was not
 162 explored although piles were sometimes equipped with a shoe attached to one of the
 163 double-wall pipes. The presence of the shoe resulted in significant reduction in the
 164 amount of plugging experienced during pile installation. The pile with a rounded tip
 165 pushed more soil outward compared to the pile with a flat tip. The installation radial
 166 total stress and excess pore pressure were shown to be directly related to the degree of
 167 soil plugging, and increased linearly as IFR reduced.

168 The unique feature of the PCC pile casing tip has created significant uncertainty
 169 regarding soil flow around the tip, and consequently in the prediction of soil
 170 movements inside and outside the casing. There are two geometric differences
 171 between the PCC pile casing and traditional steel pipe pile: (i) the conical shape of the
 172 tip formed by the hinged plates, and (ii) the larger wall thickness ratio (t/R). It is
 173 therefore imperative to provide insight into the effects of the casing tip geometry and
 174 large ratio of t/R on the mobilized soil flow mechanisms around the installing casing

base.

There have been investigations on caisson wall tip geometry and its effect on the soil movement during caisson installation. These were through field measurements during actual installation and finite element analyses (Audibert et al. 2003; Andersen et al. 2005; Clukey 2005; Zhou and Randolph 2007). In practice some caissons have been fabricated with an external taper or bevel at the tip in an attempt to push more soil outward during penetration (Newlin 2003; Audibert et al. 2003; Clukey 2005; Lee et al. 2005). The aim has been to reduce the inside heave based on the low ratios of caisson wall thickness to its radius (i.e. $t/R = 0.01\sim0.02$) and caisson penetration depth to its radius (i.e. $d/R = 4\sim14$). They concluded that a beveled tip (over full or half thickness of the skirt) is effective in terms of displacing more soil outside the caisson. During both self-weight and suction-assisted installation of caissons, the soil heave inside the caisson was about 20% less for the beveled caisson than for the flat-tipped one.

1.3 Objective of Present Study

This paper reports the results from an extensive investigation of the effect of PCC pile casing tip geometries on the soil movements inside and outside of the installing casing with relatively high ratios of t/R and d/R . Large deformation finite element (LDFE) analysis using the RITSS (i.e. remeshing and interpolation technique with small strain) method was conducted in an attempt to provide insight into the casing installation mechanisms in uniform clays. A detailed parametric study, varying the casing and its tip geometries and soil strength, leads to optimize the tip geometry to avoid plugging inside the casing during installation, and to develop expressions for estimating soil vertical and lateral movements outside the casing and soil plugging inside the casing.

In turn, these expressions can be used to design PCC pile construction sequence and to calculate the concrete volume required to fill the inside cavity.

2. Numerical Study

2.1 LDFE Analysis

Large deformation analyses were undertaken using RITSS (Hu and Randolph 1998a,b) coupled with the finite element package AFENA (Carter and Balaam 1995) developed at the University of Sydney. This method falls within what are known as arbitrary Lagrangian-Eulerian (ALE) finite element methods (Ghosh and Kikuchi 1991), whereby a series of small strain analysis increments (using AFENA) are combined with fully automatic remeshing of the entire domain, followed by interpolation of all field values (such as stresses and material properties) from the old mesh to the new mesh.

2.2 Geometry and Parameters

This study has considered a PCC pile annular casing of outside diameter D (radius R), inside diameter D_i (radius R_i), total thickness of casing t , penetrating into a uniform clay deposit as illustrated schematically in Figure 1d, with the undrained shear strength of clay, s_u , and effective unit weight γ' (considering the water table near the ground surface). The thickness of the inner pipe is t_1 . At the installation phase, the hinged plates form an angle β to the horizontal, and touch the inner pipe of the casing at a distance of w from the inner pipe tip (i.e. casing tip length).

In order to select realistic parameters, a survey was carried out through reported case histories of PCC pile installation (e.g. Liu et al. 2007, 2009). The diameter of piles, D , ranges from 1.0 to 1.5 m, and penetration depth, d , from 5 to 25 m (Liu et al. 2009;

Ding et al. 2011). The thickness of PCC pile casing, t , varies between 0.1 m and 0.15 m. The angle of the hinged plates are typically $\beta = 15^\circ$ to 75° , and the casing tip length is $w = 0.01$ to 1 m. The selected parameters for this study are assembled in Table 1, encompassing most cases of practical interest. A total of ~100 analyses were carried out. Computation times increased with increasing casing penetration depth. This is because the number of elements increased fairly sharply as a denser mesh was required to maintain beneath and around the penetrating casing to ensure computation accuracy. Typical computation times on a fast desktop computer were ~1 day and 3 days for a casing penetration of $13.75R$ and $27.5R$ respectively.

2.3 Analysis Details

The axisymmetric soil domain was chosen as $30D$ in diameter and $30D$ in depth. Hinge and roller boundary conditions were applied along the base and vertical sides of the soil domain respectively. Six-noded triangular elements with three internal Gauss points were used in all the FE analyses. The casing-soil interfaces were simulated using elastoplastic nodal joint elements (Herrmann 1978) distributed along the casing-soil contact. A typical mesh for the casing penetration in a uniform clay deposit is shown in Figure 2.

The simulation of penetration was achieved by specifying downward displacement increment of the rigid casing. At the casing interface the normal strength of the nodal joint elements was assigned as infinitely high to prevent any soil penetrating into the casing pipes or move ‘normally’ outward from any surface of the pipes once the soil was in contact with the surface, while soil movement along the surfaces was permitted. For ‘vertical penetration’ of the casing, it was deemed reasonable to assume that there was no development of tension between the advancing casing and

the contacted soil. The shear strength of the nodal joint elements was limited to αs_u , where α is the interface friction coefficient and s_u is the local undrained shear strength of the soil.

For extracting soil deformation δ_r , the original location of a fixed point was stored as a history variable. After each remeshing, the new/updated location of the fixed point was historically stored, and the deformation of the fixed point was calculated by using the new/updated coordinates and the original coordinates. For outside and inside soil heave δ_z and δ_{zi} , the coordinates of the new/updated boundary nodes were used to calculate the displacement of the boundary as the coordinates of the original soil surface are known.

The soil was modelled as a linear elastic-perfectly plastic material obeying a Tresca yield criterion. Considering the relatively fast jacking rate of casings in the field, all analyses simulated undrained soil conditions and adopted a Poisson's ratio $\nu = 0.49$ (sufficiently high to give minimal volumetric strain, while maintaining numerical stability) and friction and dilation angles $\phi = \psi = 0$ in total stress analysis. The geostatic stress conditions were modelled using $K_0 = 1$, with the corresponding influence addressed considering $K_0 = 0.8$.

