Scale Issues and Interpretation of Ball Penetration in Stratified Deposits in Centrifuge Testing

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Abstract: Full-flow ball penetrometer is now routinely used in centrifuge testing for characterizing single layer clay, silt, sand and stratified soil samples. The behavior of the standard ball penetrometer (including the shaft) used in the field penetrating through single and two-layer uniform clays has recently been investigated. However, the ball penetrometers used in centrifuge testing has either similar or higher area ratio (of the shaft to the ball) and significantly greater equivalent prototype diameter compared to the standard one used in the field. The thickness of the soil layers however are scaled accurately mimicking strength profiles in the field, leading to lower relative thickness of the soil layers. Large deformation finite element (LDFE) analyses were therefore carried out for the centrifuge ball penetrometers to investigate its performance in characterization of single and double layer clays.

The results were validated against plasticity solutions and other previously published FE

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17 results prior to undertaking a detailed parametric study, exploring a range of normalized soil
18 properties and layer thickness. Three commonly used centrifuge balls were studied. For
19 single layer uniform clay, the area ratio of shaft to ball was shown to have significant
20 influence on the deep bearing factors and the critical penetration depth of attaining that factor.
21 For two-layer uniform clays, the undrained shear strength of the top layer was mostly
22 underestimated due to the lower thickness of that layer relative to the centrifuge ball diameter.
23 In addition, the shear strength of the bottom layer was mostly overestimated due to trapping
24 of stiff clay at the base of the ball advancing in stiff-over-soft clay deposits. For accurate
25 interpretation of soil undrained shear strength from centrifuge ball penetration resistance, a
26 framework has been proposed accounting for these effects, with the LDFE data used to
27 calibrate the framework.

28 **CE Database subject headings:** Ball penetration tests; Clays; Layered soils; Flow
29 patterns; Shear strength; Numerical analysis; Site investigation.

Introduction

A ball penetrometer was suggested some years ago (Vallejo 1982), however it appears to have been taken up again only recently (Watson et al. 1998; Newson et al. 1999; Boylan et al. 2007). The standard ball penetrometer used in the field is spherical in shape, having a diameter of $D = 113$ mm (area of 100 cm^2) with a lightly sand blasted surface and projected area typically 10 times that of the shaft. The penetration tests are carried out at a rate of 20 mm/s.

This device allows full flow around the probe (apart from a small region where the shaft connects to the object), reducing significantly the need to correct the measured bearing resistance for the ambient overburden stress which is a necessity for cone penetration test (CPT). The undrained shear strength, s_u , is therefore deduced according to

$$s_u = \frac{q_u}{N_b} \quad (1)$$

where N_b is the bearing capacity factor for the ball penetrometer. In single layer clay, either shallow bearing capacity factor, $N_{b,ss}$, or limiting deep one, $N_{b,sd}$, is used depending on the mobilized failure mechanism (Zhou et al. 2013).

A number of investigations have been carried out on ball penetrometer response in single layer uniform clay through experimental, numerical and analytical work (e.g. Randolph et al. 2000; Einav and Randolph 2005; Zhou and Randolph 2007; Zhou and Randolph 2009; Yafate et al. 2009; DeJong et al. 2011; Pinkert and Klar 2013; Klar et al. 2014). To profile the undrained shear strength of soils in centrifuge tests and in offshore site investigations, ball bearing factor, $N_{b,sd}$, from plasticity solutions for the shaft area to ball projected area ratio $a = A_s/A = 0$ (e.g. Randolph et al. 2000; Einav and Randolph 2005) are commonly used in practice. The values are listed in Table 1. The effect of shaft is therefore neglected. Recently,

Zhou and Randolph (2011) and Zhou et al. (2013) examined the influence of a using LDFE analysis and upper bound solution. They provided 2.4~4.3% lower $N_{b, sd}$ factors, compared to the lower bound plasticity solutions, for the field ball penetrometer of $a = 0.1$ (Table 1).

Centrifuge modelling is now routinely used to assess the performance of offshore foundations in model scale. This allows correct scaling of stresses due to soil self-weight in experimental testing. Ball penetrometer of diameter $D = 5\sim 15$ mm (1~3 m in prototype at 200 g testing) is increasingly used for characterizing single layer clay and layered deposits with interbedded sand and clay layers. Typically ball projected areas are 11.1 to 4 times of the shaft area ($a = 0.09\sim 0.25$). Three critical aspects associated with the centrifuge ball penetrometers include: (a) different shaft area ratios from the field penetrometer; (b) different penetration depth needed to attain deep bearing factor; (c) lower soil layer thickness relative to the ball diameter.

For the centrifuge ball with $D = 1.8$ m (prototype) the shaft area ratio of $a (= 0.25)$ is relatively high. The corresponding $N_{b, sd}$ factor is about 6.2% lower ($N_{b, sd} = 11.2$ compared to the lower bound solution of 11.95 for $a = 0$ and $\alpha = 0.2$, Table 1; Zhou and Randolph 2011). A centrifuge ball with $D = 3$ m and $a = 0.09$ favors in this regards due to the lower a value. However, the larger diameter exacerbates other issues, as discussed below.

The depth of attaining $N_{b, sd}$ is H_d/D , indicating that shallow bearing capacity factors ($N_{b, ss}$) are required to be used for penetration less than H_d/D . For the field ball in single layer clay, $H_d < 1$ m (Zhou et al. 2013). However, for the centrifuge balls, H_d may be greater than 10 m in prototype (discussed later). The interpretation of soil strength using shallow and deep bearing factors can potentially make a remarkable difference, which is critical for shallow as well as deep foundations (mudmats, skirted foundations, spudcans) and pipelines.

For layered soil, the thickness of each layer relative to the ball diameter is critical as this is directly related to the development of full capacity within that layer. Zhou et al. (2013) investigated this factor and suggested that, for relatively thin layers ($t/D < 6\sim 8$), correction factors are required to be applied to the shear strength calculated using Equation 1. This becomes a major issue for centrifuge testing on stratified deposits. Thin layers of $t = 2\sim 4$ m are often encountered in the field, which are also simulated in centrifuge testing. This thickness is sufficient for the field ball to develop limiting resistance ($t/D = 17.7\sim 35.4$), but not for the centrifuge balls ($t/D = 0.7\sim 4 < \sim 8$), and hence an adjustment factor is essential for accurate interpretation of the undrained shear strength of that layer.

