Field experience of the piezoball in soft clay

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ABSTRACT: This paper presents the results of a series of piezoball penetration and dissipation tests carried out at two well characterized soft soil sites in Ireland. Piezoball data are compared with piezocone data, in addition to other in situ and laboratory test results. Using the standard N factor of 10.5 resulted in an undrained shear strength profile which is in very good agreement with Tbar profiles from previous studies. Interestingly, results of dissipation tests show that dissipation around the piezoball is faster than around the cone, when the different diameters are accounted for.

1 INTRODUCTION

The advantages of full-flow penetrometers such as the Tbar and Ball over the conventional cone penetrometer have been amply demonstrated (e.g. Chung & Randolph 2004, Randolph 2004, Boylan et al. 2007). The rational for replacing the cone with either a Tbar or ball is primarily attributable to the difficulty in establishing an appropriate cone factor (N) for deriving s_u from cone resistance (Chung & Randolph 2004). This difficulty is partly due to the need to correct the measured cone resistance for overburden pressure and partly due to the uncertainty regarding the soil failure mechanism as the soil is displaced past the penetrating cone. The above deficiencies of the cone penetrometer are overcome by full-flow penetrometers. More recently (Low et al. 2007; DeJong et al. 2008) a pore pressure element has been added to the ball penetrometer to allow for pore pressure measurements (during both installation and dissipation) in a similar manner to the CPTu.

This paper presents the results of piezoball penetration and dissipation tests carried out at two soft soil sites in Ireland. The merits of the piezoball over the conventional piezocone are assessed by comparing these results with previously published in-situ and laboratory data.

2 TESTING EQUIPMENT

2.1 *Piezocone*

Piezocone tests were carried out using two piezocones; the first with a diameter of 35.7 mm and a projected area of 10 cm^2, and the second with a diameter of 44.4 mm and a projected area of 15 cm^2. The 10 cm^2 and 15 cm^2 piezocones have a calibrated net area ratio, α, of 0.793 and 0.869 respectively. Both cones measure pore pressure at the u_2 position. Tests were carried out at the standard testing rate of 20 mm/s (Lunne et al. 1997).

Figure 1. Piezoball showing equator, mid-face and tip filter positions

2.2 *Piezoball*

The piezoball was constructed from hardened steel with a diameter of 113 mm and a projected area of 100 cm^2 (i.e. 10 times that of the standard CPTu). The piezoball was designed so as to screw on to the 10 cm^2 piezocone load cell. Tip resistance and pore pressure are measured by the piezocone load cell and transducer. As with the piezocone, tests were carried out at the standard rate of 20 mm/s.

The piezoball design is similar to that employed by DeJong et al. (2008), in that it comprises several modular components that can be interchanged to facilitate pore pressure filter locations at the tip, mid-face and equator (see Figure 1b). The piezoball filters were custom fabricated from polyethylene with an average pore size of 30 – 60 microns, similar to that of the CPTu filters. The filters were saturated with silicone oil in a chamber under a vacuum of approximately 100 kPa for about 8 hours, after which time air was bled back into the chamber to force the silicone oil into the filters. The filters, which were stored in silicone oil until use, were fitted to the piezoball while submerged in the silicone oil, and the voids filled with oil before attaching to the piezocone shaft. A latex membrane was fitted to the piezoball prior to the test to ensure the filter saturation was maintained.

3 SITE DETAILS

3.1 *Athlone*

The Athlone site is located within the River Shannon flood plain, west of the river, north of Athlone town in Ireland. The sediments consist of a layer of peat on top of a layer of calcium, or ‘calc’, marl overlying a layer of grey organic clay and then brown laminated clay. The water table is generally no more than 1 m beneath ground level. The tests carried out in this study were concentrated on Profile D, as referred to in Long & O’Riordan (2001). A comprehensive investigation of the Athlone soils has been reported by Long & O’Riordan (2001) and are summarized on Figure 2a.

