Experience with a dual pore pressure element piezoball

Cathal Colreavy BEng

PhD Candidate, Centre for Offshore Foundation Systems, The University of Western Australia, Crawley, Australia

Conleth D. O'Loughlin PhD

Associate Professor, Centre for Offshore Foundation Systems, The University of Western Australia, Crawley, Australia

Mark F. Randolph PhD

Fugro Chair in Geotechnics, Centre for Offshore Foundation Systems, The University of Western Australia, Crawley, Australia

Piezoballs, which are full-flow ball penetrometers incorporating pore pressure measurements, are an attractive soft soil characterisation tool as they allow measurement of the intact and remoulded strength and the consolidation coefficient in a single test. The merit of full-flow penetrometers as a reliable tool that is superior to the cone in quantifying the strength of soft clay is gaining acceptance. Much of the recent focus on piezoballs has been on the pore pressure measurement location. Prompted by recent studies that highlight the merit of measuring pore pressure concurrently at more than one measurement location, this paper considers a new centrifuge-scale piezoball, with simultaneous pore pressure measurement at the equator and mid-face positions. Results from centrifuge tests in normally consolidated kaolin clay form the basis for the examination and yield coefficients of consolidation that are consistent with values derived using a number of different methods. Although the mid-face position appears to be the more sensible pore pressure measurement position for dissipation tests, consideration of the values measured at both positions provide strong indications of the drainage response during penetration that is shown in the paper to be important for deriving coefficients of consolidation from subsequent dissipation phases.

Notation

A_p	probe projected area	T	non-dimensional piezofoundation dissipation time ($c_h t/D^2$)
A_s	shaft projected area	T^*	non-dimensional dissipation time ($c_h t/D^2 I_r^{0.5}$)
B_{ball}	piezoball pore pressure parameter	T_b	non-dimensional piezoball dissipation time ($c_h t/D_b d I_r^{0.25}$)
B_q	piezocone pore pressure parameter	t	dissipation time
c_h	horizontal coefficient of consolidation	U	normalised excess pore pressure ($\Delta u/\Delta u_i$)
c_{op}	operative coefficient of consolidation (from piezofoundation tests)	u_0	hydrostatic pore pressure
c_v	vertical coefficient of consolidation	u_{ball}	piezoball pore pressure
D	probe diameter	u_{EQ}	pore pressure at piezoball equator
D_b	piezoball diameter	u_{MF}	pore pressure at piezoball mid-face
D_e	probe effective diameter	v	penetration velocity
d	penetrometer shaft diameter	V'	non-dimensional penetration velocity (vD/c_h)
e_{cs}	void ratio at $p' = 1$ kPa on virgin consolidated line	V'_{50}	non-dimensional penetration velocity at a resistance that is an average of the drained and undrained values
G_s	soil specific gravity	$V'_{50, \Delta u}$	non-dimensional penetration velocity at an excess that is an average of the drained and undrained values
g	Earth's gravitational acceleration	z_p	prototype depth
I_r	rigidity index of soil	α	unequal area ratio
M	slope of the critical state line in $q-p'$ plane	Δu_{EQ}	excess pore pressure at piezoball equator
N	bearing capacity factor	Δu_i	initial excess pore pressure
q	penetration resistance	Δu_{MF}	excess pore pressure at piezoball mid-face
q_{app}	applied piezofoundation pressure	Δu_2	excess pore pressure at piezocone shoulder
q_{bnet}	net piezoball penetration resistance		
q_{cnet}	net piezocone penetration resistance		
q_{Tnet}	net T-bar penetration resistance		
s_u	undrained shear strength of soil		

κ	slope of unloading–reloading line
λ	plastic compression ratio
λ	slope of normal compression line
σ_v	in situ total vertical stress
σ'_v	in situ effective vertical stress
ϕ'	angle of internal friction

1. Introduction

Most of the early research into full-flow penetrometers focused on their use as a strength-profiling tool (Chung and Randolph, 2004; Stewart and Randolph, 1991, 1994; Watson *et al.*, 1998). The benefits of full-flow penetrometers in strength profiling arise from improved resolution afforded by the higher projected area of the full-flow probe compared with a cone, and near equal pressure above and below the probe due to the full-flow soil mechanism (neglecting the relatively small cross-sectional area of the penetrometer shaft). Conversion factors for transforming full-flow penetrometer resistance to soil strength have rigorous theoretical solutions (Martin and Randolph, 2006; Randolph and Houlsby, 1984; Randolph *et al.*, 2000) with little influence from in situ stresses or soil stiffness, in contrast to the cone in which the resistance is affected by both. It is recommended that full-flow penetrometer tests include episodes of cyclic remoulding, allowing the degradation of strength from the intact to the fully remoulded value to be quantified and also as a check on load cell offsets (Randolph *et al.*, 2007). The ball penetrometer is particularly suited for offshore use as (unlike the T-bar) the axisymmetry avoids load cell bending and the geometry is suited for down-hole testing. Pore pressure sensors have recently been added to the ball penetrometer, leading to the term 'piezoball' (Boylan *et al.*, 2007; Colreavy *et al.*, 2010; DeJong *et al.*, 2008; Low *et al.*, 2007; Peuchen *et al.*, 2005), allowing consolidation characteristics to be assessed during a pause in the penetration where the pore pressure is monitored during dissipation, similar to dissipation phases in a cone penetrometer test.