Following the proposed model of Einav and Randolph (2005), the Tresca soil model can be extended in order to take the combined effects of rate dependency and softening (e.g. Hossain and Randolph 2009). However, for installation of casings, the rate dependency of the shear strength and strain softening should have negligible influence on the casing behavior as it can be mapped close to triaxial test (Randolph et al. 2007; Zhou et al. 2015). It is evident that the study by Xu et al. (2006) reported matching results to the field monitoring data without considering softening explicitly

in their model. Furthermore, for investigating installation of suction caissons, the effects of rate dependency and softening have not been modelled rather an interface friction coefficient α was used (Zhou and Randolph 2006; Chen et al. 2009; Westgate et al. 2009; Vásquez et al. 2010; Zhou et al. 2015). As such, those effects were not considered in the soil constitutive model implemented in this study, and an appropriate interface friction coefficient α was used.

3. Validation of Numerical Study

Field data of the distribution of soil displacement outside of a PCC casing were reported by Liu et al. (2009) as a function of lateral distance from the casing centre and penetration depth. The experimental site is located in a northern suburb of Shanghai on the deltaic deposit of the Yangtze River. The site consisted of three-layer deposit, including (from the surface): (i) 2 m layer of coarse-grained fill; (ii) 10 m thick deposit of soft silty clay; (iii) Pleistocene stiff clay. The undrained shear strengths were $s_u = 13.9$ kPa for the middle layer, and 28.6 kPa for the bottom layer (Liu et al. 2009). The clay sensitivity was $S_t = \sim 5$. This numerical model used in this study focuses on undrained response, and as such, for the top layer, a somewhat equivalent s_u of 18 kPa was considered. It was believed that the corresponding influence will be minimal as the top layer was thin (thickness = 2 m) compared to the casing installation depth of 15.3 m. The outer and inner diameter of the casing were $D = 1.02$ m ($R = 0.51$ m) and $D_i = 0.74$ m ($R_i = 0.37$ m) respectively, with the casing thickness $t = 0.14$ m ($t/R = 0.28$) and the casing tip (or inner pipe) thickness $t_1 = 0.01$ m. The hinged plates formed an angle of $\beta = 60^\circ$ with $w = 0.11$ m ($w/R = 0.22$). The depth of the pile was 15.3 m.

To monitor the ground responses during the casing installation, the soil deposit in the vicinity of the casing was highly instrumented with (a) five survey targets placed at radial distances of 1.5, 2, 3.5, 5 and 10 m from the casing centre to allow measurement of ground surface heave and lateral movement, (b) three inclinometers at radial distances of 1, 2, and 3.5 m to measure lateral ground movements, (c) six pressure cells in two columns at radial distances of 1 and 2 m and vertical depths of 3, 6, and 9 m to record lateral total stresses. Further details of instrumentation can be found in Liu et al. (2009).

Figure 3 shows a comparison between the field data and the LDFE/RITSS simulation using these parameters and adopting $\alpha = 0.1$ (Group I-A, Table 1). Figure 3a displays the evolution of the soil heave outside the casing, δ_z , with the casing tip penetration, d , at radial distances of $r/R = 2.94, 3.92, 6.86$ from the centre of the casing. Figures 3b and 3c plot the variation of soil lateral displacement, δ_r , with soil depth z from the ground surface at a lateral distance of $r/R = 1.96$ and 3.92 , respectively. These results are for the casing installation depth of $d/R = 5.69$. Excellent agreement can be seen between the computed and measured soil deformation over the breadth and depth of the soil domain near the installing casing.

Centrifuge test data for a PCC pile installing in clay with $s_u = 0.5 + 1.54z$ kPa were reported by Xu et al. (2006) and Zhang (2012). The kaolin clay deposit was first consolidated through centrifuge spinning at 250g, and then the tests were carried out at 125g, leading to an overconsolidation ratio of 2. The model pipe pile with a flat tip was made from duraluminium, with the surface roughened by means of sandblasting to model fully rough interface consistent to a PCC pile (see Figure 1c). The equivalent prototype outer diameter and thickness of the pile were $D = 1.28$ m and $t = 0.168$ m,

respectively. The result from the LDFE simulation (using these parameters and adopting $\alpha = 1.0$ to simulate fully rough interface; Group I-B, Table 1) is compared with a typical measured profile in Figure 4, with very good agreement obtained over the full penetration depths.

These validation analyses have confirmed the suitability of the LDFE/RITSS method in capturing the soil movements and assessing the penetration resistance during casing or pipe pile penetration in clay. Moreover, although the field soil and the clay used in the centrifuge test have sensitivity $S_t > 1$, without soil strain softening model, the LDFE results confirm that a suitable friction coefficient α can capture its effect for the casing installation problem. The results of the parametric study listed in Table 1 are discussed in detail below.

4. Parametric Study, Results and Discussion

For PCC pile casing installation in uniform clay, the soil flow mechanisms around the hinged plates and soil plug and deformation inside the casing are influenced by five factors, including (a) the penetration depth relative to the radius of the casing, d/R ; (b) the thickness relative to the radius of the casing, t/R ; (c) the casing tip length relative to the radius of the casing, w/R ; (d) the hinged plates angle, β ; and (e) the normalized soil strength, $s_u/\gamma'R$. In the following sub-sections, the discussion will focus on the effects of these factors on soil movements and casing penetration resistance.

4.1 Effect of Penetration Depth (d/R)

In order to illustrate the effect of normalized penetration depth on the soil failure mechanisms, a typical case is selected with relative thickness of $t/R = 0.24$, hinged plate angle $\beta = 75^\circ$, coefficient of friction $\alpha = 0.1$, and normalized strength $s_u/\gamma'R = 3.33$ (Group II, Table 1). With the progress of installation of the casing, two

341 interesting mechanisms are revealed, as illustrated in Figure 5 through plotting
342 instantaneous (resultant) velocity vectors. At shallow penetration ($d/R = 2$, Figure 5a),
343 the soil flow around the tip is directed predominantly outward, with slight inward
344 movement. Thus the soil outside the casing heaves up more profoundly than the soil
345 inside the casing. At this shallow penetration stage, the inner soil is heaved (i.e. not
346 'plugged' with any downward movement).

347 At deep penetration ($d/R = 21.2$, Figure 5b), two distinctive features are seen: (i) a
348 somewhat cavity expansion type failure is mobilized at the face of the hinged plate,
349 rather than flowing towards the surface, which augments radial stress on the adjacent
350 soil; and (ii) the inner soil is 'plugged' with downward movement. The latter is a
351 common and critical phenomena for driving pipe (or open ended) piles. The inner soil
352 cylinder develops sufficient resistance to prevent further soil intrusion and the pile
353 becomes 'plugged'. The inner soil heave becomes negative, which increases with
354 penetration depth. The plugged casing penetration mode is accompanied by larger soil
355 displacements outside the casing. The plugging phenomenon is not observed for
356 installation of offshore caissons (e.g. Zhou and Randolph 2007). Instead, the inside
357 soil heave is one of the key features that dictates the caisson installation depth. This is
358 because of its relatively much lower wall thickness ratio ($t/R \sim 0.02$) and shallower
359 penetration depth ($d/R < 4\sim 14$). The effects of wall thickness ratio and penetration
360 ratio on soil movements will be discussed in more details later.