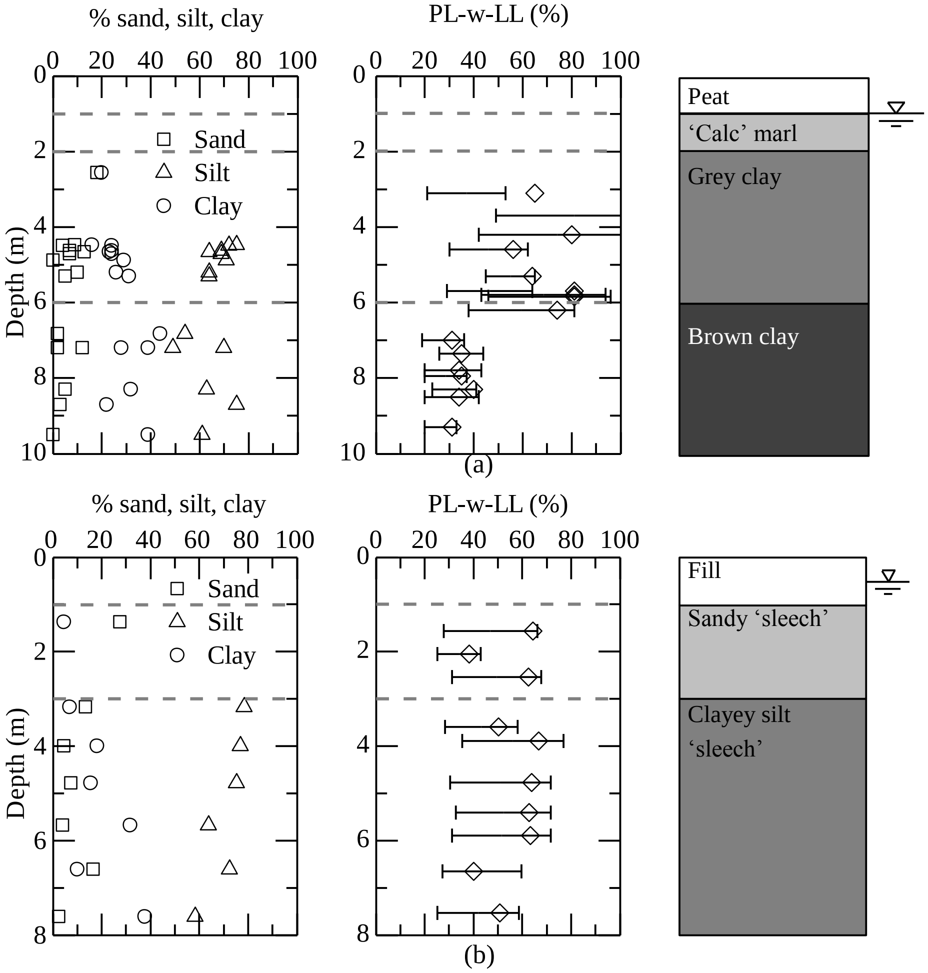


Figure 2. (a) Athlone material properties (Long & O'Riordan 2001); and (b) Belfast material properties (Lehane et al. 2003).

3.2 *Belfast*

The Belfast site is located on the south side of Belfast Lough, 10 km north east of Belfast city, Northern Ireland. The stratigraphy is made up of approximately 1 m of recently placed fill which overlies 2 m of sandy silt, which in turn overlies 6 m of soft clayey silt 'sleech'. The 'sleech' material was laid down over the past 3000 years in shallow waters. The soil properties of the Belfast deposits have been well characterized by Bell (1977) and Lehane et al. (2003) and are summarized on Figure 2b.

4 TEST RESULTS

4.1 *General*

Piezocone and piezoball penetration tests were carried out at both Athlone and Belfast. Piezocone resistances have been corrected for overburden and pore pressure effects (Lunne et al. 1997). Due to the full-flow behavior of the soil around the ball and Tbar, the pore pressure and overburden stress acts on both the top and bottom and hence there is little need to apply a correction to determine s_u (Randolph 2004).

