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A comparison of different sized piezocones in UK clays

Comparaison de piézocônes de dimensions différentes dans les argiles anglaises

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ABSTRACT
Results are presented comparing various sizes and configurations of piezocones in UK clays. Most correlations with geotechnical data were developed based on 10cm^2 CPT and CPTU results, but little has been reported on the effects of size of device, both diameter and area of friction sleeve, on the measured results. It is shown that for commercially available 10 and 15 cm^2 equipment: measured cone resistance is a function of individual cone geometry but cone resistance corrected for pore pressure effects is unaffected by cone size, measured sleeve friction would appear to be very similar for most of the cones although some differences noted. Cones with reduced sensitivity can be affected by electrical noise in soft deposits. The new accuracy classes of the IRTP 1999 are considered.

RÉSUMÉ
Les résultats comparant des piézocônes à dimensions et configurations différentes sont présentés. La plupart des corrélations géotechniques sont basées sur les CPT et CPTU de 10 cm^2, et très peu est rapporté sur les effets de dimensions du cône sur les mesures, entre autres les effets du diamètre et de la superficie du manchon de friction. Pour les équipements commerciaux de 10 et 15 cm^2, la résistance en pointe est fonction de la géométrie du cône, mais la résistance en pointe corrigée ne semble pas être affectée par le diamètre du cône. Le frottement sur le manchon semble être le même pour la plupart des cônes, bien que certaines différences soient notées. Les cônes dans les argiles molles et ayant faible sensibilité peuvent être affectées par les courants électriques. Les nouvelles classes de précision de l'IRTP 1999 sont examinées.

1 INTRODUCTION

The Cone Penetration Test (CPTU) with measurement of pore pressure is one of the more powerful site investigation tools available to the industry. The CPTU (piezocone) has three main applications in the site investigation process, to:

- determine sub-surface stratigraphy and identify materials present,
- estimate geotechnical parameters, and,
- provide results for direct geotechnical design.

However one must have confidence in the results being obtained. During the gathering of data for the UK national report to the International Symposium on Penetration testing (CPT95) (Powell et al 1995) it was found that in the UK the most commonly used CPT device was the 15 cm^2 friction cone and not the 10 cm^2 device more commonly used elsewhere in the world. The 10 and 15 cm^2 refer to the cross sectional area, A_n, in Figure 1; the cones also having different sleeve areas, A_s. The International Reference Test Procedure for the CPT/CPTU (IRTP 1999) only deals with the 10 cm^2 cones but allows for variation in x-sectional area: 5cm^2 to 20 cm^2. Most of the correlations developed for the CPT and CPTU are based on the results from 10 cm^2 test equipment. It is known that many factors can affect the results of CPT tests if care is not taken in the specification of the equipment and testing, however little has been reported on the effects of size of device, both diameter and area of friction sleeve, on the measured results. This paper summarises testing undertaken with 10 and 15 cm^2 piezocones on BREs well documented clay test bed sites. Full details of the study will be reported elsewhere. The findings should give added confidence to the use of 15 cm^2 cone penetrometers in practice.

2 THE SITES

Results have been gathered from 8 well documented test bed clay sites and data from 4 of these will be presented in this paper to illustrate the findings – 1 heavily overconsolidated clay, 1 glacial clay till and 2 'soft' clays. Details of their basic properties are given in Table 1.

3 PORE PRESSURE CORRECTIONS

It is well established that pore water pressures in the ground generated as a result of the cone penetration influence the measured results (Lunne at al., 1997). Due to the "inner" geometry of a cone penetrometer the ambient pore water pressure will act on the shoulder area behind the cone and on the ends of the friction sleeve. This is illustrated in Figure 1. This effect is often referred to as "the unequal area effect" and influences the total stress determined from the cone and friction sleeve. For the cone resistance the unequal area is represented by the cone area ratio 'a' which is approximately equal to the ratio of the cross-sectional area of the load cell or shaft, A_n, divided by the projected area of the cone A_c as shown in Figure 1. The corrected total cone resistance is given by the equation:

$$q_t = q_c + u_2(1-a) \tag{1}$$

where u_2 is the pore pressure acting behind the cone.
This effect was first identified when the CPT was used for deep water investigations in which it was observed that the cone resistance q_c was not equal to the water pressure.

