Typical values of the CPT cone factor, N_{kt}, in Auckland clays

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ABSTRACT

The near surface geology of the Auckland area generally comprises alluvial soils, volcanic tuff/ash and/or residual soils. These soils may be expected to display different engineering characteristics given their different geological origins. The soils are mostly cohesive and the undrained shear strength, s_u, is of geotechnical interest. The cone penetration test (CPT) allows an estimate of s_u to be made via application of bearing capacity theory using a cone factor, N_{kt}. Typically, N_{kt} varies from 10 to 18, depending on the soil type, so it is often necessary to compare with a reference test to determine the N_{kt} factor that is appropriate for the soil type on a site-specific basis. In this study, we have undertaken flat dilatometer tests (DMT) next to CPT tests at various sites in Auckland with the DMT acting as the reference test. In this way, typical N_{kt} factors for the different geological units have been suggested.

1   INTRODUCTION

The undrained shear strength of a cohesive soil can be estimated using the cone penetration test (CPT). This is usually done by utilising a cone factor, N_{kt}. The N_{kt} value is generally not known and can vary over a large range depending on geology and soil type. This often leaves the geotechnical engineer having to guess what N_{kt} value to use, if there are no reference tests to help establish a site specific correlation. The purpose of this study is to help provide an indication of what N_{kt} values may be applicable to the different soil types in Auckland by using the DMT test as a reference test.

In this study, the authors have selected 50 side-by-side CPT and DMT tests from various sites of various geological units across Auckland. The results have been compared to help determine suitable N_{kt} values.

2   BRIEF GEOLOGY OF AUCKLAND SOILS

The geology of Auckland is shown on the GNS Geological Map and described in the associated booklet (Kermode, 1992). In general terms, the near surface soils in the Auckland area are predominately cohesive (silts and clays) but have been formed by different geological processes. The most recent deposits (Holocene) are marine sediments in the harbours and under reclaimed land, and localised areas of stream and flood plain alluvium. A large proportion of the surface geology of Auckland is alluvium of the Tauranga Group (mostly Pleistocene), which comprise mostly firm to stiff silts and clays, but also contains Pumice material from the Taupo Volcanic Zone as well as significant deposits of peat in places. More recent volcanic deposits from the Auckland Volcanic Field provide a coverage of tuff and ash (as well as Basalt lava flows and scoria) over parts of Auckland. The tuff and ash have generally weathered to form soft to very stiff sandy or silty clays. The volcanic soils can be interbedded or interspersed with the sedimentary alluvial deposits. The Waitemata Group sandstones and siltstones (Miocene), which

underlie most of the Auckland area, form a mantle of residual soil (silts and clays, some sand) over a deep weathering profile. The Waitemata Group residual soils often present at, or near the surface. To the east of Auckland, uplifted Greywacke (Mesozoic) through the line of the Hunua ranges, is exposed in Waiheke and Motutapu Islands of the Hauraki Gulf, weathering to clays at the surface.

Although the near surface soils are mostly clay-like, they vary in plasticity and silt content, are sandy in places, are usually layered and almost always non-homogeneous. This adds a further complication to the varying geological origins, which provide different clay minerology and (macro and micro) structural effects. This makes establishing correlations to geotechnical soil parameters difficult and standard correlations that are based on well behaved 'text book' soils may not be applicable.

3   UNDRAINED SHEAR STRENGTH

The undrained shear strength, s_u, is not a unique soil property. It varies depending on the mode of failure, the stress state of the soil, anisotropic effects and rate of failure. Furthermore, in situ tests may not necessarily be fully drained, as may be the case for silty soils, and so not truly represent undrained shear strength.

