Session Report 1: CPT Equipment & Procedures

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1 INTRODUCTION

There are only 17 papers allocated to this session and maybe this is an indication of the maturity of the development in and the use of CPT and its associated add-on modules.

The papers in this session concentrate on using existing CPT/CPTU equipment in new ways and in new countries, developments in CPT/CPTU technology and equipment, and new/updating of add-on technology. The papers are mainly for land-based investigations but some deal with shallow and deep water offshore applications.

It should be said, however, that some of the 'developments' are only at the conceptual or laboratory model stage and there is a lack of field data with which to validate or truly assess their potential.

Lunne (2010), in his Mitchell lecture paper to this conference, reviews equipment development for offshore CPT testing from the historical perspective, present day developments and future requirements. Since the 1970's, the offshore industry has driven much of the developments in the CPT/CPTU and as Lunne highlights much of this has been in pushing equipment/techniques, although it has also contributed to improving the basic CPT/CPTU equipment and very much to our understanding of the interpretation of the data.

It is a little surprising given the imminent publication of the EN/ISO standard on CPTU (CEN/ISO 2010) that we are not seeing developments to improve basic equipment accuracy in order to fulfill the application classes covered by that document.

2 EXISTING CPT/CPTU EQUIPMENT REVISITED

Within this group of submissions there are papers looking at using existing equipment in new situations and ground types, as well as comparing different cones relating to size and national practice.

2.1 *New situations*

Yoon & Tumay discuss the use of a mini-coiled CPT system in South Korea based on the Louisiana State University system. The system is intended for rapid testing of the softer soils in the area and is contained in a small van assembly. The system utilises a $2cm^2$ cone and can penetrate up to 15m with the coiled rods. The authors have calibrated the system against $10cm^2$ results and say that there is generally good agreement between the two cones implying no size effects. It appears that the results presented are for q_c and so no account has been taken of porewater pressure effects on the cone resistance, were the area ratios very similar? It would have been useful to see the corrected (q_t) results.

On a similar theme of light weight equipment *Anilionis* presents and discusses the advantages of lightweight equipment in terms of mobilisation etc and their use in Lithuania. He discusses the results obtained and says that the cones used would fulfil Application Class 1 of the imminent EN ISO 22476-1. If this is the case then it is reassuring that this quality of cone data is available and in use. We will hopefully see further developments in improved accuracy of measurements from CPT/CPTU in general with the wider adoption of the new CEN/ISO CPTU standards.

Garcia & Devincenzi in their paper suggest how using essentially land based drilling and sampling equipment, operated from a jack up, can yield better performance (in terms of cost and production) than can be obtained using down-hole techniques when working in the nearshore environment, i.e. in water depths up to 40m. They undertake the CPT using a separate jacking system but are utilising the hydraulics from the drilling machine to operate the jacks. The set-up is said to be robust, simple and versatile and allows continuous coring, sampling and in situ testing. Similar arrangements have been utilised by others in the past.

Sacchetto & Trevisan look at the use and interpretation of CPT while drilling (CPTWD) which is a most powerful tool when testing to significant depths and through difficult horizons. They acknowledge that the results of CPTWD might be affected by both the fact that penetration is often slower with this device than with the standard CPTU and the pressures exerted by the closeness of the drilling bit behind the CPT. In order to understand the effect of rate on the CPTU results they undertook standard CPTU testing at several testbed sites using rates of 20, 15 and 7.4 mm/sec. They concluded that the rate effects were much more significant in sands than in the clays and comment that the porewater pressure measurements appeared unaffected (it is assumed that this is why only q_c is discussed in the paper). Their results for clays were similar to those reported elsewhere (e.g. Lunne et al 1997) but it is a little surprising that the effects in sand were greater than those in clays. They conclude that rate effects appear to be a major explanation for differences between CPTWD and CPT results and this should be allowed for when interpreting the data.

