The friction sleeve measurement in CPTU – Does size matter? - A new study

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ABSTRACT: Friction sleeve measurements (f_s) from Piezocone tests have often been criticised as being unreliable or the least reliable of 3 measurements. This has been attributed to the cone types, either by measuring system, subtractive or dual compressive load cells or manufacturing differences. Recent work has shown that slight differences in the relative diameters of the cone and friction sleeve can have significant effect on f_s. Manufacturers have been shown to interpret the allowable tolerances set in standards in different ways, but still fulfilling the standards. If correct, then the above findings with regards to f_s could have great significance to the allowable wear tolerances specified in standards (ISO and ASTM) and thereby used by the manufacturers, as well as explaining historical differences in results.The paper confirms earlier findings of the effects of diamater differnces on the results of f_s but suggests that soil type may play a more important role than previously suggested. Recomemdations for changes to standards are also made.

Keywords: friction sleeve, piezocone test (CPTU), diameters, tolerances

1. Introduction

Over the years many studies have been undertaken to look at how different manufacturers piezocones perform in different soil types [e.g.1,2] and why different results are sometimes obtained. Advances in cone design and the better understanding of the various factors that influence the measured parameters has meant that nowadays it is often the case that very consistent results are obtained for corrected cone resistance (q_t) and porewater pressure (u_2) when different cones are used on the same site. However, friction sleeve measurements (f_s) are still often criticised for being unreliable or at best the least reliable of the 3 measurements made by the CPTU [1,3]. Lunne and Andersen [4] suggested that the lack of consistency/accuracy in these measurements could be attributed in part to:

- Porewater pressure effects on the ends of the sleeve
- Tolerance in dimensions between the cone and the sleeve
- Surface roughness of the sleeve
- Load cell design and calibration

To the last item one might also say mechanical design of the cone.

The first of the above list has been minimised by the present-day cones being designed with equal (and ideally small) end areas. It can also of course be correct for if the porewater pressure is known at both ends of the friction sleeve.

The third and fourth items will only be discussed briefly later in the paper.

With regards to the second point then [5-7] have shown the potential importance of this topic and it is this area that the present paper continues to address.

The main two international standards on CPT and CPTU, ISO 22476-1 [8] and ASTM standard (D 5778-12) [9] both specify very similar allowable tolerances for the cone penetrometer for both the cone and friction sleeve dimensions. The cone diameter, d_c, shall be between 35.3mm and 36.0mm, but currently only the ASTM says with an 'ideal' diameter of 35.7mm (which corresponds very closely to 10cm^2). For the friction sleeve the requirements for both are that the friction sleeve diameter, d_s, should be equal to or greater than the cone diameter, d_c, but with a maximum difference of +0.35mm (i.e., $d_c \leq d_s \leq d_c + 0.35mm$). However, the ISO 22476-1 says d_s shall be less than 36.1mm. (In theory therefore the ASTM could previously have been taken to imply a maximum friction sleeve diameter of 36.35mm, but now the very recent D 5778-20 says it cannot be greater than 36.1 and so is now aligned with the ISO 22476-1.

These are requirements both for manufacturing and operation. Powell [10] showed then the manufactures interpret this in slightly different ways; some manufactures produce their cones with diameters around 35.75mm with a tolerance and some produce them much closer to the maximum 36mm arguing that this allows for greater wear. For the friction sleeve they produce them between 35.9mm and 36.1mm, but all with maximum tolerance range of 0.1mm. Typically the resulting difference between cone and friction sleeve based on each manufacture's tolerances is between +0.075mm and +0.2mm with maximum possible based on manufacturing tolerances of 0.0mm to +0.3mm. In operation it is not unknown for the differences to reach the maximum allowable of 0.35mm (or greater!!).

The purpose of this present study was to confirm or otherwise the findings of [5,6] and if confirmed to try and influence future standards etc for CPT and CPTU.

1.1. The plan

As in the work of [5,6] a series of friction sleeves of known diameter were manufactured to fit onto a standard cone. The primary cones used in this work were Gouda

10cm^2 (DP10), which with a standard sleeve typically results in the friction sleeve being 0.1mm larger than the cone diameter. The special sleeves were therefore manufactured to be -0.1mm, 0.15mm, 0.35mm and 0.45mm smaller or bigger than the standard. This resulted in sleeves with diameters equal to the cone (-0.1mm) and 0.1mm, 0.25mm, 0.45mm and 0.55mm larger than the cone. The latter two diameters exceed the allowable differential in diameters in the standards but would help to exaggerate the effects if any.