The determination of the cone area ratio 'a', is best made by the use of a simple calibration vessel and not by idealized geometrical considerations (See Lunne et al., 1997).

Table 1 - Description of sites

SITE	Water Content %	Plastic Limit	Plasticity Index	% Clay	Unit weight kN/m^3
Cowden, UK Cowden is a glacial till site. The profile consists of firm to stiff dark brown silty clay with occasional rock fragments, over the upper 5 m. This zone is fissured and weathered. Below this there is a layer of firm, occasionally soft to firm, grey brown silty clay with a similar assortment of coarse rock fragments. At the base of this, at 10 to 12 m, there is a sand layer. (Powell and Butcher 2002)	17-18	18-21	17-20	30-32	21-22
Canons Park, UK The clay deposit on the site forms three distinct layers, a top reworked stratum containing a gravel layer, down to 4 to 4.5 m, followed by the weathered London Clay to a depth of about 7m overlying the unweathered blue London Clay. The gravel layer lies between 0.5 and 3 m and varies in thickness over the site. The gravel is in a matrix of clay, with little if any stone to stone contact. (Hight et al., 2002a, Powell and Uglow, 1988)	27-30	28-30	40-46	40-44	19.2-19.8
Bothkennar, UK The uppermost 20m consists of very soft to soft black silty clay and clayey silt, with some laminations of fine sand, with minor overconsolidation of the site. (Hight et al., 2002b)	54-68	27-32	35-44	20-36	15.2-16.2
Pentre, UK The soil profile consists of 80m of quaternary sediments which comprise a 3 to 4 m thick surface layer of alluvium overlying essentially normally consolidated very silty clays. (Lunne et al 1997, Powell and Uglow, 1988)	25-35	15-22	10-25	8-22	18-19.9

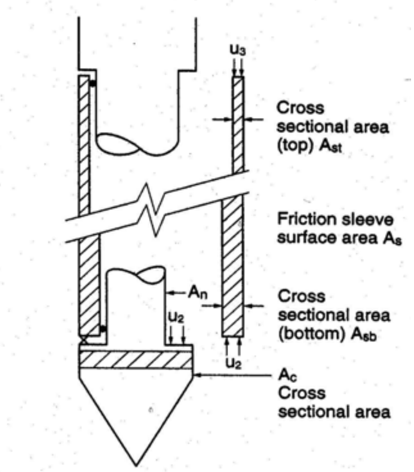

Figure1. Section through Piezocone showing pore water pressure effects on measured parameters (right-hand section displaced)

This effect was first identified when the CPT was used for deep water investigations in which it was observed that the cone resistance q_c was not equal to the water pressure.

The determination of the cone area ratio 'a', is best made by use of a simple calibration vessel, determination by simple idealised geometrical considerations should be avoided (See Lunne et al., 1997).

Many cone penetrometers have values of cone area ratios ranging from 0.9 to 0.55, but sometimes this ratio may be as low as 0.38. A cone area ratio as low as 0.38 should be considered unacceptable when using the CPT in very soft fine grained soils as the correction becomes a major contribution to q_t with potentially increased loss of accuracy. Ideally it should be close to 1.0 and cones have been manufactured that attempt to achieve this. The area ratios for the cones used in this study ranged from 0.66 to 0.89.