The location of the pore pressure measurement will affect the measured pore pressure response (Boylan *et al.*, 2010). At the tip of the piezoball, where the soil is undergoing large compressive stresses in saturated soil, high pore pressures will be generated. At the equator (one half diameter from the piezoball tip), where the soil is primarily experiencing pure shearing, the generated pore pressure will be lower and may be positive or negative depending on the tendency of the soil to dilate or contract. At the mid-face (midway between the tip and equator), the pore pressure response will be somewhat between that at the tip and that at the equator. Each of these three measurement locations have been considered in previously reported centrifuge and field studies (Boylan and Long, 2006; Boylan *et al.*, 2010; Colreavy *et al.*, 2012; Kelleher and Randolph, 2005; Low *et al.*, 2007; Mahmoodzadeh and

Randolph, 2014) (Figure 1), but with no current consensus as to the 'optimal' location; noting that the optimum may be more than one concurrent measurement. Kelleher and Randolph (2005) showed that pore pressure measured at the piezoball equator location exhibited a greater sensitivity to changes in the soil stratigraphy compared with the piezocone. Both Colreavy *et al.* (2010) and Low *et al.* (2007) found that dissipation times for the piezoball equator position were longer than that for the piezocone, for a piezoball diameter of about 2.2–3.2 times the cone diameter. However, the reverse was found for dissipation times at the piezoball mid-face position for a piezoball with a diameter 1.5 times the cone diameter (Mahmoodzadeh and Randolph, 2014).

Mahmoodzadeh and Randolph (2014) showed the benefit of measuring pore pressure at more than one location. Their centrifuge study was carried out by combining the response from separate tests using two piezoballs with mid-face and equator pore pressure measurements in the respective penetrometers. Their work is extended here through a centrifuge study using a newly developed dual pore pressure element piezoball that measures pore pressure concurrently at the mid-face and equator positions. The benefits of measuring pore pressure in one device rather than from two separate tests include reduced testing times and greater reliability in the pore pressure profiles given that even with the attempts made to ensure a homogenous sample, there may still be some differences between test locations. The potential for this new device to measure intact and remoulded strength and the coefficient of consolidation accurately in a single test is examined through standard penetrometer tests and tests involving cyclic remoulding episodes, penetration pauses and penetration velocity changes.

2. Centrifuge testing

The centrifuge tests were carried out at 100g using the 40g-tonnes 1.8 m radius fixed-beam centrifuge located at the University of Western Australia (UWA). The test series involved in-flight penetration of a newly designed piezoball penetrometer (described in the following section) into normally consolidated kaolin clay. Penetration was achieved using an electrically driven actuator with two degrees of freedom that allowed multiple tests to be carried out in flight without stopping the centrifuge. The actuator control software (PACS, De Catania *et al.*, 2010) allows complex load or displacement test sequences to be the input before the test, a feature that was utilised in the twitch, cyclic remoulding and dissipation tests (under displacement and load control) described in this paper.

2.1 Test equipment

A new dual element piezoball was designed and fabricated for the tests described here (Figure 2). The spherical probe of the piezoball has a diameter $D_b=20$ mm and is connected to a

Figure 1. Examples of piezoballs used in previous studies: (a) Kelleher and Randolph (2005) and Low *et al.* (2007); (b) Boylan and Long (2006); (c) Colreavy *et al.* (2012); (d) Boylan *et al.* (2010); and (e) Mahmoodzadeh and Randolph (2014) (centrifuge)

shaft of diameter $d=5$ mm (giving a shaft to ball area ratio of 0.06). Strain gauges are located near the base of the shaft (mid-gauge position is 15 mm above the ball) to measure the net bearing pressure during penetration and extraction. The strain gauge section is covered by a protective sleeve that eliminates any signal variations associated with lateral pressures on the gauges. The wall thickness of the strain gauge section of the shaft was designed for a safe working load of 440 N, equivalent to a resistance of 1400 kPa for this 20 mm dia. piezoball.

The piezoball is fitted with two Kyowa (PS-10KC) side entry total pressure sensors with a diameter of 6 mm and a measurement range of ± 1 MPa, which when coupled with a filter allowed simultaneous measurement of pore water pressure at the mid-face and equator positions. For ease of saturation, the pressure sensors were located as close as possible to the filter media. This was achieved by locating the sensors in cylindrical voids created in the upper hemisphere of the piezoball, such

that the sensing diaphragm of the pressure sensor was just above the measurement location. The void above each pressure sensor was then filled with a stiff epoxy to maintain the spherical shape of the penetrometer. A 1 mm dia. fluid channel, up to 8 mm long, connects the filter position to the sensing diaphragm of the pressure sensor. The filters are circular rings of polyethylene, 1.3 mm high and 1.5 mm deep, with an average pore size of 35 μm . This material was chosen as the circular filter rings can be easily cut without specialist tools; previous use as pore pressure filters in piezocones and model foundations at UWA has shown it to be adequate in preventing filter clogging in clay. A ceramic filter with an average pore size of 10 μm may be more appropriate for use in silt. Saturation was achieved by placing the penetrometer (with the filter in place) in silicon oil under a vacuum of 100 kPa for 24 h before testing. Saturation was maintained by keeping the probe under oil or water before testing and checking it both before and after the penetration tests by cycling the penetrometer up and down in

Figure 2. Dual-element piezoball: (a) completed piezoball; (b) section view; and (c) schematic representation

the free water above the soil to check that there was no apparent hysteresis in the insertion and extraction pore pressure response.

Additional penetration tests were carried out using a T-bar and piezocone. The T-bar penetrometer consists of a cylindrical bar 5 mm × 20 mm (diameter × length) attached perpendicularly to the end of a 4.5 mm dia. shaft (shaft to probe area ratio of 0.2). The piezocone penetrometer – 10 mm in diameter and an apex angle of 60° – measures pore pressure at the u_2 position, just behind the cone shoulder. The piezocone filter was cut from the same polyethylene material and the saturation procedure was the same as described for the piezoball.