McCallum et al look at the interesting problems of undertaking CPT testing in Polar snow with a view to using CPT for design and construction of polar infrastructure. They want to start to use CPTs in place of the more traditional Swiss rammsonde. They discuss the equipment being developed, the driving frames and packaging into a container. They show the influence of temperature changes from +23^oC to -20^oC on the zero load readings of the cones to be used and suggest that at temperatures below 8^oC cones should be allowed to equilibrate for at least an hour and that below 0^oC then zero load shifts should be expected during a test. Changes in zero readings of over 200kPa can be expected between +5 and -20^oC. This problem of zero load shifts and zero load readings at representative temperatures is often overlooked even when working in normal deposits and can have particularly important effects in soft deposits (Boylan et al 2008). It is stipulated in the new standards (CEN/ISO 2010) that cones should be equilibrated to as close as possible to ground temperature if the highest application classes are to be achieved. *McCallum et al* discuss the various problems likely to be encountered in undertaking and interpreting CPTs in snow. This is preparation work for using the equipment in a real situation and it will be interesting to see how this work progresses.

Peuchen et al look at establishing a method of obtaining assessments of u_2 pore pressure values from u_1 measurements. As they point out there are occasions when it is more useful/practical to test with CPTUs that have a u_1 filter rather than u_2, but u_2 is required for cone resistance correction. They also discuss how the relationship between u_1 and u_2 will vary with soil behavioural type (SBT), stress history, soil strength and sensitivity and how this would relate to the Robertson (1990) SBT chart in terms of Q_t (normalise cone resistance) against F_r (normalised friction ratio). From data available to them from various sites they derive a correlation that basically involves Q_t and F_r and gives a 'k' factor ($\Delta u_2/\Delta u_1$) by which Δu_1 is multiplied in order to derive a value for Δu_2. They point out potential problems including the need to use an iterative process in deriving k as it is required for q_t and thence Q_t. They validate the equation against data from other sites and say the error is typically below 3%. *Peuchen et al* do note that whilst the equation performed well in clayey soils there were more problems in soils with a more complex structure. The author of this report has tried the method on data available from a study of triple element piezocone tests (CPTU3) on European testbed sites (Shields et al, 1996; Powell & Lunne, 2010). Figure 1 shows the ratio of predicted to measured values of k as k_{meas}/k_{pred} for a number of these sites. A ratio close to 1 implies a remarkably good prediction whilst values less than 1 would mean that the u_2 derived would be too high (hence q_t also) and with values greater than 1 u_2 is too low. It can be seen that on several sites the ratios are close to 1 and very uniform with depth whilst for others the values vary significantly with depth especially in more silty layers. Within a profile significant differences can occur and this is consistent with comments by *Peuchen et al* in layered soils. The authors have developed what looks to be a useful correlation but it is suggested that care should be taken with its use until more validation has been undertaken. It should be noted that the new CEN/ISO (2010) standard says that u_2 should preferably be measured and used to correct for q_t if the measurements are to be used to interpret parameters; otherwise this conversion of u_1 to u_2 is potentially an added error. The combined chart of Robertson's and the ratio $\Delta u_2/\Delta u_1$ may well be a very useful additional soil behaviour classification tool in the future when both pressures are measured and should be pursued.

2.2 *National Practice*

Liu et al compare Chinese practice in CPT equipment and testing with the more International CPTU equipment and procedures. In China cones have generally been $15cm^2$ and measuring either cone and sleeve friction as one measurement or more recently as a 'friction' cone measuring cone resistance (q_c) and sleeve friction (f_s). They undertook comparative studies between the $15cm^2$ Chinese friction cone and an international standard $10cm^2$ CPTU on 5 sites, comprising various clay and alluvial deposits. It is a pity that they have not shown the actual CPT and CPTU profiles as this would have given greater insight into the sites and results and would have greatly en-