361 The quantified soil heaves inside and outside the casing are displayed in Figure 6.
362 Figure 6a shows measured normalized inner soil heave, δ_{zi}/R , as a function of
363 normalized penetration depth, d/R ($\beta = 75^\circ$, $w/R = 0.4$, $t/R = 0.24$, $\alpha = 0.1$, $s_u/\gamma'R =$
364 3.33 , $I_r = 167$; Group II, Table 1). Shallow penetration depths were associated with

heaving of the inner soil above the original ground surface (positive δ_{zi}/R). The curve attains the peak at $d \sim 7R$ – just before the formation of the plug. With the progress of penetration ($d/R > 7$), the soil plug inside the casing moves downward with the casing and hence δ_{zi}/R reduces and becomes negative. This is critical in terms of supporting the concrete poured during the construction phase. Since the soil plug formation can generate a cavity inside the casing, which may allow the uncured concrete to flow inward after withdrawing the casing. The results are also presented in terms of PLR (Equation 1) in Figure 6b. With the progress of casing installation, similar to Figure 6a, PLR initially increases (> 1) as the inner soil heaves above the original ground surface, and then decreases and finally becomes < 1 with the formation of cavity.

Figure 6c illustrates the distribution of normalized outer soil heave, δ_z/R , corresponding to vertical penetration depth d/R and radial distance r/R . As observed from the soil flow patterns (Figure 5) and as expected, the soil heaving (or δ_z/R) reduces with increasing lateral distance from the casing centre, and increases with penetration depth. For instance, at $d/R = 20$ the heave is $\delta_z/R = 0.01$ for $r/R = 10$, which is about 96% lower compared to $\delta_z/R = 0.24$ for $r/R = 2$. At $r/R = 5$, the soil heave (δ_z/R) increases from zero at $d/R = 2$ to 0.03 at $d/R = 20$. For commonly used PCC piles ($d < 50R$), the soil heave becomes negligible ($\delta_z/R < 0.05$) for soil beyond the region of $r/R = 5$.

The lateral movement of soil during pile casing installation is the critical measure to assess the influence to the adjacent installed piles. To demonstrate the effect of penetration depth on normalized lateral displacement, δ_r/R , the distributions of soil lateral displacement along the soil depth are plotted in Figure 7 for a range of $d/R = 3 \sim 12$, but with identical soil strength $s_u/\gamma'R = 3.33$ and hinge plate angle $\beta = 75^\circ$ (w/R

389 $= 0.4$, $t/R = 0.24$, $\alpha = 0.1$; Group II, Table 1). For a relatively small radial distance of
390 $r/R = 4$ (Figure 7a), the δ_z/R profiles initially increase with increasing soil depth with
391 peak lateral displacements reached at the depth of plate tip penetration (i.e. at $z \sim d$).
392 For both flat and beveled tip caisson, Zhou and Randolph (2007) also reported peak
393 stresses at the penetration depth of the caisson tip. As the radial distance increases to
394 $r/R = 8$ (Figure 7b), the overall lateral displacements reduce significantly. The δ_z/R
395 profiles first reduce to their local minimums at $z \sim 2.5$ m, and then rise sharply to their
396 peaks at $z \sim d$, except for the short pile casing with $d = 3$ m due to limited penetration
397 depth. The peak displacements are about 1/3 compared to those for $r/R = 4$. The
398 magnitude of peak lateral displacement is of concern for installation design.

399 **4.2 Effect of Relative Thickness (t/R)**

400 In order to explore the effect of the relative (total) thickness of the casing on the
401 distribution of the inner and outer soil displacement, the normalized soil heaves inside
402 the casing of various relative casing thicknesses $t/R = 0.3$, 0.24 and 0.2 , with $w/R =$
403 0.02 , $s_u/\gamma R = 3.33$, $I_r = 167$, are plotted in Figure 8a for a constant hinge angle of $\beta =$
404 45° (Group III, Table 1). It is apparent that plugging occurs at a similar penetration
405 depth of $\sim 10R$ (compared to $d \sim 7R$ for $w/R = 0.4$; see Figure 6a). The maximum
406 heave increases with increasing casing thickness to accommodate greater volume of
407 the object penetrating in the ground. The rate of post peak reduction of δ_{zi}/R is greater
408 for higher t/R . The inside heaves reduce to the initial ground surface level at $d/R \sim 30$
409 for all three cases. Due to the higher heave reduction rate with the thicker pile casing,
410 it has more potential to have plugging effect with further penetration. The PLR in
411 Figure 8b shows a trend similar to Figure 8a. It should be noted that changes of PLR
412 depend on the volume of soil flowing from outside to inside of the casing or the

reverse, and the diameter of the casing. Consequently, the degree of changes is less profound in Figure 6b, but more profound in Figure 8b.

4.3 Effect of Hinged Plate Dimensions (w/R and β)

To examine the influence of w/R and β on the soil failure mechanisms, two groups of analyses have been carried out varying hinged plate dimensions, giving $w/R = 0.02$ and 0.4 and $\beta = 15\sim 75^\circ$, but with identical $s_u/\gamma'R = 3.33$, $t/R = 0.24$, $\alpha = 0.1$ and $I_r = 167$ (Groups IV and V, Table 1). Figure 9 shows the soil flow patterns for $w/R = 0.02$, 0.4 and $\beta = 30^\circ, 60^\circ$ at a shallow penetration depth of $d/R = 1.6$. By comparing Figure 9a with Figure 9b, for the same w/R of 0.4 , the effect of hinged plate angle β is not so obvious apart from slightly less heave difference between inside and outside the casing for lower plate angle β due to more downward soil movement beneath the plate. However, as w/R reduces to 0.02 (i.e. negligible or similar to flat tip pipe pile), for $\beta = 60^\circ$ the proportion of outward soil flow is greater than that of inward flow, leading to greater outer soil heave (see Figures 9a and 9c). The reverse is true for $\beta = 30^\circ$ (see Figures 9b and 9d), significant reduction of w/R (nearly negligible) has turned the direction of soil flow, and the soil is mostly flowing inward. This results in around triple soil heave inside the casing compared to that outside adjacent to the casing wall (Figure 9d). Therefore, it can be confirmed that the casing tip length has shielding effect on the soil flow mechanisms that prevents soil flowing inside the casing at shallow penetration depths. For identical w/R of 0.02 (Figures 9c and 9d), more soil is directed outward by greater plate angle. This is consistent with the findings from penetration of double-walled pile with a shoe (Paikowsky et al. 1989; Doherty and Gavin 2011) and of caisson with tapered tip (Zhou and Randolph, 2007).

