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**Soil Flow Mechanisms of Full-Flow Penetrometers in Layered Clays
through Particle Image Velocimetry Analysis in Centrifuge Test**

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ABSTRACT

This paper reports the soil flow mechanisms observed in centrifuge tests around full-flow (T-bar and ball) penetrometers in layered clays. The layered clay samples consisted of soft-stiff, stiff-soft, soft-stiff-soft, and stiff-soft-stiff soil profiles. Particle image velocimetry (PIV), also known as digital image correlation (DIC), allowed accurate resolution of the flow mechanism around the faces of the T-bar and half-ball penetrated adjacent to a transparent window. For the T-bar, overall a full symmetrical rotational flow around the T-bar dominated the behavior. A novel *trapped cavity mechanism* was revealed in stiff clay layers, with the evolution of the trapped cavity being tracked. No soil plug was trapped at the base of the advancing T-bar regardless of penetration from stiff to soft layer or the reverse. For the ball, two key features of the soil flow mechanism were identified, including (i) a combination of vertical flow, cavity expansion type flow and rotational flow for a fully embedded ball; and (ii) a stiff soil plug trapped at the base of the ball advancing in a stiff-soft clay deposit. For both penetrometers, a squeezing mechanism mobilised as they approached a soft-stiff layer interface.

KEYWORDS: centrifuge modelling; penetrometers; clays; failure; site investigation

39 **NOTATION**

40	c_v	coefficient of consolidation
41	d	penetration depth of penetrometer tip
42	Δd	penetration depth interval
43	D	diameter of penetrometers (D_t for T-bar and D_b for ball)
44	D_s	diameter of shaft of ball penetrometer
45	$D_{t,c}$	diameter of miniature T-bar used for characterisation
46	$D_{b,c}$	diameter of miniature ball used for characterisation
47	h	layer thickness (h_1, h_2, h_3 for corresponding layer)
48	N_p	resistance factor of penetrometers (N_t for T-bar and N_b for ball)
49	q	measured resistance
50	q_{net}	net resistance of penetrometer
51	s_u	undrained shear strength (s_{u1}, s_{u2}, s_{u3} for corresponding layer)
52	t	vertical distance from penetrometer tip to layer interface
53	v	penetration velocity of penetrometers
54	$v_{\text{soil particle}}/v_{T\text{-bar}}$	penetration rate of traced soil element relative to T-bar penetration

- 55 x horizontal distance from centreline of penetrometer
- 56 γ' effective unit weight ($\gamma'_1, \gamma'_2, \gamma'_3$ for corresponding layer)

58 INTRODUCTION

59 Accurate characterisation of seabed sediments is crucial for safe and cost-effective design
 60 of offshore foundations. Recent exploration of hydrocarbon products in deep water has
 61 placed more reliance on in-situ site investigation testing, such as vane shear testing and
 62 push-in penetrometer testing, due to the difficulty and high cost in obtaining high-quality soil
 63 samples for laboratory tests. Unlike vane shear test, push-in penetrometers (cone, T-bar, ball)
 64 generally provide continuous or near-continuous resistance profile and hence higher
 65 resolution of soil strength profile and layer interfaces. This study focuses on the full-flow
 66 T-bar and ball penetrometers (Fig. 1; Randolph *et al.* 1998; Newson *et al.* 1999; Kelleher and
 67 Randolph 2005; Peuchen *et al.* 2005). The penetration resistance of full-flow penetrometers
 68 is primarily attributable to the soil flow around the probe. These penetrometers are
 69 increasingly being included in deep water soft soil characterisation program mainly due to (a)
 70 relatively large projected area (5~10 times larger than the cone penetrometer), giving high
 71 resolution of penetration resistance profile, and (b) negligible influence of overburden and
 72 pore pressure to the total resistance i.e. measured resistance q = total resistance = net
 73 resistance q_{net} . The undrained shear strength profile of fine-grained seabed sediments is
 74 therefore deduced according to

$$75 \quad [1] \quad s_u = \frac{q_{\text{net}}}{N_p}$$

76 where N_p is the penetrometer resistance factor (N_t for the T-bar and N_b for the ball). The

T-bar and ball penetrometers have also been the common tools for characterising fine-grained sediments in both centrifuge and 1g laboratory experiments (e.g. Hossain *et al.* 2011).

The evolving soil flow mechanisms along the penetrometer penetration depths dictate the values of N_p . However, due to the lack of experimental investigation, a priori assumption was made in terms of the flow mechanisms and corresponding analytical solutions have been derived. For the T-bar with a large length-diameter ratio (i.e. $4 \sim 6.25$), plasticity solutions for pile and pipe for shallow (Murff *et al.* 1989; Aubeny *et al.* 2005; Randolph and White 2008) and deep (Randolph and Houlsby 1984; Martin and Randolph 2006) embedment are considered. The assumed mechanisms are illustrated in Figs. 2a~2c. Analytical solutions for an embedded ball were reported by Randolph *et al.* (2000), with the assumed mechanism shown in Fig. 3a.

Recently, T-bar and ball penetration in clay is treated through large deformation finite element (LDFE) analysis. Pushing a plane strain cylinder bar continuously from the soil surface, White *et al.* (2010) found two mechanisms: shallow mechanism with an open cavity above the bar and deep flow-round mechanism around the fully embedded bar (Fig. 2d); while Tho *et al.* (2012) identified a trapped cavity above a smooth bar up to a penetration of $10D_t$ in a relatively stiff clay ($s_u/\gamma' D_t > 3$, where γ' is the soil effective unit weight and D_t is the bar diameter; Fig. 2e). The trapped cavity leads to a 12% lower N_t compared to a flow-round mechanism, indicating that the soil strength could be underestimated if the resistance factor for a flow-round mechanism is adopted. No investigation has been carried

97 out on T-bar penetration in layered clays.

98 For the ball penetrometer in single layer clay, LDFE analyses for a pre-embedded ball have
99 been performed by Zhou and Randolph (2009) and Zhou and Randolph (2011), with the latter
100 focused on the effect of the shaft-ball area ratio ($a = D_s^2/D_b^2$; where D_s is the shaft diameter
101 and D_b is the ball diameter). A combined mechanism of cavity expansion and localised
102 backflow was exposed, as shown in Fig. 3b. The resistance factor N_b for a ball with a shaft, as
103 has also been investigated by Zhou *et al.* (2013, 2016), was shown to be lower than that of a
104 spherical ball ($a = 0$).