Since the friction sleeve has 'end areas' that will be exposed to pore water pressure the measured sleeve friction will also be influenced by the pore water pressure effects (see Figure 1). When excess pore pressures are generated the pore pressures are normally different at the upper (u_3) and lower (u_2) ends of the friction sleeve. Using the terminology in Figure 1 the corrected sleeve friction, f_t, can be given by:

$$f_t = f_s - \left(\frac{u_2.A_{sb} - u_3.A_{st}}{A_s} \right)$$

The magnitude of the correction can be reduced by having equal end areas ($A_{sb} = A_{st}$) and making these end areas as small as possible.

Lunne et al. suggest that ‘If u_3 is not measured then it is recommended that the correction should not be carried out’. This will be discussed later in the paper.

It has been shown that when applying the correction to q_c consistent results can be obtained in terms of the corrected cone resistance q_t when comparing a variety of $10cm^2$ cones with different internal geometries (Lunne et al., 1997).

4 THE PIEZOCONES

The specifications of the commercially available piezocones, 3 of $10cm^2$ and 2 of $15cm^2$ are given in Table 2. All have shoulder filters for pore water pressure measurements. The cones were calibrated over the range of loads likely to be encountered on the sites. For a discussion on the problems of accuracy and precision in commercial testing see Lunne at al. (1997) for more detail; it should also be noted that these cone penetrometers were working at the bottom end of their ranges in terms of capacity. As a result, some cones had problems with electrical noise becoming significant and affecting readings whilst others with sufficient sensitivity to overcome this had problems with zero stability.

Table 2, Details of Cone penetrometers used.

Cone	Cross Sectional Area – cone A_c cm^2	Surface Area Friction Sleeve A_s cm^2	Area ratio a
1	15	300	0.72
2	10	150	0.76
3	10	150	0.81
4	15	200	0.66
5	10	N/A	0.89

5 RESULTS

The cone penetrometers generally measure 3 parameters, namely the cone resistance (q_c), the sleeve friction (f_s) and the pore fluid pressure (u). It has been usual to present these measurements as profiles plus the friction ratio ($R_f = f_s/q_c$ expressed as a percentage).

As a result of the foregoing discussion all measured cone resistances were corrected for pore water pressure effects but sleeve frictions were left uncorrected as u_3 was not measured. Friction ratios were calculated as $R_f = q_t/f_s$.

Table 3 Accuracy classes

Test class	Measured parameter	Allowable minimum accuracy	Maximum length between measurements
1	Cone resistance	50 kPa or 3%	20 mm
	Sleeve friction	10 kPa or 10%	
	Pore pressure	5 kPa or 2%	
	Inclination	2°	
	Penetrated depth	0.1 m or 1%	
2	Cone resistance	200 kPa or 3%	20 mm
	Sleeve friction	25 kPa or 15%	
	Pore pressure	25 kPa or 3%	
	Inclination	2°	
	Penetrated depth	0.2 m or 2%	
3	Cone resistance	400 kPa or 5%	50 mm
	Sleeve friction	50 kPa or 15%	
	Pore pressure	50 kPa or 5%	
	Inclination	5°	
	Penetrated depth	0.2 m or 2%	
4	Cone resistance	500 kPa or 5%	100 mm
	Sleeve friction	50 kPa or 20%	
	Penetrated length	0.1 m or 1%	

Note: The allowable minimum accuracy of the measured parameter is the larger value of the two quoted. The relative or % accuracy applies to the measurement rather than the measuring range or capacity.

Class 1 is meant for situations where the results will be used for precise evaluations of stratification and soil type as well as parameter interpretation in profiles including soft or loose soils. For Classes 3 and 4, the results should only be used for stratification and for parameter evaluations in stiff or dense soils. Class 2 may be considered more appropriate for stiff clays and sands.