At a deep penetration depth of $d/R = 21.2$, deep failure patterns mobilized with $\beta =$

437 15°, 45° and 75° and minimum casing tip $w/R = 0.02$ are illustrated in Figure 10. It
438 can be seen that the lower the plate angle, the greater the proportion of soil inward
439 movement (or the lower the outward deformation). This leads to increase the soil
440 plugging level inside the casing.

441 The soil heaves inside and outside the casing for all plate angles are presented in
442 Figure 11 with minimum casing tip ($w/R = 0.02$). An average plugging (inside soil
443 downward movement) depth can be assumed as $d/R \sim 8$ (see Figure 11a). The
444 proportion of soil inward movement prior to the plugging and subsequent rate of
445 vertical downward displacement increase with decreasing β . It is important to note
446 that, for casing with $\beta \leq 45^\circ$ and penetration $d/R \leq 22.5$, the inside soil movement,
447 δ_{zi}/R , remains positive. This means that there is no cavity formed inside the casing,
448 thus no additional concrete is required after the casing withdrawal. The reverse trend
449 is appeared in Figure 11a for soil heaving outside the casing δ_z/R , as is also observed
450 from the failure mechanisms. The lower plate angle is associated with predominant
451 soil deformation inside the casing and hence lower outside soil heaving.

452 Evolution of soil heave inside an installing caisson with $t/R = 0.02$, $w/R = 0$ and $\beta =$
453 76° , as reported by Zhou and Randolph (2007), is also included in Figure 11a for
454 comparison. For $d/R \leq \sim 8$, the results are slightly higher than the ones for the casing
455 with $t/R = 0.24$, $w/R = 0.02$ and $\beta = 75^\circ$. However, for $d/R > \sim 8$, soil plugging occurs
456 for the casing with significantly higher t/R , leading to decreasing δ_{zi}/R with increasing
457 d/R . In contrast, soil heaving continues to occur for the caisson with lower t/R ,
458 resulting in an increase in δ_{zi}/R with increasing d/R .

459 The effect of hinged plate angle β on lateral soil movements outside the casing is

presented in Figures 11c and 11d for shallow and deep casing penetrations respectively ($r/R = 2$, $t/R = 0.24$, $w/R = 0.02$, $\alpha = 0.1$, $s_u/\gamma'R = 3.33$, $I_r = 167$; Group V, Table 1). The lateral displacement profiles at both penetration depths ($d/R = 6$ and 21.3) show that the peak lateral displacement occurs at the level of the casing tip ($z \sim d$). For a shallow penetration depth ($d/R = 6$ in Figure 11c), the lateral displacement increases with increasing hinged plate angle, β at all soil depths, reflecting the influence of more laterally outward soil deformation (Figure 10a).

However, this trend is reversed with deeper penetration at $d/R = 21.3$ (Figure 11d). For $z/R \geq 14$, the peak lateral displacement reduces with increasing cone tip angle β . This feature attributes the fact that a lower cone tip angle corresponds to higher rate of heave reduction inside the pile (i.e. plugging) after its peak is reached at $d/R \sim 8$ (Figure 11a), resulting in more outward (cavity expansion type) flow and hence lateral displacement.

4.4 Effect of Normalized Soil Strength ($s_u/\gamma'R$)

In the above sections, normalized soil strength (or strength ratio) has been fixed as $s_u/\gamma'R = 3.33$ ($s_u = 10$ kPa). To examine the effect of soil strength ratio and soil stiffness, three cases with different soil strength ratios and two cases with different Young's modulus are investigated (Groups VI and VII, Table 1). Soil heaves inside the casing and lateral displacements outside the casing are plotted in Figure 12 ($t/R = 0.30$, $\beta = 45^\circ$, $w/R = 0.02$, $\alpha = 0.1$). From Figure 12a, the inner soil heaving occurs at a similar rate for all soils analyzed with stronger soil showing slightly lower heave at the peak. However, after the peak or onset of plugging at $d/R \sim 10$, the soil vertical downward displacement occurs at a similar rate, leading to earlier replenishing of

heave for stronger soil. Again, the *PLR* in Figure 12b shows a trend similar to Figure 12a.

Soil lateral movements are plotted in Figures 12c and 12d to show the effects of soil strength ratio and Young's modules. It is apparent that both soil strength ratio and Young's modules have minimal effects on soil lateral displacements.

5. Optimization of Casing Tip

Besides the study of soil movements discussed previously, the penetration resistance of pile casing during installation is also investigated. The influence of casing tip geometry on the casing penetration resistance is displayed in Figure 13. It is apparent that the effect of w/R is negligible and the effect of β is minimal. Three key components of total penetration resistance include tip bearing, inner and outer skin friction. For casing installation in uniform clay, though the tip geometry influences the vertical and lateral soil displacements inside and outside the casing, their effects on those three components of penetration resistance would have counterbalanced each other. Thus it is reasonable not to consider casing penetration resistance in casing tip geometry optimization.

Therefore, the optimization of the tip geometry should be based on (i) minimizing inner plugging (i.e. negative soil heave, δ_{zi}); and (ii) minimizing the extent of soil lateral displacement outside the casing. As noted previously, if soil plugging occurs, eventually δ_{zi} may be negative and a cavity may form above the plugged soil. Additional concrete will then be necessary to fill the cavity during withdrawal of the casing. Therefore, minimizing the cavity depth will minimize the required concrete volume. As noted previously, more inward flow will also increase the capacity of the constructed PCC pile (i.e. contributions from both end bearing and inner and outer

frictional resistances), and reduce the time to regain soil strength or increase the degree of strength regain of clay deposit within the set-up period (restricting generation and distribution of excess pore pressure).

If the extent of lateral soil displacement is large, the adjacent PCC pile construction may affect the previously installed piles before it is fully cured. If this is the case, the pile installation sequence needs to be staggered, which will complicate the installation process and increase the construction cost. The radial total stress will also be high.

Based on this discussion and the results presented, to ensure the quality and cost-effectiveness of PCC pile construction, it is suggested that the minimal tip length of $w = 0.01$ m should be used to eliminate the shielding effect, and hence to allow more inward soil flow. Smaller hinged plate angle β is beneficial for augmenting proportion of inner soil flow. However, very small angle may adversely increase the difficulty in opening up the plates during pouring concrete and subsequent casing withdrawal. Therefore, $\beta = 45^\circ$ is recommended as it gradually (nearly) replenishes the inner soil heave with the original ground surface for the commonly used PCC pile length of $d/R = 10\sim 50$ (Liu et al. 2007; Liu et al. 2009).

