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CPT sounding and the scale of variability of Auckland residual soil

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ABSTRACT

The cone penetration test (CPT) provides a huge amount of data in comparison with other in situ test procedures - complete sets of readings every 10 mm or so of penetration. Some years ago a site in Albany was investigated with 30 closely spaced CPT soundings to a depth of 10 m. The intention of this paper is to take the analysis of the data gathered further in order to understand better the scale of the variability of the properties of the residual soil common around the Auckland region. We have data at two scales: vertical and horizontal. In the vertical direction, there are one thousand readings over the 10 m depth of each sounding. In the horizontal direction, there are 30 CPT soundings within a square of 8m side, the closest being at 1 m spacing. We will present our explorations of the properties in terms of an autocorrelation function and by determining the average distance between zero crossings of the de-trended q_c data.

Keywords: Residual soil, variability, scale of variability, CPT.

1 INTRODUCTION

Much of Auckland is covered with residual soil derived from the in situ weathering of the Waitemata group sandstones and siltstones. Unlike soils of sedimentary origin the properties of these materials cannot be understood within a framework based on effective stress history. Given that the process of forming residual soil is one of chemical alteration of the Waitemata group sandstones and siltstones ("soft" rocks with unconfined compressive strengths up to a few MPa), one might expect that this is a random process and will result in soils which exhibit variability from point to point over quite short distances. As evidence for this suggestion we offer the observation that the shear strength properties of these materials, at low effective confining pressures, from a number of sites around the Auckland region are extremely variable, (Kikkawa et al 2008), and also that the Atterberg limits extend over a wide range plotting roughly along the A-line in the Casagrande classification chart (although this may also be a consequence of whether the original material is of sandy or silty composition).

The purpose of the original investigation work, reported by Holland and Pender (2008), was to perform an intensive investigation using closely spaced CPT profiles to develop a better feeling for the inherent variability of the material. The purpose of this paper is to take the analysis if the data further and quantify the scale of variability of the cone penetration resistance in the vertical direction. Variability observed in cone penetration profiles will be reflected in variability of strength and stiffness of the soils, which in turn is of significance for soil-structure interaction and other foundation design considerations.