Figures 2 and 3 show some of the results, but as collective plots for all cones, for the stiff clay of Canons Park and the glacial clay till of Cowden. For each site there appears to be little difference between the results for q_t, f_s , and R_f from the different piezocones. The results for the pore water pressures were somewhat erratic as in heavily overconsolidated stiff clays u_2 pore pressures are typically negative or very small and in the glacial clay at Cowden loss of saturation caused by the displacement of stones makes measurement difficult (see Lunne et al., 1986, Hight et al., 2003a, Powell and Butcher 2003, for details). Figure 3d shows a composite pore water pressure plot for Cowden combining the results of many profiles to help establish a typical u_2 profile. Even so these effects will have little affect on the assessed q_t for the Canons park site and to a lesser extent Cowden as the pore pressures are small compared to the measured q_c and so corrections would be small also. For Cowden some reduction in scatter may have been achieved if consistent pore water pressures had been achieved. Although great care was taken with this testing work the scatter in results is no more than would have typically been obtained when using only one cone type in these deposits as a result of factors such as zero shift, sensitivity of the cone etc mentioned above. In fact greater scatter has been obtained on all the sites investigated as a result of different CPT contractors undertaking work. It can be seen in Figure 4 that when the data are plotted to an expanded scale then the agreement in even the fine detail is quite remarkable.

For the Pentre site differences were much more evident in q_c for the different cones. However, as can be seen in Figure 5, once plotted in terms of q_t and also f_s, u_2 and R_f there would appear to be good agreement, again within typical scatter bands. Signs of saturation problems at shallow depth are evident in the pore pressure profiles. When plotted to expanded scales in Figure 6 good agreement in detail can be seen although with cone 3 the effects of noise/sensitivity are beginning to be seen in the measurements by the more spiky nature of the plots. This gets worse in friction as this is a subtractive cone (see Lunne et al., 1997) and so the noise in both load cells is magnified. There may be some tendency for the measured friction results to vary with cone type but there was no definitive trend with the general scatter (see later also).

Very similar agreements are also evident at Bothkennar (Figure 7), the softest of the sites investigated. Here the corrections for q_c were even larger (larger pore pressures as a % of q_c) as seen in Figure 7a, but good agreement in q_t is very apparent as shown in Figure 7b. Agreement in q_t values will always be affected by the reliability of the pore water pressure measurements and so poor saturation or inaccuracies in calibration will affect q_t. The problems of noise and lack of measurement sensitivity are highlighted by comparing Figures 7c & d and 7e & f where the scatter in results evident in Figures 7d and 7f as a result of zero shifts is masked in Figures 7c and 7g by the noise from cones 3 and 4; however all data are still contained within the same scatter band, although as with Pentre there is possible an underlying trend for cones with larger potential area corrections to fall to the upper bound of the scatter range (this is discussed further by Lunne and Powell, 2005) and might imply the effect of the correction highlighted in equation 2. The noise problem mentioned above also results in loss of definition within the profile. The most consistent measurement was the pore pressure (Figure 7c) provided good saturation was achieved (see left hand profile for 'poor' saturation). Lunne and Powell (2005) also found that for the soft Norwegian Onsøy clay the penetration pore pressure is a much more repeatable measurement compared to the cone resistance, even after this has been corrected for pore pressure effects.

Although the results have been shown to agree and to be within typical scatter bands, the new IRTP specifies ‘Accuracy classes’ for CPT testing need to be considered. These are detailed in Table 3. Shown on the various Figures are the 'ranges' of accuracy specified for the classes relevant to the soil types. It can be seen that Canons Park and Cowden would in general be quite close to fulfilling the Class 2 requirements despite different cone being used and the consistency in profile shape would imply the zero differences being a significant effect. For the soft soils of Pentre and Bothkennar then these fully fulfil Class 2 and are falling close to the required accuracy requirements for Class 1 it is unlikely that this would be achieved routinely in soft deposits with the cones generally available in practice. In fact a similar statement to this is contained within the IRTP 1999. It should be mentioned that a new European standard is under preparation and will be valid from late 2006. The ‘Allowable mini-accuracy’ values in Table 3 will be modified in that document.