6. Design Guidelines on PCC Pile Construction

For designing PCC pile spacing and construction sequence, the extent of soil lateral displacement during installation of a casing should be estimated accurately and taken into account. Figure 14a shows the design chart for soil lateral displacement during PCC pile casing installation in $\delta_r/R_{eq} - r/R_{eq}$ space (where R_{eq} is the radius of solid pile with area equivalent to PCC pile). R_{eq} has introduced instead of R to compare this study results with the curve proposed by Randolph (2003) for steel or reinforced concrete pipe piles. The design curve in Figure 14b can be expressed by Equation 3

531 (through regression analysis) to formulate the soil lateral displacement (δ_r/R_{eq}) as a
 532 function of casing installation depth (d/R) and distance from the pile centre (r/R_{eq}).
 533 The common design criterion is that when the lateral displacement is below 10 mm (=
 534 0.01 m), its influence on an adjacent pile can be ignored (Liu et al. 2009). Based on
 535 this criterion and the most commonly installed PCC piles of $R_{eq} \sim 0.32$ m ($t=120$ mm,
 536 $D = 1$ m), the critical pile spacing ratio is $R_{cr} = 0.01/0.32 = 0.031$ as shown Figure 14a.
 537 For any pile spacing falling above the R_{cr} line, a staggered piling sequence might need
 538 to be considered.

539 The design formulas for soil heaves inside and outside the casing are expressed
 540 (through regression analysis) by Equations 4 and 5 with $R^2 = \sim 0.98$, based on the
 541 LDFE results in Figures 14c and 14d. Figure 14c shows clearly that, with the three
 542 casing relative thicknesses ($t/R = 0.3, 0.24$ and 0.13) studied, there is cavity formed
 543 inside the casing till penetration depth reaches $d/R = 30$ (or $d/D = 15$). The soil heave
 544 outside the casing (δ_z in Figure 14d) disappears very quickly when the radial distance
 545 (r) reaches half of the casing penetration depth ($0.5d$), which means the soil heave
 546 becomes less significant and expands over a wider zone with increasing radial
 547 distance from the pile.

548 [3]
$$\frac{\delta_r}{R_{eq}} = 0.17 \left[\left(\frac{r}{R_{eq}} \right) / \left(\frac{d}{R} \right)^{0.4} \right]^{1.32}$$

549 [4]
$$\frac{\delta_{zi}}{t} = 0.0022 \left(\frac{d}{R} \right)^3 - 0.1353 \left(\frac{d}{R} \right)^2 + 2.1949 \left(\frac{d}{R} \right) - 2.3755$$

550 [5]
$$\frac{\delta_z d}{R_{eq}^2} = 0.04 \left(\frac{r}{d} \right)^{-1.83}$$

Addition of more field data in Figures 14a~d may increase the robustness of the equations.

7. Effect of K_0

The results of all penetration analyses presented so far were obtained considering $K_0 = 1$. Analyses have also been performed considering $K_0 = 0.8$, as the value was used by Zhou and Randolph (2006, 2007) in (total stress) modelling continuous penetration of caissons. Figures 6a and 6c show inner and outer heave profiles, respectively, for $K_0 = 0.8$, as examples, along with corresponding results for $K_0 = 1$. Only small reductions in soil heaves and enhancement of cavity depth ($< 3\%$) were computed throughout full penetration.

8. Concluding Remarks

The effect of the tip geometry of PCC pile casing on soil movements during installation in uniform clay was investigated. An extensive parametric study was performed using large deformation FE (LDFE) analyses, varying casing (and hence PCC pile) diameter and thickness and its tip geometry (i.e. conical angle and tip length). The soil movements inside and outside the casing and extent of lateral distortion around the periphery of the installing casing were assessed, leading to optimization of the casing tip.

The tip geometry (β and w) was shown to have significant influence on soil movements, but negligible effect on casing penetration resistance. To minimize the soil plugging/cavity inside the casing, while maintaining easy opening of the hinged plates during pouring concrete, the optimal tip geometry was found to have its hinged plates angle $\beta = 45^\circ$ with minimal casing tip length of $w/R = 0.02$.

Design formulas (Equations 3~5) have been proposed to predict lateral extent of soil displacement and soil heaving inside and outside the casing during its penetration. The predicted lateral movement of soil outside the casing can be used to plan the spacing and sequence of PCC pile installation, and to ensure the quality of the installed PCC piles. The estimated depth of soil plugging or cavity above the plugged soil inside the installed casing can provide an indication of concrete required to fill the cavity.

9. Acknowledgements

The research presented here was undertaken with support from 111 Project of China (B13024), the Department of Industry, Innovation, Science, Research and Tertiary Education (DIISRTE) Australia China Science and Research Fund (Group Mission ACSRF00300) and the Australian Research Council (ARC) Discovery Grant (DP1096764). The third author is an ARC Discovery Early Career Researcher Award (DECRA) Fellow and is supported by the ARC Project DE140100903. The work forms part of the activities of the Centre for Offshore Foundation Systems (COFS), currently supported as a node of the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering and as a Centre of Excellence by the Lloyd's Register Foundation.

References

- Andersen, K., Murff, J., Randolph, M.F., Clukey, E.C., Erbrich, C.T., Jostad, H., Hansen, B., Aubeny, C., Sharma, P., and Supachawarote, C. 2005. Suction anchors for deepwater applications. *In Proc.*, 1st Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG), Perth, 3-30.
- API 2007. API Recommended practice 2A-WSD. American Petroleum Institute.
- Audibert, J.M.E., Clukey, E.C., and Huang, J. 2003. "Suction caisson installation at Horn Mountain – a case history." *In Proc.* 13th Int. Offshore and Polar Engineering Conference, Hawaii, 762-769.
- Carter, J.P., and Balaam, N.P. 1995. AFENA users' manual. Centre for Geotechnical Research, The University of Sydney.
- Choi, Y., and O'Neill, M. 1997. Soil plugging and relaxation in pipe pile during earthquake motion. *Journal of Geotechnical and Geoenvironmental Engineering*, **123**(10): 975-982.
- Clukey, E.C. 2005. Suction caisson soil displacement during installation. *In Proc.* Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG, 229-234. London: Taylor and Francis.
- Ding, X., Liu, H.L., Liu, J., and Chen, Y. 2011. Wave propagation in a pipe pile for low-strain integrity testing. *Journal of Engineering Mechanics*, **137**(9): 598-610.
- Doherty, P., and Gavin, K.G. 2011. Shaft capacity of open-ended piles in clay. *Journal of Geotechnical and Geoenvironmental Engineering*, **137**(11): 1090-1102.
- Gavin, K.G., and Lehane, B.M. 2003. The shaft capacity of pipe piles in sand. *Canadian Geotechnical Journal*, **40**: 36-45.

616 Ghosh, S. and Kikuchi, N. 1991. An arbitrary Lagrangian-Eulerian finite element
617 method for large deformation analysis of elasticviscoplastic solids. Comput.
618 Methods Appl. Mech. Engng, **86**(2): 127-188.

619 Herrmann, L.R. 1978. Finite element analysis of contact problems. Journal of the
620 Engineering Mechanics Division, ASCE, **104**(EM5): 1043-1057.

621 Hu, Y., and Randolph, M.F. 1998a. A practical numerical approach for large
622 deformation problems in soil. Int. J. Numerical and Analytical Methods in
623 Geomechanics, **22**(5): 327-350.