105 The ball penetrometer (including a shaft) penetrating continuously from the surface of single
106 layer and soft-stiff and stiff-soft clay deposits has been investigated by Zhou *et al.* (2013,
107 2016) through numerical analysis. A shallow mechanism with an open cavity above the
108 penetrating ball and a deep flow-round mechanism along with a sustained cavity above were
109 reported. The effect of soil layering on the mobilised flow mechanisms, and critically on
110 trapping of a stiff soil plug beneath the advancing ball, was shown to be significant.

111 However, evolution of soil flow mechanisms with the penetration of the full-flow
112 penetrometers has yet to be revealed through direct observation and subsequent
113 quantification. Recently, half-model test against a window followed by particle image
114 velocimetry (PIV), also known as digital image correlation (DIC), analyses has been a
115 popular technique in centrifuge testing for revealing the true soil flow mechanisms (e.g.

Hossain and Randolph 2010; Paniagua *et al.* 2013; Arshad *et al.* 2014; Hossain 2014; Mo *et al.* 2015, 2017; Stanier *et al.* 2015). The technique has been adopted in this study for observing the true soil flow mechanisms around the advancing T-bar and ball penetrometers in layered clays. Of particular interest was to quantify the effect of soil layering on the mobilised soil flow mechanisms in soft-stiff, stiff-soft, soft-stiff-soft and stiff-soft-stiff deposits. The identified soil flow mechanisms have been compared with the conventional mechanisms based on the plasticity solutions.

CENTRIFUGE MODELLING

Incorrect modelling of the strength ratio, $s_u/\gamma'D$, will lead to inaccurate assessment of soil flow mechanisms, in particular the transition to localised flow around the penetrometer with backflow into the cavity (Hossain *et al.* 2005, Hossain and Randolph 2010). In this study, the soil stress profile with depth and heaving of the seabed surface as the penetrometer penetrates are most conveniently replicated by centrifuge modelling.

The experimental program was carried out at 50g in the beam centrifuge at the University of Western Australia (Randolph *et al.* 1991). The experimental set-up is shown in Fig. 4. A purposely designed PIV strongbox with a Plexiglas window was built to allow the observation of soil deformations through the window. The PIV box has an internal size of 337 mm (length) $\times$ 100 mm (width) $\times$ 299 mm (depth), and it was fitted tightly at one side of a standard strongbox of the beam centrifuge (see Figs. 4a and b). The window was facing the

135 opposite side of the standard strongbox where a camera was mounted for capturing images.

136 **Model penetrometers**

137 Two model penetrometers machined from duralumin were used (Fig. 5a). The surfaces of the
 138 penetrometers were relatively smooth ($1\sim6\ \mu\text{m}$; Lehane and White 2005). The model T-bar
 139 consisted of a cylindrical bar of diameter (D_t) 15 mm and length 100 mm ($0.75\ \text{m} \times 5\ \text{m}$ at 50
 140 g) with a 15 mm cylindrical shaft connected to the middle of the bar, which allowed to push
 141 one face of the bar adjacent to the strongbox window (and spanning across the PIV
 142 strongbox; see Fig. 4b), permitting the soil deformation to be captured by the camera. To seal
 143 the contact between the window and the probe face preventing any soil ingress, two O-ring
 144 strips were fitted into the machined grooves along the two opposite ends of the bar.

145 For the ball penetrometer, by contrast, a half-model of 20 mm diameter (D_b , 1 m at 50g)
 146 attached with a 10 mm half cylindrical shaft (D_s) facilitated penetration adjacent to the
 147 window. A 7 mm thick board was connected to the back of the shaft at 30 mm ($1.5D_b$) away
 148 from the half sphere. This was to strengthen the shaft, minimising potential backward
 149 bending, while allowing the soil to flow back around and above the penetrating ball. Again,
 150 an O-ring was fitted along the periphery of the flat face of the half-ball, and was compressed
 151 against the window during penetration.

152 The cylindrical bar and ball size of 15 mm and 20 mm, respectively, were chosen sufficiently
 153 large to allow reasonably detailed images of the soil flow patterns. A load cell was fitted in

between the top of the shaft of the penetrometers and the centrifuge actuator to measure load-penetration responses in the displacement controlled system.

Fig. 5b shows the schematic diagram of the two penetrometers in layered clay, with d referring to the distance from the tip of the probes to the surface of the soil and t to the distance from the invert of the penetrometer to the underlying soil layer interface. The layer shaded with light grey represents stiff layer, which is used consistently throughout the paper.

The T-bar and ball were penetrated at rates of $v = 0.2$ mm/s and 0.15 mm/s respectively, ensuring undrained conditions (Finnie and Randolph 1994) with a dimensionless velocity $V = vD/c_v = 37$ ($c_v = \sim 2.6$ m²/year) for both penetrometers, while allowing adequate picture taking frequency for PIV analysis.

Sample preparation and soil strength characterisation

Kaolin clay slurry was deaired and pre-consolidated under two final pressures of 100 and 400 kPa to produce soft and stiff clay samples respectively. According to the predesigned thicknesses of the layers (listed in Table 1), rectangular blocks were sliced from the pre-consolidated samples and slid in the PIV strongbox. To add texture to the white kaolin for PIV analysis and to track the deformation of one layer into another layer, green and black flock powders were sprinkled respectively on the stiff and soft clay layer sides facing the window (Dingle *et al.* 2008; Hossain and Randolph 2010).