For stiff-over-soft clay deposits, the height of the soil plug trapped at the base of the ball and forced down into the underlying soft layer will also be markedly higher for the centrifuge ball. A corresponding influence is necessary to be taken into account in assessing the shear strength of the bottom layer.

In this study, an extensive investigation was carried out through LDFE analyses in uniform, stiff-over-soft and soft-over-stiff clays. Three ball penetrometers commonly used in centrifuge testing were considered: Ball1: $D_m = 9$ mm, $a = 0.25$; Ball2: $D_m = 6$ mm, $a = 0.25$; Ball3: $D_m = 15$ mm, $a = 0.09$. The results for the field ball penetrometer with $a = 0.1$ can be found in Zhou et al. (2013).

Large Deformation FE Analysis

Geometry and Parameters

This study has considered a spherical ball penetrometer of diameter D , penetrating into a two-layer deposit as illustrated schematically in Figure 1. The top layer of clay has uniform undrained shear strength s_{ut} , effective density γ'_t , and thickness t , which is underlain by a clay layer of uniform undrained shear strength s_{ub} , effective density γ'_b , and (nominally) infinite

depth. Analyses were undertaken simulating the centrifuge ball penetrometers of model diameter $D_m = 5, 6, 9$ and 15 mm, attached with a shaft of area ratio $a = 0.09$ or 0.25 . The acceleration level was considered between 50 and 200 , which is used routinely in centrifuge testing. The corresponding equivalent prototype diameter of the ball penetrometers ranges from $D = 0.25$ to 3 m.

This study is concentrated on simulating undrained shear strength profiles of deep to ultra deep water soft clay deposits of single layer soils, and shallow to moderate water two-layer seabed sediments of stiff-over-soft and the reverse stratifications. Practical ranges of soil properties, as reported in the literature, are summarized by Zhou et al. (2013). The selected parameters for this study are assembled in Tables 2 and 3, encompassing a range of parameters of practical interest.

Analysis Details

The RITSS (remeshing and interpolation technique with small strain) technique was proposed by Hu & Randolph (1998a) for dealing with large deformation problems in geotechnical engineering. This technique has been implemented in the finite element package AFENA (Carter and Balaam 1995), developed at the University of Sydney, and applied for many analyses of continuously penetrating foundations, pipelines, suction caisson anchors and penetrometers (Hu and Randolph 1998a, 1998b; Lu et al. 2000, 2004; Randolph et al. 2008; Zhou and Randolph 2009; Hossain and Randolph 2010; Zhou and Randolph 2011; Zhou et al. 2013). 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 variables (such as stresses and material properties) from the old mesh to the new mesh.

The axisymmetric soil domain was chosen as $10D$ in diameter and $20D$ in depth to ensure that the boundaries were well outside the plastic zone. Hinge and roller 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 ball-soil interface was simulated using elastoplastic nodal joints (Herrmann 1978) distributed along the ball-soil contact. A rigid ball was simulated with the interface friction coefficient, α , which limited the interface shear stress to αs_u .

Constitutive Law and Material Properties

The soil was modelled as a linear elastic-perfectly plastic material obeying a Tresca yield criterion. The parameters needed for the model are two elastic parameters, including Young's modulus (E) and Poisson's ratio (ν). These two elastic parameters define the assumed elastic response below the failure envelope, and friction (ϕ) and dilation (ψ) angles describe the plastic response at failure. The plastic parameter used in the model is the undrained shear strength of clay (s_u), with s_u defining the size of the yield surface. The elastic parameters for clay are considered to be independent of stresses and a constant value throughout the penetration process was used. A uniform stiffness ratio of $E/s_u = 500$ was taken throughout the clay profile. The stiffness ratio is within the range commonly adopted for soft clays, but the precise value has negligible effect on the results presented. Considering the relatively fast penetration of field penetrometers, all the analyses simulated undrained conditions and adopted a Poisson's ratio $\nu = 0.49$ (sufficiently high to give minimal volumetric strains, while maintaining numerical stability) and friction and dilation angles $\phi = \psi = 0$. The geostatic stress conditions were modelled using $K_0 = 1$, as the stable penetration resistance (once backflow is fully established) has been found to be unaffected by the value of K_0 (Zhou and Randolph 2009). Although there is some effects of the value of K_0 on shallow penetration

resistance, the difference in ball penetration resistances for $K_0 = 1$ and (e.g.) 0.6 is found to be less than 3.5% for the soils analyzed in this study.

Validation

For the ball with $a = 0$, Zhou et al. (2013) validated the LDFE results against lower and upper bound plasticity solutions and previously published FE results, with excellent agreement obtained (Table 1). For ball penetrometers including shaft, validation was carried out against FE solutions reported by Zhou and Randolph (2011), as also illustrated in Table 1.

In this study, analyses were carried out for the balls with $a = 0.09$ and 0.25 (Group SI, Table 2) which are commonly used in centrifuge tests. The ball bearing factor is calculated as

$$N_b = \frac{q_u}{s_u} = \left[\left(\frac{P}{A} \right) - \gamma' \frac{V_e}{A} \right] \frac{1}{s_u} \quad (2)$$

where P is the penetration resistance, A is the projected area of the ball and V_e is the volume of the embedded ball (including the shaft). The resulted values of deep bearing factor, $N_{b, sd}$, for $a = 0.09$ and 0.25 are also listed in Table 1, giving 1.6~4.2% and 4.3~7.7% lower factors than the lower bound solutions for $\alpha = 0$ to 1.0 . These values display consistent trend with the ones reported by Zhou and Randolph (2011) ($a = 0.11$ and 0.25 , $\alpha = 0.2$; Table 1).