The plan was to undertake comparative testing on a number of sites both testbed and commercial sites depending on availability. When time allowed repeat testing with the different diameters of friction sleeve would also be undertaken in order to look at natural variability in repeat measurements with the same sleeve. So far during this ongoing study 4 sites have been utilised, 2 were testbed sites and 2 commercial testing sites covering soft clay, glacial clay till, sand and chalk. The sites will be referred to in the following as Bothkennar [11], Cowden [12] as testbed sites and Otterham and Newbury the commercial sites.

The Bothkennar Site. This site had previously been a national testbed site but has now been returned to wetlands as a bird sanctuary. However, permission was obtained to utilise an area of the site. The site consists of up to 20m of soft estuarine clay which appears slightly cemented.

The testbed sites at Cowden is a glacial clay till with interbedded sand and gravel layers

The Commercial sites investigated were at Otterham comprising a sand layer (Thanet sand) overlying weathered white Chalk and at Newbury comprising superficial Head Deposits overlying Chalk with weathering features.

1.2. Background

Holtrigter et al. [5, 6] had seen that, based on single profiles with each sleeve diameter, as the diameter of the friction sleeve increased then so did the resulting measurement of sleeve friction. They found that they could improve the agreement for the friction sleeve results by applying corrections, firstly for potential end bearing effects on the enlarged friction sleeve (simply related to exposed end bearing, on the end of the friction sleeve), and related to q_t and then a correction for sleeve enlargement. The authors of this paper found this approach to show the most potential after considering other alternatives and so have adopted this approach.

Their equations comprise two components, as shown in Eq. (1) below:

$$f_s = f_{s(q_t)} + f_{s(f)} \qquad (1)$$

where:

f_s is the measured sleeve friction

$f_{s(q_t)}$ is the component due to end bearing on the friction sleeve edge

$f_{s(f)}$ is the component due do actual friction on the sleeve

$f_{s(q_t)}$ is calculated as:

$$f_{s(qt)} = \frac{\pi q_t (d_s^2 - d_c^2)}{60}$$

where:

q_t is the corrected cone resistance in MPa

d_s is the sleeve diameter in mm

d_c is the cone diameter in mm

and the divisor of 60 is derived from the difference between sleeve and cone area divided by the sleeve surface area equal to 15000 mm^2 and adjusted for units

If the cone diameter is equal to sleeve diameter, then $d_s^2 - d_c^2 = 0$, so no correction for end bearing is required, $f_s = f_{s(0)}$.

$f_{s(f)}$ can be expressed as:

$$f_{s(f)} = f_s - f_{s(q_t)} = f_s - \left[\frac{\pi q_t (d_s^2 - d_c^2)}{60}\right]$$

The overall correction on measured sleeve friction to be equivalent to that from a cone penetrometer with equal cone and sleeve diameters is calculated using Eq. (2) below:

$$f_{s(0)} = f_{s(f)}(1 - m_{sf}(d_s^2 - d_c^2)) \qquad (2)$$

where:

m_{sf} is the gradient of the linear relationship, used as a correction factor in Eq. (2). So the values of $f_{s(0)}/f_{s(f)}$ are plotted against $d_s^2 - d_c^2$, showing a linear relationship with a slope equal to m_{sf}.. The value may be a constant for a given soil type. Holtrigter and Thorp [5] showed that for the majority of their sites a value of 0.0084 (0.0084 for sand and clay-0.0094 for alluvium) would work with slight variations but for one residual soils site m_{sf} needed to be 0.019.