Kamei (1996) showed that anisotropy is a significant factor by comparison of isotropic consolidated triaxial tests (CIU) with K_0 (coefficient of earth pressure at rest) consolidated triaxial tests (CK_0U). Figure 1 shows that the CK_0C tests give lower undrained shear strengths than the CIU tests, both in compression and extension. This figure also shows that tests in extension are significantly less than tests in compression, which illustrates variation due to mode of failure. Mayne (2016) also illustrated the effect of failure mode on s_u, as illustrated in Figure 2. There may be a factor of 6 between the highest and lowest measured undrained shear strengths – of the same soil! The figure also illustrates the hierarchy of s_u from highest to lowest, being: field vane test, triaxial compression, direct simple shear (DSS) and triaxial extension.
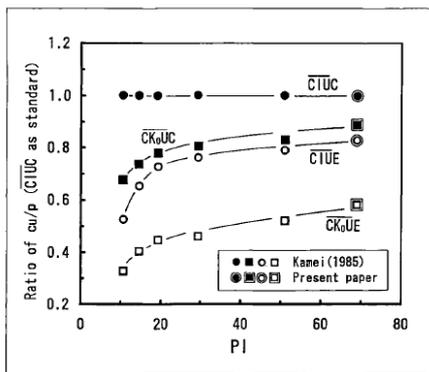

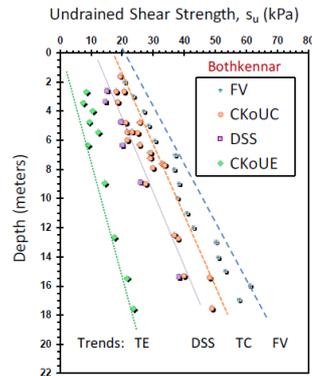Figure 1: s_u variation between isotropic and K_0 consolidated triaxial tests (Kamei, 1996)

Figure 2: s_u variation between tests of different failure mode (Mayne, 2016)

This presents a problem as to which test to use as a reference test when correlating to another test, in this case, the CPT. Mayne (2016) suggests that the DSS mode is most appropriate. This mode presents s_u results that fall more-or-less mid-way between the other test modes and thus provides an 'average' result. It is also the mode that best relates to the SHANSEP method (Stress History and Normalised Soil Engineering Properties) (Ladd et al 1977) and theory of critical state soil mechanics (Wroth, 1984). The DSS represents the simplest form of shearing.

2

By the SHANSEP method (Ladd et al. 1977):

$$s_u = 0.22.OCR^{0.8} \tag{1}$$

where

σ'_{vo} = the effective overburden pressure and OCR = overconsolidation ratio.

The terms 0.22 and 0.8 in equation (1) are averaged values of a narrow range of variables determined experimentally. A similar relationship can be derived theoretically using critical state soil mechanics (CSSM) (Wroth, 1984):

$$s_u = \tfrac{1}{2} \sin\phi'.\sigma'_{vo}.OCR^{\Lambda} \tag{2}$$

where

ϕ' = effective angle of friction and $\Lambda = 1 - c_s/c_c$.
and

c_s and c_c = swelling and compression index, respectively

Both the SHANSEP method and the CSSM methods are related to the DSS mode of undrained shear strength.

3.1   Undrained shear strength from CPT

The undrained shear strength of clays can be estimated from CPT results using the following equation (Lunne et al.):

$$s_u = q_{net}/N_{kt} \tag{3}$$

where

q_{net} = net cone resistance ($q_c - \sigma_{vo}$) and N_{kt} = cone factor

Equation (3) is a direct application of bearing capacity theory, where N_{kt} is then the bearing capacity factor for the cone. N_{kt} is determined empirically, usually by correlation to a reference test. Typically, N_{kt} is between 10 and 18, with an average of 14 (Robertson and Cabal, 2015).

There are other methods of estimating s_u, such as by using effective cone resistance, by using excess pore water pressure, by cavity expansion, or by critical state soil mechanics (Mayne, 2016). However, equation (3) is the most common method.