The penetration resistances for both the CPTu and piezoball for both sites are shown in Figure 3. The cone profile is higher than the Tbar and piezoball, similar to field experiences in Bothkenner (Boylan et al. 2007) but contrary to centrifuge experiences of Burswood clay (Chung et al. 2006). In the grey clay q_{ball}/q_{net} is on average 0.85, while in the brown clay the ratio is lower, at 0.60. Both the CPTu and piezoball penetration resistance is seen to increase with depth in the grey clay but reduce (or stay tolerably constant) with depth in the brown clay. This is in line with previous experience with the CPTu at Athlone (e.g. Long & O'Riordan 2001) and is also reflected in Tbar profiles reported by Long & Gudjonsson (2004) for Athlone. The latter Tbar penetration resistances are generally in good agreement with the piezoball penetration resistances which is in keeping with the observations of Chung et al. (2006) and Boylan et al. (2007) that the resistance measurements for full flow penetrometers are broadly similar.

Pore pressure profiles for a number of CPTu and piezoball with pore pressure measurement at the equator, u_{eqball}, tests are compared on Figure 3a, as well as one piezoball profile with pore pressure measurement at the mid-face position, u_{mball},. The u_{eqball} profile is consistently lower than the corresponding CPTu profile; this is line with previous findings reported by Low et al. (2007) for a piezoball with pore pressure measurements at the equator and by Boylan et al. (2007) for pore pressure measurement close to the piezoball tip. Interestingly, u_{mball} is generally in line with the u_{eqball} profiles. Large reductions in the pore pressure in some of the CPTu and piezoball profiles at 3 m, 4.5 m, 7 m and 8 m correspond to dissipation tests.

The piezoball resistance for Belfast is compared with a previously established CPTu profile reported by Lehane et al. (2003). The data originate at the base of the fill at 3 m depth and increase with depth. The profiles in both cases show very similar trends. Unlike Athlone, the piezoball resistance profile is higher than the piezocone throughout most of the stratum. At the bottom of the stratum, both resistance profiles are in line. Pore pressures were also obtained for the piezoball, at the u_{eqball} position. This profile is compared with a CPTu u_2 profile in Figure 3b. Similarly to Athlone, the piezoball pore pressure is lower than the corresponding CPTu profile. The large reduction in pore pressure in both profiles at 4m and 6m correspond to dissipation tests.

4.2 *Undrained shear strength*

The undrained shear strength may be determined from the penetration resistance using:

$$s_u = q / N \tag{1}$$

where q is the penetration resistance (net tip resistance in the case of the piezocone and measured tip resistance in the case of the piezoball) and N is a bearing capacity factor (N_{kt} for the piezocone and N_{ball} for the piezoball).

Guidance on selection of an appropriate N_{kt} is limited and each site usually requires calibration using laboratory s_u determinations on high quality undisturbed samples (Chung & Randolph 2004).

