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## Correction for CPT $f_s$ errors due to variation in sleeve diameter

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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. It has been shown that the diameter of the friction sleeve in relation to the cone tip diameter has an effect on the sleeve friction measurements ( $f_s$ ). Testing standards (e.g. ASTM D 5778-12) allow a tolerance range such that the friction sleeve can be equal to, or up to 0.35 mm greater than the cone tip diameter. Cone penetrometers with larger friction sleeve diameters show higher  $f_s$  measurements (Holtrigter, et al. 2014). The most accurate results are generally considered to be when the friction sleeve and cone tip are of the same diameter (Cabal and Robertson 2014). In this study, friction sleeves of different diameter have been used in side-by-side piezocone testing on two test sites in New Zealand to investigate the variation to sleeve friction measurements with sleeve diameter. By empirical correlation of these tests the equation to allow correction for this effect (Holtrigter et al. 2014) has been further developed.

### 1 INTRODUCTION

It is widely considered that the sleeve friction measurement,  $f_s$ , is the least reliable of the three measurements provided by the piezocone. In comparative studies of side-by-side piezocone tests performed by different contractors, the  $f_s$  measurements show the most variation (Tigglemann & Beukema 2008, Lunne 2010). Lunne and Andersen (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

In side-by-side piezocone testing at three sites in New Zealand, Holtrigter et al. (2014) showed that the comparative diameter of the cone tip and the friction sleeve affected the  $f_s$  measurements. In that study four or five different diameter friction sleeves were used in the side-by-side tests, with the same diameter cone tip. The same piezocone by the same manufacturer was used in the side-by-side tests so that the only variable of the four listed above was the size difference between the sleeve and cone tip diameters.

In the side-by-side tests, the cone tip diameter was kept constant at 35.7 mm. Friction sleeve diameters of 35.6 mm, 35.7 mm, 35.85 mm, 36.05 mm

and 36.15 mm were used, corresponding to -0.1 mm, 0.0 mm, +0.15 mm, +0.35 mm and +0.45 mm greater than the cone diameter, respectively. It should be noted that ASTM D 5778-12 allows a tolerance between sleeve and cone tip diameters of between 0.0 mm and 0.35 mm.

The results of the side-by-side tests showed that the  $f_s$  measurements (and friction ratio,  $R_f$ ) increased with increasing difference between sleeve and cone diameters, as illustrated in Figure 1.

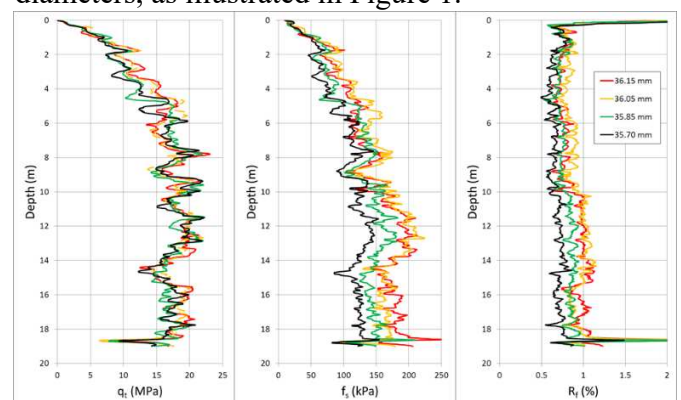


Figure 1. Illustration of increasing  $f_s$  and  $R_f$  with increasing sleeve diameters (Holtrigter et al. 2014)

As a reference, it was suggested that the  $f_s$  measurements relating to the test results where the sleeve diameter was equal to the cone tip diameter presents the ‘correct’ result for  $f_s$ . Cabal and Robertson (2014) showed that the  $f_s$  measurements relating to a

sleeve diameter equal to the cone tip diameter more precisely related to the results of residual undrained shear strengths measured by adjacent field vane tests (Figure 2). A further adjacent CPT test using a larger diameter sleeve showed higher  $f_s$  measurements.

