The effect of sleeve diameter on $f_s$ measurements

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**ABSTRACT:** The sleeve friction measurement, $f_s$, is considered to be the least reliable of the three measurements in piezocone testing. One possible contributing factor may be friction sleeves of variable diameters greater than that of the cone tip. In this study, friction sleeves of different diameter have been used in side-by-side piezocone testing on three test sites to investigate the possible variation to sleeve friction measurements with sleeve diameter. The results suggest that there is an effect due to sleeve diameter, with larger measured sleeve friction values for sleeves of larger diameter (in relation to the cone tip diameter). A correlation has been found between the relative diameters of the cone and sleeve by considering the effect of the end resistance acting on oversized sleeves and on empirical comparison between the side-by-side tests. A formula to allow correction for this effect has been suggested.

1 INTRODUCTION

A considerable amount of Cone Penetration Testing (CPT) has been undertaken in the Christchurch area of New Zealand to evaluate liquefaction following the Canterbury earthquakes of September 2010 and February 2011. Many of these sites have CPTs done by different contractors using cones from different manufacturers in close proximity. Observations from some of these sites have shown significant differences in $f_s$ values between the different companies. It has also been observed that cones using larger friction sleeve diameters (in relation to the cone diameter) tend to show higher $f_s$ values than those of smaller sleeve diameters. The variations in $f_s$ have, in some cases, lead to significant differences in liquefaction vulnerability and post liquefaction settlement on the same site. To investigate a possible correlation between sleeve diameter and $f_s$ measurements, side-by-side CPTs were carried out with friction sleeves of different diameters. These tests were carried out on three test sites; one in clay and two in sand.

2 ACCURACY OF SLEEVE FRICTION MEASUREMENTS

Many authors have found the CPT sleeve friction measurement, $f_s$, to be the least reliable of the three measurements provided by the piezocone (e.g. Tiggelmann & Beukema, 2008, Lunne, 2010). In a comparative study between 11 CPT companies in The Netherlands, Tiggelmann & Beukema (2008) found that there was variation in both $q_c$ and $f_s$ measurements between the results of the different companies, but the $f_s$ values provided the greatest variation. Lunne (2010) also compares the results of piezocone tests between 4 different companies in an off-
shore investigation. In that study the $q_c$ and $u_2$ values were practically identical, whereas the $f_s$ values showed large variation. The variation in $f_s$ was largely thought to be due to the difference in pore water pressure acting at each end of the friction sleeve (Lunne, et al. 1997). This effect is reduced with the now common use of equal area friction sleeves, however, as Lunne (2010) points out, there must be some other effects as tests in sand have also shown large differences in $f_s$ values (with very low porewater pressures).

Given the large variation in $f_s$ values, Lunne (2010) suggested that it is not possible to utilize this measurement to its full potential (e.g. as advocated by Robertson, 2009). Similarly, Long & Donohue (2010) suggest that the sleeve friction values be used with caution due to the variation between equipment types.

Lunne and Anderson (2007) suggest that the lack of accuracy in $f_s$ measurement is primarily due to the following factors:

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

Boggess and Robertson (2010) considered the main variables to be pore pressure effects on the end of the sleeve and load cell design/calibration, suggesting that tolerances provided in CPT standards have dealt with dimension effects and sleeve roughness.

However, the anecdotal evidence from the tests in Christchurch suggests that the effect of the tolerance between cone and sleeve diameters is perhaps more significant than previously thought. In this study we have considered only the cone and sleeve diameter effect. The other three possible factors mentioned above are considered to be negated as the same piezocone by the same manufacturer is used. The only variable is the size of the friction sleeve diameter.

### 3 CONE AND SLEEVE DIAMETERS

The ASTM standard (D 5778-12) specifies the tolerances for the cone tip and friction sleeve dimensions. The diameter of the cone tip, $d_c$, is required to be between 35.3 mm and 36.0 mm, with an ‘ideal’ diameter of 35.7 mm. The standard specifies that the friction sleeve diameter, $d_s$, be equal to the cone diameter, $d_c$, with a tolerance of between 0.0 mm and 0.35 mm greater than $d_c$.

Most cone manufacturers construct their piezocones with the cone tip diameter to the ideal 35.7 mm. However, the friction sleeve diameters generally range between manufacturers from 0.0 mm to 0.45 mm greater than the tip diameter.

### 4 EQUIPMENT AND PROCEDURES

For this study, a piezocone manufactured by Pagani Geotechnical Equipment from Italy has been used. The same piezocone was used at each test site. The piezocone has a 50 MPa capacity load cell for the end resistance and 500 kPa capacity sleeve friction load cell. The friction sleeve has equal end areas. The porewater pressure element is at the $u_2$ position.