Four boxes of soil samples were prepared with the layer profiles as soft-stiff, stiff-soft,

173 soft-stiff-soft, stiff-soft-stiff sediments (Table 1). In each box, characterisation tests were
 174 carried out in-flight using a miniature T-bar penetrometer, with model dimensions 5 mm in
 175 diameter ($D_{t,c}$) and 20 mm long, and a ball penetrometer, with a diameter of 9 mm ($D_{b,c}$) in
 176 model scale. The load cell for these miniature penetrometers was located just above the bar or
 177 ball. The T-bar and ball were penetrated at rates of 1 mm/s and 1.25 mm/s respectively,
 178 which were sufficiently fast to ensure undrained conditions in the kaolin clay (Finnie and
 179 Randolph 1994). The undrained shear strengths for the soft and stiff clay layers were deduced
 180 as 7.5 kPa and 29.1 kPa, respectively, using a T-bar resistance factor of 10.5 (Randolph and
 181 Houlsby 1984) and a ball resistance factor of 11.2 (for the shaft-ball diameter ratio of 0.5;
 182 Zhou and Randolph 2011). Note, only the penetration resistance of the layers with thickness
 183 sufficient to mobilise the full (ultimate) penetration resistance of those layers, precluding the
 184 influence of the adjacent layers, were considered for the strength calculation. Moisture
 185 content tests were conducted after all penetration tests. The effective unit weight (γ') of the
 186 soft layer was $\sim 7.0 \text{ kN/m}^3$ and that of the stiff layer was $\sim 7.4 \text{ kN/m}^3$.

187 **Image capture and PIV analysis**

188 A Prosilica GC2450C digital still camera was set up in continuous shooting mode to capture
 189 images of the penetrating penetrometer and the surrounding soil throughout the tests. The 5
 190 megapixel digital images were taken at every 0.05 mm penetration depth increment for both
 191 T-bar and ball penetrometers. A 50-mm grid consisting of 24 control points (black dot on a
 192 white background) was installed within the Plexiglas window. A centroiding technique, based

on the coordinates of the control points, was implemented to calibrate the image space to the object space. In this way, any subsequent image-space displacement of the control markers incurred by the camera movement was evaluated. Full details of the PIV and photogrammetric analysis can be found in White *et al.* (2003) and Stanier *et al.* (2015).

RESULTS AND DISCUSSION

Throughout this section, due to the symmetry of the penetrometers, soil failure mechanisms are presented using soil displacement vectors on the left and displacement contours on the right. The displacement fields were resulted from a penetration interval of $\Delta d = 2.2$ mm. The vectors were scaled up by a factor of 4 to provide a clear resolution. The displacement contours obtained through the normalisation of the soil displacement by the probe penetration interval ranged from 0.1 to 0.9.

Soil flow mechanisms: T-bar penetrometer

T-bar penetration in soft-stiff clay

Fig. 6 depicts the soil flow mechanisms in a two-layer soft-stiff clay deposit ($h_1/D_t = 12.4$, $s_{u2}/s_{u1} = 3.88$; B1, TB1; Table 1). The transition from a shallow mechanism with an open cavity to a stabilised deep full flow-round mechanism (Figs. 6a~6c) is observed in the top soft clay layer. At $d/D_t = 2$ (Fig. 6a), the soil flow is directed mostly downward, outward, followed by upward towards the surface, resulting in an open cavity above the advancing T-bar. The lateral soil displaced zone extends to $x/D_t = 1.8$. With the increase of penetration

212 depth and hence soil stress level ($d/D_t = 5.9$; Fig. 6b), the soil upward flow turns gradually to
 213 around the T-bar flow, leading to the closure of the cavity just above the T-bar. This inward
 214 movement of soil also narrows the cavity gap to $\sim 1/3 D_t$ at $\sim 1 D_t$ above the T-bar. At $d/D_t =$
 215 9.8 (Fig. 6c), the soil backflow above the T-bar closes the cavity completely and a full
 216 flow-round mechanism is observed. By comparing the observed flow-round mechanism with
 217 the analytical solution (Fig. 2a), similar features in the failure zone and streamlines can be
 218 identified. However, it is also noted that the velocity contours in Fig. 6c (right part) shows
 219 that the soil velocity under the T-bar is higher than that above the T-bar. This is due to the
 220 fact that soil behaves differently under compression and extension. In contrast, the plastic
 221 solution adopts a fourfold symmetry assumption, i.e. the flow field is identical below and
 222 above the T-bar.

223 With the T-bar proximity to the soft-stiff layer interface by $t/D_t = 0.4$ ($d/D_t = 11.8$; Fig. 6d), a
 224 squeezing out mechanism dominates the behavior being restricted by the underlying stiff clay
 225 layer with $s_{u2}/s_{u1} = 3.88$, leading to negligible deformation in the lower layer and of the layer
 226 interface. Therefore, a clean T-bar with no trapped soil plug enters the stiff clay layer. The
 227 soil flow gradually becomes localised, with the soft clay above the advancing T-bar being
 228 pushed up by the backfilled stiff clay ($d/D_t = 13.9$; Fig. 6e).

229 More insight of the mechanism in the top soft layer can be found through tracking the
 230 trajectory of a few typical soil elements. Five soil elements (M1~M5) at $\sim 4.4 D_t$ above the
 231 layer interface and five elements (N1~N5) at just $\sim 0.3 D_t$ above the interface were tracked, as

shown in Fig. 7. The lateral distances between the elements and the centerline of the T-bar are $x/D_t = 0.6, 0.7, 1, 2, 3$, respectively. The horizontal displacement (Δx) and vertical displacement (Δy) of each element due to the incremental penetration of the T-bar from $y_1/D_t = 3$ above to $y_2/D_t = 2.7$ below the original level of the element provide the whole trajectory of the element.

Fig. 8a shows the trajectories of soil elements M1~M5, indicating generally a rotational flow around path (e.g. for M1 labelled as $O \rightarrow A \rightarrow B \rightarrow C \rightarrow D$). As expected, larger soil movements are associated with the elements closer to the centerline. Downward movement becomes shallower and lateral outward movement shorter as the element is further away from the centerline (i.e. increasing x/D_t). As the T-bar approaches and leaves element M1, the normalised incremental horizontal ($\Delta x/D_t$) and vertical ($\Delta y/D_t$) displacements are plotted in Fig. 8b as a function of y/D_t ('-ve' means above the original level of the element). Both $\Delta x/D_t$ and $\Delta y/D_t$ change sharply, i.e. increase followed by decrease, only for $y/D_t = \pm 1$, which is termed as 'active zone'. For $\Delta y/D_t$, the peak value appears at $y/D_t = 0$ (at B in Fig. 8a) i.e. when the T-bar tip is at the original level of the element, while for $\Delta x/D_t$, the peak value appears at $y/D_t = 0.5$ (at C in Fig. 8a) i.e. when the center of the T-bar reaches the original level. Finally, element M1 eventually rests at $0.07D_t$ above and $0.13D_t$ away from its original location after being displaced by the T-bar penetration.