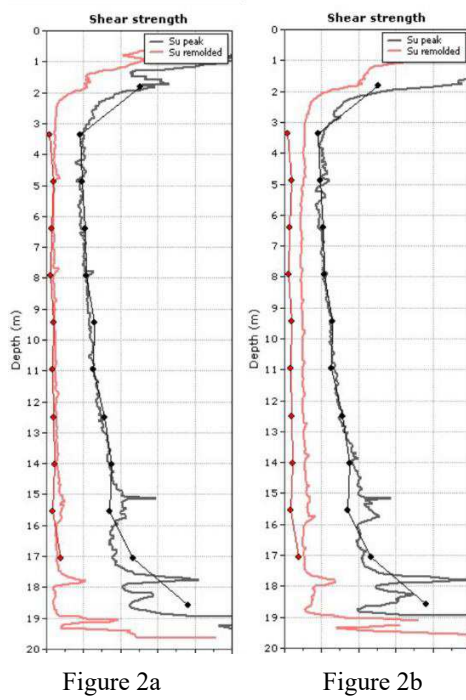


Figure 2. Comparison of  $f_s$  measurements of differing sleeve diameter and field vane tests (Cabal and Robertson 2014). Figure 2a. Equal size cone & sleeve. Figure 2b. Over size sleeve.

Holtrigter et al. (2014) suggested that the variation in  $f_s$  measurements between cones with equal sleeve and tip diameter and those with larger diameter sleeves was due to:

- End resistance ( $=q_t$ ) on the edge of the sleeve that protrudes from the cone tip
- Increased friction along the sides of the sleeve due to increased volume of displacement

A correction (Equation 1, below) was suggested for adjusting the  $f_s$  measurements of oversized cones to ‘corrected’ values relating to sleeves of equal diameter to the cone diameter. Please note that Equation 1 has been corrected for a typo that appeared in the original paper.

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

The first factor in the equation relates to correcting for end resistance on the edge of the sleeve and the second factor is an empirically derived correction for the additional friction due to volume expansion of the sleeve.

In this paper the results of two further sites are discussed.

## 2 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 end resistance and 1,600 kPa capacity sleeve friction load cell. The friction sleeve has equal end areas. The pore water 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 35.7 mm, 35.85 mm, 36.05 mm and 36.15 mm have been used. These correspond to differences to cone diameter ( $d_s - d_c$ ) 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 two test sites CPTs were performed with different friction sleeves as side-by-side tests approximately 1.0 m in horizontal distance apart.

## 3 TEST SITES AND RESULTS

Two test sites were selected. Both are clay sites in Auckland, New Zealand. The sites are:

- Huapai (Pleistocene alluvium)
- Herald Island (residual soil)

The results of the measured data from each of the sites are shown in Figures 3 and 4. The results show reasonable agreement between the end resistance,  $q_t$ , but a noticeable visual difference in the friction sleeve values,  $f_s$ . This difference also translates to the friction ratio values,  $R_f$ .

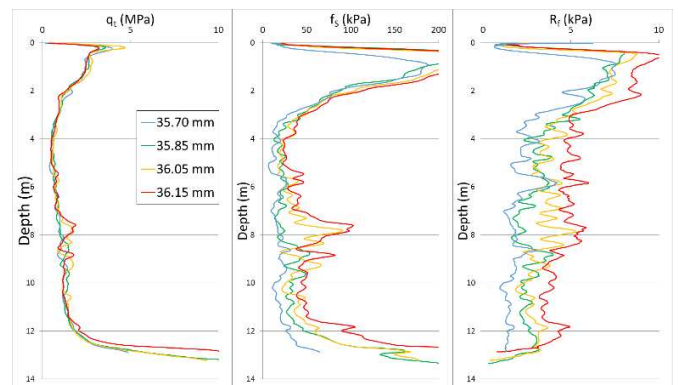


Figure 3. Raw data from Huapai site.