624 Hu, Y., and Randolph, M.F. 1998b. H-adaptive FE analysis of elasto-plastic non-
625 homogeneous soil with large deformation. Computers and Geotechnics, **23**(1-2):
626 61-83.

627 Igoe, D., Doherty, P., and Gavin, K.G. 2010. The development and testing of
628 aninstrumented open-ended model pile. Geotechnical Testing Journal, **33**(1): 72-
629 82.

630 Igoe, D., Gavin, K.G., and O’Kelly, B.C. 2011. Shaft capacity of open-ended piles in
631 sand. Journal of Geotechnical and Geoenvironmental Engineering, **137**(10): 903-
632 913.

633 Indraratna, B., Chu, J., and Rujikiatkamjorn, C. 2015. Applications of PCC piles for
634 highway and highway-speed railway construction in China. *In* Ground
635 improvement case histories: embankments with special reference to consolidation
636 and other physical methods. Elsevier Ltd., ISBN: 978-08-100192-9.

637 Iskander, M. 2010. Behaviour of pipe piles in sand. Springer, New York.

638 Iskander, M. 2011. On the design of instrumented double-wall model piles used to
639 investigate plugging of open-ended pipe piles. Geotechnical Testing Journal,
640 **34**(2): 1-8, GTJ103096.

641 Lee, Y.C., Audibert, J.M.E., and Tjok, K-M. 2005. Lessons learned from several
642 suction caisson installation projects in clay. *In* Proc. Int. Symp. on Frontiers in
643 Offshore Geotechnics, ISFOG, 235-241. London: Taylor and Francis.

644 Lehane, B.M., and Gavin, K.G. 2001. Base resistance of jacked pipe piles in sand.
645 *Journal of Geotechnical and Geoenvironmental Engineering*, **127**(6): 473-480.

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

649 Liu, H. L., Chu, J. C. J. and Deng, A. 2009. Use of large-diameter, cast-in situ
650 concrete pipe piles for embankment over soft clay. *Canadian Geotechnical*
651 *Journal*, **46**(8): 915-927.

652 Newlin, J.A. 2003. Suction anchor piles for the NA Kika FDS mooring system. Part
653 2: installation performance. *In* Proc. Conf. on Deepwater Mooring Systems:
654 Concepts, Design, Analysis, and Materials, ASCE, Houston, 55-77.

655 Paik, K., and Lee, S. 1993. Behavior of soil plugs in open-ended model piles driven
656 into sands. *Marine Georesource and Geotechnology*, **11**: 353-373.

657 Paik, K., and Salgado, R. 2003. Determination of bearing capacity of open-ended
658 piles in sand. *Journal of Geotechnical and Geoenvironmental Engineering*, **129**(1):
659 46-57.

660 Paik, K., Salgado, R., Lee, J., and Kim, B. 2003. Behavior of open- and closed-ended
661 piles driven into sands. *Journal of Geotechnical and Geoenvironmental*
662 *Engineering*, **129**(4): 296-306.

663 Paikowsky, S.G., Whitman, R.V., and Baligh, M.M. 1989. A new look at the
664 phenomenon of offshore pile plugging. *Marine Geotechnology*, **8**(3): 213-230.

665 Paikowsky, S.G., and Whitman, R.V. 1990. The effects of plugging on pile
666 performance and design. *Canadian Geotechnical Journal*, **27**(4): 429-440.

667 Randolph, M.F. 2003. Science and empiricism in pile foundation design.
668 *Geotechnique*, **53**(10): 847-876.

669 Randolph, M.F., Low, H.E., and Zhou, H. 2007. In situ testing for design of pipeline
670 and anchoring systems. Keynote Lecture, *In Proc. 6th Int. Offshore Site*
671 *Investigation and Geotechnics Conference: Confronting New Challenges and*
672 *Sharing Knowledge*, London, **1**: 251-262.

673 Xu, X., Lehane, B.M., Gaudin, C., Zhang, T., and Liu, H.L. 2006. Centrifuge studies
674 of single and group displacement piles in clay. *In Proc. 6th Int. Conf. on Physical*
675 *Modeling in Geotechnics*, Hong Kong, 895-900.

676 Zhang, T. 2012. The experiment and numerical study of reinforced mechanism of
677 large diameter cast-in-place concrete pipe pile. PhD Thesis, Hohai University.

678 Zhou, H., and Randolph, M.F. (2006). Large deformation analysis of suction caisson
679 installation in clay. *Canadian Geotechnical Journal*, **43**(12), 1344–1357.

680 Zhou, H., and Randolph, M.F. (2007). Effect of caisson-tip geometry on flow pattern
681 of foil plug. *In Proc. 6th Int. Offshore Site Investigation and Geotechnics*
682 *Conference: Confronting New Challenges and Sharing Knowledge*, London,
683 UK, 11-13.

684 Zhou, M., Hossain, M.S., Hu, Y., and Liu, H. (2015). Installation of stiffened caissons
685 in non-homogeneous clays. *Journal of Geotechnical and Geoenvironmental*
686 *Engineering*, ASCE, DOI: 10.1061/(ASCE)GT.1943-5606.0001381.

687 **List of Symbols**

688	A	projected area of pipe pile
689	D	outer diameter of PCC casing
690	D_i	inner diameter of PCC casing
691	d	penetration depth of base of hinged plates
692	d_t	penetration depth of tip of PCC casing
693	I_r	soil rigidity index
694	K_0	horizontal earth pressure coefficient
695	L	length of soil plug inside PCC casing
696	R	outer radius of PCC casing
697	R_{eq}	radius of solid pile with area equivalent to PCC pile
698	R_{cr}	critical ratio of pile spacing due to installation effect
699	R_i	inner radius of PCC casing
700	s_u	undrained shear strength of soil
701	t	total thickness of PCC casing
702	t_1	thickness of inner pipe of PCC casing
703	w	casing tip length - distance from inner pipe tip to base of hinged plates
704	z	depth below soil surface
705	α	coefficient of interface friction

706	β	angle of hinged plates to horizontal
707	δ_r	lateral (radial) displacement of soil outside PCC casing
708	δ_z	soil surface heave outside of PCC casing
709	δ_{zi}	soil surface vertical displacement inside PCC casing
710	γ'	effective unit weight of soil

711 **Number of Table: 1**

712 **Table 1. Summary of LDFE analyses performed**

713 **Number of Figure: 14**

714 **Figure 1** General view of PCC pile installation and geometry: (a) PCC pile
715 casing and tip; (b) Installation process; (c) PCC pile after construction;
716 (d) Geometric definitions of PCC pile casing

717 **Figure 2** Typical initial mesh for PCC pile casing installation (axes in m)

718 **Figure 3** Comparison of soil heave and lateral displacement from numerical
719 analysis and field measurement ($t/R = 0.26$, $\beta = 60^\circ$, $w/R = 0.2$, $\alpha =$
720 0.1 ; Group I-A, Table 1): (a) Soil heave outside casing; (b) Lateral
721 displacement at $r/R = 2$ and $d/R = 6$; (c) Lateral displacement at $r/R = 4$
722 and $d/R = 6$