2.2 Sample preparation and soil properties

Tests were conducted in two samples of normally consolidated kaolin clay. Commercially available kaolin clay has been used as a proxy for natural clay in centrifuge tests at UWA for over two decades and its properties are now well understood. The geotechnical properties of UWA kaolin clay were first reported by Stewart (1992) as summarised in Table 1. Checks on these properties, made periodically in the intervening years, confirm

Property	Value
Liquid limit	61%
Plastic limit	27%
Soil particle specific gravity, G_s	2.6
Angle of internal friction, ϕ'	23°
Critical state friction constant, M	0.92
Void ratio at $p' = 1$ kPa on critical state line, e_{cs}	2.14
Slope of normal consolidation line, λ	0.205
Slope of swelling line, κ	0.044
Parameter $A = (\lambda - \kappa)/\lambda$	0.785

Table 1. Characteristics of kaolin clay (from Stewart, 1992)

that the properties listed in Table 1 still pertain to recently sourced UWA kaolin. Of particular interest to this study is the coefficient of consolidation of UWA kaolin. Several studies have reported the vertical coefficient of consolidation, c_v , of UWA kaolin as assessed through one-dimensional Rowe cell tests conducted over a 20-year period. Some of these results are summarised in Figure 3. Collectively, the data show the expected

Figure 3. Vertical coefficient of consolidation for kaolin clay as assessed from Rowe cell tests (after Stewart, 1992; House *et al.*, 2001; Richardson *et al.*, 2009)

increase in c_v with effective stress level. The House *et al.* (2001) and Stewart (1992) datasets are in good agreement, with c_v increasing from about $0.09 \text{ mm}^2/\text{s}$ at 50 kPa to $0.16 \text{ mm}^2/\text{s}$ at 200 kPa . The more recent Richardson *et al.* (2009) dataset indicates slightly lower values of c_v by about 26% on average.

Dry kaolin powder was mixed with water under vacuum for about 24 h to form a slurry with a moisture content of 120%. The slurry was then poured slowly through a hose from the base of the mixer into a centrifuge ‘strongbox’ with internal dimensions $650 \text{ mm} \times 390 \text{ mm} \times 335 \text{ mm}$ (length $\times$ width $\times$ height). A 10 mm layer of sand was placed at the base of the strongbox before pouring the clay slurry to ensure that there was no hydraulic gradient between the top and base of the sample during and after consolidation. The sample was consolidated in flight for 5 days at the eventual test acceleration of $100g$, with additional slurry added to the sample to ensure a final sample height of 215–225 mm ($21.5\text{--}22.5 \text{ m}$ in equivalent prototype scale, z_p) was achieved.

3. Penetrometer testing

The undrained shear strength, s_u , of soil can be deduced from the undrained penetration resistance, q , through the use of a

bearing factor, N , with

$$1. \quad s_u = \frac{q}{N}$$

However, for a piezocone the uneven distribution of overburden and pore pressure around the penetrometer probe requires that the measured tip resistance is corrected to obtain the net resistance using (Lunne *et al.*, 1997)

$$2. \quad q_{\text{cnet}} = q - [\sigma_v - u_2(1 - \alpha)]$$

where q_{cnet} is the net piezocone resistance, σ_v is the vertical total stress and α is the unequal area ratio calibrated in a pressure chamber as 0.8. In the case of the piezocone, this correction can be significant, particularly where ambient pressures are high. As the in situ pressure acts all around the T-bar or piezoball probe (with the exception of the small shaft area at the top of the probe), the correction is usually much lower (Chung and Randolph, 2004), with the net resistance expressed as

$$3. \quad q_{\text{bnet}} \text{ or } q_{\text{Tnet}} = q - [\sigma_v - u_0(1 - \alpha)] \frac{A_s}{A_p}$$

where q_{bnet} and q_{Tnet} are the net piezoball and T-bar penetration resistance, respectively, u_0 is the hydrostatic pore pressure and A_s/A_p is the ratio of the shaft projected area to the probe projected area. The unequal area ratio, α , was calibrated in a pressure chamber to be 0.84 and 0.79 for the piezoball and T-bar, respectively.

As demonstrated by Finnie and Randolph (1994), the drainage conditions around an advancing penetrometer depend on the penetration velocity, v , the probe diameter, D , and the coefficient of vertical consolidation. Chung *et al.* (2006) showed that the consolidation around an advancing penetrometer depends more on the projected area of the penetrometer rather than the diameter. Therefore, in the case of the T-bar, the drainage conditions are related to the effective diameter, D_e , defined as the diameter of a circle with the same projected area as that of the penetrometer probe. The non-dimensional velocity, V' , is used as a measure of the drainage conditions

$$4. \quad V' = \frac{vD_e}{c_h}$$

To date, the preference has been to use the coefficient of vertical consolidation, c_v in Equation 4, where c_v was typically based on results from laboratory oedometer or Rowe cell tests. However, as argued by Lehane *et al.* (2009), the coefficient of horizontal (rather than vertical) consolidation, c_h , may be

more appropriate as this is more likely to govern the drainage response. Furthermore, as c_h rather than c_v is measured during an in situ piezocone or piezoball dissipation test, it may be argued that the degree of drainage generated during a penetrometer test may be more readily quantified using the consolidation coefficient measured during the same penetrometer test. V' rather than the more common V is used here to reflect the use of c_h and not c_v in Equation 4.

4. Results and discussion

4.1 Penetration tests

Examples of net penetration resistance profiles obtained from each penetrometer are shown in Figure 4(a). The penetration velocity in each test was adjusted such that vD_e was constant and hence V' (Equation 4) and the drainage response was equivalent for each penetrometer. A value of $V'=30$ was targeted for each test, based on an assumed average $c_h=0.4 \text{ mm}^2/\text{s}$ over

the penetration depth such that $vD_e=11.28 \text{ mm}^2/\text{s}$ and the penetration velocity, $v=0.56$, 1 and 1.13 mm/s for the piezoball, T-bar and piezocone, respectively. The net penetration resistance for the three penetrometers are broadly similar, with the exception of apparently stronger soil beneath the levels at which dissipation phases were conducted. Notably, the net piezocone penetration resistance, q_{cnet} , is close to the net T-bar resistance; this is somewhat surprising given that cone resistance is generally associated with higher bearing factors to translate net penetration resistance to undrained shear strength. At depths $>7 \text{ m}$, the piezoball resistance is $\sim 10\%$ higher than the T-bar resistance, similar to observations from previous studies (DeJong *et al.*, 2011; Low *et al.*, 2010).