LDFE Analysis in Single Layer Uniform Clay

Soil Failure Mechanisms and Critical Depths

Figure 2 illustrates the soil flow mechanisms for a centrifuge ball (Ball1, $D = 1.8$ m, $a = 0.25$) penetrating from the surface of a uniform clay with $s_u/\gamma'D = 0.93$ ($\alpha = 0.3$; Group SII, Table 2). During initial penetration, the failure mechanism extends upward to the surface, leading to surface heave and formation of a cavity above the ball. With further penetration ($d_{in}/D = 1.46$, Figure 2a), soil begins to flow back gradually onto the top of the ball. When a deep

penetration depth is reached ($d_{in}/D = 2.88$, Figure 2b), soil flow becomes fully localized around the ball, i.e. a full flow-round or deep localized failure mechanism attains. The cavity depth above the ball penetrometer is defined as H_c , and the depth of first appearing a deep localized flow is marked as H_d . For this case with $a = 0.25$, the normalized cavity depth can be measured as $H_c/D = 1.44$ and deep flow-round failure depth as $H_d/D = 2.44$. Figure 2c shows a mechanism similar to Figure 2b, but for $a = 0.09$ (changed that deliberately for this analysis only to investigate the effect of a) with other parameters unchanged (Ball1, $D = 1.8$ m, $s_u/\gamma'D = 0.93$, $\alpha = 0.3$; Group SII, Table 2). After the initiation of soil backflow above the penetrating ball, the smaller the shaft is the deeper the depth is necessary to complete the full back flow, and hence the higher the H_c and H_d .

The depth of initial deep penetration mechanism (H_d/D) is always greater than the limiting cavity depth (H_c/D). This is because, after the cavity is stabilized, further penetration is needed for attaining the deep failure mechanism. From the analyses of Groups SIII and SIV (Table 2), the normalized depths H_c/D and H_d/D are plotted in Figure 3 as a function of $s_u/\gamma'D$ (for $\alpha = 0.3$). All the data show a unique trend for each case, which may be expressed as follows (with $R^2 \approx 0.98$).

$$\frac{H_c}{D} = 1.2 \left(\frac{s_u}{\gamma'D} \right)^{0.5} - 0.09 \left(\frac{s_u}{\gamma'D} \right)^{0.056} \quad \text{for } a = 0.25 \quad (3)$$

$$\frac{H_d}{D} = 2.3 \left(\frac{s_u}{\gamma'D} \right)^{0.4} - 0.08 \left(\frac{s_u}{\gamma'D} \right)^{0.85} \quad \text{for } a = 0.25 \quad (4)$$

$$\frac{H_c}{D} = 2.1 \left(\frac{s_u}{\gamma'D} \right)^{0.95} - 0.22 \left(\frac{s_u}{\gamma'D} \right)^{1.12} \quad \text{for } a = 0.09 \quad (5)$$

$$\frac{H_d}{D} = 4 \left(\frac{s_u}{\gamma'D} \right)^{0.66} - 0.44 \left(\frac{s_u}{\gamma'D} \right)^{0.65} \quad \text{for } a = 0.09 \quad (6)$$

198 For $a = 0.1$, Zhou et al. (2013) reported H_c/D and H_d/D as

$$199 \quad \frac{H_c}{D} = 2.68 \left(\frac{s_u}{\gamma' D} \right)^{0.8} - 0.1 \left(\frac{s_u}{\gamma' D} \right)^{1.49} \quad \text{for } a = 0.1 \quad (7)$$

$$200 \quad \frac{H_d}{D} = 3.1 \left(\frac{s_u}{\gamma' D} \right)^{0.8} - 0.1 \left(\frac{s_u}{\gamma' D} \right)^{1.54} \quad \text{for } a = 0.1 \quad (8)$$

201 The corresponding curves are also included in Figure 3.

202 **Framework for Assessing Undrained Shear Strength**

203 A design framework for assessing undrained shear strength using ball penetrometer data was
 204 proposed by Zhou et al. (2013). The required inputs include (i) H_d , (ii) deep bearing factor,
 205 $N_{b,sd}$, (iii) shallow bearing factor, $N_{b,ss}$, (iv) buoyancy factor, $N_{b,sb}$ and (v) operative
 206 penetration depth, d .

207 The first required data, H_d , can be obtained using Equations 4 and 6. For $d_{in} > H_d$, graphical
 208 and numerical values of $N_{b,sd}$ are given in Table 1, which can be expressed as (for $\alpha = 0$ to
 209 0.7)

$$210 \quad N_{b,sd} = 10.13 + 5.53\alpha - 1.22\alpha^2 \quad \text{for } a = 0.25 \quad (9)$$

$$211 \quad N_{b,sd} = 10.65 + 4.75\alpha - 0.43\alpha^2 \quad \text{for } a = 0.1 \quad (10)$$

$$212 \quad N_{b,sd} = 10.7 + 4.77\alpha - 0.28\alpha^2 \quad \text{for } a = 0.09 \quad (11)$$

$$213 \quad N_{b,sd} = 10.97 + 5.07\alpha - 0.94\alpha^2 \quad \text{for } a = 0 \quad (12)$$

214 For $d_{in} \leq H_d$, the undrained penetration resistance of a ball penetrometer, q_b , can be expressed
 215 as (Zhou et al. 2013)

$$216 \quad q_b = N_{b,ss}s_u + N_{b,sb}\gamma'd \quad (13)$$

217 Shallow bearing factor, $N_{b,ss}$, is defined as a proportion of the deep bearing factor, $N_{b,sd}$ (i.e.
 218 $N_{b,ss}/N_{b,sd}$), that varies with the penetration depth normalized by H_d (i.e. d_{in}/H_d). Figure 4
 219 displays the variations of shallow bearing factor for $\alpha = 0.3$ (Groups SIII and SIV, Table 2).
 220 Simple expressions can be derived fitting these data as

$$221 \quad N_{b,ss} = 3 + (N_{b,sd} - 3) \left(\frac{d_{in}}{H_d} \right)^{0.537 \left(\frac{s_u}{\gamma' D} \right)^{-0.216}} \leq N_{b,sd} \quad (a = 0.25) \quad (14)$$

$$222 \quad N_{b,ss} = 3 + (N_{b,sd} - 3) \left(\frac{d_{in}}{H_d} \right)^{0.372 \left(\frac{s_u}{\gamma' D} \right)^{-0.378}} \leq N_{b,sd} \quad (a = 0.09) \quad (15)$$

223 The corresponding guidelines for calculating the buoyancy factor, $N_{b,sb}$, and operative
 224 penetration depth, d , are detailed in Zhou et al. (2013).

