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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 investigation 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.

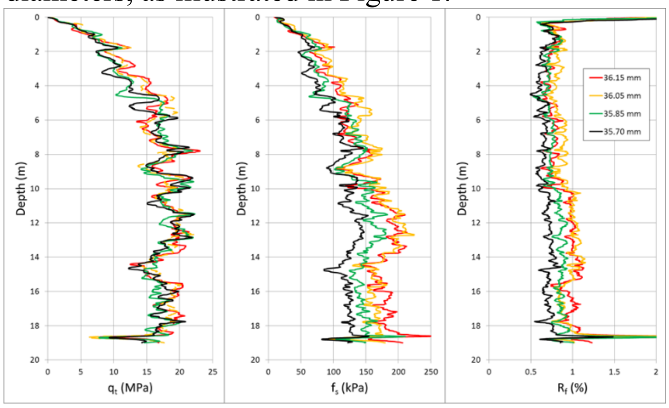

Figure 1. Illustration of increasing f_s and R_f with increasing sleeve diameters (Holtrigter et al. 2014)

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.

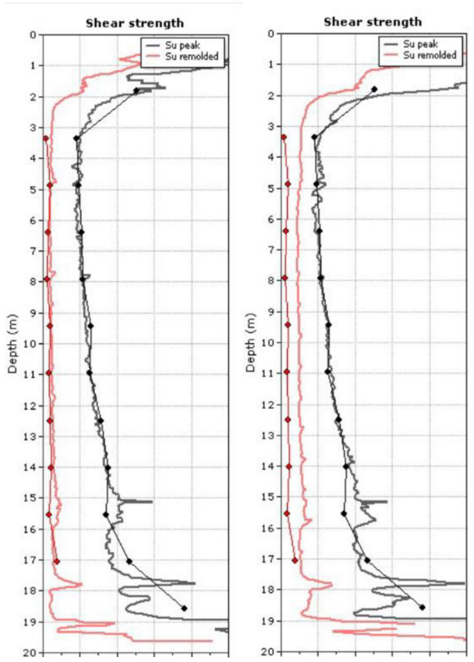

Figure 2a Figure 2b

Figure 2. Comparison of fs 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 PROCEEDURES

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 (Pleisocene 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.

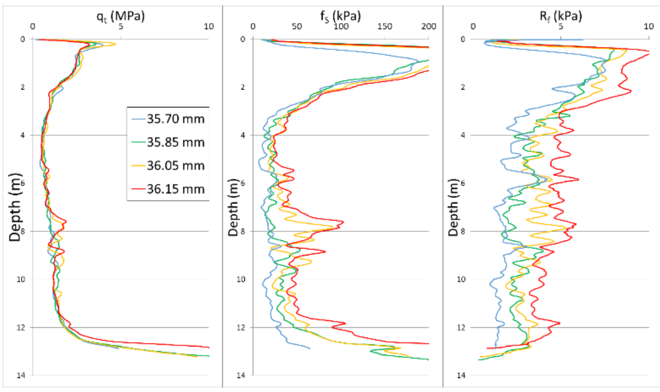

Figure 3. Raw data from Huapai site.

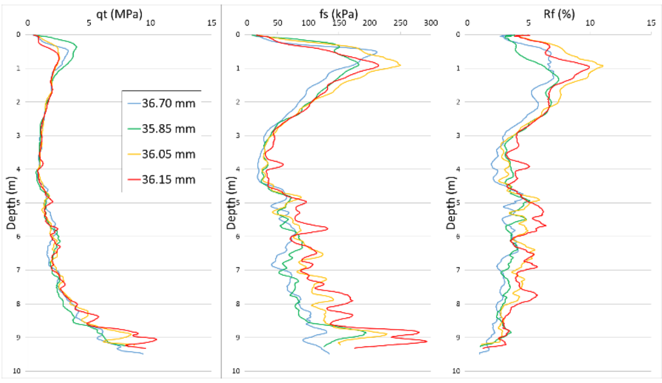

Figure 4 Raw data from Herald Island site.