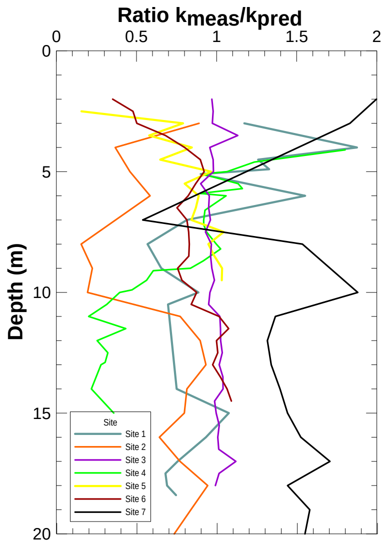

Figure 1. Ratio of measured and predicted k factors

hanced the understanding of the comparisons made. They say they show the differences as ratios of q_{ccptu}/q_c (this maybe q_t/q_c as there is a little confusion in the paper) and f_{scptu}/f_{scpt}. Unfortunately they do not tell us the area ratio value 'a' for their Chinese cones and so it is hard to have a feel for how significant the differences in correction to q_c could be. The ratios of the parameters from the two cones vary from very close to 1 on some sites to as low as 0.5 and as high 1.5 on others. It is good to see studies of this type and the data should prove valuable as Chinese practice moves more towards International practice.

3 NEW EQUIPMENT/PROCEDURES

As mentioned earlier the number of papers presented to this session that can be described as 'new' in terms of CPT/CPTU equipment or procedures is surprisingly few but 4 papers can be said to fall into this topic.

3.1 *New equipment*

Kim et al look at the use of fiber Bragg grating (FBG) for both strain and temperature measuring within a CPT. In contrast to *McCallum et al* they investigate the potential effects of temperature changes generated during penetration on the measurements obtained by the CPT. They describe the development of a 7mm diameter CPT (a 1mm gauge length electrical strain gauge in used), the FBG temperature sensor (thinner than a toothpick), and a FBG load cell. They discuss the concept of the FBG real-time temperature compensation method which requires subtracting the wavelength change due to temperature from that measured by the load cell element. The temperature sensor shows a highly linear calibration over a range 3-21^{o}C. Testing was undertaken in a sandy clay in a calibration chamber. They show that during penetration the electrical strain gauge system gives a reducing q_c with depth, the FBG temperature sensor shows a temperature increase with depth and then how the measurements made with the temperature compensated FBG system show a reasonably constant value of q_c with depth. They undertake an in situ temperature calibration of the electrical measuring system and deduce that when this compensation is allowed for then a very similar profile of essentially constant q_c with depth is obtained from the electrical strain gauge system (it is a pity that they had not undertaken the temperature zero shift for the electrical system at the same time as the FBG calibration). This concept is very interesting and what is really needed now is to see what happens if it is used at full scale. Could this type of system overcome the potential errors that can arise from zero shifts as discussed above?