By combining Eq. (1) and Eq. (2) the full correction on the measured friction sleeve can be obtained from Eq. (3):

$$f_{s(0)} = \left(f_s - \left[\frac{\pi q_t (d_s^2 - d_c^2)}{60}\right]\right)(1 - m_{sf}(d_s^2 - d_c^2)) \qquad (3)$$

1.3. The results

At Bothkennar a total of 10 profiles were completed, 2 with each of the 5 different friction sleeves. The same cone penetrometer was used throughout all testing works. Fig. 1 shows the profiles as q_c, f_s, q_t, and u_2 (note: to allow for slight differences in depth the profiles in all Figures in the paper have been plotted with data averaged of depth intervals). The great consistency in q_c, q_t and u_2 is immediately obvious as is the larger scatter seen in f_s and R_f. It can be seen that the larger the friction sleeve diameter the higher the resulting measured friction and friction ratio which matches what was found in the Holtrigter work.

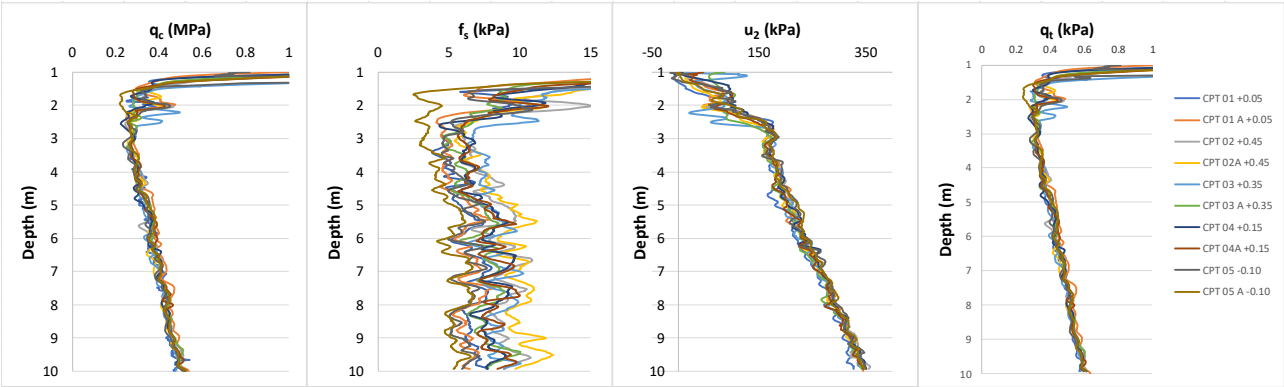

Figure 1 Bothkennar profiles for measured q_c, f_s , q_t, and u_2.

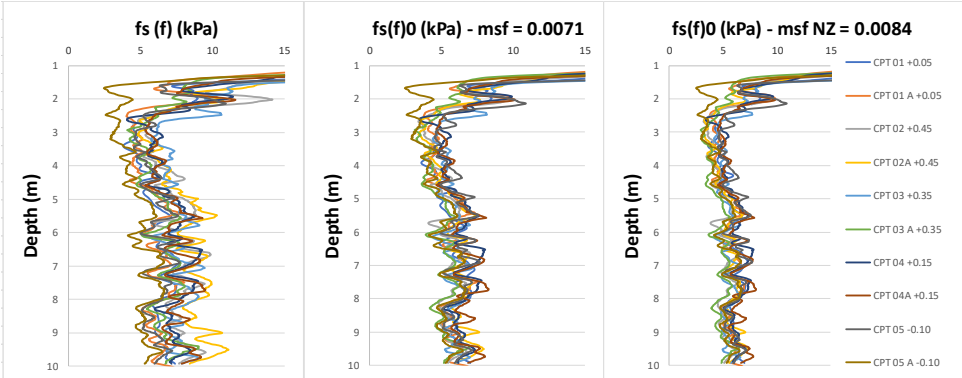

Figure 2 Bothkennar corrected f_s profiles.

There was generally excellent repeatability in the profiles of f_s with the same diameter sleeve which was encouraging.

There was, however, some evidence of temperature variations at shallower depths in some profiles which was seen to affect the sleeve results, and this explains the slightly larger scatter above 4m. Using the Holtrigter approach and plotting $f_{s(0)}/f_{s(f)}$ against $d_s^2 - d_c^2$ then it can be seen in Fig. 3 that for Bothkennar a value of m_{sf} of 0.0071 was derived based on testing below 4m. In Fig. 2 it can then be seen that using the above equations f_s improves through $f_{s(f)}$ to $f_{s(0)}$ with an excellent agreement using this value of m_{sf}.