The tracked trajectories of the five elements near the soil layer interface (N1~N5 in Fig. 7) are shown in Fig. 9. The effect of squeezing can be quantified comparing the various features

252 of the trajectories in Fig. 9 (with the influence of the underlying stiff layer; $s_{u2}/s_{u1} = 3.88$)
 253 with those in Fig. 8 (without the influence of the underlying layer). As the T-bar approaches
 254 and leaves the elements, while trends of the trajectories are very similar, (i) the maximum
 255 downward movement of e.g. element N1 (at B in Fig. 9a) is around half of that of element
 256 M1 (at B in Fig. 8a); (ii) at point B, the maximum lateral displacement of element N1 is three
 257 times the vertical displacement (Fig. 9b), whereas that of element M1 is about the same as
 258 vertical displacement; and finally (iii) element N1 travels back close to its original position
 259 but element M1 does not with the stronger soil backflow at the soft-stiff interface. This
 260 phenomenon indicates that the degree of soil backflow is augmented due to the effect of
 261 squeezing where approaching an underlying stiff layer.

262 The observed trajectories of the soil elements are also compared with those from limit
 263 analysis in Fig. 10a for the soil particles at $x/D_t = 0.6, 0.7, 1$ (i.e. soil elements M1~M3 in
 264 Fig. 7, $\sim 4.4D_t$ away from the layer interface). The trajectories from the analytical solution by
 265 Martin and Randolph (2006) were calculated at $x/D_t = 0.6, 0.7, 1$ and plotted in terms of
 266 absolute coordinate by translating the starting point to the origin of the coordinate. Four
 267 features can be summarised from the comparison in Fig. 10a. First, the lateral movements
 268 from the limit analysis and centrifuge test are generally consistent, except for element M3.
 269 Second, there are large downward movements ($\Delta y/D_t > 0$) in the centrifuge test for all the
 270 elements considered, but no downward movement in the analytical solution. Third, the
 271 analytical solution presents a zero lateral movement (i.e. $\Delta x/D_t = 0$) at the end for all the

elements (M1~M3). However, in the centrifuge test, all the elements end with a positive lateral movement (i.e. $\Delta x/D_t > 0$). Fourth, the absolute total vertical displacement from the analytical solution is 2~3 times higher than that measured in the centrifuge test.

The differences identified from Fig. 10a largely reflect that the behavior in the rigid-plastic material considered in the analytical solution is different to that in the elasto-plastic soil used in the centrifuge test. Furthermore, the analytical solution started adopting a fourfold symmetric assumption i.e. considering an identical flow fields in compression and extension (i.e. under and above the T-bar). This contrasts the quantified different velocity contours under and above the penetrating T-bar from a centrifuge test (Fig. 6c), as noted previously.

The measured velocity of soil movement is illustrated through the ratio of particle velocity and T-bar velocity ($v_{\text{soil particle}}/v_{\text{T-bar}}$) in Fig. 10b. The relative positions of the soil particle and the T-bar at four points (A, B, C, D) in Fig. 8 are also shown in the inset plots of Fig. 10b. As the T-bar approaches and leaves element M1, the normalised velocity increases from 0.025 to 0.3 to 0.4 (A to B to C), forms a peak at around C, decreases to 0.18 (at D), followed by a drastic drop to 0.025 (i.e. inactive) when the top of the T-bar is below the initial level of element M1. In contrast, the maximum relative velocity ($v_{\text{soil particle}}/v_{\text{T-bar}}$) predicted by the analytical solution can exceed 1.

However, it should be noted that the above different features observed in the trajectories from the analytical solution and centrifuge test may not necessarily lead to a significant

discrepancy in corresponding bearing capacity factors. This is because the bearing capacity from the plastic theory is only related to the calculated dissipated work in the assumed deforming regions (mobilised zone around T-bar).

T-bar penetration in stiff-soft clay

Fig. 11 displays the soil flow mechanisms in a two-layer stiff-soft clay deposit ($h_1/D_t = 12.4$, $s_{u2}/s_{u1} = 0.26$; B2, TB2; Table 1). The soil flow mechanisms in the top stiff clay layer ($s_{u1}/\gamma'_1 D_t = 5.24$; without the influence of the underlying layer) are largely similar to those in the top soft clay layer of the soft-stiff clay deposit ($s_{u1}/\gamma'_1 D_t = 1.42$, Figs. 6a~c). The only exception, interestingly, is an enclosed open cavity trapped above the advancing T-bar in the stiff clay ($s_{u1}/\gamma'_1 D_t = 5.24$, Figs. 11b~c) for $d/D_t \geq 4.7$, hindering the mobilisation of the full flow-round mechanism. This phenomenon was also reported by Tho *et al.* (2012) through numerical analysis of a pipe penetration in uniform single layer clay with $s_u/\gamma' D_t > 3$, and the trapped cavity was termed as ‘deep cavity mechanism’ (i.e. ‘Gap’ in Fig. 2e).

With the progress of the T-bar penetration in the top stiff clay layer, the trapped cavity becomes narrower due to continual soil backflow. When the T-bar tip is at the layer interface ($d/D_t = 12.4$; Fig. 11d), the localised flow-round mechanism mobilises partly in the underlying soft layer, leading to the deformation of the layer boundary. At $d/D_t = 14$ (Fig. 11e) with the T-bar in the soft clay layer, a column of stiff clay formed above the T-bar maintains the trapped cavity. Eventually, the T-bar separates from the top stiff clay layer and

the trapped cavity disappears at $d/D_t = 14.7$ (Fig. 11f). In Figs. 11e and 11f, there is no stiff soil plug trapped at the base of the advancing T-bar with relatively smooth interface.