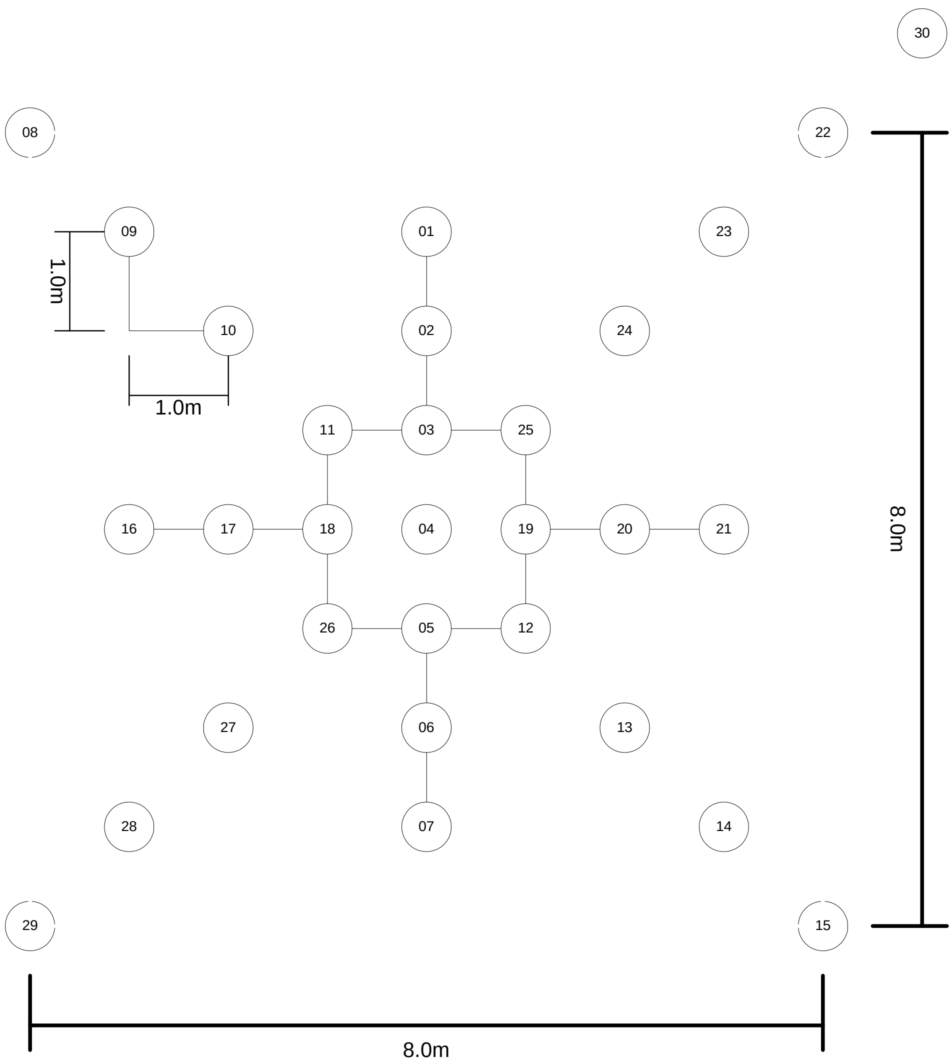

Figure 1. Layout of the cone penetration soundings

As far as we are aware intensive investigations of this type have not been done previously in Auckland residual clay. Further similar investigations are needed to round out the conclusions of this paper.

The site investigated was near Corinthian Drive in Albany north of Auckland. A total of 30 CPT probings were done to a depth of about 10 m from the ground surface. The layout of CPT probings is shown in Figure 1 with soundings on a 1 m grid. The CPT recording interval was 10 mm. The CPT work was done with one rig and one operator over a two day period, March 13 and 14, 2002.

2 MEAN AND STANDARD DEVIATION

At each depth the mean values of the 30 penetration records were calculated. All records showed a very distinct spike at a depth of about 2.1 m, this was taken as a marker and all depths herein are expressed in relation to the position of this spike. The interpretation of the penetration resistance focussed on vertical variability within the CPT records as the geological origin of the material, and the CPT records themselves, indicate changes in the material with depth. The lowest friction ratio readings are associated with the soil near the ground surface, so this region will be ignored as it is probably fill. The spike in the q_c at about 2 m depth is assoc-