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:

$$fs = fs(qt) + fs(f) \tag{2}$$

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.

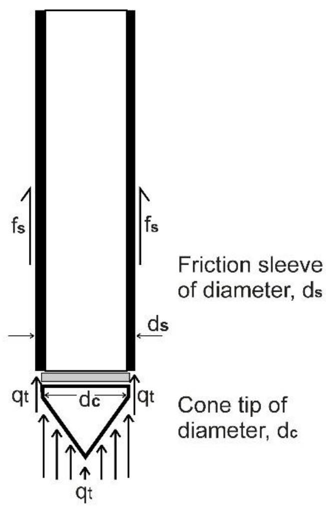

Figure 5. End resistance effect on oversize friction sleeve

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 cm^2) to give an equivalent sleeve friction value. In this way, Equation 3 below is derived.

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

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 $f_{s(f)}$.

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

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

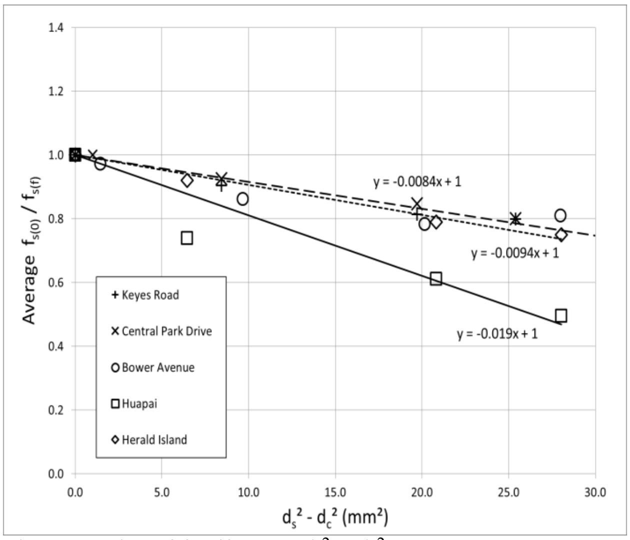

Figure 6. Plot of $f_{s(0)}/f_{s(f)}$ vs $d_s^2 - d_c^2$

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

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

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:

$$f_{s(0)} = f_{s(f)} \text{ x } [1 - m_{fs}(d_s^2 - d_c^2) \tag{6}$$

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:

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

This equation was then applied to the data at both sites, with m_{sf} = 0.0094 for the Huapai site and msf = 0.012 for the Herald Island site. The resulting measured and corrected fs 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.