The dashed line in Figure 4(a) represents an undrained strength ratio $s_u/\sigma'_v=0.18$ (where $s_u=q_{net}/N$) using the commonly adopted bearing factor $N=10.5$ (Chung and Randolph, 2004). This s_u/σ'_v ratio is similar to (although slightly higher)

Figure 4. Penetration profiles of: (a) net penetration resistance for piezoball, T-bar and piezocone; (b) excess pore pressure for piezoball mid-face and equator, and piezocone u_2 measurement locations

$s_u/\sigma'_v = 0.16$ from other recent studies on UWA kaolin (Chow *et al.*, 2014; Hu *et al.*, 2014; Morton *et al.*, 2014; Richardson *et al.*, 2009).

Figure 4(b) compares the pore pressure generated around the dual piezoball and piezocone during penetration. There is good agreement between piezoball tests for the excess pore pressure developed at both measurement locations. Interestingly, the excess pore pressure at the piezoball mid-face position, Δu_{MF} , is very close to the piezocone excess pore pressure at the u_2 position, Δu_2 , consistent with observations from a recent centrifuge study using separate mid-face and equator piezoballs (Mahmoodzadeh and Randolph, 2014).

Further analysis of the piezoball excess pore pressure profiles are provided in Figure 5. Figure 5(a) shows that the excess pore pressure at the equator, Δu_{EQ} , is 55–60% of that measured at the mid-face and is reasonably constant with depth. In contrast, the pore pressure parameter $B_{ball} = (u_{ball} - u_0)/q_{bnet}$

(where u_{ball} is the pore pressure measured at the mid-face, u_{MF} , or equator, u_{EQ} , position, Figure 5(b)) shows an increase to 3.5 m before decreasing, with eventual values of $B_{ball} = 0.4$ and 0.65 for the equator and mid-face, respectively. Conversely, $B_q (= (u_2 - u_0)/q_{cnet})$ for the piezocone shows no sharp rise at shallow depths and actually increases with depth from 0.6, close to the surface, to reach the value of B_{ball} for the mid-face at ~6 m. This initial rise and subsequent fall in B_{ball} is considered to be due to slight under consolidation of the upper part of the sample; hence, there is some residual excess pore pressure prior to the penetrometer tests and lower penetration resistance (Figure 4(a)).

4.2 Cyclic remoulding tests

A number of the piezoball and T-bar penetration tests included cyclic remoulding episodes, where the penetrometer was moved vertically by $\pm$ three diameters for a minimum of ten cycles about a discrete depth. This not only allows the fully remoulded soil strength to be quantified, but provides a basis for

Figure 5. Excess pore pressure response during undrained penetration: (a) ratio of excess piezoball equator to mid-face pore pressure and (b) pore pressure parameter

making corrections to the net resistance, accounting for changes in soil buoyancy and load cell changes associated with the changing acceleration field in the centrifuge (Sahdi *et al.*, 2014; White *et al.*, 2010). Typical piezoball and T-bar cyclic remoulding data are provided in Figure 6. The cyclic numbering notation recommended by Randolph *et al.* (2007) is

adopted, where the initial penetration is labelled as 0.25 and the first extraction as 0.75. In this case, the piezoball net penetration resistance was adjusted by 12 kPa to remove the offset in the final penetration and extraction net resistance values. The T-bar net penetration resistance did not need adjusting. The net penetration resistance reduces during each cycle, reflecting the

Figure 6. Piezoball and T-bar cyclic remoulding test results: (a) net resistance; (b) excess pore pressure; (c) net piezoball and T-bar resistance degradation; (d) excess pore pressure evolution;

and (e) pore pressure parameter evolution (only insertion data shown)

gradual remoulding of the soil, reaching a steady state after approximately seven cycles (Figure 6(c)). After ten cycles, the net penetration resistance is 0.4 times the initial resistance, indicating a sensitivity (in terms of penetration resistance) of 2.5 which is typical of that reported in previous studies on UWA kaolin (Chen and Randolph, 2008; O'Loughlin *et al.*, 2013; Sahdi *et al.*, 2014; Watson *et al.*, 2000).

Observations of the pore pressure response provide further insight into soil behaviour during cyclic remoulding. Previous field studies (e.g. Colreavy and O'Loughlin, 2012) typically show that the pore pressure reduces during the first few piezoball cycles, but reaches a steady-state value in fewer cycles than the penetration resistance. This was attributed by DeJong *et al.* (2008) to the breaking down of the macro-structure of the soil, which may be complete within a few cycles; however, in subsequent cycles the degradation is due to remoulding of soil clusters that may take place at constant volume and consequently not induce any changes in excess pore pressure. In those previous studies, the cyclic remoulding followed directly from the initial penetration, whereas in the centrifuge tests considered here, the cyclic remoulding followed a dissipation period during which the pore pressure decayed to the hydrostatic value. Consequently, the pore pressure response during cyclic remoulding (shown in Figure 6(d)) does not follow that observed in other studies (e.g. Boylan *et al.*, 2010; Colreavy and O'Loughlin, 2012). Rather both Δu_{MF} and Δu_{EQ} drop suddenly from the value associated with initial penetration (cycle number 0.25) to a value that is 0.47 and 0.55 times the initial value during the second penetration (cycle number 1.25) at the mid-face and equator measurement locations, respectively. In subsequent penetrations, Δu_{MF} and Δu_{EQ} both rise steadily before becoming stable by the fourth penetration (cycle number 3.25). At the end of cycling, Δu_{MF} and Δu_{EQ} are 0.53 and 0.69 times their respective initial values.