225 **Results and Discussion: Two-Layer Uniform-Over-Uniform Clay**

226 ***Soil Failure Mechanisms***

227 Figure 5 shows the soil flow mechanism for a centrifuge ball (Ball1, $a = 0.25$, $\alpha = 0.3$; Group
 228 DI, Table 3) penetrated deeply in the bottom layer of uniform-over-uniform clay deposits.
 229 For soft-over-stiff clay (see Figure 5a), the soil flow is fully localized around the ball and no
 230 soil from the top layer is trapped at the base of the advancing ball. From Equation 4, H_d/D
 231 can be calculated as 2.81 for $s_{ut}/\gamma'_t D = 1.85$. In addition, a depth from the layer interface is
 232 required to avoid the effect of the underlying layer. Thus the top layer thickness of $2D$ is not
 233 sufficient for mobilizing the limiting resistance. An adjustment factor is therefore required for
 234 accurate quantification of the top layer shear strength, s_{ut} , from the measured result, s_{utm} . As
 235 no soil is trapped at the base of the ball, no correction is required for the measured bottom
 236 layer shear strength, s_{ubm} , i.e. $s_{ub} = s_{ubm}$.

For the reverse deposit (stiff-over-soft clay in Figure 5b), the underlying soft layer attracted the soil flow downward and hence soil backflow was delayed. Apparently, the open cavity depth is nearly equal to the thickness of the top layer, indicating that the fully localized failure mechanism did not attain in the top layer. Again, an adjustment factor is required for accurate quantification of s_{ut} . In contrast to the ball penetration in soft-over-stiff clay, a soil plug is trapped at the base of the ball and that is forced down into the underlying layer (see Figure 5b). Therefore, an adjustment is also required for the measured bottom layer shear strength, s_{ubm} , for accurate quantification of s_{ub} .

Parametric Study

Penetration of centrifuge ball penetrometers in two-layer clays is studied varying: (a) the diameter of the centrifuge balls (considering a number of model ball diameters as well as centrifuge test gravity level); (b) the thickness of the top layer relative to the ball diameter, t/D ; (c) the strength ratio between bottom and top soil layers, s_{ub}/s_{ut} ; and (d) the normalized strength of the top layer, $s_{ut}/\gamma' tD$. The cases studied here are summarized in Table 3.

Effect of Diameter of Centrifuge Ball Penetrometer (D) and Top Layer Thickness Ratio (t/D)

To explore the effect of the centrifuge ball diameter on the form of the penetration resistance profile, the results of various ball diameters of $D_m = 6, 9$ ($a = 0.25$, Ball1 and Ball2), and 15 mm ($a = 0.09$, Ball3) are plotted in Figures 6a and 6b. The top layer thickness was kept constant of $t_m = 20$ mm (in Group DII, Table 3). Carrying out the tests at 200 g will give $D = 1.2, 1.8$ and 3.0 m, and $t = 4$ m (see Figures 6a and 6b). The results are presented in terms of measured undrained shear strength, s_u , as a function of penetration depth of the ball invert, d_{in} , with s_u calculated reorganizing Equation 2 according to

$$s_u = \frac{q_u}{N_{b, sd}} = \left[\left(\frac{P}{A} \right) - \gamma' \frac{V_e}{A} \right] \frac{1}{N_{b, sd}} \quad (16)$$

The values of $N_{b, sd}$ for different a were taken from Table 1. For stiff-over-soft clay ($s_{ub}/s_{ut} = 0.33$, Figure 6a), in the top layer, neither of the profile attains to the full capacity for this 4 m thick layer. This often misleads the interpreted shear strength of the layer. It is common that this characterization test is interpreted as the undrained shear strength of the top layer being 17.3 or 20.7 or 25.3 kPa, depending on the model ball diameter (D_m), instead of the actual s_{ut} of 30 kPa. This indicates the effect of sensing the bottom soft layer i.e. the relative thickness of the top layer t/D ($= 1.33 \sim 3.33$) is insufficient for allowing the resistance profile to establish the full capacity of the layer. For the bottom layer, in contrast, the strength can be interpreted as 10.7 kPa instead of the actual s_{ub} of 10 kPa. This is caused by the influence of the trapped soil plug (see Figure 5b).

Figure 6b shows the profiles for the identical layer geometry, but with the reverse strength profile of soft-over-stiff clay ($s_{ub}/s_{ut} = 3$). Similar to Figure 6a, the thickness of the top layer is insufficient to allowing for establishing the full capacity of that layer, which would lead to misinterpretation of s_{ut} . For the bottom layer, interpretation shows correct $s_{ub} = 30$ kPa owing to the absence of any trapped soil plug at the base of the advancing ball (see Figure 5a). Note, for the remainder of the paper, data in normalized penetration resistance, $q_u/N_{b, sd}$, form will be used.

The effect of t/D has also been examined varying the thickness of the top layer, t . For stiff-over-soft clay, the normalized resistance profiles are plotted in Figure 7a, as a function of normalized penetration depth d_m/D , for a range of t/D from 1 to 10, but with identical strength ratio of $s_{ub}/s_{ut} = 0.25$ and interface friction ratio of $\alpha = 0.3$ (Ball1, $D = 1.8$ m, $a = 0.25$; Group DIII, Table 3). The shear strength profiles for layered clays are bracketed by the

lines for single layer uniform clays with either top or bottom layer accurate shear strength. It is seen that (a) the strength of the top layer is fully mobilized for $t/D \geq 8$; (b) the difference between the measured peak strength and accurate strength of the top layer increases with reducing t/D ; (c) the stabilized resistance in the bottom layer is about 8% higher than that on uniform clay with bottom layer strength.

For soft-over-stiff clay, the results of various $t/D = 1\sim 8$, with $s_{ub}/s_{ut} = 2$ and $\alpha = 0.3$ are plotted in Figure 7b (Ball1, $D = 1.8$ m, $a = 0.25$; Group DIII, Table 3). A minimum top layer thickness of $t/D = 4$ is required for mobilizing the full capacity of the layer, and the stabilized resistance in the bottom layer merges with that on uniform clay with bottom layer strength.

This means for centrifuge test on stiff-over-soft clay deposit with $t/D < 8$ and soft-over-stiff deposit with $t/D < 4$, an adjustment factor is required to be applied on the measured strength to obtain the accurate strength of the layer. For soft bottom layer, the slight increase in penetration resistance owing to the influence of the trapped stronger soil from the top layer has to be taken into account when interpreting the strength of that layer.