Colreavy et al present an interesting study of comparisons of Tbar, piezoball and CPTU in very soft soils in Ireland. They describe their own newly built piezoball (similar in design to others) that have been produced and the detailed saturation procures that were adopted. They compare the shear strength profiles derived from the different in-situ tests with results from field vane tests and conclude that whilst the piezoball and Tbar agree with each other and perform well, there are, at times, difficulties in selecting N_{kt} factors for the CPTU that give a satisfactory fit with the vane results. They rightly point out that the N_{kt} factors they used were selected from Karlsrud et al (2005) and are based on laboratory triaxial compression strengths tests and that this may well explain some of the problem. It is worth noting that not only are these factors derived from laboratory tests but are additionally from tests on ' high quality block samples' and as shown previously (e.g. Powell 2001) significant differences in N_{kt} values can occur depending on the sampling method used e.g. piston sampling vs block samplers. They show, for Athlone site, that they would need an N_{kt} of closer to 20 to get some level of agreement; it is worth noting that if they had selected an N_{kt} from some of the previous historical and more recent correlations linked to Plasticity Index and field vane strengths (Aas et al 1986, Lunne et al 1997, Powell 2005) then they may have selected values in the range 18-20. However if this latter approach was applied to the Belfast site data then the derived strengths from the CPTU would be much lower than the vane results. It is known that CPTU in these very soft deposits is difficult in terms of accuracy, zeros load readings and calibration at low loads and hence the benefits of the higher loads from piezoball and Tbar may be a further factor in the problems with the CPTU data. The reporter has experience of sets of piezoball tests undertaken at different times at one site giving different profiles; you can never eliminate errors that are a result of poor procedures. It is a little concerning that, given our knowledge that we need to change our cone factors depending on the shear strength we are correlating with (i.e. vane, DSS, CAUC etc), the authors say that there is evidence that when using the piezoball or Tbar an N factor equal to 10.5 can be used to correlate with vane and laboratory tests. Figure 2 (Boylan et al 2007) seems to imply something different. Are we oversimplifying the piezoball and Tbar?

While most of the *Colreavy et al* paper concentrates on the strength interpretation, it is interesting to see their study into dissipation testing using the Piezoball. They compared the results with those from CPTU dissipation tests and comment on their similarity. The results, as they say, seem promising but need more investigations in order to fully assess their potential. They say that that reducing the diameter of the ball would help reduce testing times; but surely this would have to be balanced against the advantage of the ball in giving higher measureable loads during penetration part of testing.

Boggess & Robertson look at the problems of testing near surface seafloor sediments in deep water. They raise the problems and possible sources of inaccuracies in sleeve friction measurements in general and also the problems of load cell capacities

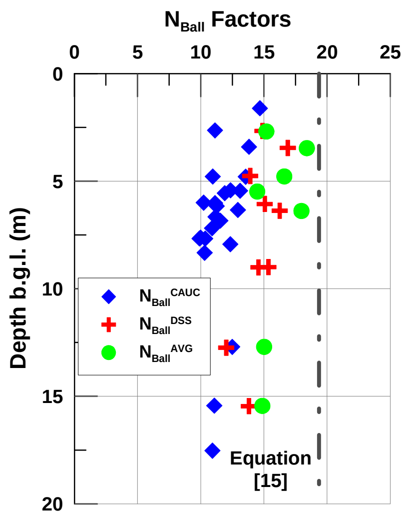

Figure 2. N_{Ball} against depth varying with shear strength source (Boylan et al, 2007)

and offsets when working in deep water. Lunne (2010) also raises this topic and shows examples of the big variations in friction sleeve results on one site with different cones (see Lunne and Powell 2010 for full details). *Boggess & Robertson* discuss the potential error in friction sleeve measurements resulting purely from the geometry of the cone as a result of the differences in the end areas of the friction sleeves (unequal end area effect) and the fact that the pore water pressures are different at each end can create an error in the friction sleeve measurements. Ideally you need to know the end areas of the friction sleeves and also the porewater pressure at the u_2 and u_3 positions to fully undertake the correction (Note: as with the end area correction for cone resistance, it is better to obtain the area correction by calibration than by physical measurement, significant differences in the theoretical and calibrated values can occur, e.g. for one cone then by theory the value b value was 0.00149 but by calibration 0.0009. The forthcoming CEN/ISO standard recommends calibration, CEN/ISO2010). They give an example of how the f_s values could be up to 74% in error for the example given by Lunne (2010) for Onsoy (this is based on a ratio between u_3/u_2 of 0.75; Powell & Lunne (2010) show that ratios as low as 0.3 occur in some silty soils and this would make the error even worse). In Figure 3 (data from Lunne and Powell, 2010) the average f_s data from the example from Lunne (2010) is shown both uncorrected and then corrected using a u_3/u_2 ratio of 0.75 and whilst the scatter in f_s is reduced to some extent the correction does not go anywhere near bringing the sleeve friction results together; this implies that there is much more that needs to be understood about friction sleeve results in soft soils. All is not straight forward with corrections to friction sleeve results even when using a triple element piezocone, as shown in the two examples in Figure 4. In the first case we see that the friction sleeve results when corrected are quite believable but in the second case the corrected results are close to zero or even negative, why this should be is still not fully understood. It should always be remembered that when testing in soft soils the load cells are often at their most inaccurate being towards the bottom of their ranges and this may be a factor, along with load cell configurations (*Boggess & Robertson*), although in general the results from any one cone are repeatable! In the offshore environment simply lowering the cone to the sea bed applies pressures to the cone and if the sleeve has unequal end areas then *Boggess & Robertson* show that significant zero offsets will occur. *Boggess & Robertson* and Lunne (2010) both suggest that