6 CONCLUSIONS

From the study undertaken it can be concluded that based on commercially available 10 and 15 cm^2 equipment:

- Measured cone resistance is a function of individual cone inner geometry.
- Corrected cone resistance appears unaffected by cone size when pore water pressure effects are taken into account.
- Measured sleeve friction would appear to be very similar for all cones and, within a general scatter band, implying it to be independent of sleeve diameter and sleeve area.

However in soft soils the inaccuracies may mask end area effects.

- It appears that there is little difference between 200 and 300 cm^2 friction sleeves on 15 cm^2 cone penetrometers.
- Cones with reduced sensitivity can be affected by electrical noise in soft deposits.
- Different cones give same shaped profiles at all levels of detail; inaccuracies in zeroing may be biggest factor in data scatter.
- Most consistent parameter especially in soft soil is the pore water measurements provided good saturation is achieved and maintained.
- Provided care is taken in calibration and cone set up then results from 10 and 15 cm^2 cones are generally comparable in clay soils.

The general implications for practice are that correlations based on 10 cm^2 can be used with the same confidence for 15 cm^2 cones. However there are general considerations of accuracy applicable to all cones when the new accuracy classes of the IRTP 1999 are considered, especially in soft soils.

The information available with regard to 15 cm^2 cones will be significant in concluding the debate on size of friction sleeves when standardisation of the 15cm^2 devices is completed.

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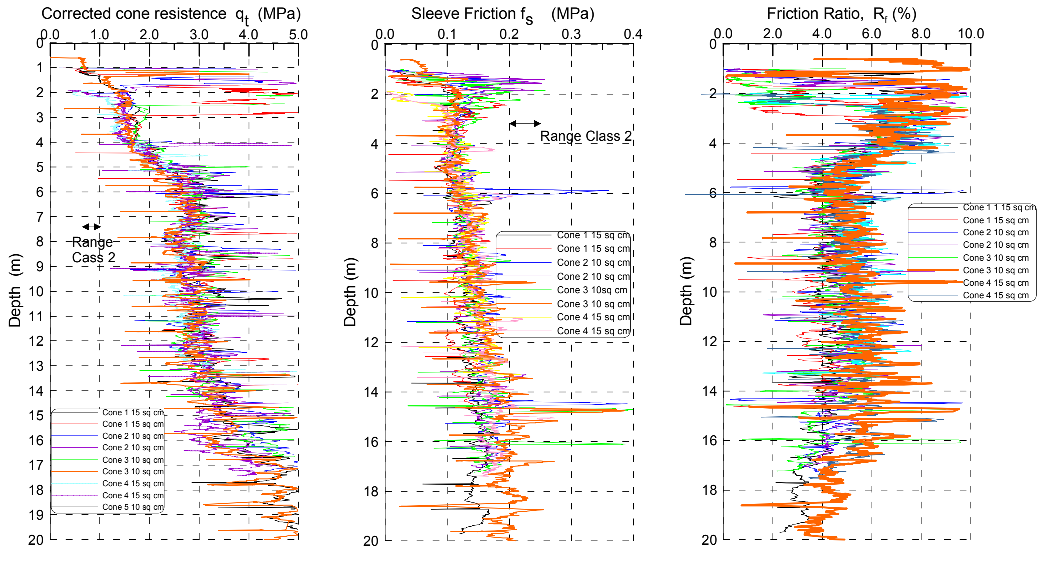
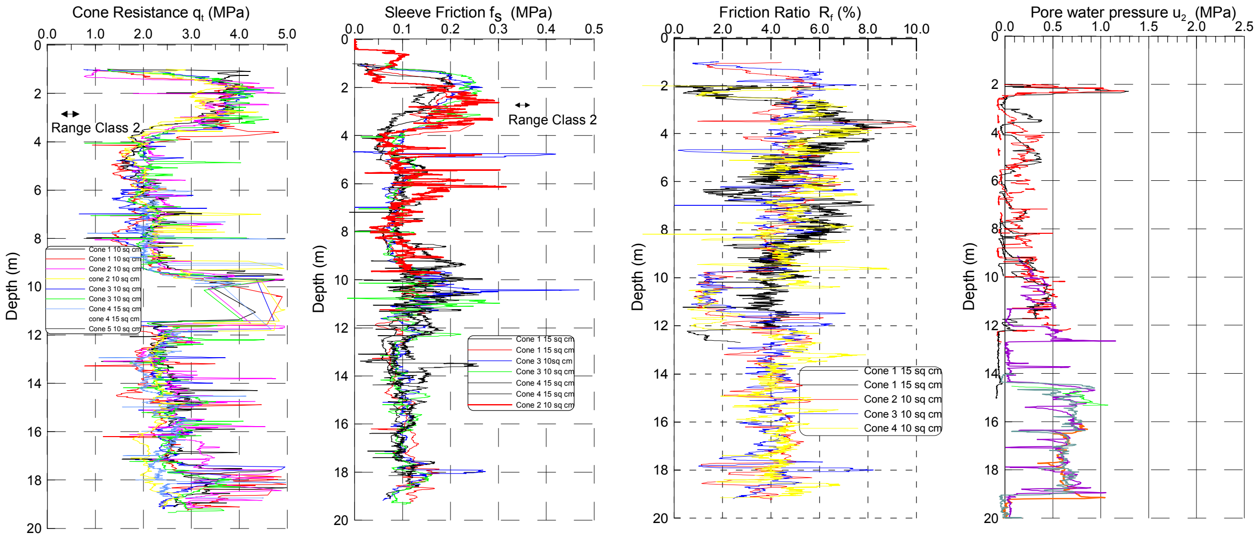