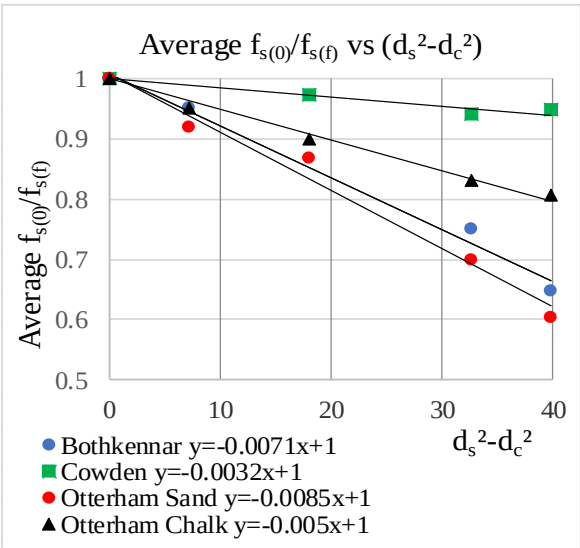

Figure 3 Plot of $f_{s(0)}/f_{s(f)}$ against $d_s^2 - d_c^2$.

If 0.0084 was used, as suggested by [6], then measured sleeve friction is slightly overcorrected with the larger sleeves falling below the equal diameter sleeve (see Fig. 2). For completeness the effect of correcting in this way is shown in Fig. 4 for R_f.

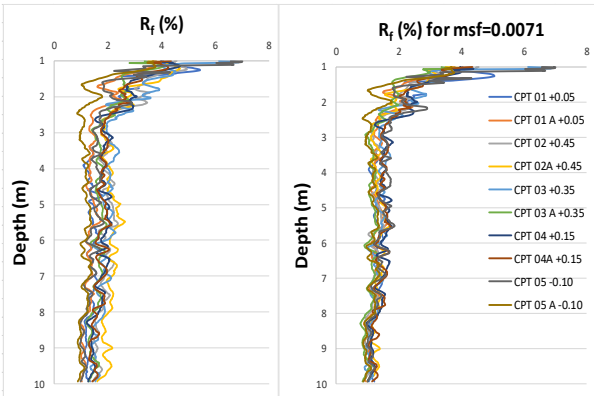

Figure 4 Bothkennar uncorrected and corrected R_f profiles.

The testbed site at Cowden was the first to be investigated in this study, initially using cone tips of reducing size to simulate the same effects. However, the results were rather confusing showing little or no effect on relative size of the friction sleeve and this was thought to be operational and equipment issues and so was decided they should be ignored until tests could be done with the cones mentioned earlier in this paper and used on all other sites. Fig. 5a and Fig. 5b show the results.

It can be seen that except in the upper few metres then the measured friction sleeve results look quite good and are again (as in the earlier discarded visit) quite consistent.

Subsequent correction for end bearing effects show a possible improvement $f_{s(f)}$ and trying to derive a value for m_{sf} results in a very low value, possibly about 0.0032 (see Fig. 3). Results from a further subsequent visit gave a very similar outcome. The R_f profiles are also shown for completeness in Fig. 6a.

At Otterham again 10 profiles were completed 2 with each of the 5 different friction sleeves. Fig. 5b shows the results of the initial friction sleeve measurements in the sand layer alongside the corrected ones using a derived value of m_{sf} of 0.0085 (see Fig. 3).

The improved consistency in the corrected sleeve friction measurements is seen along the those for R_f in Fig. 6b.

In Fig. 7a and Fig. 8a the data are presented for the Chalk layer from 2.5m when using the derived value of m_{sf} of 0.005 (see Fig. 3) and the subsequent improvement on R_f.