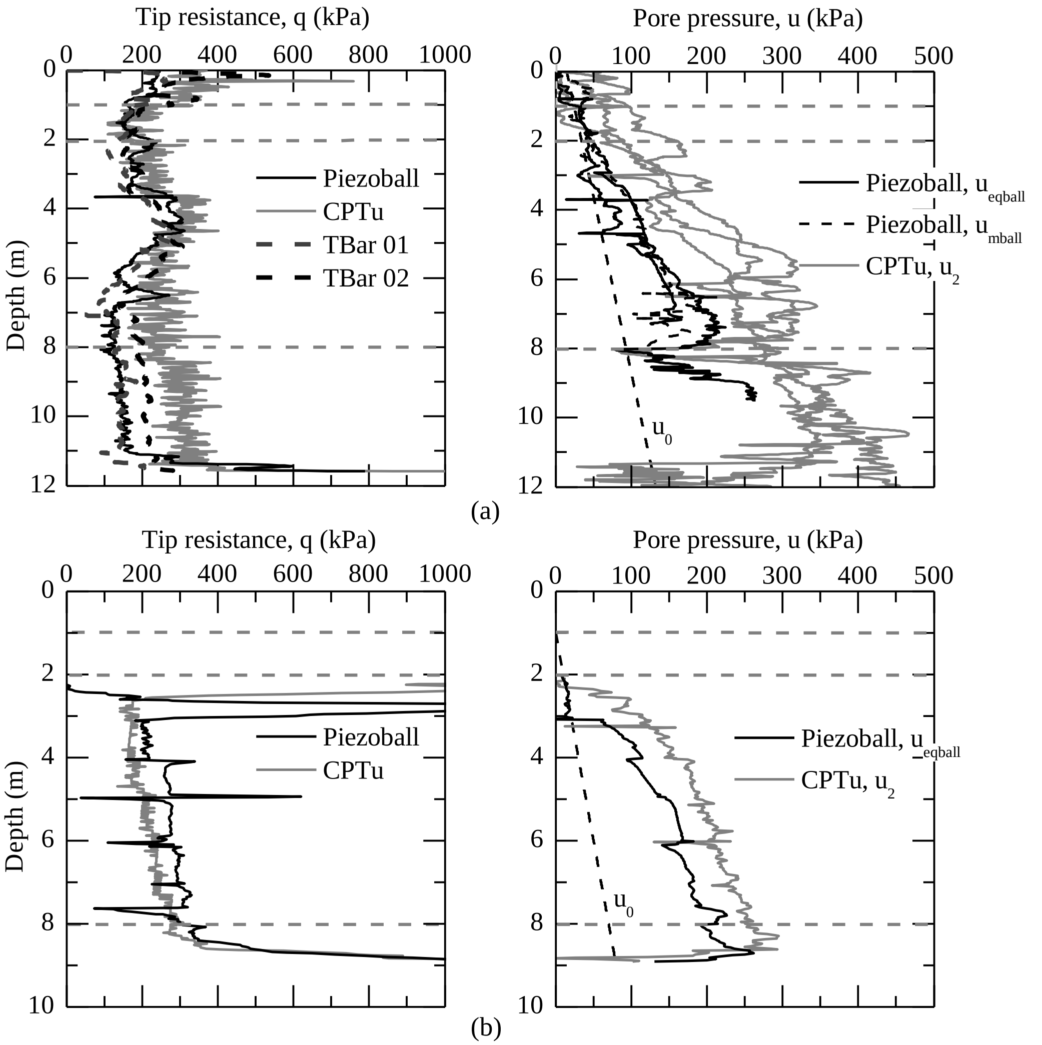


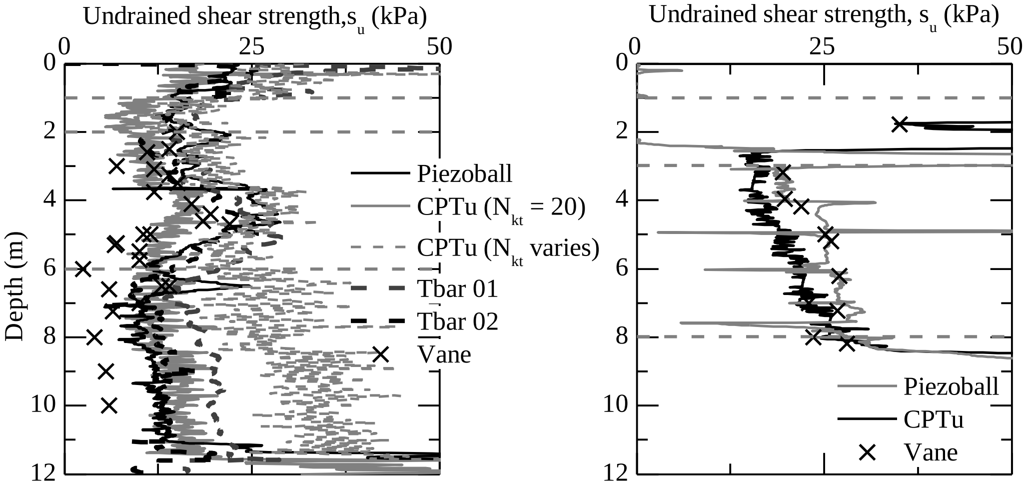
Figure 3. (a) Athlone resistance profiles (with T-bar resistance profiles from Long & Gudjonsson 2004); and (b) Belfast resistance profiles (with CPTu data from Lehane et al. 2003).