The excess pore pressures during each extraction phase are lower than during the penetration phase. This difference is largest at the mid-face as, during penetration, the mid-face location is on the leading face where compressive stresses are expected to generate excess pore pressures. During extraction, the mid-face is on the trailing face and the excess pore pressures fall to 20% of that during initial penetration in the first extraction, before falling close to 0 for the next three extractions. It is reasonable to expect that Δu_{EQ} would be similar during penetration and extraction as the equator is in the same relative position during penetration and extraction. However, Δu_{EQ} is lower during extraction due to the presence of the shaft that interferes with the symmetry of the pore pressure field. Both Δu_{MF} and Δu_{EQ} on extraction take longer to stabilise than during penetration. The more rapid stabilisation in pore pressure is made clear by Figure 6(e) which plots the pore pressure parameter, B_{ball} , for both the mid-face and equator

positions with cycle number. Beyond four cycles, where the excess pore pressure remains tolerably constant, B_{ball} continues to increase, reflecting the continuous reduction in the net penetration resistance during cycling, before stabilising after eight cycles.

4.3 Dissipation tests

Dissipation tests, where the penetrometer was halted during penetration and excess pore pressures allowed to decay over time, were conducted in a number of tests at a depth of ~12 m. Examples of pore pressure responses for both the piezoball and piezocone are provided in Figure 7(a). The initial magnitudes of Δu_2 , Δu_{MF} and Δu_{EQ} are consistent with observations made from Figure 4, where similar excess pore pressure profiles are evident for the piezocone u_2 location and the piezoball mid-face location, whereas the piezoball equator excess pore pressures are about 60% of the u_2 and mid-face values. While Δu_{MF} begins to decay immediately, Δu_2 and Δu_{EQ} both show an initial rise with dissipation time, t , although in both cases the rise only amounts to ~6% of the initial value and occurs over <10 s. The piezoball excess pore pressure dissipation appears to go through two distinct phases. In the first phase, the mid-face excess pore pressure starts higher and dissipates at a higher rate compared with the equator. In the second phase (>300 s), the excess pore pressure at both locations is the same and both dissipate at the same rate.

The initial phase appears to be dominated by redistribution of pore pressure around the circumference of the piezoball, while in the second stage, the excess pore pressure around the piezoball has equalised and the subsequent dissipation is more uniform around the circumference of the probe. In absolute measures of time (i.e. not accounting for differences in probe diameter that will affect consolidation durations), excess pore pressures dissipate to 50% of their initial value more quickly for the piezoball at the u_{MF} location than for the piezocone at the u_2 location. This observation, which has also been noted by Mahmoodzadeh and Randolph (2014), is interesting as the diameter of the piezoball here is twice that of the piezocone and hence drainage path lengths are expected to be longer. This is made clearer by Figure 7(b), which plots the normalised excess pore pressure response, $U = \Delta u / \Delta u_i$, against non-dimensional time, $T^* = c_h t / D^2 I_r^{0.5}$. The initial excess pore pressure, Δu_i , was estimated at $\sqrt{t} = 0$ using the extrapolation method described by Sully *et al.* (1999). This method accounts for redistribution of pore pressure around the ball before dissipation, although in several instances Δu_i calculated using this approach gave very similar values to the measured value at $t = 0$.

The horizontal coefficient of consolidation, c_h , was determined by obtaining the best match between the piezocone u_2 excess pore pressure response and the Teh and Houlsby (1991)

Figure 7. Piezoball and piezocone dissipation profiles: (a) excess pore pressure reduction with time and (b) non-dimensional pore pressure-time response

solution (also shown in Figure 7(b)) assuming the rigidity index of $I_r = 88$ (calculated using the method proposed by Mayne (2001)). The best fit between the measured piezocone u_2 normalised pore pressure response and the Teh and Houlsby (1991) solution was obtained using $c_h = 0.42 \text{ mm}^2/\text{s}$, and this is broadly consistent with that obtained by Chow *et al.* (2014) and Cocjin *et al.* (2014) at similar stress levels. It is now even more evident that excess pore pressures dissipate more efficiently around the piezoball than around the piezocone, as both the piezoball mid-face and equator non-dimensional times for $U = 0.5$ are much lower than that for the piezocone, as also established in experimental studies in the centrifuge (Mahmoodzadeh and Randolph, 2014) and the field (Colreavy *et al.*, 2010; Low *et al.*, 2007), and also confirmed by numerical analysis (Mahmoodzadeh *et al.*, 2015). The non-dimensional time for 50% excess pore pressure dissipation, $c_h t_{50} / D_b^2$, at the equator is 67% of the piezocone value ($c_h t_{50} / D^2$), while the mid-face $c_h t / D_b^2$ is 22% of that for the piezocone. For the mid-face, this reduction in T_{50} more than compensates for the larger diameter of the ball compared with the piezocone, so that absolute t_{50} values are also smaller for the piezoball. The faster dissipation times for the piezoball is attributed to the smaller volume of soil involved in the mechanism generated during ball penetration and higher gradients of pore pressure around the ball (Low *et al.*, 2007; Mahmoodzadeh *et al.*, 2015).