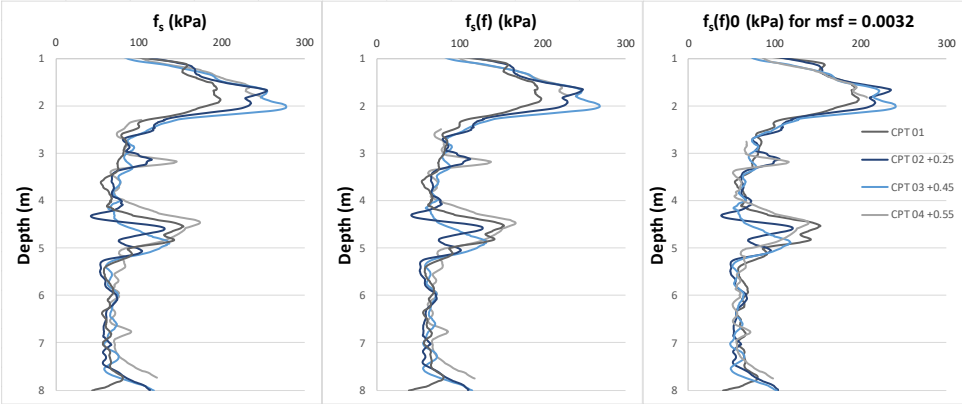

Figure 5a Cowden uncorrected and corrected f_s profiles.

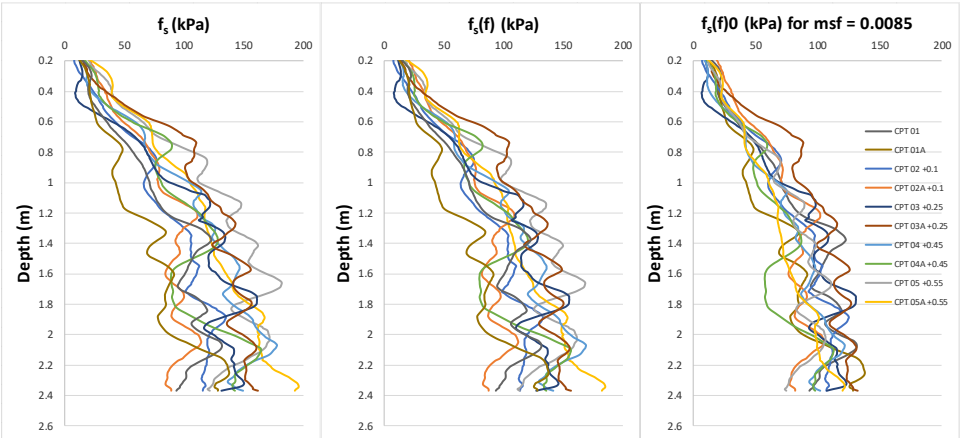

Figure 5b Otterham Sand uncorrected and corrected f_s profiles.

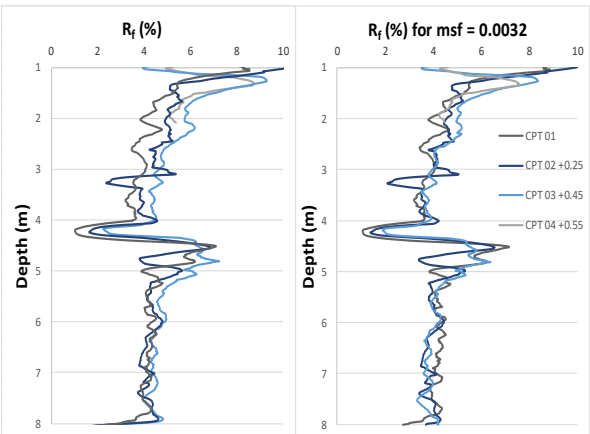

Figure 6a Cowden uncorrected and corrected R_f profiles.

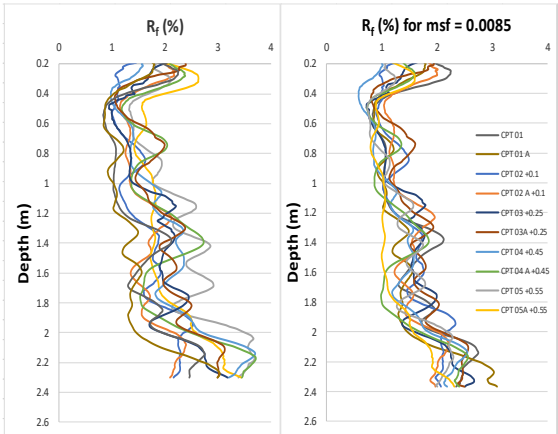

Figure 6b Otterham Sand uncorrected and corrected R_f profiles.