A number of empirical relationships such as those proposed by Karlsrud et al. (2005) have merit in avoiding this calibration. Applying the Karlsrud et al. (2005) recommendations to the Athlone site resulted in N_{kt} factors of 11.7 and 9.1 for the grey and brown clays respectively. Guidance on the choice of N_{ball} or N_{Tbar} is more straightforward. Many field and centrifuge studies have shown that s_u derived using a factor of $N_{ball} = N_{Tbar} = 10.5$ (e.g. Watson et al. 1997; DeJong et al. 2004; Chung & Randolph 2004) are consistent with expected strengths from vane and laboratory tests. Undrained shear strength profiles for Athlone using the above N values are compared on Figure 4a with prior reported in situ s_u measurements, and lead to the following observations:

1. The Karlsrud et al. (2005) recommendation resulted in CPTu s_u profiles that are approximately twice as high as corresponding profiles from the piezoball (this study), the Tbar (Long and Gudjonsson 2004) and the field vane (Long & O’Riordan 2001). However, it should be noted that the Karlsrud et al. (2005) recommendations have been calibrated against triaxial compression data while the penetrometer profiles here are calibrated against FVT results. Therefore it would be expected that using the N_{kt} determined from Karlsrud et al. (2005) would result in higher s_u values than the vane results and hence the profiles calibrated against the vane results.

2. Better overall agreement in the s_u profiles is obtained using an N_{kt} of 20 (as was used by Long & O'Riordan 2001).
3. The piezoball and Tbar s_u profiles are in good agreement with each other and the field vane s_u using the recommended $N_{ball} = N_{Tbar} = 10.5$.
4. The CPTu s_u profile diverges from the Tbar, piezoball and field vane s_u profiles in the brown clay, supporting the commonly made observation that N_{kt} tends to increase with depth (Chung & Randolph 2004, Long & Gudjonsson 2004).

Applying the Karlsrud et al. (2005) recommendations to the Belfast site resulted in $N_{kt} = 10.7$. This is close to the value of $N_{kt} = 11$ used by McCabe & Philips (2008) which was derived from Lunne et al. (1997). $N_{kt} = 10.7$ was applied to net tip resistances reported by Lehane et al. (2003). Undrained shear strength profiles for Belfast are compared on Figure 4b, with $N_{ball} = 10.5$. In contrast to Athlone, the Karlsrud et al. (2005) recommendation resulted in a CPTu s_u profile for Belfast that is in reasonably good agreement with both the piezoball and the field vane. The piezoball s_u profiles are in particularly good agreement with the field vane measurements.



(a) (b)

Figure 4. s_u profiles for (a) Athlone (with FVT results and Tbar profiles from Long & Gudjonsson 2004); and (b) Belfast (with FVT and piezocone profiles from Lehane et al. 2003).

4.3 *Dissipation test results*

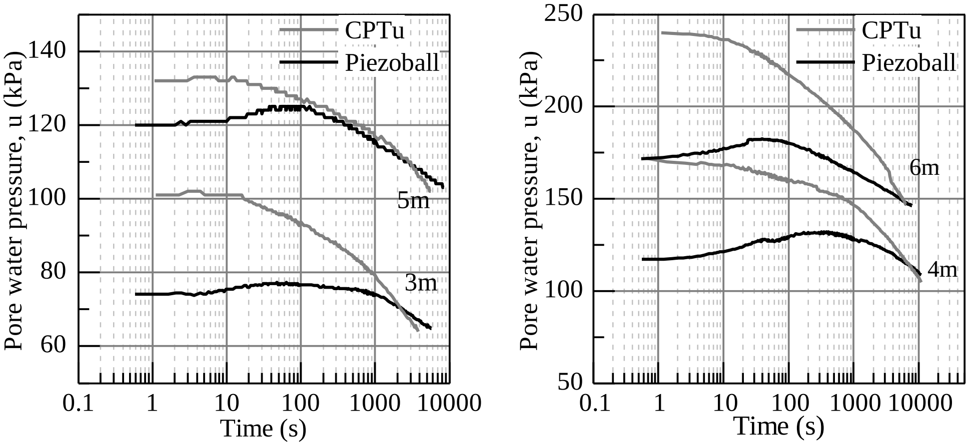
Dissipation tests were carried out at various depths at both sites using the piezoball and piezocone. The piezoball pore pressure measurement in all instances relate to the equator position. Figure 5 shows typical dissipation curves from both sites. The piezoball profile is very similar in shape to the piezocone profile. Although the initial increase in the piezoball pore pressure, observed over approximately 50 seconds, could indicate inadequate saturation, similar trends have also been observed in piezoball tests (e.g. Low et al. 2007, DeJong et al. 2008). In these cases significant efforts were made to ensure that the saturation techniques were effective and reliable, to the extent that the observed pore pressure lag was attributed to short-term equalization of the pore pressures around the probe rather than the slow response of the pore pressure measurement system.