Although a number of recent field studies have reported piezoball dissipation responses (Colreavy *et al.*, 2010; DeJong *et al.*, 2008; Low *et al.*, 2007), the assessment of these data has been mainly qualitative due to the lack of a solution equivalent to

those available for the piezocone. Mahmoodzadeh *et al.* (2015) recently developed piezoball equator and mid-face dissipation curves through large deformation finite element (LDFE) analyses using the modified Cam clay model. Their analysis found that the normalised dissipation curves were almost unique when a non-dimensional time $T_b = c_h t / D_b d I_r^{0.25}$ is used, noting the dependence on the fourth root of I_r compared with the square root of I_r used in the Teh and Houlsby (1991) solution for the piezocone. The inclusion of the shaft diameter, d , reflects the contribution to excess pore pressure from cavity expansion due to the presence of the shaft. The centrifuge data are compared with the Mahmoodzadeh *et al.* (2015) solution in Figure 8, where the LDFE solution is seen to capture the observed response quite well. The best match between U_{MF} and the LDFE solution was obtained using $c_h = 0.46 \text{ mm}^2/\text{s}$ (averaging all three dissipation curves), and this is in excellent agreement with $c_h = 0.42 \text{ mm}^2/\text{s}$ as previously back analysed from the piezocone data. Although the LDFE curve matches the measured U_{EQ} data very well, the best fit was obtained using $c_h = 0.15 \text{ mm}^2/\text{s}$, which is 2.6 times lower than that obtained from the piezocone analysis. Mahmoodzadeh *et al.* (2015) showed comparisons between centrifuge dissipations and the LDFE simulations, and acknowledged that the LDFE for U_{EQ} failed to capture the initial dissipation response.

With faster dissipation times and a robust interpretation method, the results suggest that the mid-face is the optimal location for dissipation tests.

As a final observation on interpretation of c_h values from piezoball tests, it is worth noting that the effect of a (partially)

Figure 8. Piezoball mid-face and equator dissipation profiles compared with LDFE from Mahmoodzadeh *et al.* (2015)

remoulded zone around the piezoball does not appear to affect the deduced value. Even after fully remoulding the soil by cyclic penetration and extraction of the piezoball, Low *et al.* (2008) found essentially no change in the deduced value of c_h . LDFE analysis of full-flow penetrometer cycling has shown that the final width of the failure mechanism is approximately twice the ball diameter (Zhou and Randolph, 2009). The larger failure zone, relative to that following initial penetration, might be expected to influence the pore pressure dissipation in this zone. While this may be true in the short term, it seems that the longer term dissipation relevant for estimating t_{50} and hence c_h is controlled more by the intact soil in the far field.

4.4 Piezofoundation tests

To further quantify the coefficient of consolidation, load-controlled ‘piezo-foundation’ pore pressure dissipation tests were carried out. The rigid circular piezo foundation had a diameter $D=40$ mm (model scale) and was instrumented with a pore pressure sensor in the centre of the underside of the foundation. A load cell, connected in series between the foundation shaft and the actuator, measured the applied vertical bearing pressure, q_{app} , which was held constant for each dissipation phase. The normalised pore pressure, $U=\Delta u/\Delta u_i$, response measured at $q_{app}=10, 20, 40, 80$ and 100 kPa are shown in Figure 9 together with corresponding finite-element solutions for a rigid circular surface foundation (Gourvenec and Randolph, 2010). Both the experimental data and the finite-element solution exhibit the Mandel–Cryer effect (Cryer, 1963; Mandel, 1950), whereby the pore pressure begins to increase during dissipation before reducing. This effect is due to total stress transfer from the edges to the centre of the foundation (where the pore pressure is

Figure 9. Piezofoundation pore pressure response

measured) brought about by faster consolidation at the foundation edges than at the centre (Cocjin *et al.*, 2014). Time factors $T=tc_{op}/D^2$ for the experimental dissipation data, which extend to at least $U=0.4$, were calculated by selecting operational values of the coefficient of consolidation, c_{op} (where c_{op} is an operative value representative of conditions involving both horizontal and vertical drainage with $c_v < c_{op} < c_h$) that resulted in the best match with the Gourvenec and Randolph (2010) finite-element solution. This resulted in c_{op} values increasing from $0.07 \text{ mm}^2/\text{s}$ at $q_{app}=10$ kPa to $0.16 \text{ mm}^2/\text{s}$ at $q_{app}=100$ kPa. These are compared with the coefficients of consolidation derived from the penetrometer tests and from other published data in the following section.

4.5 Comparison of c_v and c_h results

Coefficients of consolidation, c_v and c_h derived from the penetrometer and piezo-foundation tests are compared in Figure 10, together with previously published Rowe cell data (House *et al.*, 2001; Richardson *et al.*, 2009; Stewart, 1992). The horizontal coefficient of consolidation, c_h , is in the narrow range $0.15\text{--}0.52 \text{ mm}^2/\text{s}$; the lower bound relates to the piezoball equator dissipation data which are considered unreliable, as discussed previously. The more reliable estimations of c_h are in the range $0.42\text{--}0.52 \text{ mm}^2/\text{s}$, 5.2–5.6 times the Richardson *et al.* (2009) Rowe cell values and only slightly higher than $\lambda/\kappa=4.66$; these reflect the fact that the path in $e-p'$ space during a displacement controlled dissipation test lies closely parallel to an unloading–reloading line (gradient of κ) rather than a compression line (gradient of λ) in the Rowe cell test (Mahmoodzadeh and Randolph, 2014).

Figure 10. Comparison of c_h and c_v using different test methods

Consolidation coefficients derived from the piezo-foundation dissipation are sensibly bounded by c_v from the Richardson *et al.* (2009) Rowe cell data and c_h , as summarised above, due to the combined radial and vertical flow associated with the consolidation regime in this case. This operative coefficient of consolidation, c_{op} , from the piezo-foundation data are 2.1 times c_v , in close agreement with 2.7 times the same data as reported by Cocjin *et al.* (2014).