A cone tip diameter, $d_c = 35.7$ mm was used for all testing. Friction sleeves of different diameters were supplied by Pagani Geotechnical Equipment for this study. Friction sleeve diameters of 35.6 mm, 35.7 mm, 35.85 mm, 36.05 mm and 36.15 mm have been used. These correspond to differences to cone diameter ($d_c - d_s$) of -0.1 mm, 0.0 mm, 0.15 mm, 0.35 mm and 0.45 mm, respectively.
For the purposes of this study, a grease filled slot filter that has been machined to the exact size of the cone diameter has been used so as to eliminate the effect of a slightly smaller or larger diameter filter element.

At each of the three test sites CPTs were performed with different friction sleeves as side-by-side tests approximately 2.0 m in horizontal distance apart.

5 TEST SITES AND RESULTS

Three test sites were selected; two sand sites in Christchurch and one clay site in Auckland. The sites are:

- Keyes Road, Christchurch (sand)
- Bower Avenue, Christchurch (sand)
- Central Park Drive, Auckland (clay)

The results of the measured data from each of the sites are shown in Figures 1 to 3. The results show reasonable agreement between the end resistance, \( q_e \), but a noticeable visual difference in the friction sleeve values, \( f_s \). This difference also translates to the friction ratio values.

6 INTERPRETATION OF RESULTS

It is clear from the results of the side-by-side tests that the sleeve friction values, \( f_s \), (and the friction ratio values, \( R_f \)), progressively increase with increasing sleeve diameter. This is considered to be due to two effects:

1. End resistance on the edge of the sleeve that protrudes from the cone tip
2. Increased friction along the sides of the sleeve due to increased volume of displacement

Figure 4 illustrates how the end resistance can develop on the edge of the friction sleeve.
Figure 1. Raw data from Keyes Road site

Figure 2. Raw data from Bower Avenue site
Thus the measured sleeve friction, $f_s$, can be considered to have two components, as per Equation 1 below:

$$f_s = f_{s(qt)} + f_{s(f)}$$

(1)

where $f_s$ = measured sleeve friction; $f_{s(qt)}$ = component of measured sleeve friction due to end resistance on sleeve edge; and $f_{s(f)}$ = component of measured sleeve friction due to true friction on the sleeve.

### 6.1 End Resistance on Friction Sleeve

The component $f_{s(qt)}$ can be calculated by assuming that the same end resistance measured by the cone tip, $q_t$, also applies to the oversize edge of the sleeve, as illustrated on Figure 4. The force thus measured by the friction sleeve load cell will be equal to the area of the sleeve end that protrudes over the cone tip multiplied by $q_t$. This is then divided by the cone sleeve surface area (150 cm$^2$) to give an equivalent sleeve friction value. In this way, Equation 2 below is derived.

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

(2)

where $q_t$ = total cone resistance in MPa; and $d_s$ & $d_e$ in mm

By combining Equations 1 and 2, the measured $f_s$ data can then be corrected for this end resistance effect to give $f_{s(f)}$.

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

(3)
This correction for end resistance effect is illustrated in Figure 5 where this correction has been applied to the $f_s$ data of the Keyes Road site (middle graph, $f_{s(f)}$).

6.2 Relationship between end-resistance corrected $f_{s(0)}$ values

It can be seen in Figure 5 that the $f_{s(0)}$ values fall closer together than the measured $f_s$ data, but there remains a trend of increasing sleeve friction with sleeve diameter. This variation in $f_{s(0)}$ values is thought to be a function of the volume change between sleeves of increasing diameter (i.e. a function of $d_s^2 - d_c^2$).

To investigate this relationship, a comparison has been made between the $f_{s(0)}$ values corresponding to each of the various sized sleeves and the sleeve friction measured for the cone with the same size cone tip and sleeve diameter. In undertaking this comparison, some data was re-phased to align peaks. Data that was considered to be due to natural soil variation was omitted.

For the case of same sized cone and sleeve diameters, $d_s^2 - d_c^2 = 0$ and so no correction is required and $f_{s(0)} = f_s$, the measured sleeve friction. For the purposes of this study the measured sleeve friction values resulting from same size sleeve and cone are considered to represent the correct data for comparison purposes.