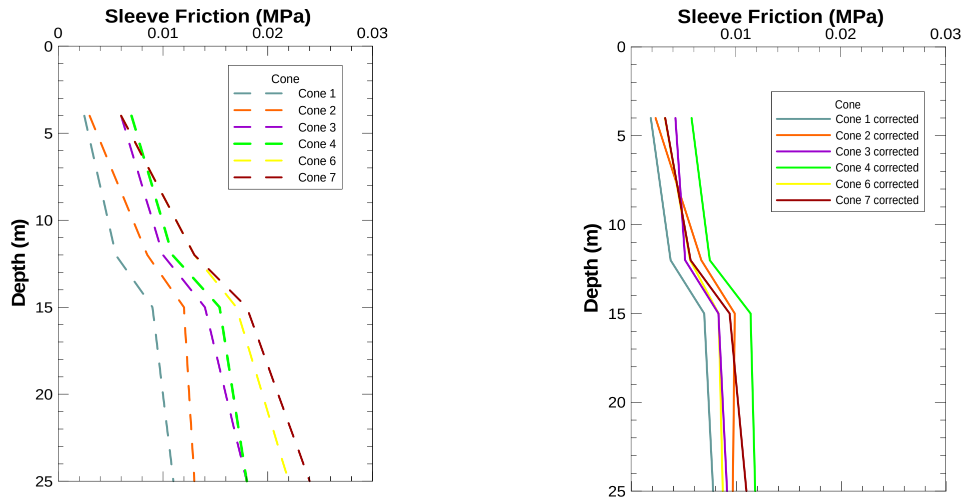

Figure 3. Uncorrected and Corrected f_s profiles for different cones at Onsoy

having equal end area friction sleeves would significantly improve the situation both with regards to sleeve friction correction and zero offsets. *Boggess & Robertson* also address the problem of accuracy of measurements and describe a new load cell that is compensated for the high hydrostatic pressures when in deep water. This is done by filling the inside of the cone with oil and using a specially designed shear load cell. It is expected that this will improve the accuracy of measurements in soft seabed sediments. They also describe a new seabed pushing frame. It will be interesting to see these developments perform. For improved accuracy, especially in sleeve friction measurements, it would appear that all cones should have separate load cells (ideally in compression) and equal end area sleeves with small end areas combined with careful test procedures.

3.2 *New procedures*

Ali et al discuss the development of a variation/addition to the general CPT test, the Cone Loading Test. After a dissipation test in a standard CPTU then the Cone