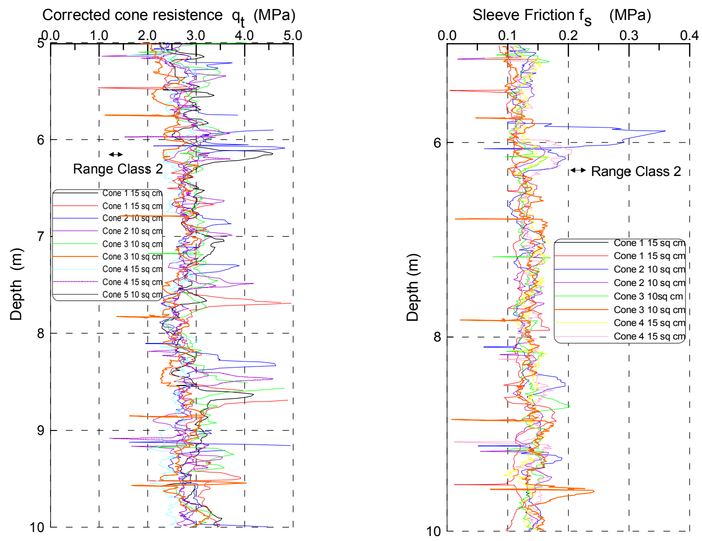
(a) (b) (c)