4.6 Variable rate penetrometer tests

As discussed previously, the penetration resistance of a penetrating probe depends on its diameter, the penetration velocity and the consolidation characteristics of the soil. Previous studies (e.g. House *et al.*, 2001; Low *et al.*, 2008; Randolph and Hope, 2004) have demonstrated the effect of adjustments to the penetration velocity on the penetration resistance and excess pore pressure. At a sufficiently high non-dimensional penetration velocity (V' , Equation 4), the penetration response will be undrained with low penetration resistance and high excess pore pressure. As V' reduces, the response moves to the partially drained region, with increases in the penetration resistance and corresponding reductions in the excess pore pressure eventually reaching a steady-state drained condition, where the penetration resistance is high and the excess pore pressure is zero. At penetration velocities higher than that required to achieve undrained conditions, the penetration

resistance increases due to viscous strain rate effects with an associated increase in the excess pore pressure, reflecting the change in total stress.

Observing the response to changes in penetration velocity may be achieved through twitch tests (House *et al.*, 2001), where the penetration velocity is successively reduced for a number of steps, with each step having a penetration distance equal to at least two probe diameters or alternatively, by conducting individual tests at different penetration velocities. The latter approach was adopted for the variable rate piezoball tests as the centrifuge sample depth was limited to about 11 piezoball diameters, which is too low for a successful twitch test. However, the sample depth corresponds to about 44 T-bar diameters, meaning that variable rate T-bar tests could be achieved using twitch tests. Partially drained piezoball penetration tests were carried out at velocities of $v=0.056$, 0.0056 and 0.002 mm/s, while T-bar twitch tests were carried out in the velocity range $v=3$ to 0.0001 mm/s. During variable rate penetration tests, the piezoball was penetrated at an initial undrained velocity $v=0.56$ mm/s for three to four diameters before reducing the velocity for the final two to three diameters. Figure 11 shows the piezoball net penetration resistance and excess pore pressure response generated at different penetration velocities. Consistent with previous studies, each reduction in velocity moves the penetration response further into the partially drained region resulting in increased penetration resistance and decreased excess pore pressure. T-bar twitch test profiles are shown in Figure 12 and exhibit similar trends, with reductions in the penetration velocity causing increases in penetration resistance.

So-called 'backbone curves' describing these changes in net penetration resistance and excess pore pressure with changes in non-dimensional velocity (Equation 4) can be generated from the data provided in Figures 11 and 12. The normalised penetration resistance backbone curve may be expressed as (Lee and Randolph, 2011; Mahmoodzadeh and Randolph, 2014)

$$5. \quad \frac{q_{net}}{q_{net(ref)}} = 1 + \frac{b}{1 + (V'/V'_{50})^d}$$

where q_{net} is the net penetration resistance (of any penetrometer), $q_{net(ref)}$ is the reference value of undrained net penetration resistance chosen at $V'=25.6$, b and d are fitting constants and V'_{50} represents the normalised velocity at which the resistance is the average of the drained and undrained values. The horizontal coefficient of consolidation, c_h , used in the calculation of V' , is selected appropriate to each considered depth interval, using $c_h=5.2c_v$ calibrated using the piezocone and piezoball dissipation data against the Richardson *et al.* (2009) Rowe cell data in Figure 10.

Figure 11. Variable rate piezoball profiles: (a) net resistance; (b) excess mid-face pore pressure; and (c) excess equator pore pressure

The net penetration resistance data from Figures 11 and 12 are shown in the non-dimensional form of Equation 4 in Figure 13(a). The T-bar data span $V' = 0.02$ – 120 ; this indicates a constant drained net penetration resistance at $V' \lesssim 0.2$, with the reducing net penetration resistance with increasing V' reaching a minimum undrained net penetration resistance at $V' = 20$, which is close to $V' = 30$ selected as the reference velocity that was expected to yield undrained conditions. Beyond $V' = 20$, the net penetration resistance increases due to viscous strain rate effects; this aspect is not captured by Equation 5, but can be quantified using extended versions of Equation 5 such as those proposed by Lehane *et al.* (2009) or Randolph and Hope (2004). The data from the piezoball tests occupy a narrower band, from $V' = 0.26$ – 25.6 , as the penetration resistance at the lowest velocity (corresponding to $V' \sim 0.1$) did not reach a steady state and was not considered in the analysis. The normalised net penetration resistance at $V' = 25.6$ is evidently similar to that of the T-bar at $V' = 20$, although this is to be expected as both the T-bar and piezoball tests were designed to target the same value of V' for the reference (undrained) case. As V' reduces, the piezoball data are initially similar to the T-bar data (i.e. at $V' = 2.56$), but then fall beneath the T-bar trend at $V' = 0.26$. However, Figure 13(b), which plots the same data using measured rather than net penetration

resistance, indicates similar trends for both the T-bar and the piezoball data. This is to be expected as the correction to the measured penetration resistance was, in relative terms, greater for the T-bar than the piezoball due to the higher shaft to ball area ratio. Although the penetration resistance correction is constant for each penetrometer, it has a relatively larger effect for the T-bar as the correction will tend to increase $q_{\text{net}}/q_{\text{net(ref)}}$ at the higher penetration resistances associated with lower penetration velocities. Equation 5 is also shown in Figures 13(a) and 13(b) using $d = 1.4$ and $V'_{50} = 1.2$ as recommended by Mahmoodzadeh and Randolph (2014), but using $b = 2.5$ for the measured penetration resistance (Figure 13(b)) although a higher value of $b = 3.5$ is required for the net penetration resistance (Figure 13(a)), as is also evident in House *et al.* (2001) and Randolph and Hope (2004).

In a similar manner to the penetration resistance, backbone curves may be generated from the piezoball excess pore pressure data and expressed as (Mahmoodzadeh and Randolph, 2014)

$$6. \quad \frac{\Delta u}{\Delta u_{\text{ref}}} = 1 - \frac{1}{1 + (V'/V'_{50, \Delta u})^f}$$

where Δu_{ref} is the (reference) excess pore pressure selected at the non-dimensional velocity associated with undrained behaviour ($V' = 25.6$) and f is a fitting constant, similar to d in Equation 5.