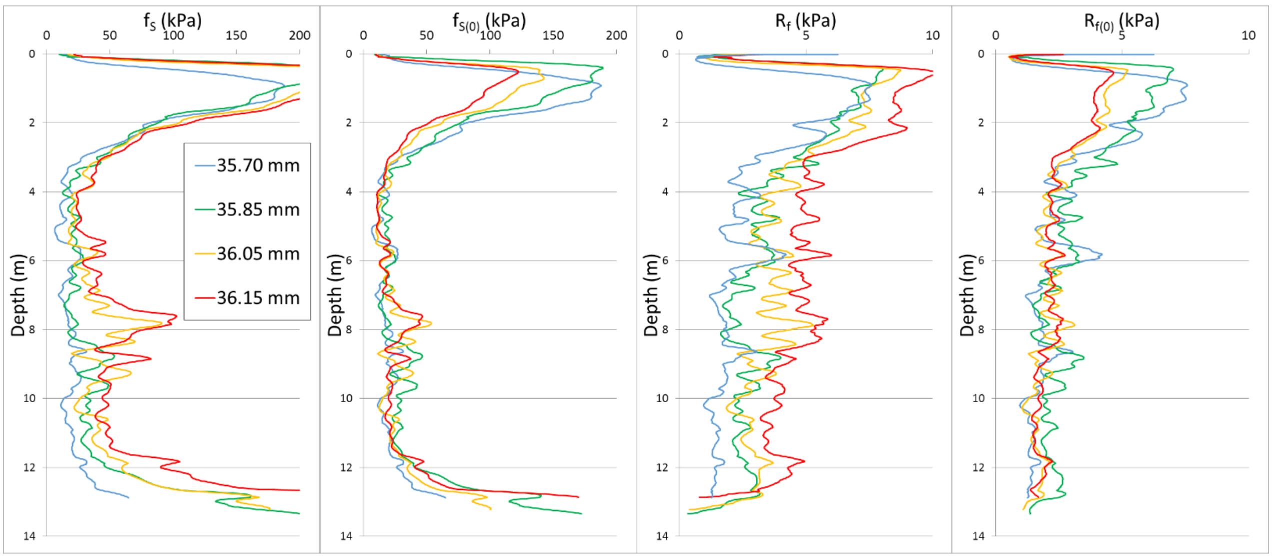

Figure 7. Huapai f_s, $f_{s(0)}$, R_f and $R_{f(0)}$.

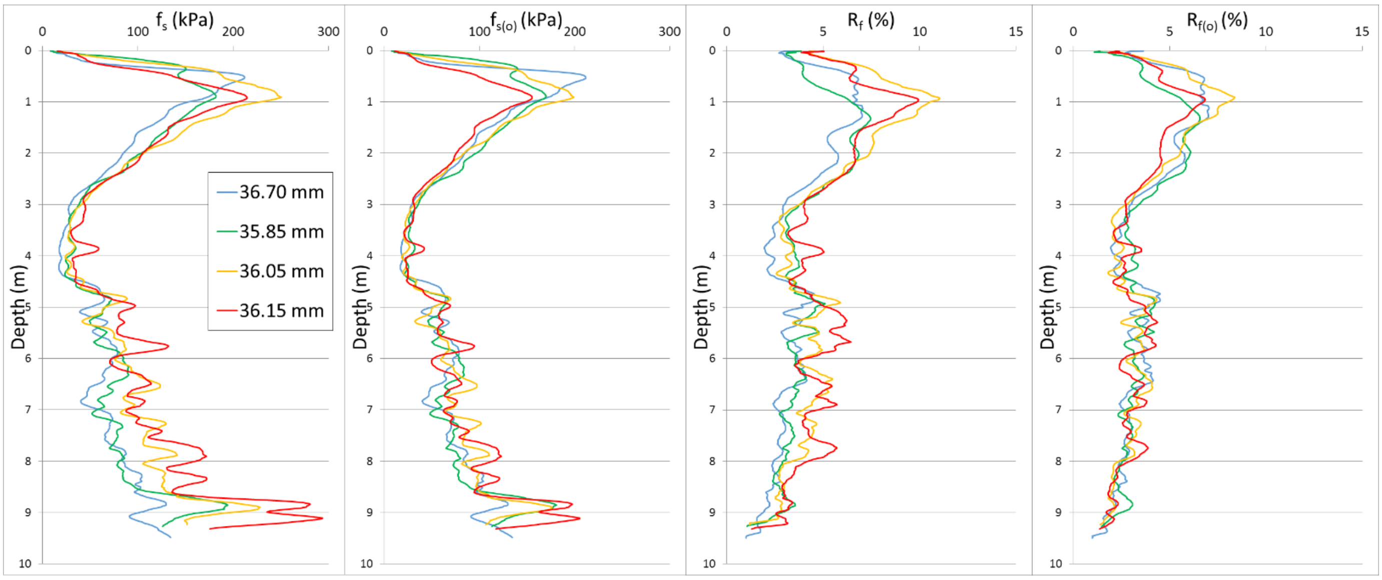

Figure 8. Herald Island f_s, $f_{s(0)}$, R_f and $R_{f(0)}$.

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 is 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.

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

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.

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