T-bar penetration in soft-stiff-soft and stiff-soft-stiff clays

The influence of three-layer clay with soft-stiff-soft layering on the evolution of the T-bar penetration mechanisms is illustrated in Fig. 12 ($h_1/D_t = 4.6$, $h_2/D_t = 5.3$, $s_{u2}/s_{u1} = 3.88$, $s_{u3}/s_{u2} = 0.26$; B3, TB3; Table 1). The squeezing mechanism in Fig. 12a is consistent to that presented in Fig. 6d for soft-stiff clay apart from earlier backflow owing to the earlier influence of the 2nd (stiff) layer caused by the thinner 1st layer ($h_1/D_t = 4.6$ in Fig. 12a vs. 12.4 in Fig. 6d). The mechanisms in Figs. 12b and 12c are very similar to what presented in Figs. 11d and 11e for stiff-soft clay apart from the absence of the trapped cavity. The existence of the top soft layer prevents the formation of a trapped cavity in the middle stiff layer (see Figs. 11c and 12b).

To examine the effect of three-layer clay with stiff-soft-stiff layering, the corresponding mobilised soil flow mechanisms are shown in Fig. 13 ($h_1/D_t = 5.2$, $h_2/D_t = 5$, $s_{u2}/s_{u1} = 0.26$, $s_{u3}/s_{u2} = 3.88$; B4, TB4; Table 1). For the 1st and 2nd stiff-soft layering ($s_{u2}/s_{u1} = 0.26$; $s_{u1}/\gamma'_1 D_t = 5.24$), the thin top stiff clay layer ($h_1/D_t = 5.2$) allows for earlier attraction of the soft layer immediately after the T-bar penetration. This delays the soil backflow and the soil deformation is directed predominantly vertically downward to the lower soft layer, leading to (i) an open cavity above the T-bar throughout the penetration in the top layer, and (ii)

329 deformation of the stiff-soft layer interface. The effect of the thickness of the top stiff layer
 330 can be seen by comparing Figs. 13b ($h_1/D_t = 5.2$) and 11b ($h_1/D_t = 12.4$) with identical
 331 strength ratio of $s_{u1}/\gamma'_1 D_t = 5.24$ and penetration depth of $d/D_t = 4.7$. The formation of the
 332 trapped cavity observed in the thick top stiff layer ($h_1/D_t = 12.4$, Fig. 11b) is absent in the thin
 333 top stiff layer ($h_1/D_t = 5.2$, Fig. 13b). This reflects the earlier influence of the underlying soft
 334 layer. The soil starts to flow back and covers the top of the T-bar (Fig. 13c). This is also
 335 consistent with the observation of Hossain and Randolph (2010) for a spudcan penetration in
 336 stiff-soft clay deposits. The mechanisms in Figs. 13c~13e are similar to Figs. 11d~11f apart
 337 from the absence of the trapped cavity above the T-bar. At the soft-stiff layer interface (i.e.
 338 2nd-3rd layering, $s_{u3}/s_{u2} = 3.88$), the squeezing mechanisms illustrated in Figs. 13f and 13g are
 339 consistent with those in Figs. 6d and 6e.

340 The influence of the mechanisms observed in Fig. 13 on the corresponding T-bar penetration
 341 resistance profile (TB4) is displayed in Fig. 14, with the locations of the soil flow
 342 mechanisms highlighted. It should be noted that the penetration resistance was measured at
 343 the top of the T-bar shaft, hence soil-shaft interaction was included in the measurement. In
 344 the top thin stiff layer, the penetration resistance profile keeps increasing with shallow failure
 345 gradually changing to deep failure. The sharp reduction in resistance results from the T-bar
 346 entering the soft clay layer. This influence from the middle soft layer can be observed in the
 347 soil flow mechanisms plotted in Figs. 13c~13e. As the proportion of the soft soil in the
 348 mobilised soil flow increases, the T-bar resistance decreases continuously while penetrating

in the middle soft layer. Once the top stiff soil separates from the advancing T-bar (Fig. 13e), the full flow-round mechanism occurs in the middle soft layer. As such, the T-bar resistance approaches the stable resistance of the soft layer. With further penetration of the T-bar (see Figs. 13f~g), the soil flow mechanism starts to involve the bottom stiff soil, hence the penetration resistance increases with increasing the involvement of the stiff soil. Clearly, the soil layering and mobilised soil flow mechanisms have significant influence on the penetration resistance profile, which should be taken into account in the interpretation of shear strength from the measured penetration resistance profile. For instance, due to the thin top layer ($h_1/D_t = 5.2$), the measured maximum resistance in the top layer is significantly lower than that at $d/D_t = 13.5$ in the bottom layer. Using a constant resistance factor would lead to significantly lower undrained shear strength of the top layer.

In summary, eight interesting features are observed in the mobilised soil flow mechanisms with the T-bar penetration in different clay layer profiles, which should influence the T-bar resistance factor and hence the interpretation of shear strength. These features include: (i) the symmetric rotational flow around the T-bar during its penetration; (ii) an open cavity with subsequent backflow induced full flow-around mechanism in the top soft clay layers (1st layer in TB1 and TB3, $s_{ul}/\gamma'_1 D_t = 1.42$, $h_1/D_t = 12.4$ and 4.6); (iii) an open cavity and a trapped cavity above the advancing T-bar in the thick top stiff layer (1st layer in TB2, $s_{ul}/\gamma'_1 D_t = 5.24$, $h_1/D_t = 12.4$); (iv) a deeper open cavity with delayed backflow in the thin top stiff layer (1st layer in TB4, $s_{ul}/\gamma'_1 D_t = 5.24$, $h_1/D_t = 5.2$); (v) squeezing mechanism close to the soft-stiff

interface with negligible deformation of the layer boundary; (vi) bending of the stiff-soft layer interface in the underlying soft layer; (vii) no trapping of soil plug at the base of the advancing T-bar regardless of penetration from stiff to soft layer or the reverse; (viii) a column of soil above the T-bar from the overlaying layer gradually being detached from the overlying layer with the progress of penetration.