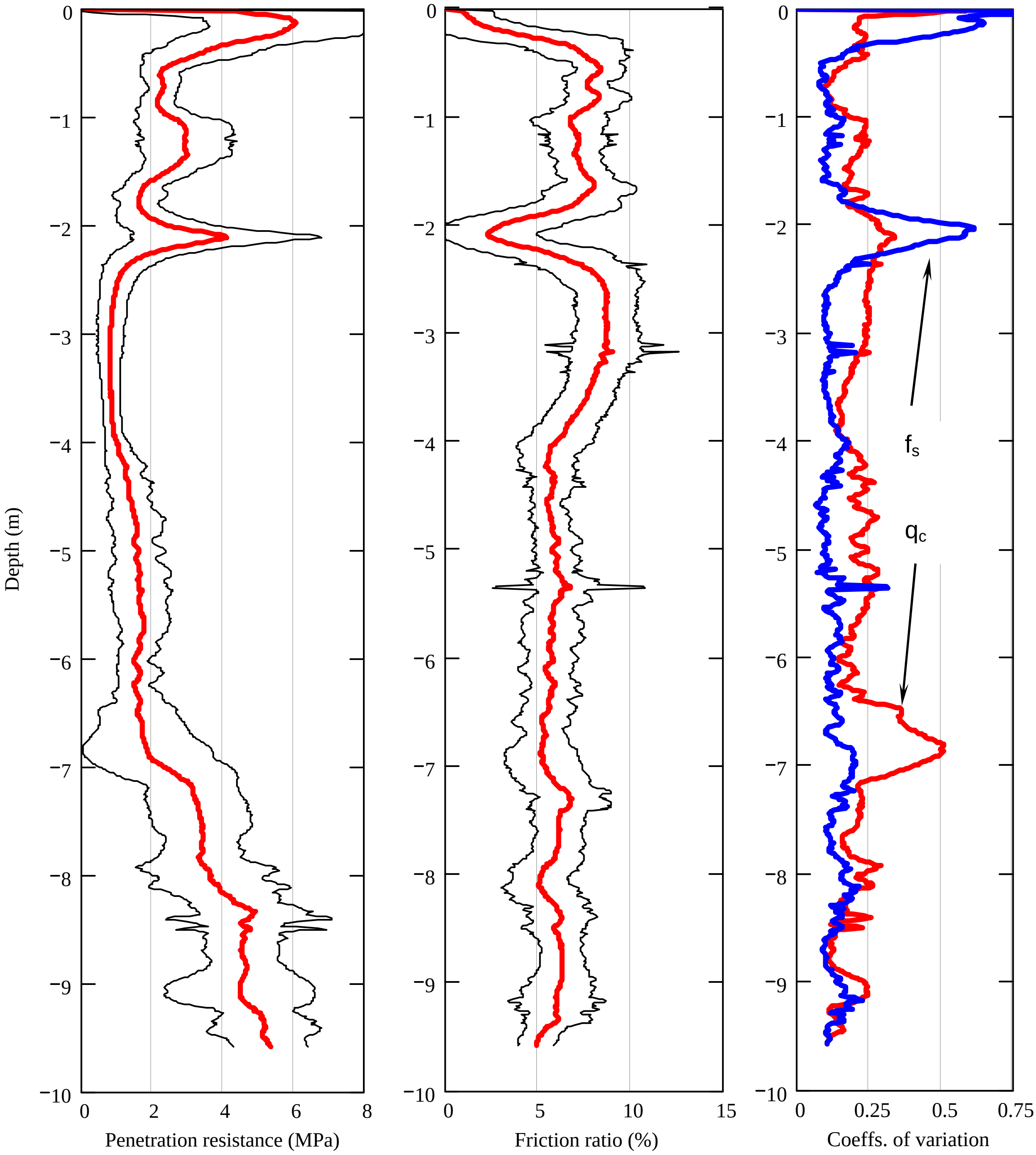

Figure 2. CPT data averaged at each depth. Left: q_c, middle: f_s, right: coefficients of variation of q_c and f_s.

iated with a low friction ratio and so this "marker bed" is probably a granular layer. Figure 2 shows that there is a more or less constant friction ratio of about 6% between about 4 m and 9.5 m. Such a value is associated, using the Douglas and Olsen (1981) classification chart, with fine grained cohesive soil yet the cone resistance towards the bottom of the soundings is too high for such materials and is more suggestive of coarser non cohesive soil. Perhaps this indicates that the CPT based classification system (Douglas and Olsen (1981) is of limited value for residual soils. In a similar vein calculating the soil behaviour type index (Robertson 2010) shows that the material is cohesive over the full depth.

Figure 2 presents a number of aspects of the data. On the left of the diagram the mean of the cone resistance at each depth is plotted as well the mean value plus and minus 1.96 standard deviations at that level (if the data fits a normal distribution then these lines give the bounds within which 95% of the data can be expected to lie). The middle graph does the same for the friction ratio. The right hand graph in the figure gives the coefficients of variation for the cone penetration resistance and sleeve friction.

The left hand side of Fig. 2, as well as indicating that the cone resistance varies with depth, also shows that the process of calculating the average q_c value at each, that is each 10 mm of penetration, has a smoothing effect on the data. This is apparent from the lines in which $\pm$1.96 times the standard deviation is plotted and even more so if the extremes of the CPT data are plotted (not included here). Below about 6 m depth the cone resistance increases gradually with depth till it reaches 7 or 8 MPa at depths of about 9 m. Values such as this would be expected to represent sandy horizons rather than clayey soil, yet from the middle plot in Figure 2 it is apparent that the friction ratio is surprisingly constant from about 4 m down, at a value which indicates cohesive soil. As explained above this may be a limitation of applying q_c – f_s classification methods to residual soils. However, the spike in the profile at about 2 m would appear to be a thin lens of cohesionless soil in which the cone resistance increases whilst the friction ratio decreases. We have yet to recover samples from the site so cannot give any direct comparison between the CPT data and other soil classification data.

The right hand diagram in Figure 2 has the coefficient of variation of q_c and f_s plotted against depth. It is of interest that the coefficient of variation of the friction ratio is generally less than that of the cone resistance. Also of note is the observation that the coefficient of variation of the cone resistance is in the range specified by Lumb (1974) for the coefficient of variation for the undrained shear strength of clays (this comment assumes the usual assumption of a constant relationship between cone penetration resistance and undrained shear strength in clays).

3 SCALE OF VARIABILITY IN THE VERTICAL DIRECTION

The standard deviation tells us how much the data is scattered about the mean value, but it tells us nothing about the distances over which these variations occur. The parameter giving this is known as the *scale of variability*. Since the CPT records so much data, it is possible for each sounding to estimate the scale of variability in the vertical direction. The CPT layout shown in Figure 1 does not have enough soundings over a large enough lateral distance to give the scale of variability in the lateral direction. Figure 2 shows that the upper 2 to 2.5 m of each CPT record varies in a complex manner and there is a “spike” in the data at a depth of about 2 m. Also it is not known to what extend the upper part of the soil profile is fill rather than natural ground. Consequently the upper 2.5 m of the soil profile was not considered in the estimates of the scale of variability.