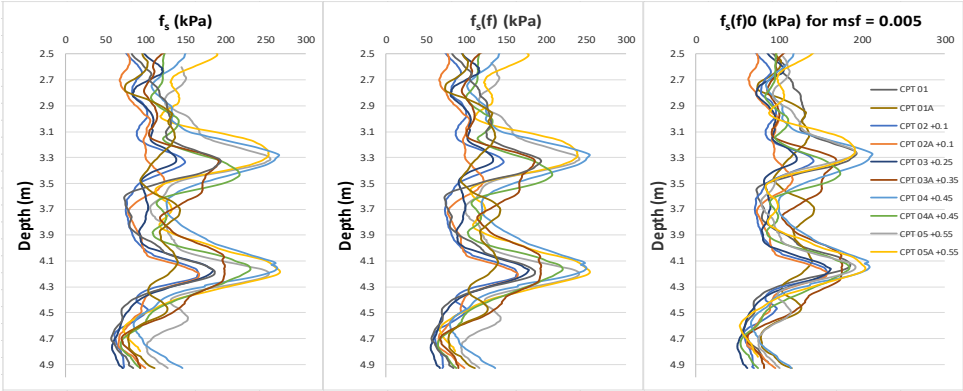

Figure 7a Otterham Chalk uncorrected and corrected f_s profiles.

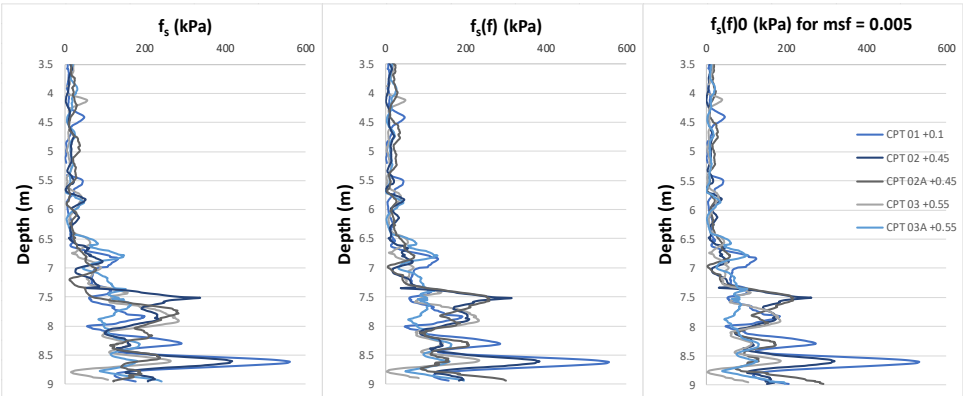

Figure 7b Newbury Chalk uncorrected and corrected f_s profiles.

At Newbury the testing was a little restricted and the ground conditions much more variable however it can be seen in Fig. 7b and Figure 8b that using the m_{sf} factor from Otterham for the chalk then some improvement in $f_{s(f)}$ can be seen especially between 3.5 and 6.5 m.

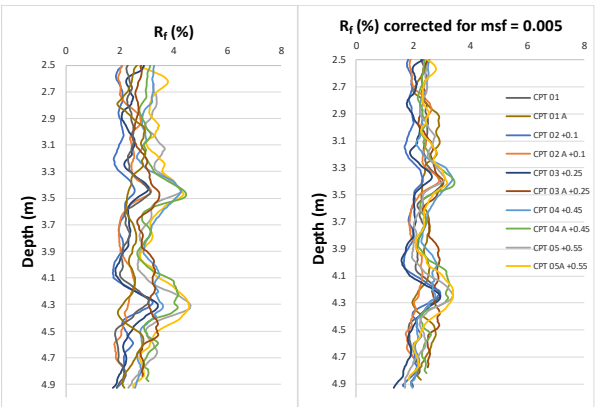

Figure 8a Otterham Chalk uncorrected and corrected R_f profiles

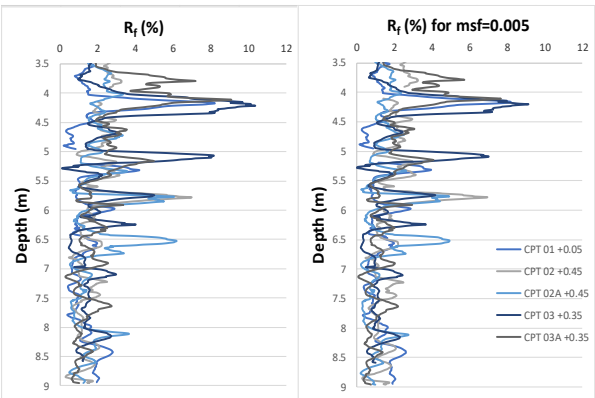

Figure 8b Newbury Chalk uncorrected and corrected R_f profiles.