3.2   Undrained shear strength from DMT

A correlation for undrained shear strength from DMT was established by Marchetti (1980), via the relationship with OCR:

$$OCR = (0.5.K_D)^{1.56} \tag{4}$$

Where

K_D = horizontal stress index (strongly correlated to K_0)

By applying the SHANSEP method, represented by equation (1), the relationship for s_u becomes:

$$s_u = 0.22.(0.5.K_D)^{1.25} \tag{5}$$

This relationship has been found to provide a reliable estimation of undrained shear strength by numerous researchers (e.g. Lacasse & Lunne, 1988 and Powell & Uglow, 1988). However, most research has been in soft to firm normally to moderately overconsolidated sedimentary clays. Marchetti (2015) stressed that equation (5) is applicable only to 'text book' clays.

4   SIDE-BY-SIDE CPT AND DMT RESULTS

25 sets of CPT-DMT sounding pairs have been selected for this study from the Ground Investigation Ltd's database. These have been supplemented by borehole information from the New Zealand Geotechnical database to assist with identifying geological units. The approximate locations where the tests were performed are shown on Figure 3. The pairs were selected based on distance between tests (less than 10m), availability of nearby borehole information and uniformity of ground conditions between tests. It was difficult to find tests that met the last criteria as most of the sites display layered soils and lateral variation.

Figure 3: Approximate locations of test sites used in this study

The data was separated into groups according to geology. The geological units chosen being; Marine Sediments; Peat; Alluvium; Volcanic soils; Residual Waitemata Group soils and; Residual Waipapa Group soils (Greywacke). Some cleaning of the data was carried out by way of depth shifts and removal of anomalies, such as inconsistent spikes in data. The data was then plotted on graphs of q_{net} vs CPT_{DMT}. These are shown on Figure 4 for the various geological units.

4.1   Marine Sediments/Intertidal Mud

There are only two data sets of Marine Sediments used in this study. These are from the tidal mudflats adjacent to the SH16 causeway on Auckland's northwestern motorway. The plot on Figure 4(a) suggests an N_{kt} of 6 with a strong correlation. The soils here are normally or very slightly overconsolidated sedimentary soils and so should behave as a 'text book' soil and so the