On left hand side of Figure 2 the mean value at each recording depth for the 30 CPT records is plotted. For the investigation of the scale of variability all the CPT data were processed as deviations from these mean values, below we refer to these as *q_c deviations*. This conversion to deviations from the mean was not an essential step in estimating the scale of variability, but it does give a convenient appreciation of the variability of the penetration resistance. All the calculations in the paper were done using Mathcad (PTC 2012).

Two methods were used herein to determine the scale of variability in the vertical direction. First, the use of the autocorrelation calculated for each vector of q_c deviations and then the Bartlett limit is used to indicate the scale of variability (Jaksa et al 1996 and 2000). Second, the method based on finding the average spacing between zero crossings of the de-trended data (Phoon and Kulhawy,1999). Both of these approaches need first to fit a least squares regression curve to the data. Herein both second and third order polynomials were considered. It was found that the sum of the squares of the residuals after the least squares calculation was always smaller for the third order curves, so these were used in the estimation of the scale of variability in the vertical direction.

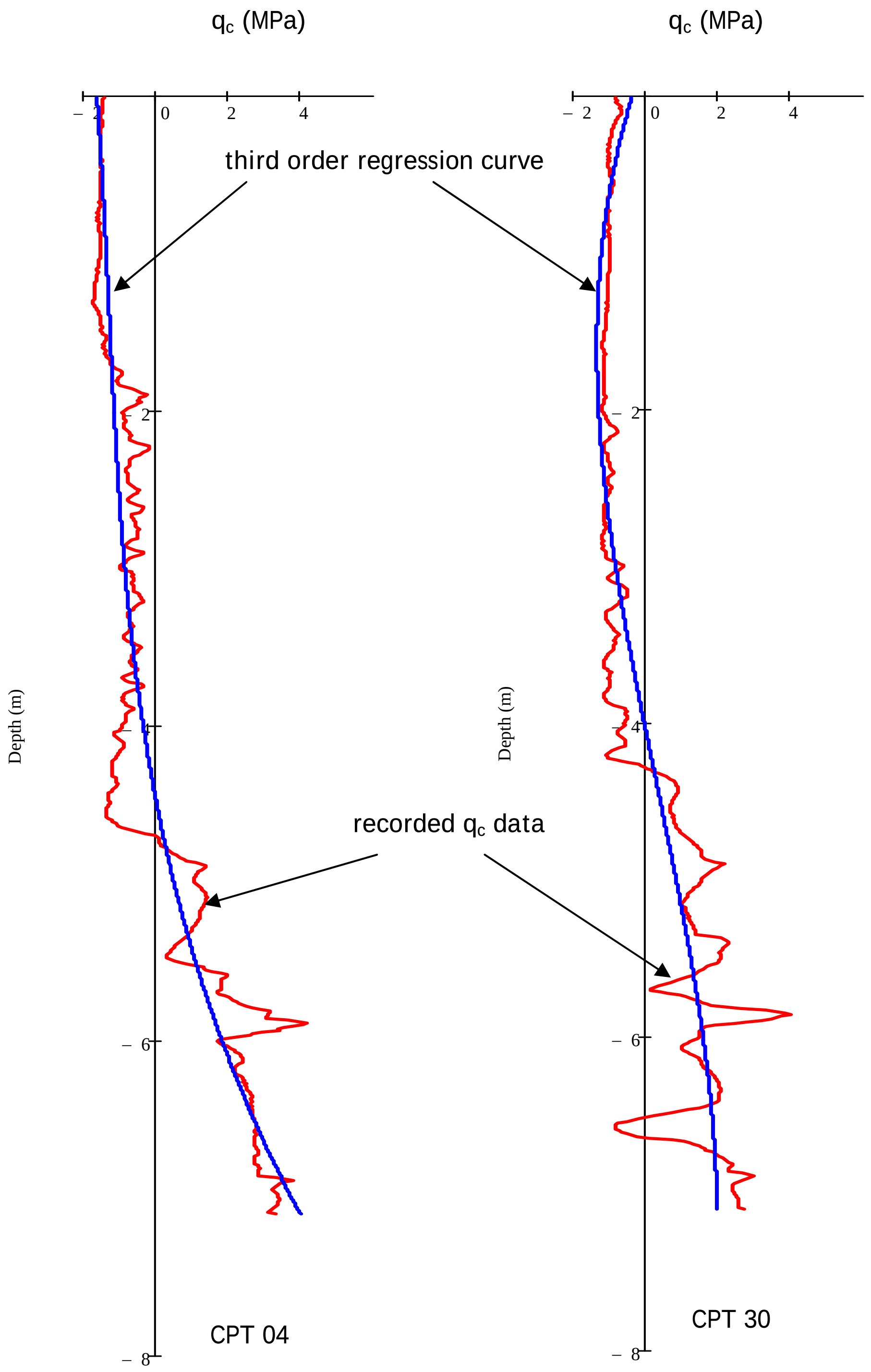

Figure 3. Data for CPT 04 and CPT 30:recorded q_c data minus the mean value at each level (q_c deviations) along with the third order polynomial regression curve.