Figure 2. Canons Park , (a) q_t (b) Sleeve friction (c) Friction ratio



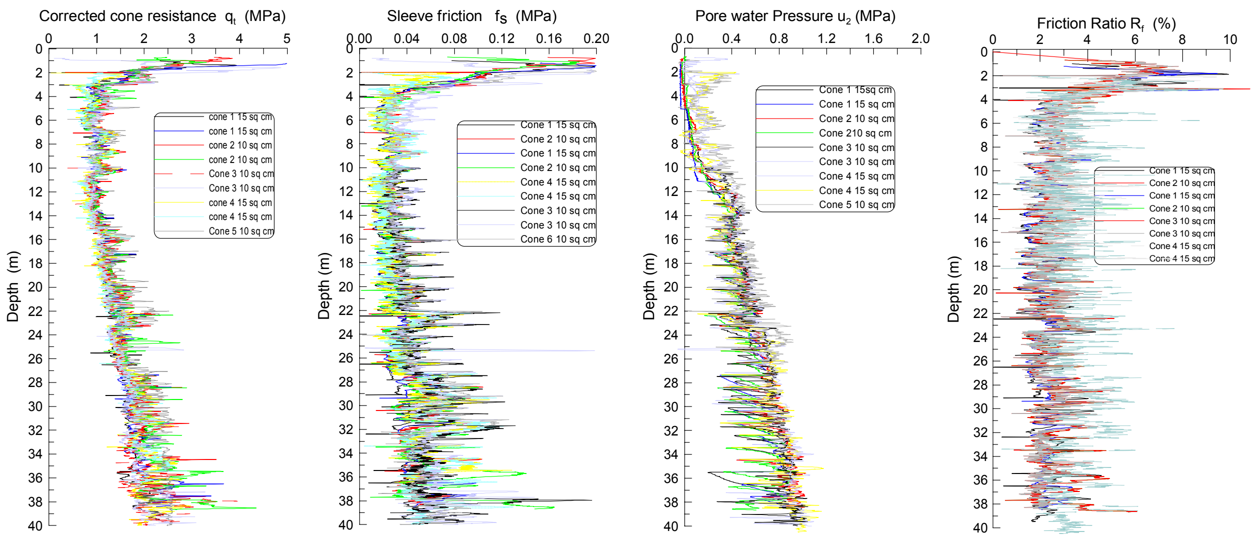
(a) (b) (c) (d)

Figure 3. Cowden, (a) q_t (b) Sleeve friction (c) Friction ratio (d) Example of Pore water pressures



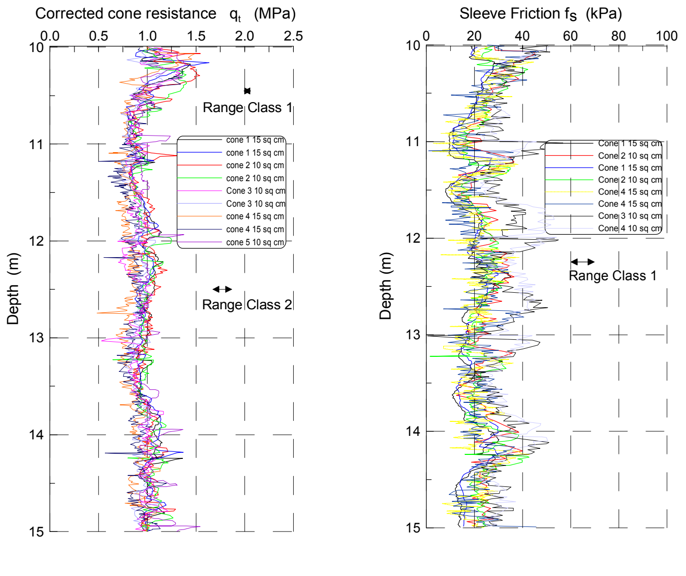
(a) (b)