2. *Discussion*

It has been shown in the previous section that the effect of testing with different diameter sleeves results in higher friction measurement the larger the diameter of the sleeve and confirms the findings from previous work [5-7]. The equations proposed by [6] seem to work well on some sites but it would appear that their suggestion of taking a global value for the m_{sf} factor on 0.0084 should be treated with caution as it has been found that this could over correct in some cases.

The m_{sf} correction is the part of the correction derived by [6] that has most impact. In Table 1 we try to show in general terms the impact of the two components of the correction, the end bearing on the sleeve and the m_{sf} correction. As a rough guide let us assume friction ratios of 1% coarse grained (sand like) and 4% fine grained (clay like) for friction sleeves 0.1mm larger than the cone. Table 1 then shows the potential size of the corrections in terms of the effect of the end area correction $f_{s(qt)}$ and then the total correction $f_{s(0)}$.(based on both m_{sf} 0.0084 and 0.005).

We can see Table 1 then in sands the end bearing correction can be up to 13% of the maximum diameter difference of 0.35mm, whilst in clay it would be only 3%. With the m_{sf} factor then the total correction rises to 32% and 24% respectively for m_{sf} 0.0084 and 0.005 for sand and 24% and 13% for clay. It can be seen that, if the difference in diameters is reduced to 0.25mm maximum then a significant reduction of the amount of correction is achieved.

Table 1. R_f change due to f_s corrections for Sand and Clay.

Cone Diameter Difference (mm)		0.1		0.25		0.35	
Soil Type (S=Sand, C=Clay)		S	C	S	C	S	C
R_f change for $f_{s(\mathrm{qt})}$ (%/kPa)		4	1	10	2	13	3
R_f change for $f_{s(0)}$ (%/kPa)	m_{sf}= 0.0084	10	7	23	17	32	24
	m_{sf}= 0.005	7	5	18	11	24	13

Lunne et al [2] showed that even when applying this correction, and also the influence of unequal porewater pressures at either end of the friction sleeve, then there were still significant differences in friction sleeve results from different cones and this might be related to mechanical differences in design, calibration (item 4 of the introduction) or even operation as in their work the testing was carried out by independent companies. Powell and Lunne [13] did show that when the same calibration system and operators were used then friction sleeve results still varied, but to a much lesser extent.

3. Conclusions

The results presented here confirm the findings from previous studies [5-7] that the effect on f_s, measurements is sensitive to the tolerance between the cone and sleeve diameters. The effect appears to occur in all soils types investigated but to varying degrees. The correction has ranges from as little as 1% to as much as 32%.

The idea put forward by [6] of using a global value for m_{sf} must be treated with caution as this may over correct in some soils and be more soil type dependent than thought.

The behaviour seen in all these studies is something that is physical and can be controlled both in manufacture and maintenance and operation. It is suggested that if the allowable tolerances for the difference between cone and friction sleeve for manufacture and operation were reduced to 0.25mm then this would mean potential errors might be reduced to at worst 25% in some soils. It is suggested that standards should be amended and adopt this differential.

The application of the equations with a reliable m_{sf} would improve things significantly but the m_{sf} has to be correct. If the diameter differential were as low as 0.1mm then likely errors would be in single figures.

It is suggested that it is a positive step forward if:

- maximum allowable difference between the diameter of the friction sleeve were reduced to 0.25mm.
- when possible, a difference of only 0.1mm should be aimed for to ensure minimum potential errors and correction.
- the cone and sleeve diameter should be reported for each test routinely.
- Should all manufacturers work to the tighter tolerances adopted by others.
- Operators need stricter guidelines for acceptable tolerances if data is to be relied upon.

If this area of potential error is managed then we now need to address the operational, calibration and design aspects that seem to be present for friction sleeve measurements.

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