723 **Figure 4** Comparison of penetration resistance between numerical result and
724 centrifuge test data ($t/R = 0.26$, $\beta = 0^\circ$, $w/R = 0$, $\alpha = 1.0$; Group I-B,
725 Table 1)

726 **Figure 5** Effect of normalized penetration depth on soil flow mechanism ($t/R =$
727 0.24 , $\beta = 75^\circ$, $w/R = 0.4$, $\alpha = 0.1$; Group II, Table 1); (a) $d/R = 2.0$; (b)
728 $d/R = 21.2$

729 **Figure 6** Effect of normalized penetration depth on inner and outer soil heave
730 ($t/R = 0.24$, $\beta = 75^\circ$, $w/R = 0.4$, $\alpha = 0.1$; Group II, Table 1): (a) Soil
731 movement inside casing; (b) Plug length ratio (PLR , Equation 1); (c)
732 Soil heave outside casing

733 **Figure 7** Effect of penetration depth on lateral displacement outside casing (t/R
734 $= 0.24$, $\beta = 75^\circ$, $w/R = 0.4$, $\alpha = 0.1$; Group II, Table 1): (a) $r/R = 4$; (b)
735 $r/R = 8$

736 **Figure 8** Effect of relative thickness on inside soil movement ($t/R = 0.24$, $\beta =$
737 45° , $w/R = 0.02$, $\alpha = 0.1$; Group III, Table 1): (a) Soil movement inside
738 casing; (b) Plug length ratio (PLR , Equation 1)

739 **Figure 9** Effect of hinged plate dimensions on soil flow mechanisms in shallow
740 penetration stage of $d/R = 1.6$ ($t/R = 0.24$, $\alpha = 0.1$; Groups IV and V,
741 Table 1): (a) $w/R = 0.4$, $\beta = 60^\circ$; (b) $w/R = 0.4$, $\beta = 30^\circ$; (c) $w/R = 0.02$,
742 $\beta = 60^\circ$; (d) $w/R = 0.02$, $\beta = 30^\circ$

743 **Figure 10** Effect of hinged plate angle on soil flow mechanism in deep
744 penetration stage of $d/R = 21.2$ with minimum casing tip $w/R = 0.02$
745 ($t/R = 0.24$, $\alpha = 0.1$; Group V, Table 1): (a) $\beta = 15^\circ$; (b) $\beta = 45^\circ$; (c) $\beta =$
746 75°

747 **Figure 11** Effect of hinged plate angle on soil movement ($t/R = 0.24$, $w/R = 0.02$,
748 $\alpha = 0.1$; Group V, Table 1): (a) Soil movement inside casing; (b) Soil
749 heave outside casing (at penetration depth $d/R = 21.2$); (c) Lateral
750 displacement at $d/R = 6$ and $r/R = 4$; (d) Lateral displacement at $d/R =$
751 21.2 and $r/R = 4$

752 **Figure 12** Effect of soil strength and Young's modules on soil deformation ($t/R =$
753 0.30 , $\beta = 45^\circ$, $w/R = 0.02$, $\alpha = 0.1$; Groups VII and VIII, Table 1); (a)
754 Soil movement inside casing; (b) Plug length ratio (PLR , Equation 1);
755 (c) Lateral displacement at $r/R = 4$ and $d/R = 24$; (d) Lateral
756 displacement at $r/R = 4$ and $d/R = 12$

757 **Figure 13** Effect of casing tip geometry on penetration resistance ($t/R = 0.24$, w/R
758 $= 0.02$, $\alpha = 0.1$; Group VI, Table 1); (a) Effect of w/R ; (b) Effect of β

759 **Figure 14** Design chart for estimating soil deformation during PCC pile casing
760 installation: (a) Lateral displacement of soil; (b) Design chart of lateral
761 displacement of soil; (c) Soil movement inside casing; (d) Soil heave
762 outside casing

Analysis	t/R^*	β (°)	w/R *	t_1 (mm)	α	$I_r = 0.33E/s_u\#$	$s_u/\gamma R$ #*	Notes
Group I-A	0.26	60	0.20	8	0.1	5 (top layer) 2.9 (mid layer) 10.1 (bottom layer)	--	Comparison with field test data
Group I-B	0.26	0	0	--	1.0	167	3.33	Comparison with centrifuge test data
Group II	0.24	75	0.40	10	0.1	167	3.33	Investigation of the effect of penetration depth, d/R
Group III	0.30 0.24 0.20	45	0.02	10	0.1	167	3.33	Investigation of the effect of thickness, t/R
Group IV	0.24	75	0.02 0.40	10	0.1	167	3.33	Investigation of the effect of casing tip length, w/R
Group V	0.24	15 30 45 60 75	0.02 0.40	10	0.1	167	3.33	Investigation of the effect of hinged plate angle, β
Group VI	0.24	15 30 45 60 75	0.02 0.16 0.24	10	0.1	167	3.33	Investigation of tip geometry on penetration resistance, w/R and β
Group VII	0.30	45	0.02	10	0.1	167 333 500	3.33 6.66 9.99	Investigation of the effect of soil strength ratio $s_u/\gamma R$
Group VIII	0.30	45	0.02	10	0.1	1000 500	3.33	Investigation of the effect of soil Young's modulus E/s_u

* $R = 0.5$ m, (except 0.51 m in Group I)

$s_u = 10$ kPa, (except 10, 20 and 30 kPa in Group VII)

* $\gamma' = 6$ kN/m³

Number of Figure: 14

- Figure 1** General view of PCC pile installation and geometry: (a) PCC pile casing and tip; (b) Installation process; (c) PCC pile after construction; (d) Geometric definitions of PCC pile casing
- Figure 2** Typical initial mesh for PCC pile casing installation (axes in m)
- Figure 3** Comparison of soil heave and lateral displacement from numerical analysis and field measurement ($t/R = 0.26$, $\beta = 60^\circ$, $w/R = 0.2$, $\alpha = 0.1$; Group I-A, Table 1): (a) Soil heave outside casing; (b) Lateral displacement at $r/R = 2$ and $d/R = 6$; (c) Lateral displacement at $r/R = 4$ and $d/R = 6$
- Figure 4** Comparison of penetration resistance between numerical result and centrifuge test data ($t/R = 0.26$, $\beta = 0^\circ$, $w/R = 0$, $\alpha = 1.0$; Group I-B, Table 1)
- Figure 5** Effect of normalized penetration depth on soil flow mechanism ($t/R = 0.24$, $\beta = 75^\circ$, $w/R = 0.4$, $\alpha = 0.1$; Group II, Table 1): (a) $d/R = 2.0$; (b) $d/R = 21.2$
- Figure 6** Effect of normalized penetration depth on inner and outer soil heave ($t/R = 0.24$, $\beta = 75^\circ$, $w/R = 0.4$, $\alpha = 0.1$; Group II, Table 1): (a) Soil movement inside casing; (b) Plug length ratio (PLR , Equation 1); (c) Soil heave outside casing
- Figure 7** Effect of penetration depth on lateral displacement outside casing ($t/R = 0.24$, $\beta = 75^\circ$, $w/R = 0.4$, $\alpha = 0.1$; Group II, Table 1): (a) $r/R = 4$; (b) $r/R = 8$