Figure 4. Canons Park expanded plots , (a) q_t (b) Sleeve friction



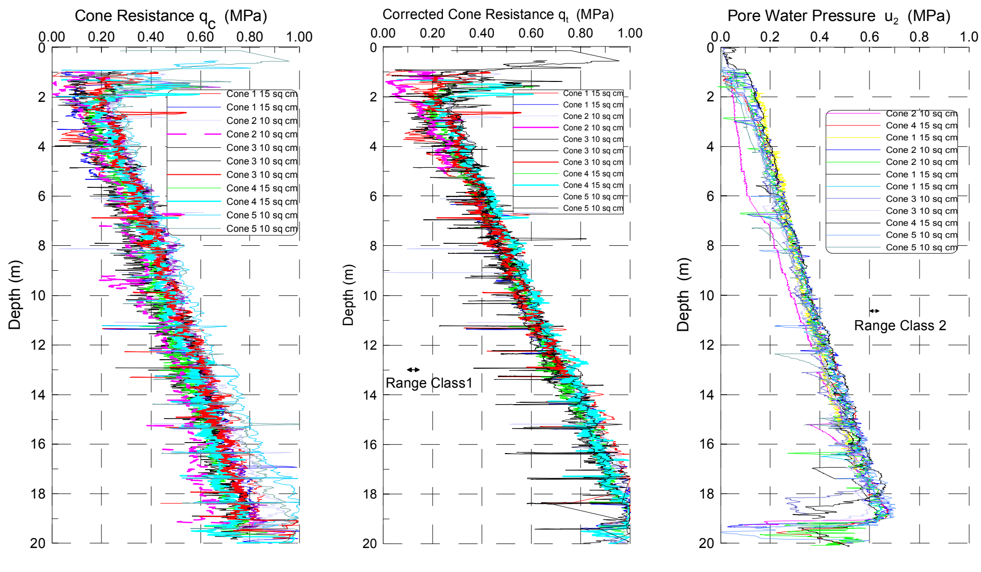
(a) (b) (c) (d)

Figure 5. Pentre, (a) q_t (b) Sleeve friction (c) Pore water pressure (d) Friction ration



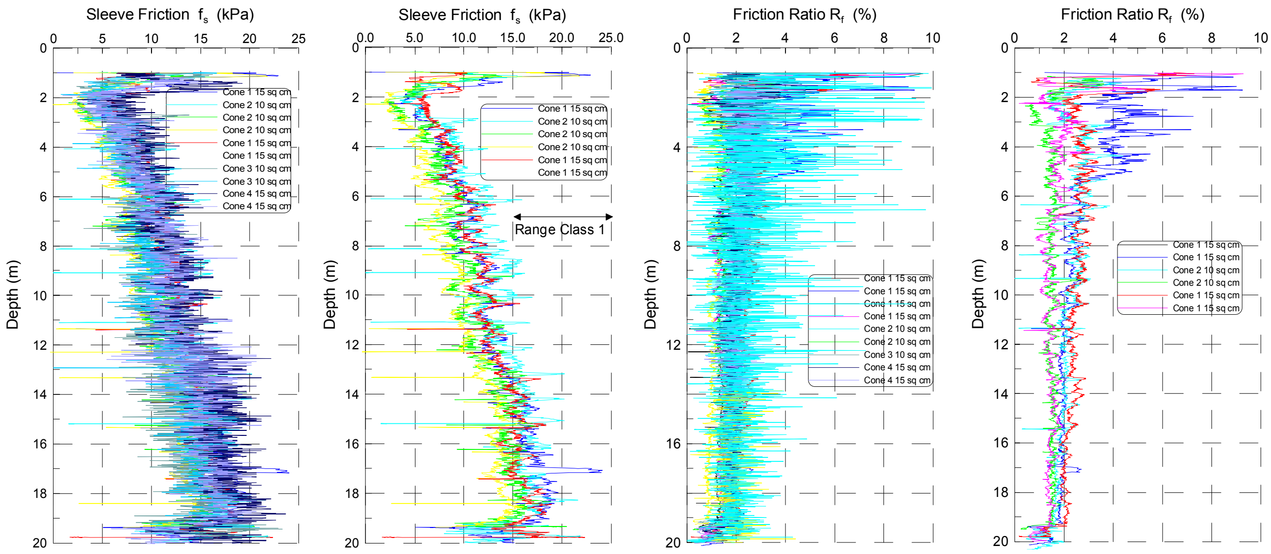
(a) (b)

Figure 6 Pentre expanded plots, (a) q_t (b) Sleeve friction



(a) (b) (c)

Figure 7 Bothkennar, (a) q_c (b) q_t (c) u_2



(d) (e) (f) (g)

Figure 7 ctd. (d) All f_s profiles, (e) f_s without cones 3 and 4 (f) R_f all profiles, (g) R_f without cones 3 and 4