A comparison between the piezoball and piezocone dissipation data is facilitated by using the normalized time factor, T^*:

$$T^* = c_h t / r^2 \sqrt{I_r} \tag{2}$$

where t is the dissipation time, c_h is the horizontal coefficient of consolidation, r is the penetrometer radius and I_r is the rigidity index (G/s_u, where G is the shear modulus determined from the dilatometer for Athlone and the seismic CPTu for Belfast (Lehane et al. 2003)). Since there was an increase in pore pressure at the start of the dissipation test, the actual initial pore pressure was determined using a square root of time plot (Low et al. 2007). The coefficient of consolidation, c_h, was determined from the piezocone data in accordance with the Teh and Houlsby (1991) method. Since there is currently no theoretical solution for interpreting piezoball dissipation results, the c_h value determined from piezocone tests is used in both the piezoball and piezocone interpretation.

Figure 6 compares the piezocone and piezoball normalized dissipation curves. Interestingly, the piezoball and piezocone normalized time factors are similar, which infers that the rate of dissipation is faster around the ball than around the cone when the different diameters are accounted for (d_{ball} ~$3d_{cone}$). This is in line with previous findings (Low et al. 2007, DeJong et al. 2008) and shows the clear potential for using the piezoball for estimating consolidation properties, particularly where the piezoball is standardized at a smaller diameter.



(a)

(b)

Figure 5. Piezocone and piezoball dissipation curves for (a) Athlone; and (b) Belfast

5 CONCLUSIONS

A series of piezoball penetration and dissipation tests have been presented in order to assess the merits of using the piezoball to characterize soft soil sites. Results of these tests have been evaluated against piezocone tests, in addition to other in situ and laboratory results.

s_u profiles from both sites are seen to be in good agreement with established profiles using the piezoball. The difficulty in choosing an appropriate N_{kt} factor for the cone is highlighted. Dissipation tests using the piezoball have been shown to have significant potential for assessing the consolidation characteristics of a soil, once a suitable theoretical framework has been developed, especially where the piezoball diameter is standardized at a smaller diameter.

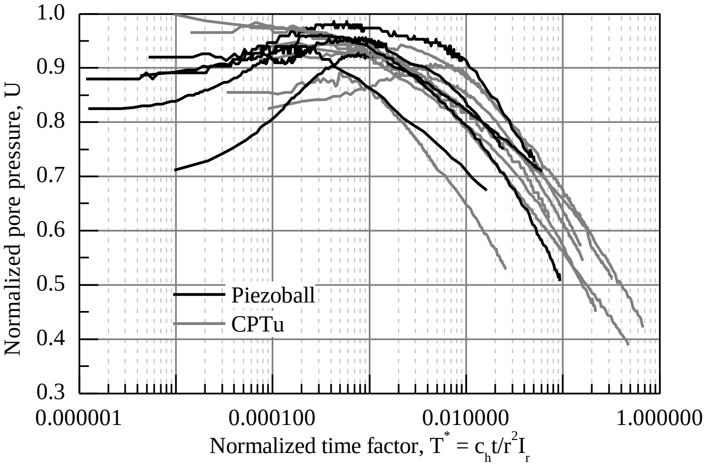


Figure 6. Normalized piezocone and piezoball dissipation curves from Athlone and Belfast

REFERENCES

Bell, A. 1977. Laboratory Studies of the Belfast Estuarine Deposits. PhD Thesis, Queen's University of Belfast.