The graph in Figure 6 shows the average results of the comparative study. In this graph, the values of $f_{s(0)}/f_{s(0)}$ show a linear relationship with $d_s^2 - d_c^2$. This gives Equation 4 below.

$$f_{s(0)} = f_{s(f)} \times [1 - 0.0084(d_s^2 - d_c^2)]$$

(4)
where $f_{s(0)}$ = sleeve friction equivalent to that of an equal diameter cone and sleeve

![Figure 6: Plot of $f_{s(0)}/f_{s(f)}$ vs. $d_s^2 - d_c^2$](image)

By applying Equation 4 to the $f_{s(f)}$ values at the Keyes Road site, the corrected $f_{s(0)}$ values shown in Figure 5 are obtained (right hand graph), which show close agreement.

By combining Equations 3 and 4, an overall correction direct from the raw sleeve friction values, $f_s$, can be obtained, as shown in Equation 5 below:

$$f_{s(0)} = f_s - \left[ \frac{\pi q d (a_s^2 - a_c^2)}{60} \right] \times [1 - 0.0084(d_s^2 - d_c^2)] \quad (5)$$

This equation was then applied to the data of all three sites. The resulting measured and corrected data for $f_s$ and $R_f$ are shown in Figures 7-9 for the sites at Keyes Road, Bower Avenue and Central Park Drive, respectively.
Figure 7: Keyes Road \( f_s, f_{s(0)}, R_f \) and \( R_{f(0)} \)

Figure 8: Bower Avenue \( f_s, f_{s(0)}, R_f \) and \( R_{f(0)} \)
7 DISCUSSION

From the results of this study, it would appear that the effect on \( f_s \) measurements is sensitive to the tolerance between the cone and sleeve diameters. The effect appears to be more pronounced in denser sands and stiffer clays. The suggested correlation (Equation 5) appears to work well in both sands and clays and for stiff/dense soils as well as soft/loose soils. The correlation also appears to work for sleeves of diameters less than that of the cone tip (-0.1 mm in this study). For sleeves where the sleeve diameter is less than the cone tip, \( q_t \) is taken as zero in Equation 5.

The sensitivity of this effect on \( f_s \) measurements puts greater reliance on regular checking of cone and sleeve dimensions as wear on these components will have an effect. ASTM D 5778-12 allows a tolerance of up to 0.35 mm between the cone and sleeve, but within this tolerance there is a significant difference in the effect on \( f_s \). Even differences as little as 0.1 mm appear to have an appreciable effect. In sandy or gravely soils, wear can occur rapidly. The effect on \( f_s \) is also likely to be more pronounced in these soil types. As little as one day’s wear in such soils could result in significant error in \( f_s \) measurement.

It is considered that cones and sleeves manufactured to the same diameter (ideally 35.7 mm) would be preferable. For friction sleeves that have diameters greater than the cone tip, either due to wear or by manufacture, a correction such as that suggested by Equation 5 should be applied. In abrasive soils, it is suggested that cone and sleeve measurements be recorded daily and corrected accordingly.

8 CONCLUSIONS

From the side-by-side tests undertaken in this study it has been shown that different \( f_s \) measurements are obtained with piezocones of different sleeve and cone diameters. Piezocones with sleeve diameters larger than the cone tip result in larger \( f_s \) measurements than those obtained using a piezocone with equal diameter sleeve and cone. Increasingly larger sleeves (in relation to cone size) create increasingly larger \( f_s \) measurements. The increased \( f_s \) measurements are thought to be due to a combination of end-resistance on the edge of the oversized sleeve plus
increased friction due to the displacement volume increase of the larger sleeve. The $f_s$ measurements appear to be sensitive to these effects and significant error can arise, particularly in stiff/dense soils.

From empirical correlation between the side-by-side tests, Equation 5, below has been derived to allow correction of this effect.

$$f_{s(0)} = f_s - \left[ \frac{\pi q_s (d_s^2 - d_c^2)}{60} \right] \times \left[ 1 - 0.0084 (d_s^2 - d_c^2) \right]$$

(5)

This equation has been found to provide a reasonable correction to the $f_s$ values measured in the three test sites in this study. The correction appears to work well for both sands and clays and for soft/loose soils as well as stiff/dense soils. The correction also appears to work for a large range of cone and sleeve diameter tolerances (-0.1 mm to 0.45 mm).

Further research will be required to confirm or refine this correlation for other sites and using piezocones from different manufacturers. It is considered preferable for piezocones to be manufactured with equal diameter sleeve and cone tips to minimize this effect. This may also lead to more consistent measurements between cones from different manufacturers. Tighter tolerances in standards may also be required.

9 REFERENCES