The measured piezoball excess pore pressure data are fitted to Equation 6 in Figure 14 using $f = 1.1$ and $V'_{50, \Delta u} = 1$ and 1.2 for the mid-face and equator positions, respectively. The tight

cluster of normalised excess pore pressure points at each penetration velocity suggests that, unlike the penetration resistance, the two diameters of penetration were sufficient for the excess pore pressure to reach steady conditions. The lower power exponent used in Equation 6 compared with Equation 5 ($f = 1.2$, $d = 1.4$) infers that the slope of the backbone curve is more moderate for the excess pore pressure response, indicating that for normalised velocities close to V'_{50} , the excess pore pressure is less sensitive to changes in velocity than the penetration resistance, although the effect of velocity extends over a wider velocity range.

Figure 12. Variable rate T-bar profiles: (a) velocity and (b) net resistance

4.7 Partial drainage indicators

As demonstrated by DeJong and Randolph (2012), any partial drainage in the penetration phase prior to a dissipation test could lead to estimations of c_h that may be in error by up to one order of magnitude. To investigate the effect of partial drainage on subsequent dissipation tests, several piezoball dissipation tests were carried out following the variable rate penetration tests described previously. Dissipation profiles following the partially drained penetrations are shown in Figure 15. The initial excess pore pressures at the start of each dissipation reflect the values shown in the variable rate profiles given in Figure 11. The lower penetration velocities also lead to a quicker redistribution of excess pore pressure around the circumference of the piezoball at the beginning of the test. For example, the excess pore pressure profiles for the two measurement locations are virtually indistinguishable after 20 s for the dissipation following a penetration with $V' = 0.26$, whereas it takes over 300 s for the excess pore pressures to redistribute for the dissipation following a penetration with $V' = 25.6$.

Figure 16 replots the mid-face dissipation profiles from Figure 15 as normalised excess pore pressure, U , against

Figure 13. Piezoball and T-bar backbone curves of: (a) net penetration resistance and (b) measured penetration resistance

Figure 14. Piezoball excess pore pressure backbone curves:
(a) mid-face and (b) equator

Figure 15. Piezoball dissipation profiles following variable rate penetration

non-dimensional time, T_b (as defined earlier in the paper). T_b values have been calculated using $c_h = 0.3 \text{ mm}^2/\text{s}$ as established from the match between the dissipation profile following undrained penetration ($V' = 25.6$) and the Mahmoodzadeh *et al.* (2015) LDFE solution; noting that this value is similar to $c_h = 0.46 \text{ mm}^2/\text{s}$ interpreted from a separate dissipation test (Figure 8). It is now evident that the dissipation times increased as the preceding penetration non-dimensional velocity and consequently, the initial excess pore pressure reduced. This has consequences for dissipations that follow partially drained penetration, as analysis of the dissipation data will result in erroneous estimates of c_h . For example, if the initial penetration

Figure 16. Non-dimensional piezoball dissipation profiles for the piezoball mid-face measurement location

was conducted at $V' = 0.26$ and the subsequent dissipation data were matched with the Mahmoodzadeh *et al.* (2015) LDFE solution, the resulting c_h would be ~ 6.5 times lower than that obtained for a dissipation following undrained penetration ($V' = 25.6$).

Given the implications on the interpretation of c_h from a dissipation test, it is clearly important to assess the drainage conditions during the penetration prior to a dissipation test. Ideally, the penetration resistance and excess pore pressure response in the penetration phase would indicate the drainage conditions during penetration. The backbone curves in Figures 13 and 14 show the effect of changing drainage

Figure 17. Excess pore pressure parameter as a partial consolidation indicator

conditions on the penetration resistance and excess pore pressure. However, since these changes are relative to undrained conditions, these curves cannot be used as an indicator of drainage conditions in any single test. The relative magnitudes of excess pore pressure and net penetration resistance will also vary with changing drainage conditions. This is demonstrated by Figure 17, which indicates that for UWA normally consolidated kaolin clay, partially drained conditions will occur at $B_{ball} < 0.9$ and 0.6 (for the mid-face and equator positions, respectively). However, more data that would improve the definition of these dependencies would improve confidence in these indicative limits for undrained penetration.

5. Conclusions

Measurement of intact and remoulded shear strength and the consolidation characteristics of soil are important parameters required for the design of geotechnical structures, particularly those located offshore. Although the ability of full-flow penetrometers to reliably measure both intact and remoulded soil strength are well established, the merits of pore pressure measurements on the same penetrometer are still being explored. This paper considers centrifuge data obtained with a new model scale piezoball penetrometer that simultaneously measures pore pressures at both the equator and mid-face positions. The main findings from this study are as follows.

- Dissipation times at the piezoball mid-face are shorter than those at the piezocone shoulder, despite the piezoball having a diameter that is twice that of the piezocone. This has positive implications for site investigations as it offers an opportunity for reducing overall testing durations and hence reduces costs.
- Interpretation of the mid-face pore pressure dissipation response, using recently developed methods based on

LDFE analyses, resulted in deduced coefficients of consolidation that compare favourably with interpretations of piezocone dissipation data. Poorer agreement was found for the equator position, which supports the use of the mid-face position for dissipation testing.

- The importance of ensuring that undrained conditions are maintained in the penetration phase prior to a dissipation test was examined by carrying out dissipation tests following partially drained penetration. In the case of the mid-face position, a reduction in penetration velocity of two orders of magnitude would have resulted in an underestimation of the horizontal coefficient of consolidation by a factor greater than six.
- Partial drainage indicators during penetration were shown to be useful to ensure the reliability of deduced consolidation coefficients. Results from variable rate penetrometer tests indicate that the effects of the penetration velocity extend over a wider velocity range for excess pore pressure than for the penetration resistance. Consequently, factors based on excess pore pressure measurements during penetration, such as the ratio of the excess pore pressure to the net penetration resistance, are viewed as having the highest potential in 'warning' that undrained penetration may not be occurring.

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