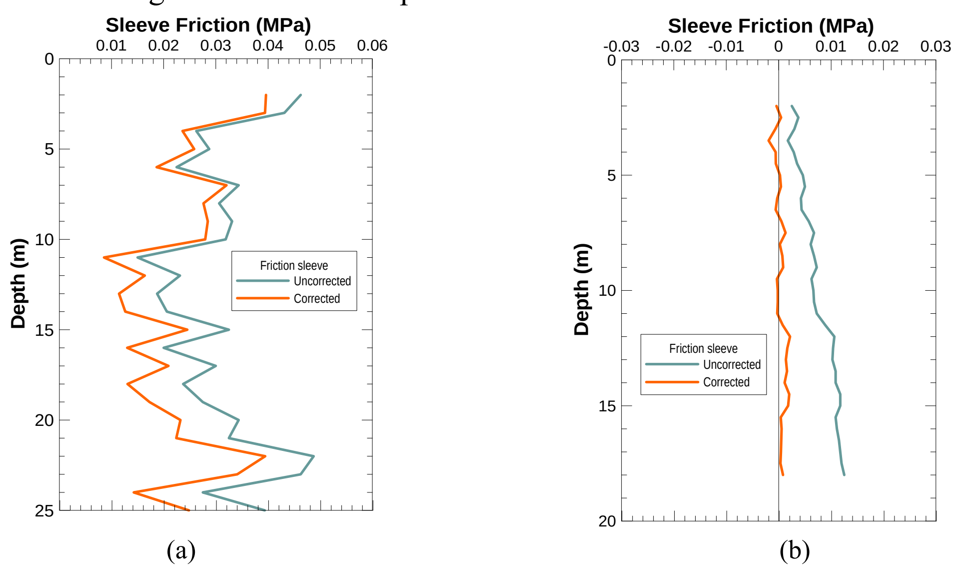

Figure 4. (a) Correction and (b) Over correction of Sleeve Friction

Loading Test is undertaken. This comprises applying an axial loading to the cone in increments whilst measuring the induced displacements (an incremental maintained load test); unload/reload loops can also be undertaken. They discuss the test aspects and present test results from tests in sand in the centrifuge. They compare the unload/reload moduli derived from plate load tests (also in the centrifuge) with those from the new Cone Loading Test; they obtain very good correlations between the two. They acknowledge the limitations of the study to date (centrifuge, small scale and only sand) and state that it is intended to extend this study to field tests. The findings will be most interesting.

4 ADD-ON DEVICES

We have 6 papers to the session that can be grouped in the category of add-ons to the CPT/CPTU. These may be further sub-dived into those add-ons that we have heard of before and those that can be considered as new additions.

4.1 *Old favourites*

Within this sub group of papers *Dijkstra & Broere* present laboratory test results on a newly developed resistivity sensor to measure soil density around the cone. They look at the influence of penetration on the measured in-situ density and this has been done in the centrifuge. The probe is similar to others previously developed (e.g Campanella, 2008) and uses sets of 4 conductors at any one level (the probe used had 3 sets of conductors). The probe was 'wished in place' by pumping the sand into place around the probe. Set in a loose state it was then later densified by shaking the container. The probe was pushed deeper into the samples during flight. They show how the density measurements change during penetration. Despite not being able to measure absolute densities consistent qualitative results were obtained. They show that the density changes are a function of penetration distance and the act of penetration changes the density of the sand immediately adjacent to the probe. This is an interesting study and it would be useful to know how they intend to take this work forward.

Continuing the theme of electrical resistivity measurements *Peixoto et al* discuss the use of a resistivity probe for detection of pollution plumes. They say that little is available with regards to what are relevant reference values to be used for detecting concentrations when testing in tropical soils. Their work is laboratory based but using the same configuration as in typical field devices. They discuss the factors affecting the measurements and look at the effects of moisture content and frequency which they identify as being much more important in these tropical soils. This is a very interesting study which they are hoping to extrapolate in the future to field testing.