By comparing with the existing soil flow mechanisms from limit analyses (i.e. shallow penetration mechanism in Fig. 2c and full flow-round mechanism for deep penetration in Fig. 2a), the observed soil flow mechanisms in thick soft clay layer illustrated in Figs. 6a and 6c are similar to the plasticity solutions. However, all other soil flow mechanisms observed in single stiff clay layer and in layered clays are remarkably different from the plasticity solutions. This necessitates the establishment of a new interpretation framework based on T-bar resistance factors associated with the revealed soil flow mechanisms.

Soil flow mechanisms: ball penetrometer

The soil flow mechanisms for the axisymmetric ball penetrometer will be discussed in this section in comparison with those for the plane strain T-bar presented in Figs. 6~13.

Ball penetration in soft-stiff clay

Fig. 15 displays the soil flow mechanisms in a two-layer soft-stiff clay deposit ($h_1/D_b = 9.3$, $s_{u2}/s_{u1} = 3.88$; B1, Ball1; Table 1). A shallow failure mechanism in Fig. 15a leads to a cavity formation above the ball. The cavity is closed up when a deep penetration is reached in Fig.

15c. Compared to the deep mechanism with a full flow-round for the T-bar (Fig. 6c), the deep mechanism for the ball shows dominant downward soil flow underneath the penetrometer with insignificant soil movement above it (Fig. 15c). This dominant downward flow leads to a classical cavity expansion type failure beneath the ball. To further explore the deep mechanism around the ball in Fig. 15c, streamlines of soil flow around the ball are presented in Fig. 16 (i.e. the left side). Based on the streamlines, the displacement field can be divided into three zones: (i) A-zone in the extension line of the shaft; (ii) B-zone between A-zone and H-line, where H-line is the horizontal level $0.3D_b$ above the ball invert; (iii) C-zone between H-line and the ball shaft. The soil in A-zone directs predominantly downward, and the soil in C-zone flows around the ball that induces soil backflow and hence closes the cavity. The soil in B-zone flows downward followed by laterally outward, which is a cavity expansion type failure.

A squeezing mechanism mobilises when the ball approaches the soft-stiff soil layer interface (Fig. 15d). As the ball enters the bottom stiff clay layer (Fig. 15e), the predominant soil flow occurs in the bottom stiff layer (i.e. below H-line) without any trapped soft soil plug at the base of the ball. The absence of the trapped soft upper soil layer in the lower stiff layer is consistent with the T-bar penetration.

Ball penetration in stiff-soft clay

Fig. 17 shows the soil flow mechanisms during the ball penetration in a two-layer stiff-soft clay deposit ($h_1/D_b = 9.3$, $s_{u2}/s_{u1} = 0.26$; B2, Ball2; Table 1). The soil flow mechanism in Fig.

17a for the top stiff clay ($s_{u1}/\gamma'_1 D_b = 3.93$) is very similar to that in Fig 15c for the top soft clay ($s_{u1}/\gamma'_1 D_b = 1.07$). However, the extension of soil displacement is deeper in Fig. 17a due to attraction of the lower soft layer. Different from the trapped cavity formation observed in Fig. 11c for the T-bar ($s_{u1}/\gamma'_1 D_t = 5.24$), no trapped cavity can be seen in Fig. 17a for the ball. As the ball approaches and passes through the stiff-soft layer interface (Figs. 17b~d), the soil flow is predominantly directed vertically downward to the lower layer with no upward movement. This leads to the deformation of the layer interface and the trapping of a stiff clay plug at the base of the ball advancing in the bottom soft clay layer. Note, by contrast, no stiff soil plug is trapped at the base of the plane strain T-bar.

Ball penetration in soft-stiff-soft and stiff-soft-stiff clays

The evolution of soil flow mechanisms during the ball penetration in a three-layer clay with soft-stiff-soft layering is illustrated in Fig. 18 ($h_1/D_b = 3.4$, $h_2/D_b = 4.0$, $s_{u2}/s_{u1} = 3.88$, $s_{u3}/s_{u2} = 0.26$; B3, Ball3; Table 1). In the 1st-2nd clay layers (i.e. soft-stiff), the soil flow mechanisms in Figs. 18a~b are consistent to the patterns illustrated in Figs. 15d~e for the soft-stiff clay deposit. In the 2nd-3rd layers (i.e. stiff-soft), the predominant downward soil deformation pattern and trapping of a stiff soil plug at the base of the ball in Figs. 18c and d are similar to those in Figs. 17c and d. The stiff soil column formed above the ball is present up to $d/D_b = 9.8$ i.e. $2.4D_b$ penetration in the bottom soft layer (Fig. 18d).

The corresponding soil flow mechanisms during the ball penetration in the three-layer clay

with stiff-soft-stiff layering are shown in Fig. 19 ($h_1/D_b = 3.9$, $h_2/D_b = 3.7$, $s_{u2}/s_{u1} = 0.26$, $s_{u3}/s_{u2} = 3.88$; B4, Ball4; Table 1). The thin top stiff layer shows long column of stiff clay follows the ball into the middle soft layer, which is similar to the thin stiff layer in Fig. 18d. However, in Figs. 19a~d, the open cavity remains above the penetrating ball when it enters the middle soft layer. This is due to the thin top stiff layer and the effect of the soft middle layer as discussed in the T-bar section (Figs. 13a~c). With the progress of the ball penetration in the 2nd (soft) layer (Figs. 19d~f), the cavity is replenished, and the stiff soil column is separated from the ball. As the ball passes through the 2nd to 3rd (i.e. soft to stiff) layers, the squeezing mechanism and its entrance to the bottom soft layer (Figs. 19g and h) are the same as those observed in the soft-stiff clay deposit (Figs. 15d and e).

In summary, for the axi-symmetric ball, there are three main contrasting features compared to the plane strain T-bar. First, for a deeply embedded ball, the soil flow mechanism is a combination of vertical flow in A-zone, cavity expansion type flow in B-zone and rotational flow around mechanisms in C-zone (i.e. in the top $0.7D_b$ section of the ball) instead of a flow-round mechanism. Second, no trapped cavity can be found above the advancing ball. Third, with the ball passing through the stiff-soft interfaces, a stiff soil plug is observed at the base of the ball advancing in the soft layer, which means the axi-symmetric ball penetrometer is more prone to trapping a soil plug.