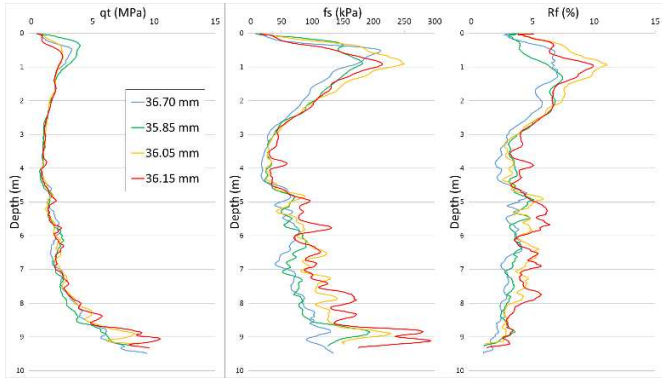


Figure 4 Raw data from Herald Island site.

## 4 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 5 illustrates how the end resistance can develop on the edge of the friction sleeve. Thus the measured sleeve friction,  $f_s$ , can be considered to have two components, as per Equation 2:

$$f_s = f_{s(qt)} + f_{s(f)} \quad (2)$$

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.

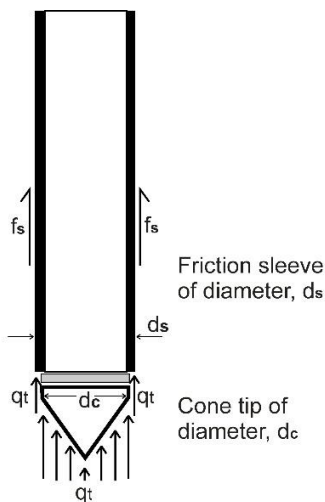


Figure 5. End resistance effect on oversized friction sleeve

### 4.1 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 5. 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 ( $150 \text{ cm}^2$ ) to give an equivalent sleeve friction value. In this way, Equation 3 below is derived.

$$f_{s(qt)} = \frac{\pi q_t (d_s^2 - d_c^2)}{60} \quad (3)$$

Where  $q_t$  = total cone resistance in MPa; and  $d_s$  &  $d_c$  in mm

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

$$f_{s(f)} = f_s - f_{s(qt)} = f_s - \left[ \frac{\pi q_t (d_s^2 - d_c^2)}{60} \right] \quad (4)$$

### 4.2 Relationship between end-resistance corrected $f_{s(f)}$ values and reference $f_s$ values

The correction given in Equation 4 accounts for the end resistance effect. Holtrigter et al. (2014) found that his correction does not fully account for the difference in measured  $f_s$  values for the various size sleeves. The further effect is considered 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  $f_{s(f)}$  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.

For the case of same sized cone and sleeve diameters,  $d_s^2 - d_c^2 = 0$  and so no correction is required and  $f_{s(f)} = f_s$ , 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 average values of  $f_{s(0)}/f_{s(f)}$  are plotted against  $d_s^2 - d_c^2$ . The results of this study and also those of the previous study (Holtrigter et al. 2014) are shown. In the previous study, the points for the three sites tested in that study

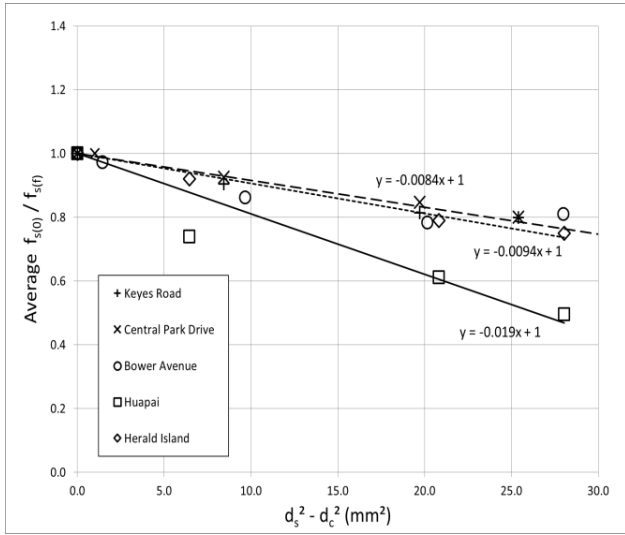


Figure 6. Plot of  $f_{s(0)}/f_{s(f)}$  vs  $d_s^2 - d_c^2$

showed a linear relationship with a gradient of -0.0084 giving Equation 5, below.