Effect of Strength Ratio (s_{ub}/s_{ut})

In order to explore the effect of the strength ratio on the form of the penetration resistance profile, the results of various strength ratio, $s_{ub}/s_{ut} = 0.18\sim 2$, with $s_{ut}/\gamma'_i D = 1.85$ and $\alpha = 0.3$ are plotted in Figure 8 for a constant thickness ratio of $t/D = 2$ (Ball1, $D = 1.8$ m, $a = 0.25$; Group DIV, Table 3). The full penetration profile for single layer uniform clay with the top layer soil strength is included in Figure 8. The measured peak shear strength in the top layer and the depth of attaining the peak value increase with decreasing strength ratio. In both top and bottom layers, the lower the strength ratio is, the higher the error for measured shear strength or the greater the adjustment factor required.

Effect of Normalized Strength of Top Layer ($s_{ut}/\gamma'_t D$)

From the investigation on uniform clays, it was found that the soil normalized strength has significant effect on the depth of open cavity and deep localized failure i.e. on H_c and H_d (Equations 3~6), and penetration resistance profile. Figure 9 focuses on this issue with the penetration responses for $s_{ut}/\gamma'_t D = 1.39$ to 4.63 are compared directly for two different strength ratios $s_{ub}/s_{ut} = 0.2$ and 2 ($t/D = 4$ and 2 respectively; Group DV, Table 3). For this identical strength ratio and thickness ratio on each type of layered deposit (stiff-over-soft or soft-over-stiff), in the top layer, the difference between the measured and accurate shear strengths increases marginally as $s_{ut}/\gamma'_t D$ increases. In the bottom layer, this effect is appeared to be negligible.

Quantified Effects: New Chart for Adjusting Ball Factor

Based on the results discussed previously, it can be seen that the penetration resistance of the centrifuge balls in the top layer is influenced by three factors: t/D , s_{ub}/s_{ut} and $s_{ut}/\gamma'_t D$; and that the bottom layer is influenced by the trapped stronger soil, which is shown to be a function of s_{ub}/s_{ut} (while $\alpha = 0.3$). To develop design charts quantifying the effects of these factors on ball penetrometer resistance in centrifuge test, two group of analyses were conducted (Groups DVI and DVII, Table 3), with t/D varying from 1 to 10.

For stiff-over-soft clay, the peak value of the top layer is defined as the measured undrained shear strength of that layer s_{utm} , and the steady state shear strength in the bottom layer is defined as the measured undrained shear strength of that layer s_{ubm} . For soft-over-stiff clay, either the steady state value (if the profile attains) or the measured shear strength at the layer interface is taken as s_{utm} , and the steady state value in the bottom layer is considered as s_{ubm} . The difference between the measured shear strength s_{utm} and s_{ubm} (using Equation 16) and the accurate value s_{ut} and s_{ub} are defined respectively as T_{de} (decrease) for the top layer and B_{in}

330 (increase) for the bottom layer as below

$$331 \quad T_{de} = \frac{(s_{ut} - s_{utm})}{s_{ut}}$$

$$332 \quad (17) B_{in} = \frac{(s_{ubm} - s_{ub})}{s_{ub}} \quad (18)$$

333 The calculated values of T_{de} from all relevant analyses (Groups DVI and DVII, Table 3) are
 334 plotted in Figures 10a~10d as a function of t/D , s_{ut}/s_{ub} and $s_{ut}/\gamma'_t D$. A best fit through the data
 335 allows the adjustment factor to be approximated as

336 For stiff-over-soft clay

$$337 \quad T_{de} = 0.08 \left[1 + 9.86 \left(\frac{s_{utm}}{\gamma'_t D} \right)^{0.12} \right] \left[1 - 0.79 \left(\frac{s_{ubm}}{s_{utm}} \right)^{0.71} \right] / \left(\frac{t}{D} \right)^{1.32} \quad \text{for } a = 0.25 \quad (19)$$

$$338 \quad T_{de} = 0.07 \left[1 + 10.07 \left(\frac{s_{utm}}{\gamma'_t D} \right)^{0.14} \right] \left[1 - 0.68 \left(\frac{s_{ubm}}{s_{utm}} \right)^{0.74} \right] / \left(\frac{t}{D} \right)^{1.24} \quad \text{for } a = 0.09 \quad (20)$$

339 and for soft-over-stiff clay

$$340 \quad T_{de} = 0.32 \left[1 + 0.798 \left(\frac{s_{utm}}{\gamma'_t D} \right)^{0.485} \right] \left[1 - 0.588 \left(\frac{s_{utm}}{s_{ubm}} \right)^{-0.03} \right] / \left(\frac{t}{D} \right)^{2.039} \quad \text{for } a = 0.25 \quad (21)$$

$$341 \quad T_{de} = 0.35 \left[1 + 0.8 \left(\frac{s_{utm}}{\gamma'_t D} \right)^{0.5} \right] \left[1 - 0.6 \left(\frac{s_{utm}}{s_{ubm}} \right)^{-0.03} \right] / \left(\frac{t}{D} \right)^{1.98} \quad \text{for } a = 0.09 \quad (22)$$

342 The profiles indicate that T_{de} reduces with increasing t/D and becomes negligible for $t/D \geq 8$
 343 (for stiff-over-soft clay) and $t/D \geq 4$ (for the reverse) at least for the range of parameters
 344 investigated. This is consistent with the previous findings from Figure 7. The corrected or
 345 accurate value of s_{ut} is then used for adjusting the measured s_{ubm} , as discussed below. The

values of B_{in} are plotted in Figures 11a and 11b as a function of s_{ubm}/s_{ut} , which can be approximated as

For stiff-over-soft clay

$$B_{in} = 0.35 \exp \left[-4.04 \left(\frac{s_{ubm}}{s_{ut}} \right) \right] \quad \text{for } a = 0.25 \quad (23)$$

$$B_{in} = 0.3 \exp \left[-5.7 \left(\frac{s_{ubm}}{s_{ut}} \right) \right] \quad \text{for } a = 0.09 \quad (24)$$

and for soft-over-stiff clay

$$B_{in} = 0$$

Clearly the values of B_{in} diminish as s_{ubm}/s_{ut} approaches unity.