In contrast to the mechanisms in plasticity solutions (Fig. 3), where a full flow-round mechanism is displayed, three soil flow zones are observed in the centrifuge test for the

deeply embedded ball. The zones consist of vertical flow, cavity expansion flow and rotational flow. This combined soil flow mechanism around the penetrating ball should play an important role in the ball penetration resistance profiles in layered clay deposits.

CONCLUDING REMARKS

This paper presents the soil flow mechanisms from a series of centrifuges tests on T-bar and ball penetrations in soft-stiff, stiff-soft, soft-stiff-soft, and stiff-soft-stiff clay deposits. Digital images of the T-bar and ball penetrating through the layered clay samples against a transparent window were captured by using a high-speed camera. The particle image velocimetry (PIV), also known as digital image correlation (DIC), technique was adopted to process the images aiming at quantifying the soil displacement field around the full-flow penetrometers during their penetration tests. In turn, the evolution of soil flow mechanisms during the continuous penetration of the penetrometers was characterised. The key conclusions drawn from the revealed mechanisms are listed below.

For the T-bar penetrometer, it was found that

1. Overall a full symmetrical rotational flow-round the T-bar dominated the T-bar behavior.
2. A trapped cavity mechanism was mobilised above the advancing T-bar in the stiff clays.
3. Regardless of stiff-soft or soft-stiff layering, no trapped soil plug from the upper layer

was observed at the base of the advancing T-bar and pushed into the lower layer.

4. A squeezing mechanism was mobilised as the T-bar approached a soft-stiff layer interface; and an interface downward bending was occurred as the T-bar approached a stiff-soft interface.

For the ball penetrometer, most of the mobilised soil flow patterns were similar to those for the T-bar as both are full-flow penetrometers. Only a few different features were identified due to the axisymmetric ball compared to the plane strain T-bar:

1. A combination of vertical flow, cavity expansion type flow and rotational flow dominated the ball behavior.
2. No trapped cavity was formed above the ball penetrating through any clay deposit.
3. For stiff-soft layering, a stiff soil plug was trapped at the base of the advancing ball, which was forced into the underlying soft layer.

Finally, the revealed soil flow mechanisms contrasted the mechanisms in conventionally used analytical solutions. Future extensive parametric studies are therefore needed to establish a framework for more accurate interpretation of undrained shear strength from full-flow penetrometer data.

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569

Table 1. Centrifuge test program

Box	Test	Soil description	Layer thickness								
			h_1^*	$h_1^\dagger$	$h_1/D_t^\#$	h_2^*	$h_2^\dagger$	h_2/D_t	h_3^*	$h_3^\dagger$	h_3/D_t
			(mm)	(m)	$h_1/D_b^\#$	(mm)	(m)	h_2/D_b	(mm)	(m)	h_3/D_b
B1	TB1	Soft-stiff	185.4	9.27	12.4	84.6	4.23	5.6	--		
	Ball1				9.3			4.2			
B2	TB2	Stiff-soft	185.9	9.295	12.4	84.1	4.205	5.6	--		
	Ball2				9.3			4.2			
B3	TB3	Soft-stiff-soft	68.4	3.42	4.6	79.8	3.99	5.3	121.8	6.09	8.1
	Ball3				3.4			4.0			6.1
B4	TB4	Stiff-soft-stiff	77.4	3.87	5.2	74.9	3.745	5.0	117.7	5.885	7.8
	Ball4				3.9			3.7			5.9

* Model scale

† Prototype scale

Normalised by the diameter of the T-bar and ball used for exposing soil flow mechanisms

Number of Figure: 19

Fig. 1. Push-in penetrometers in field investigation and centrifuge testing

Fig. 2. Existing mechanisms for T-bar penetrometer: (a) full-flow mechanism (modified from Randolph and Houlsby 1984); (b) pre-embedment less than half diameter (modified from Murff *et al.* 1989); (c) pre-embedment larger than half diameter (modified from Aubeny *et al.* 2005); (d) shallow failure mechanism and flow-round mechanism (modified from White *et al.* 2010); (e) trapped cavity mechanism (modified from Tho *et al.* 2012)

Fig. 3. Existing mechanisms for ball penetrometer: (a) flow-round mechanism (modified from Randolph *et al.* 2000); (b) combined mechanism (modified from Zhou and Randolph 2011)

Fig. 4. Setup of PIV testing in beam centrifuge: (a) photograph before a PIV T-bar test (b) schematic representation

Fig. 5. Centrifuge model: (a) model penetrometers; (b) schematic diagram of penetrometers penetration in layered clay

Fig. 6. Soil flow mechanisms from T-bar penetration in soft-stiff clay (B1, TB1; Table 1):
(a) $d/D_t = 2.0$; (b) $d/D_t = 5.9$; (c) $d/D_t = 9.8$; (d) $d/D_t = 11.8$; (e) $d/D_t = 13.9$

Fig. 7. Schematic diagram of tracked soil elements

Fig. 8. Displacement paths of soil elements at $\sim 4.4D_t$ above soft-stiff interface during continuous T-bar penetration (B1, TB1; Table 1): (a) trajectories of soil elements M1~M5; (b) horizontal and vertical displacements of soil element M1

Fig. 9. Displacement paths of soil elements at $\sim 0.3D_t$ above soft-stiff interface during continuous T-bar penetration (B1, TB1; Table 1): (a) trajectories of soil elements N1~N5; (b) horizontal and vertical displacements of soil element N1

Fig. 10. (a) Comparisons of observed trajectories of M1~3 and analytical solutions (Martin and Randolph 2006); (b) Normalised velocity of soil element M1

Fig. 11. Soil flow mechanisms from T-bar penetration in stiff-soft clay (B2, TB2; Table 1): (a) $d/D_t = 1.5$; (b) $d/D_t = 4.7$; (c) $d/D_t = 9.7$; (d) $d/D_t = 12.4$; (e) $d/D_t = 14.0$; (f) $d/D_t = 14.7$