- Figure 8** Effect of relative thickness on inside soil movement ($t/R = 0.24$, $\beta = 45^\circ$, $w/R = 0.02$, $\alpha = 0.1$; Group III, Table 1): (a) Soil movement inside casing; (b) Plug length ratio (PLR , Equation 1)
- Figure 9** Effect of hinged plate dimensions on soil flow mechanisms in shallow penetration stage of $d/R = 1.6$ ($t/R = 0.24$, $\alpha = 0.1$; Groups IV and V, Table 1): (a) $w/R = 0.4$, $\beta = 60^\circ$; (b) $w/R = 0.4$, $\beta = 30^\circ$; (c) $w/R = 0.02$, $\beta = 60^\circ$; (d) $w/R = 0.02$, $\beta = 30^\circ$
- Figure 10** Effect of hinged plate angle on soil flow mechanism in deep penetration stage of $d/R = 21.2$ with minimum casing tip $w/R = 0.02$ ($t/R = 0.24$, $\alpha = 0.1$; Group V, Table 1): (a) $\beta = 15^\circ$; (b) $\beta = 45^\circ$; (c) $\beta = 75^\circ$
- Figure 11** Effect of hinged plate angle on soil movement ($t/R = 0.24$, $w/R = 0.02$, $\alpha = 0.1$; Group V, Table 1): (a) Soil movement inside casing; (b) Soil heave outside casing (at penetration depth $d/R = 21.2$); (c) Lateral displacement at $d/R = 6$ and $r/R = 4$; (d) Lateral displacement at $d/R = 21.2$ and $r/R = 4$
- Figure 12** Effect of soil strength and Young's modules on soil deformation ($t/R = 0.30$, $\beta = 45^\circ$, $w/R = 0.02$, $\alpha = 0.1$; Groups VII and VIII, Table 1): (a) Soil movement inside casing; (b) Plug length ratio (PLR , Equation 1); (c) Lateral displacement at $r/R = 4$ and $d/R = 24$; (d) Lateral displacement at $r/R = 4$ and $d/R = 12$
- Figure 13** Effect of casing tip geometry on penetration resistance ($t/R = 0.24$, $w/R = 0.02$, $\alpha = 0.1$; Group VI, Table 1): (a) Effect of w/R ; (b) Effect of β

Figure 14 Design chart for estimating soil deformation during PCC pile casing installation: (a) Lateral displacement of soil; (b) Design chart of lateral displacement of soil; (c) Soil movement inside casing; (d) Soil heave outside casing

(a) PCC pile casing and casing tip

(b) Installation process

(c) PCC pile after construction

(d) Geometric definitions of PCC pile casing

Figure 1 General view of PCC pile installation and geometry

Figure 2 Typical initial mesh for PCC pile casing installation (axes in m)

(a) Soil heave outside casing

(b) Lateral displacement at $r/R = 2$ and $d/R = 6$

(c) Lateral displacement at $r/R = 4$ and $d/R = 6$

Figure 3 Comparison of soil heave and lateral displacement from numerical analysis and field measurement ($t/R = 0.26$, $\beta = 60^\circ$, $w/R = 0.2$, $\alpha = 0.1$; Group I-A, Table 1)

Figure 4 Comparison of penetration resistance between numerical result and centrifuge test data ($t/R = 0.26$, $\beta = 0^\circ$, $w/R = 0$, $\alpha = 1.0$; Group I-B, Table 1)

Figure 5 Effect of normalized penetration depth on soil flow mechanism ($t/R = 0.24$, $\beta = 75^\circ$, $w/R = 0.4$, $\alpha = 0.1$; Group II, Table 1)

(a) Soil movement inside casing

(b) Plug length ratio (PLR, Equation 1)

(c) Soil heave outside casing

Figure 6 Effect of normalized penetration depth on inner and outer soil heave

($t/R = 0.24, \beta = 75^\circ, w/R = 0.4, \alpha = 0.1$; Group II, Table 1)

(a) $r/R = 4$

(b) $r/R = 8$

Figure 7 Effect of penetration depth on lateral displacement outside casing (t/R

$= 0.24, \beta = 75^\circ, w/R = 0.4, \alpha = 0.1$; Group II, Table 1)

(a) Soil movement inside casing

(b) Plug length ratio (PLR, Equation 1)

Figure 8 Effect of relative thickness on inside soil movement ($t/R = 0.24$, $\beta = 45^\circ$, $w/R = 0.02$, $\alpha = 0.1$; Group III, Table 1)

(a) $w/R = 0.4$, $\beta = 60^\circ$ (axes in m)

(b) $w/R = 0.4$, $\beta = 30^\circ$ (axes in m)

Figure 9 Effect of hinged plate dimensions on soil flow mechanism in shallow penetration stage of $d/R = 1.6$ ($t/R = 0.24$, $\alpha = 0.1$; Groups IV and V, Table 1)

Figure 10 Effect of hinged plate angle on soil flow mechanism in deep penetration stage of $d/R = 21.2$ with minimum casing tip $w/R = 0.02$ ($t/R = 0.24$, $\alpha = 0.1$; Group V, Table 1)

(a) Soil movement inside casing

(b) Soil heave outside casing (at penetration depth $d/R = 21.2$)

(c) Lateral displacement at $d/R = 6$ and $r/R = 4$

(d) Lateral displacement at $d/R = 21.2$ and $r/R = 4$

Figure 11 Effect of hinged plate angle on soil movement ($t/R = 0.24$, $w/R = 0.02$, $\alpha = 0.1$; Group V, Table 1)

(a) Soil movement inside casing

(b) Plug length ratio (PLR, Equation 1)

(c) Lateral displacement at $r/R = 4$ and $d/R = 24$

(d) Lateral displacement at $r/R = 4$ and $d/R = 12$

Figure 12 Effect of soil strength and Young's modules on soil deformation ($t/R = 0.30$, $\beta = 45^\circ$, $w/R = 0.02$, $\alpha = 0.1$; Groups VII and VIII, Table 1)

(a) Effect of w/R

(b) Effect of β

Figure 13 Effect of casing tip geometry on penetration resistance ($t/R = 0.24$, $w/R = 0.02$, $\alpha = 0.1$; Group VI, Table 1)

(a) Lateral displacement of soil

(b) Design chart of lateral displacement of soil

(c) Soil movement inside casing

(d) Soil heave outside casing

Figure 14 Design chart for estimating soil deformation during PCC pile casing installation