Proposed Interpretation Procedure and Validation

A new interpretation framework is presented in Figure 12 as a flowchart that can be used for assessing undrained shear strength profile in single and double layer uniform clay from centrifuge ball penetrometer data. The performance of the proposed framework is validated against two centrifuge test data (referred to as case 1 and case 2). The tests were performed in samples of kaolin clay (liquid limit, $LL = 61\%$; plastic limit, $PL = 27\%$; $G_s = 2.6$; Stewart 1992). For case 1, a ball penetrometer of $D = 1.8$ m, $a = 0.25$ (Ball1) penetrated in soft-over-stiff clay deposit. The relative thickness of the top soft layer of $t/D = 5.83$ is greater than the minimum t/D required (4) for mobilizing the steady state resistance in the top layer. For the bottom stiff layer, there was no effect of trapping stiff soil plug. As such, the measured undrained shear strengths in the top and bottom layers, s_{utm} and s_{ubm} , can be considered as the accurate soil strengths. This was confirmed by the deduced undrained shear strengths from separate T-bar ($D = 1$ m) penetration tests on top and bottom layer clay deposits (Figure 13a).

For case 2, ball (Ball1, $D = 1.8$ m, $a = 0.25$) penetration test was conducted in stiff-over-soft clay. As the top stiff layer relative thickness of $t/D = 1.94$ is much smaller than the minimum thickness required (8) for mobilizing the steady state resistance, the peak value of the top layer, s_{utm} , and the steady state value of the bottom layer s_{ubm} were used with correction factors in the soil strength interpretation. The measured profile, interpreted lines, and actual undrained shear strength profiles of the layers (from separate T-bar tests) are shown in Figure 13b, showing the accuracy of the proposed interpretation framework.

Combined Effects Strain Rate and Strain Softening

Following Einav and Randolph (2005), Zhou and Randolph (2007) and Zhou and Randolph (2009), the Tresca soil model was extended to take the combined effects of rate dependency and progressive softening into account. Some analyses were carried considering typical parameters for a circular object penetration in kaolin clay ($\delta_{em} = 0.3$, $\mu = 0.1$, $\xi_{95} = 15$, $\dot{\gamma}_{ref} = 1\%/h$; Low et al. 2008; Hossain and Randolph 2009; Zhou and Randolph 2009). The results show that the combined effects of strain rate and strain softening on the normalized resistance (i.e. interpreted s_u) is found to be less than 3%. For instance, for Ball1 ($D = 1.8$ m, $a = 0.25$), $\alpha = 0.3$, strength ratio $s_{ub}/s_{ut} = 0.5$, and thickness ratio $t/D = 2$, the computed peak resistance in the top stiff layer is around 7% higher compared to that in the ideal rate independent, non-softening clay. However, as the corresponding value of deep bearing capacity factor, $N_{b,sd}$ is also higher (consistent with Zhou and Randolph 2009), the resultant effect on the interpreted s_u becomes trivial ($< 3\%$). Therefore, for normal clays (e.g. kaolin), the proposed interpretation framework can be used in assessing undrained shear strength with reasonable accuracy. Further investigation is required to quantify the effects of strain rate and strain softening for other clays with, for instance, high sensitivity.

Concluding Remarks

This paper reports the investigation of centrifuge ball penetrometers in single and double layer clays. The LDFE/RITSS method was used to simulate continuous penetration of ball penetrometers from the soil surface. The effects of relatively large ball diameter and different area ratio of shaft to ball were studied extensively with the aim of accurate interpretation of soil strength profile when a ball penetrometer is used for soil characterization in centrifuge tests.

For single layer uniform clay, the deep bearing capacity factors of centrifuge ball penetrometers with area ratios of 0.09 and 0.25 were respectively to be 2.5~3.5% and 5.5~6.5% lower than that of the no-shaft ball. The minimum penetration depth required to reach the deep bearing factor depended on the cavity formation and can be calculated using Equations 4 and 6.

For centrifuge ball penetration in double layer clay with stiff-over-soft stratigraphy, the relative top layer thickness of $t/D \geq 8$ was required for establishing the accurate shear strength of the layer. For $t/D < 8$, the measured shear strength was required to be adjusted by using Equations 17, 19 and 20. In the bottom layer, trapped stronger soil augmented the measured strength, which should be adjusted using Equations 18, 23 and 24 for interpreting the accurate strength of the layer.

For centrifuge ball penetration in double layer clay with soft-over-stiff stratigraphy, the relative top layer thickness of $t/D \geq 4$ was required for establishing the accurate strength of the layer. For $t/D < 4$, the measured shear strength was required to be adjusted. The adjustment factor can be calculated using Equations 17, 21 and 22. In the bottom layer, no soil was shown to be trapped at the base of the advancing ball, and hence the measured shear strength can be taken as the accurate strength of the layer.

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425 **Notation**

426	A	ball projected area
427	A_s	shaft cross-section area
428	a	ratio of shaft cross-section area to ball projected area (A_s/A)
429	B_{in}	factor for difference between measured and actual shear strength of bottom
430		layer
431	D	diameter of ball
432	d	operative penetration depth of ball
433	d_{in}	penetration depth of ball invert
434	f_d	factor for local heave
435	H_c	open cavity depth
436	H_d	flow-round failure depth
437	N_b	bearing factor of ball penetrometer
438	$N_{b, sb}$	buoyancy factor of ball penetrometer
439	$N_{b, sd}$	bearing factor of ball penetrometer in single layer clay at steady state
440	$N_{b, ss}$	bearing factor of ball penetrometer in single layer clay at shallow embedment
441	P	penetration resistance
442	q_b	undrained penetration resistance of ball penetrometer
443	q_u	ultimate bearing pressure

444	s_u	undrained shear strength of soil
445	s_{ub}	undrained shear strength of bottom soil layer
446	s_{ut}	undrained shear strength of top soil layer
447	s_{ubm}	measured undrained shear strength of bottom soil layer in centrifuge test
448	s_{utm}	measured undrained shear strength of top soil layer in centrifuge test
449	T_{de}	factor for difference between measured and actual shear strength of top layer
450	t	thickness of top soil layer
451	V_e	volume of ball (including shaft) embedded in soil (below mudline)
452	z	depth below soil surface
453	α	ball-soil interface friction coefficient
454	γ'_b	effective unit weight of bottom soil layer
455	γ'_t	effective unit weight of top soil layer