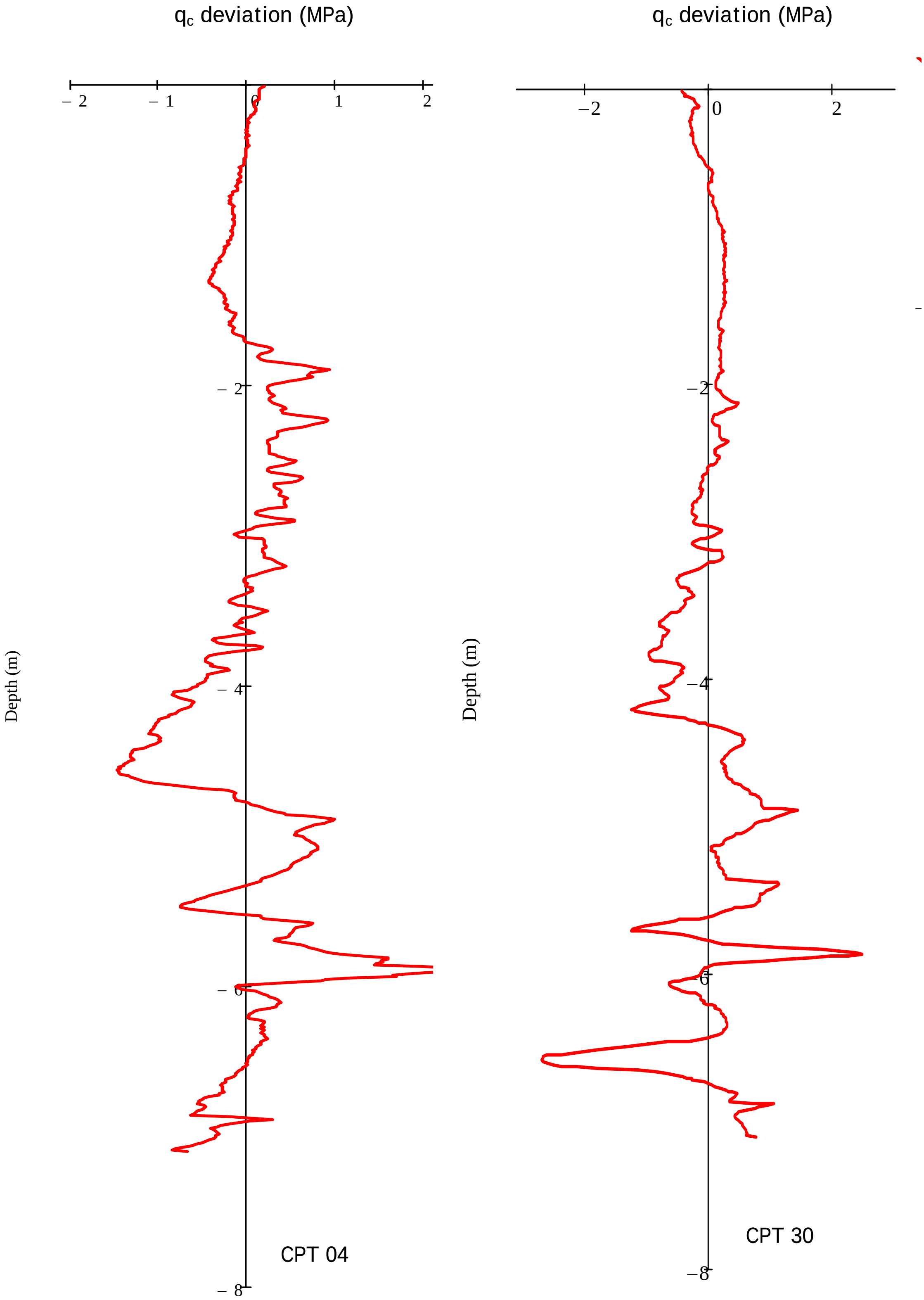

Figure 4. De-trended plots for q_c deviations for CPT 04 and CPT 30

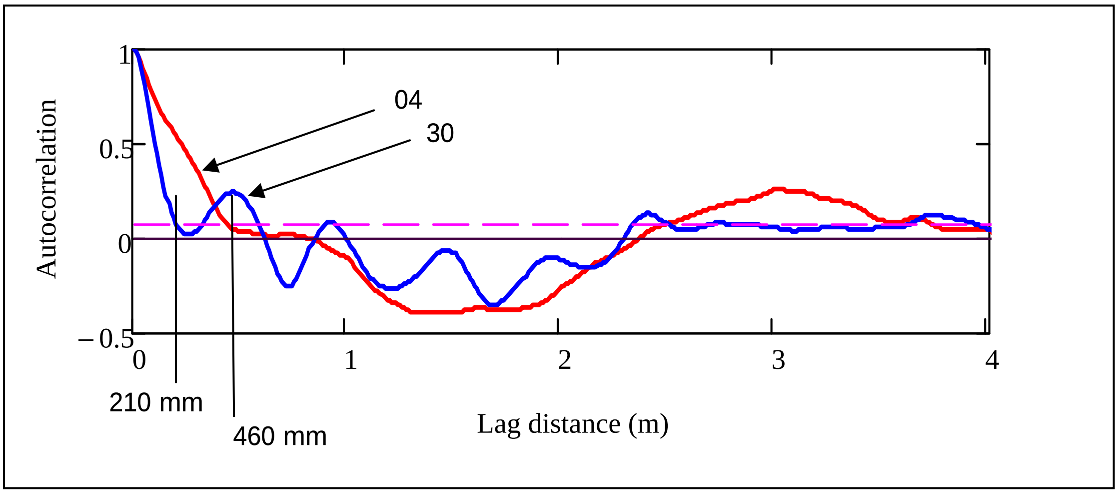

Figure 5. Autocorrelation functions for CPT 04 and CPT 30 showing the scale of variability in the vertical direction of 460 and 210 mm respectively.

The differences between the pairs of curves in Figure 3, that is the de-trended q_c deviations, are plotted in Figure 4 and are used in the estimation of the scales of variability. The autocorrelation of this vector is calculated and the function plotted as shown in Figure 5. Jaksa (2000) explains how the so-called Barlett's limits are used to estimate the scale of variability, where this limit intersects the autocorrelation function determines the scale of variability. In Figure 5 these intersections give a scale of variability in the vertical direction of 460 mm for CPT 04 and 210 mm for CPT 30.

In the second method of estimating the scale of variability also uses the data plotted in Figure 4. For this method the number of zero crossings is calculated and the average distance between the zero crossings is used as another measure of the scale of variability (Phoon and Kulhawy,1999). From this we obtain scales of variability in the vertical direction of 229 mm for CPT 04 and 470 mm for CPT 30.

4 SCALE OF VARIABILITY IN THE HORIZONTAL DIRECTION

The scale of variability in the horizontal direction is the other parameter that we need to fully characterise the properties of the material at this site. Generally it is thought that the scale of variability in the horizontal direction is rather larger than that in the vertical direction, in fact several metres is what has been found in other studies (Jaksa 2000). So rather than a number of CPTs clustered close together, as in Figure 1, a more appropriate approach would be have the soundings in a straight line at, say, one metre spacing.

5 CONCLUSIONS

Data from 30 closely spaced CPT soundings to depths of about 10 m have been analysed to improve understanding of the variability in properties of Auckland residual soils. We have three main conclusions:

- Generally the coefficient of variation for the CPT sleeve resistance is less than that of the cone resistance.
- The coefficients of variation of the q_c values at each level are in the range given by Lumb (1974) for the coefficient of variation for the undrained shear strength of clay.
- The scale of variability in the vertical direction is of the order of 200 to 500 mm.

- The scale of variability in the vertical direction determined from the autocorrelation function for each sounding and that determined by calculating the number of zero crossings in the de-trended q_c data, are similar to within a factor of about 2.

6 ACKNOWLEDGEMENTS

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