Boylan, N., Long, M., Ward, D., Barwise, A. & Georgious, B. 2007. Full flow penetrometer testing in Bothkennar clay. *Proc. 6th Int. Conf., Soc. for Underwater Technology, Offshore Site Investigation and Geotechnics (SUT-OSIG)*, London, 177 – 186.

Chung, S.F. & Randolph, M.F. 2004. Penetration resistance in soft clay for different shaped penetrometers. *Proc. 2nd Int. Conf. Geotechnical and Geophysical Site Characterization – ISC'2, Porto,* Rotterdam: Millpress, 671 – 678.

Chung, S., Randolph, M. & Schneider, J. 2006. Effect of penetration rate on penetrometer resistance in clay. *ASCE JGGE,* 132(9), 1188 – 1196.

DeJong, J.T., Yafrate, N.J., DeGroot, D.J. & Jakubowski, J. 2004. Evaluation of undrained shear strength profile in soft layered clay using full-flow probes. *Proc. 2nd Int. Conf. on Geotechnical and Geophysical Site Characterization – ISC'2, Porto*, Rotterdam: Millpress, 679 – 686.

DeJong, J.T., Yafrate, N.J. & Randolph, M.F. 2008. Use of pore pressure measurements in a ball full-flow penetrometer. *Proc. 2nd Int. Conf. Geotechnical and Geophysical Site Characterization – ISC'3, Taiwan,* London: Millpress, 1269 – 1275.

Karlsrud, K., Lunne, T., Kort, D.A. & Strandvik, S. 2005. CPTU correlations for clays. *Proc. 16th Int Conf. Soil Mechanics and Geotechnical Engineering*, Osaka, September 2, 693 – 702.

Lehane, B.M., Jardane, R.J. & McCabe, B.A. 2003. Pile group tension cyclic loading: Field test programme at Kinnegar Northern Ireland, Health and Safety Executive Research Report RR101, HSE Books, Sudbury, UK.

Long, M. & Gudjonsson, G.T. 2004. T-bar testing in Irish soils. *Proc. 2nd Int. Conf. Geotechnical and Geophysical Site Characterization – ISC'2, Porto*, Rotterdam: Millpress, 719 – 726.

Long, M. & O'Riordan, N.J. 2001. Field behaviour of very soft clays at the Athlone embankments. *Géotechnique, 51*, 293 – 309.

Low, H.E., Randolph M.F. & Kelleher, P. 2007. Comparison of pore pressure generation and dissipation rates from cone and ball penetrometers, *Proc. 6th Int. Conf., Soc. for Underwater Technology, Offshore Site Investigation and Geotechnics (SUT-OSIG)*, London, 547 – 556.

Lunne, T., Robertson, P.K. & Powell, J.J.M. 1997. Cone Penetration Testing in Geotechnical Practice. London: Chapman & Hall.

McCabe, B.A. & Philips, D.T. 2008. Design lessons from full-scale foundation load tests. *Proc. 2nd Int. Conf. Geotechnical and Geophysical Site Characterization – ISC'3, Taiwan,* London: Millpress, 615 – 620.

Teh, C.I. & Houlsby, G.T. 1991. An analytical study of the cone penetration test in clay. *Geotechnique,* 41(1), 17 – 34.

Randolph, M.F. 2004. Characterisation of soft sediments for offshore applications. *Proc. 2nd Int. Conf. Geotechnical and Geophysical Site Characterization – ISC'2, Porto,* Rotterdam: Millpress, 209 – 232.

Watson, P.G., Newson, T.A. & Randolph, M.F. 1998. Strength profiling in soft offshore soils. *Proc. 1st Int. Conf. Site Characterization – ISC '98*, Atlanta, 2, 1389 – 1394.