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Table 1. Deep bearing capacity factor for ball penetrometers, $N_{b,sd}$

α	This study: LDFE		Zhou et al. (2013): LDFE		Zhou and Randolph (2011): LDFE and Upper bound			Einav and Randolph (2005): Lower bound
	a							
	0.25	0.09	0.10	0.00	0.25	0.11	0.04	0.00
0.0	10.13	10.70	10.65	10.97				10.97
0.2	11.28	11.57	11.53		11.20	11.50	11.80	11.95
0.3	11.72	12.04	11.99					12.41
0.4	12.12	12.55	12.46					12.85
0.5	12.60	13.06	12.95					13.27
0.6	13.03	13.45	13.35					13.68
0.7	13.45	13.84	13.71					14.06
1.0	14.35	14.48	14.46	15.19				15.11

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Table 2. Summary of LDFE analyses performed on uniform clay

Analysis	$s_u/\gamma'D$	α	a	D_m (mm)	Test g- level	D (m)	Initial embedment	Notes
Group SI	0.93	0.0,0.2, 0.3,0.4, 0.5, 0.6, 0.7, 1.0	0.00, 0.09, 0.25	9	200	1.80	Pre-embedded	Comparison with plasticity solutions and LDFE results
Group SII	0.93	0.3	0.25, 0.09	9	200	1.80	Penetration from soil surface	Investigation of soil flow mechanisms
Group SIII	*	0.3	0.25	9	50, 100, 150, 200	0.45, 0.90, 1.35, 1.80	Penetration from soil surface	Investigation of the effect of normalized strength on H_c and H_d
Group SIV		0.3	0.09	15	50, 100, 150, 200	0.75, 1.50, 2.25, 3.00	Penetration from soil surface	
* $s_u = 2, 5, 10, 15, 20, 25, 30, 35, 40$ kPa; $\gamma' = 6$ kN/m ³								

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538 **Table 3.** Summary of LDFE analyses performed on two-layer clay (penetration from soil
539 surface, $\alpha = 0.3$)

Analysis	$s_{ut}/\gamma'_t D$	a	D_m (mm)	Test g- level	D (m)	t/D	s_{ub}/s_{ut}	Notes
Group DI	1.85	0.25	9	200	1.80	2.00, 4.00	2.00, 0.25	Investigation of soil flow mechanisms
Group DII	4.16, 2.78, 1.67	0.25, 0.09	6, 9, 15	200	1.20, 1.80, 3.00	3.33, 2.22, 1.33	0.33, 3.00	Investigation of the effect of diameter
Group DIII	1.85, 11.85, 1.67	0.25	9	200	1.80	1.00, 2.00, 4.00, 6.00, 8.00, 10.00	0.25, 2.00	Investigation of the effect of top layer thickness
Group DIV	1.85	0.25	9	200	1.80	2.00	0.18, 0.25, 0.50, 1.00, 2.00	Investigation of the effect of top layer shear strength
Group DV	0.83, 1.67, 1.39, 2.31, 4.63, 5.00	0.25	9	200	1.80	2.00, 4.00	0.20, 2.00	Investigation of the effect of strength ratio
Group DVI	1.16~9.26 0.19~3.7	0.25	9	50, 100, 150, 200	0.45, 0.90, 1.35, 1.80	1.00, 2.00, 4.00, 6.00, 8.00, 10.00	0.10~0.80 1.25~7.00	Investigation of adjustment for measured shear strength
Group DVII		0.09	15		0.75, 1.50, 2.25, 3.00			

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541 Figure Captions

- 542 **Figure 1** Schematic diagram of ball penetration in stiff-over-soft clay deposit
- 543 **Figure 2** Soil failure mechanisms for ball penetration in uniform clay ($s_u/\gamma' D = 0.93$, α
544 $= 0.3$; Group SII, Table 2; figure axes in m): (a) $d_{in}/D = 1.46$ ($a = 0.25$); (b)
545 $d_{in}/D = 2.88$ ($a = 0.25$); (c) $d_{in}/D = 3.44$ ($a = 0.09$)
- 546 **Figure 3** Design chart for estimating limiting cavity depth and deep failure depth for
547 ball penetration in uniform clay ($\alpha = 0.3$; Groups SIII and SIV, Table 2)
- 548 **Figure 4** Variation in normalized bearing factor, $N_{b,ss}/N_{b,sd}$, with normalized
549 embedment, d_{in}/H_d in uniform clay ($\alpha = 0.3$; Group SIII, SIV, Table 2): (a) $a =$
550 0.25 ; (b) $a = 0.09$
- 551 **Figure 5** Soil failure mechanisms for ball penetration in two-layer clay (figure axes in
552 m; Group DI, Table 3): (a) Soft-over-stiff clay ($s_{ub}/s_{ut} = 2.00$, $s_{ut}/\gamma' t D = 1.85$, D
553 $= 1.8$ m, $a = 0.25$, $t/D = 2$); (b) Stiff-over-soft clay ($s_{ub}/s_{ut} = 0.25$, $s_{ut}/\gamma' t D =$
554 1.85 , $D = 1.8$ m, $a = 0.25$, $t/D = 4$)
- 555 **Figure 6** Effect of centrifuge ball diameter, D , on measured undrained shear strength
556 profile in two-layer clays (Group DII, Table 3): (a) Stiff-over-soft clay (s_{ub}/s_{ut}
557 $= 0.33$, $t = 4$ m); (b) Soft-over-stiff clay ($s_{ub}/s_{ut} = 3.00$, $t = 4$ m)
- 558 **Figure 7** Effect of top layer thickness ratio (t/D , by varying t) on normalized
559 penetration resistance in two-layer clays (Group DIII, Table 3): (a) Stiff-over-
560 soft clay ($s_{ub}/s_{ut} = 0.25$, $s_{ut}/\gamma' t D = 1.85$, $D = 1.8$ m, $a = 0.25$); (b) Soft-over-stiff
561 clay ($s_{ub}/s_{ut} = 4.00$, $s_{ut}/\gamma' t D = 1.85$, $D = 1.8$ m, $a = 0.25$)
- 562 **Figure 8** Effect of strength ratio (s_{ub}/s_{ut}) on normalized penetration resistance in two-
563 layer clays ($s_{ut}/\gamma' t D = 1.85$, $D = 1.8$ m, $a = 0.25$, $t/D = 2$; Group DIV, Table 3)
- 564 **Figure 9** Effect of top layer normalized strength ($s_{ut}/\gamma' t D$) on normalized penetration
565 resistance in two-layer clays (Group DV, Table 3): (a) Stiff-over-soft clay
566 ($s_{ub}/s_{ut} = 0.20$, $D = 1.8$ m, $a = 0.25$, $t/D = 4$); (b) Soft-over-stiff clay ($s_{ub}/s_{ut} =$
567 2.00 , $D = 1.8$ m, $a = 0.25$, $t/D = 2$)
- 568 **Figure 10** Design charts for adjusting measured shear strength of top layer (Groups DVI
569 and DVII, Table 3): (a) Adjustment factor for $a = 0.25$, stiff-over-soft clay; (b)
570 Adjustment factor for $a = 0.09$, stiff-over-soft clay; (c) Adjustment factor for a