Fig. 12. Soil flow mechanisms from T-bar penetration in soft-stiff-soft clay (B3, TB3; Table 1): (a) $d/D_t = 4.3$; (b) $d/D_t = 9.9$; (c) $d/D_t = 12.7$

Fig. 13. Soil flow mechanisms from T-bar penetration in stiff-soft-stiff clay (B4, TB4; Table 1): (a) $d/D_t = 3.5$; (b) $d/D_t = 4.6$; (c) $d/D_t = 5.8$; (d) $d/D_t = 6.8$; (e) $d/D_t = 8.3$; (f) $d/D_t = 9.8$; (g) $d/D_t = 11.5$

Fig. 14. Resistance profile from T-bar penetration in stiff-soft-stiff clay (B4, TB4; Table 1)

Fig. 15. Soil flow mechanisms from ball penetration in soft-stiff clay (B1, Ball1; Table 1): (a) $d/D_b = 0.4$; (b) $d/D_b = 3.9$; (c) $d/D_b = 8.4$; (d) $d/D_b = 9.0$; (e) $d/D_b = 10.2$

Fig. 16. Typical streamline of ball penetration mechanism

Fig. 17. Soil flow mechanisms from ball penetration in stiff-soft clay (B2, Ball2; Table 1):

(a) $d/D_b = 8.2$; (b) $d/D_b = 9.2$; (c) $d/D_b = 10.0$; (d) $d/D_b = 10.7$

Fig. 18. Soil flow mechanisms from ball penetration in soft-stiff-soft clay (B3, Ball3;

Table1): (a) $d/D_b = 3.2$; (b) $d/D_b = 5.4$; (c) $d/D_b = 8.0$; (d) $d/D_b = 9.8$

Fig. 19. Soil flow mechanisms from ball penetration in stiff-soft-stiff clay (B4, Ball4;

Table1): (a) $d/D_b = 2.4$; (b) $d/D_b = 3.3$; (c) $d/D_b = 4.1$; (d) $d/D_b = 5.0$; (e) $d/D_b = 5.5$;

(f) $d/D_b = 6.5$; (g) $d/D_b = 7.1$; (h) $d/D_b = 8.8$

Fig. 1. Push-in penetrometers in field investigation and centrifuge testing

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Fig. 3. Existing mechanisms for ball penetrometer: (a) flow-round mechanism (modified from Randolph *et al.* 2000); (b) combined mechanism (modified from Zhou and Randolph 2011)

(a)

(b)

Fig. 4. Setup of PIV testing in beam centrifuge: (a) photograph before a PIV T-bar test (b) schematic representation

(a)

(b)

Fig. 5. Centrifuge model: (a) model penetrometers; (b) schematic diagram of penetrometers penetration in layered clay

Fig. 6. Soil flow mechanisms from T-bar penetration in soft-stiff clay (B1, TB1; Table 1): (a) $d/D_t = 2.0$; (b) $d/D_t = 5.9$; (c) $d/D_t = 9.8$; (d) $d/D_t = 11.8$; (e) $d/D_t = 13.9$

Fig. 8. Displacement paths of soil elements at $\sim 4.4D_t$ above soft-stiff interface during continuous T-bar penetration (B1, TB1; Table 1): (a) trajectories of soil elements M1~M5; (b) horizontal and vertical displacements of soil element M1

Fig. 9. Displacement paths of soil elements at $\sim 0.3D_t$ above soft-stiff interface during continuous T-bar penetration (B1, TB1; Table 1): (a) trajectories of soil elements N1~N5; (b) horizontal and vertical displacements of soil element N1

Fig. 10. (a) Comparisons of observed trajectories of M1~3 and analytical solutions (Martin & Randolph, 2006); (b) Normalised velocity of soil element M1

Fig. 11. Soil flow mechanisms from T-bar penetration in stiff-soft clay (B2, TB2; Table 1): (a) $d/D_t = 1.5$; (b)

$d/D_t = 4.7$; (c) $d/D_t = 9.7$; (d) $d/D_t = 12.4$; (e) $d/D_t = 14.0$; (f) $d/D_t = 14.7$

Fig. 12. Soil flow mechanisms from T-bar penetration in soft-stiff-soft clay (B3, TB3; Table 1): (a) $d/D_t = 4.3$; (b) $d/D_t = 9.9$; (c) $d/D_t = 12.7$

Fig. 13. Soil flow mechanisms from T-bar penetration in stiff-soft-stiff clay (B4, TB4; Table 1): (a) $d/D_t =$

3.5; (b) $d/D_t = 4.6$; (c) $d/D_t = 5.8$; (d) $d/D_t = 6.8$; (e) $d/D_t = 8.3$; (f) $d/D_t = 9.8$; (g) $d/D_t = 11.5$

Fig. 14. Resistance profile from T-bar penetration in stiff-soft-stiff clay (B4, TB4; Table 1)

Fig. 15. Soil flow mechanisms from ball penetration in soft-stiff clay (B1, Ball1; Table 1): (a) $d/D_b = 0.4$; (b)

$d/D_b = 3.9$; (c) $d/D_b = 8.4$; (d) $d/D_b = 9.0$; (e) $d/D_b = 10.2$

Fig. 16. Typical streamline of ball penetration mechanism

Fig. 17. Soil flow mechanisms from ball penetration in stiff-soft clay (B2, Ball2; Table 1): (a) $d/D_b = 8.2$; (b)

$d/D_b = 9.2$; (c) $d/D_b = 10.0$; (d) $d/D_b = 10.7$

Fig. 18. Soil flow mechanisms from ball penetration in soft-stiff-soft clay (B3, Ball3; Table1): (a) $d/D_b = 3.2$; (b) $d/D_b = 5.4$; (c) $d/D_b = 8.0$; (d) $d/D_b = 9.8$

Fig. 19. Soil flow mechanisms from ball penetration in stiff-soft-stiff clay (B4, Ball4; Table1): (a) $d/D_b = 2.4$;

(b) $d/D_b = 3.3$; (c) $d/D_b = 4.1$; (d) $d/D_b = 5.0$; (e) $d/D_b = 5.5$; (f) $d/D_b = 6.5$; (g) $d/D_b = 7.1$; (h) d/D_b

$= 8.8$