Elgun et al look at the potential uses of the magnetometer cone. Magnetometers, measuring the earth's magnetic field strength, have been used for some time for detecting buried objects which are made of or contain ferromagnetic material. In cities such as London they have seen significant use to check/clear areas for ordnance (bombs etc) before any intrusive work such as ground investigations, piling, CPTs etc were undertaken. More recently we are seeing, as in this paper, that the magnetometer is being included as an 'add on' item to the CPT so that standard CPT parameters can be collected at the same time. The authors describe a magnetometer cone that contains a tri-axial magnetometer and go on to discuss examples of its use. It very clearly detects a pipeline at 12.5m depth and they comment that ordnance can be detected up to 2m away! They give an example of using it to assess concrete pile length, in this case it is necessary to compare the measurements with a theoretical model of response and to fit the model to the measurements, it is not clear from their example what level of accuracy can be achieved nor how much steel needs to be present for this to work effectively. For sheetpile walls they mention its use for determining their lengths (as with piles) and also the locations of anchors and tie backs. It would be interesting to know what accuracies have been achieved (personal experience has shown determining sheet pile lengths of 6m to be within +/- 0.5m). This is a tool that will have an increasing role to play especially with the assessment of existing structures, as the authors say and very much so with the increasing interest in sizing of foundations for reuse (Butcher et al 2006).

4.2 *New additions*

Reiffsteck et al discuss the latest developments in a permeameter device (Permeafort) that has been modified to include a CPTU at its front end. The 'rods' behind the cone are of an enlarged diameter and the permeameter is set as a porous element in a reduced diameter section. The CPTU addition will mean that information can be readily available, from soil classification charts, on the material at the permeameter test depths. Permeability testing is said to require a pause in penetration of only 10s (coarse grained soils), testing can be performed as frequently as every 20cm. The device is being calibrated against tests in both the laboratory and field. Results so far look very promising and calibration in other situations and soil types is on-going. It could be most promising to link results from this type of test with those from CPTU dissipation tests.

Continuing on the permeameter theme *Homma et al* present a 'cone permeameter' test for estimating in situ soil moisture characteristics and hydraulic conductivity in partially saturated soils. Water is introduced into the ground through a small filter and measurements made on two tension rings above the filter as well as volume inflow, all data are recorded on a data logger. The device is a penetration test and does not appear to contain a CPT or CPTU module. They show good results between modelling and measured data in sands but there are problems in loam soils. They comment that there are still problems with the device, especially robustness of the ceramics, but these are being addressed.

Jang et al describe the development of a new 'add-on' system to the CPTU to investigate 'dynamic' properties of marine soils. Their reason for the development is that they say it is often difficult to install a suitable source in marine situations to generate shear waves to allow the use of the seismic cone (SCPT). The system uses piezobender elements that are rotated out on arms from the cone rods at some distance behind the cone. They have undertaken both model and numerical simulation tests to assess the effects of source/receiver separation, their distance away from the cone rod (swing arm length) and the disturbance effects of swinging the arms out, all with a view to establishing the optimum arrangements; the data are most interesting. They do conclude that the disturbance caused by the swing arms affects the measured shear wave velocity but comment no further. There appears to have been no trials in these model studies of retracting the arms and this could be a major problem. It would be interesting to know how, or if, they plan to develop this work.

5 CONCLUSIONS

The CPT/CPTU is a relatively mature testing technique and this is evident in the lack of papers to this session. We see techniques now moving between countries and cross correlation to other national practices. With the adoption of the new International standards there should be greater flexibility in exchanging experiences around the world but care will still be needed with differing soil types. Strict adherence to these standards should allow greater confidence in the results obtained but we will first have to prove that the equipment available is capable of achieving the accuracies required of the various Application classes. Existing equipment is often good but sometimes poorly operated or maintained.

Lunne (2010) suggests that the problem of understanding the inconsistencies in sleeve friction measurements results is one of the challenges for the future; understanding all sources of error is a topic that would usefully receive more attention and would give valuable pay back. We have been working with f_s and R_f (based on f_s) for a long time and it is uncertain what it will mean to our databases if we start to convert to f_t. Much the same as we experienced with q_c and q_t one might think.

The challenge is still there to get reliable data that can be trusted, is repeatable and accurate, especially in soft soils. We need to also maximise the amount and value of data gathered by add-on devices.

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