571 = 0.25, soft-over-stiff clay; (d) Adjustment factor for $a = 0.09$, soft-over-stiff
572 clay

573 **Figure 11** Design chart for adjusting measured shear strength of bottom layer (Groups
574 DVI and DVII, Table 3): (a) Adjustment factor for $a = 0.25$, stiff-over-soft
575 clay; (b) Adjustment factor for $a = 0.09$, stiff-over-soft clay

576 **Figure 12** Procedure for interpretation of undrained shear strength from measured ball
577 data

578 **Figure 13** Comparison the prediction using proposed approach with centrifuge data: (a)
579 Soft-over-stiff clay ($D = 1.8$ m, $a = 0.25$, $t/D = 5.83$); (b) Stiff-over-soft clay
580 ($D = 1.8$ m, $a = 0.25$, $t/D = 1.94$)

Figure 1. Schematic diagram of ball penetration in stiff-over-soft clay deposit

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2(a) $d_{in}/D = 1.46$ ($a = 0.25$)

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2(b) $d_{\text{in}}/D = 2.88$ ($a = 0.25$)

2(c) $d_{in}/D = 3.44$ ($a = 0.09$)

Figure 2. Soil failure mechanisms for ball penetration in uniform clay ($s_u/\gamma' D = 0.93$, $\alpha = 0.3$; Group SII, Table 2; figure axes in m)

Figure 3. Design chart for estimating limiting cavity depth and deep failure depth for ball penetration in uniform clay ($\alpha = 0.3$; Groups SIII and SIV, Table 2)

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4(a) $a = 0.25$

4(b) $a = 0.09$

Figure 4. Variation in normalized bearing factor, $N_{b,ss}/N_{b,sd}$, with normalized embedment, d_{in}/H_d in uniform clay ($\alpha = 0.3$; Groups SIII and SIV, Table 2)

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5(a) Soft-over-stiff clay ($s_{ub}/s_{ut} = 2.00$, $s_{ut}/\gamma'_t D = 1.85$, $D = 1.8$ m, $a = 0.25$, $t/D = 2$)

5(b) Stiff-over-soft clay ($s_{ub}/s_{ut} = 0.25$, $s_{ut}/\gamma' t D = 1.85$, $D = 1.8$ m, $a = 0.25$, $t/D = 4$)

Figure 5. Soil failure mechanisms for ball penetration in two-layer clay (figure axes in m; Group DI, Table 3)

6(a) Stiff-over-soft clay ($s_{ub}/s_{ut} = 0.33$, $t = 4$ m)

6(b) Soft-over-stiff clay ($s_{ub}/s_{ut} = 3.00$, $t = 4 \text{ m}$)

Figure 6. Effect of centrifuge ball diameter, D , on measured undrained shear strength profile in two-layer clays (Group DII, Table 3)

7(a) Stiff-over-soft clay ($s_{ub}/s_{ut} = 0.25$, $s_{ut}/\gamma' t D = 1.85$, $D = 1.8$ m, $a = 0.25$)

7(b) Soft-over-stiff clay ($s_{ub}/s_{ut} = 2.00$, $s_{ut}/\gamma' t D = 0.93$, $D = 1.8$ m, $a = 0.25$)

Figure 7. Effect of top layer thickness ratio (t/D , by varying t) on normalized penetration resistance in two-layer clays (Group DIII, Table 3)

Figure 8. Effect of strength ratio (s_{ub}/s_{ut}) on normalized penetration resistance in two-layer clays ($s_{ut}/\gamma'_t D = 1.85$, $D = 1.8$ m, $a = 0.25$, $t/D = 2$; Group DIV, Table 3)

9(a) Stiff-over-soft clay ($s_{ub}/s_{ut} = 0.20$, $D = 1.8$ m, $a = 0.25$, $t/D = 4$)

9(b) Soft-over-stiff clay ($s_{sub}/s_{ut} = 2.00$, $D = 1.8$ m, $a = 0.25$, $t/D = 2$)

Figure 9. Effect of top layer normalized strength ($s_{ut}/\gamma'_t D$) on normalized penetration resistance in two-layer clays (Group DV, Table 3)

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673 10(a) Adjustment factor for $a = 0.25$, stiff-over-soft clay

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10(b) Adjustment factor for $a = 0.09$, stiff-over-soft clay

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10(c) Adjustment factor for $a = 0.25$, soft-over-stiff clay

10(d) Adjustment factor for $a = 0.09$, soft-over-stiff clay

Figure 10. Design charts for adjusting measured shear strength of top layer (Groups DVI and DVII, Table 3)

11(a) Adjustment factor for $a = 0.25$, stiff-over-soft clay

11(b) Adjustment factor for $a = 0.09$, stiff-over-soft clay

Figure 11. Design chart for adjusting measured shear strength of bottom layer
(Groups DVI and DVII, Table 3)

Figure 12. Procedure for interpretation of undrained shear strength from measured ball data

13(a) Soft-over-stiff clay ($D = 1.8$ m, $a = 0.25$, $t/D = 5.83$)

13(b) Stiff-over-soft clay ($D = 1.8$ m, $a = 0.25$, $t/D = 1.94$)

Figure 13. Comparison between prediction using proposed design framework and centrifuge test data