$$f_{s(0)} = f_{s(f)} \times [1 - 0.0084(d_s^2 - d_c^2)] \quad (5)$$

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

In the current study, the two sites show different linear relationships, with gradients of -0.0094 and -0.019, as shown in Figure 6. This suggests that the relationship may be site or soil specific and that the equation is best presented with a variable component,  $m_{fs}$ , being the gradient of the linear relationship shown in Figure 6. Thus Equation 5 becomes:

$$f_{s(0)} = f_{s(f)} \times [1 - m_{fs}(d_s^2 - d_c^2)] \quad (6)$$

By combining Equations 4 and 6, an overall correction direct from the raw sleeve friction values,  $f_s$ , can be obtained, as shown in Equation 7 below:

$$f_{s(0)} = \left[ f_s - \left( \frac{\pi q_t (d_s^2 - d_c^2)}{60} \right) \right] \times [1 - m_{fs}(d_s^2 - d_c^2)] \quad (7)$$

This equation was then applied to the data at both sites, with  $m_{sf} = 0.0094$  for the Huapai site and  $m_{sf} = 0.012$  for the Herald Island site. The resulting measured and corrected  $f_s$  and  $R_f$  values are shown in Figures 7 and 8.

## 5 DISCUSSION

The results of this study and that of the previous studies (Holtrigter et al. 2014, Cabal and Robertson 2014) confirm that the effect on  $f_s$  measurements is sensitive to the tolerance between the cone and sleeve diameters. The effect appears to occur in both sands and clays and in soft/loose as well as stiff/dense soils.

The suggested correlation (Equation 7) appears to provide a reasonable correction. However, there is a variable ( $m_{fs}$ ) that is an unknown factor without the benefit of a reference test (with equal sleeve and tip diameters). This makes Equation 7 difficult to apply in practice. Further research is required to better understand this effect, possibly with the application of cavity expansion theory. In the meantime, it is suggested that if corrections are to be made to  $f_s$  data, a first order approximation could be made using Equation 7 with  $m_{fs} = 0.0084$ . This may not provide a complete correction, but may be more accurate than the measured  $f_s$  values for oversized friction sleeves.

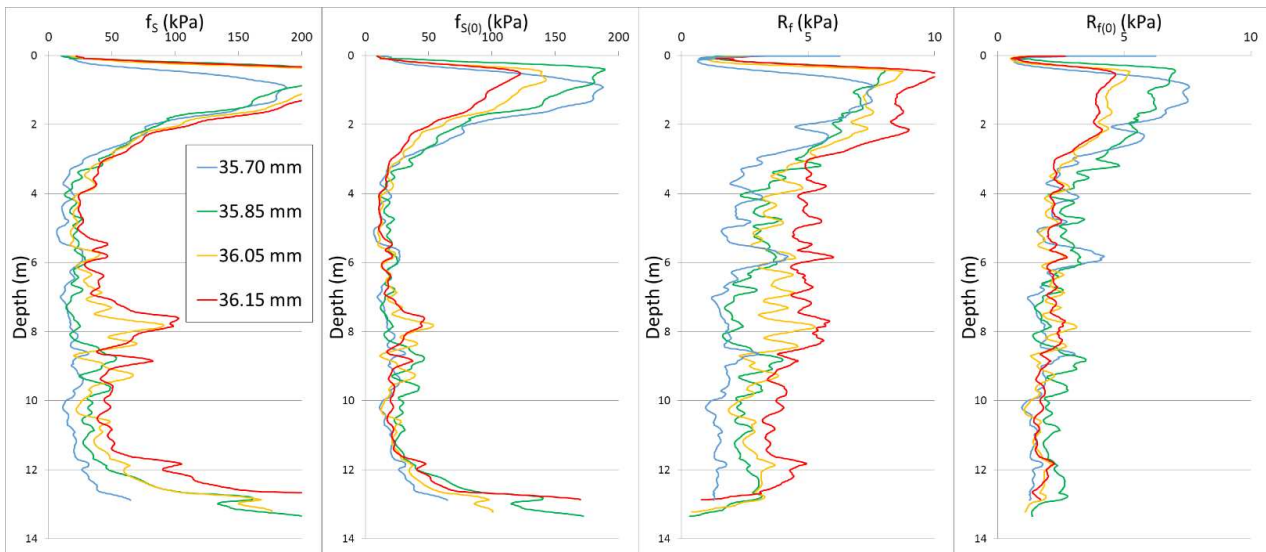


Figure 7. Huapai  $f_s$ ,  $f_{s(0)}$ ,  $R_f$  and  $R_{f(0)}$ .



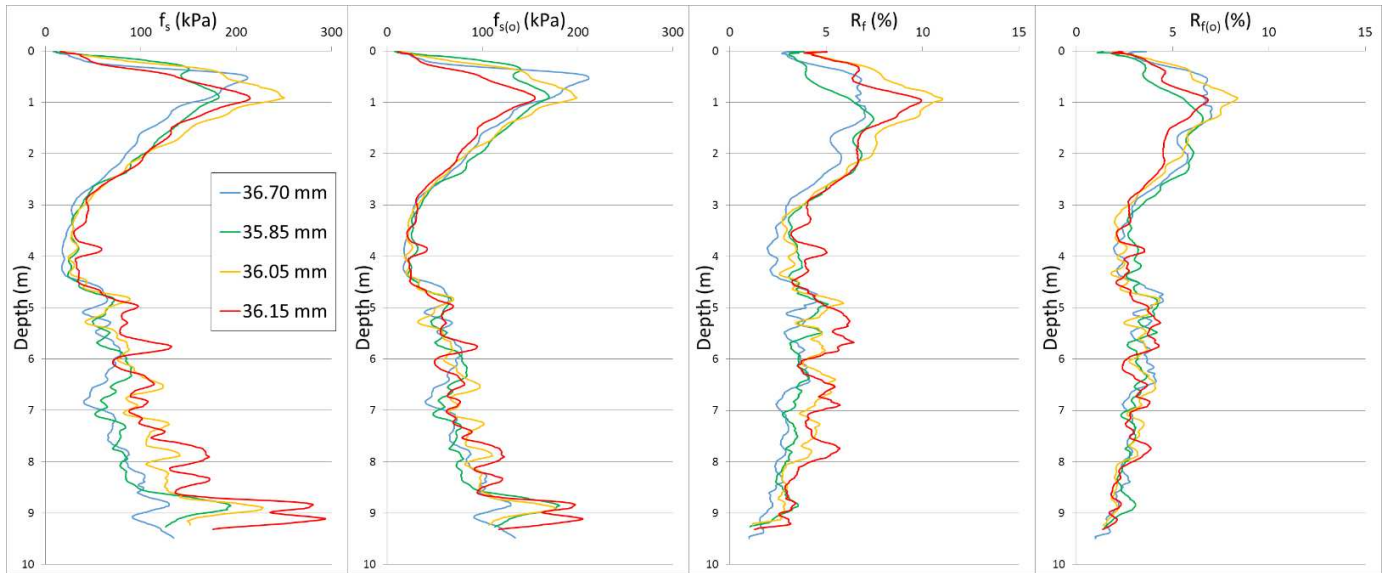


Figure 8. Herald Island  $f_s$ ,  $f_{s(0)}$ ,  $R_f$  and  $R_{f(0)}$ .

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 can have an appreciable effect. In sandy or gravely soils, wear can occur rapidly. 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 7 (with  $m_{fs} = 0.0084$ ) should be applied. In abrasive soils, it is suggested that cone and sleeve measurements be recorded daily and corrected accordingly.

## 6 CONCLUSIONS

From the side-by-side tests undertaken in this study and previous studies 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 7, below has been derived to allow correction of this effect.

$$f_{s(0)} = f_s - \left[ \frac{\pi q_t (d_s^2 - d_c^2)}{60} \right] \times [1 - m_{fs} (d_s^2 - d_c^2)] \quad (7)$$

This equation has been found to provide a reasonable correction to the  $f_s$  values measured in the test sites in this study. The correction appears to work for both sands and clays and for soft/loose soils as well as stiff/dense soils. As a first order approximation a value of  $m_{fs} = 0.0084$  can be used.

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.

## 7 REFERENCES

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