DMT derived s_u should be reliable. The $N_{kt} = 6$ seems low considering the typical range, however, Lunne et al. (1997) showed that N_{kt} decreases with increasing B_q (normalised pore pressure ratio). In very sensitive fine-grained soils, where B_q is around 1.0, the N_{kt} can be as low as 6. The CPT plots from this data set show B_q at 1.0 or slightly higher (indicating sensitive soil). In this instance, $N_{kt} = 6$ appears correct. This validates to some extent the use of the DMT as a reference test. It also highlights the need to consider the porewater pressure response and the need for good
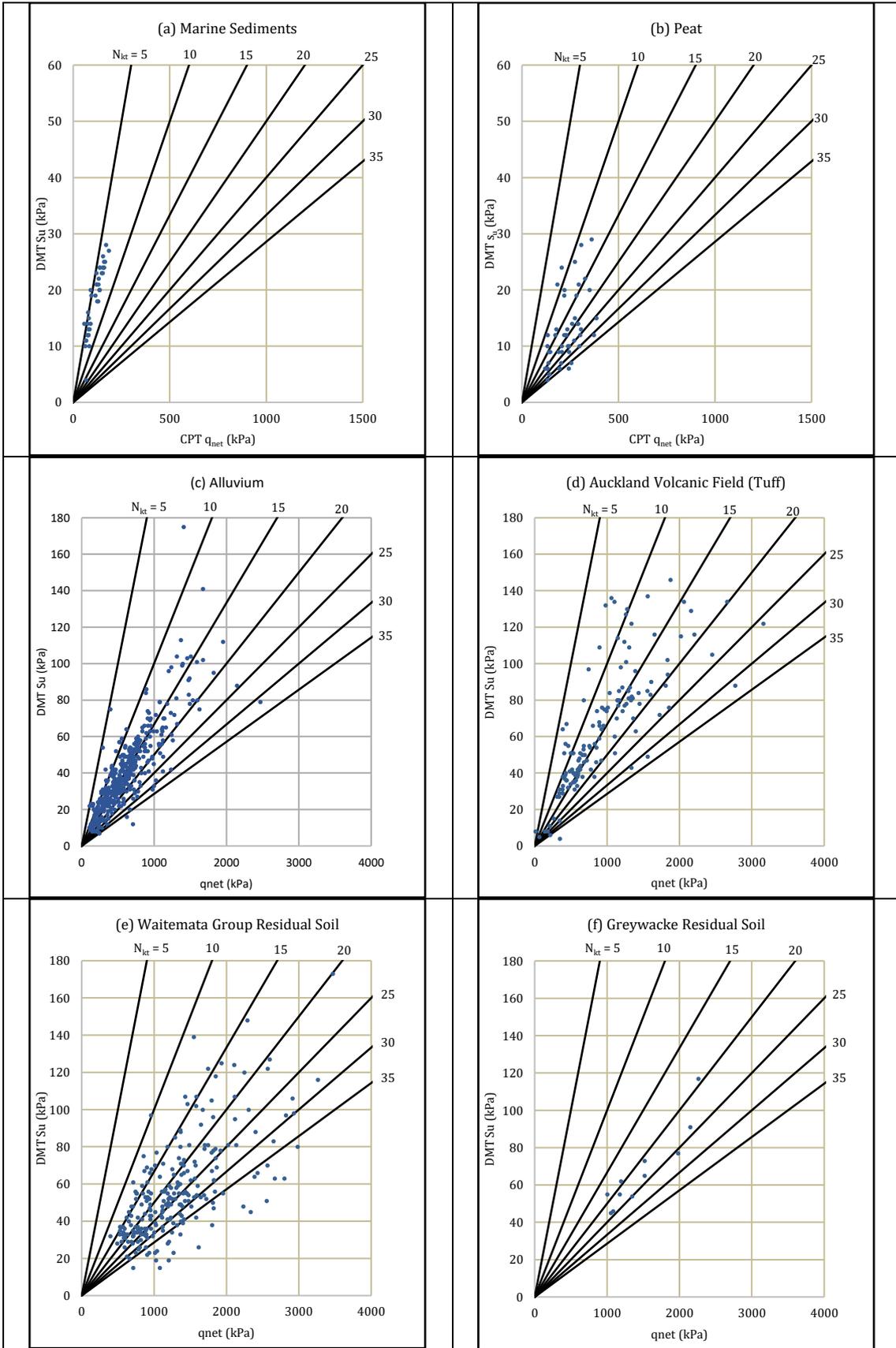
Figure 4: Plots of DMT derived s$_u$ vs. CPT q$_{net}$

u_2 readings in soft clays. Alternative methods of determining s_u by excess porewater pressure or by effective cone resistance should also be considered in these soft deposits.

Figure 5(a) shows a depth plot of DMT derived s_u overlain with the s_u derived from an adjacent CPT using $N_{kt} = 6$. The marine sediment/mud is underlain by older alluvial materials, to which $Nkt = 15$ appears to be applicable (see Section 4.3 below).

4.2   Peat

There is one DMT-CPT pair in peat soil. At this site, the peat is mostly amorphous, tending to organic clay in places and with some fibrous material. Figure 4(b) shows the resulting plot of DMT s_u and CPT q_{net}. There is considerable natural variability in this material and, therefore, it is difficult to get an exact match between the CPT and DMT data. Hence the plot shows a reasonable scatter. However, an average value of $N_{kt} = 15$ could be taken from that plot. When the DMT su is plotted with depth along with the CPT su derived from $N_{kt} = 15$, as shown in Figure 5(b) there is reasonable agreement considering the variability of the soil.

4.3   Alluvium

The data for the Alluvium set is mostly in the Puketoka Formation of the Tauranga Group, but may also include some more recent (Holocene) alluvium. The results of 11 side-by-side DMT and CPT tests in alluvial deposits are shown on Figure 4(c). There is reasonable scatter, much of which is likely the result of material variability between the tests. Most data falls within the range $N_{kt} = 10$ to 20, which is the typical range for most soils. Regression of this data gives a $N_{kt} = $ approx.15. Using this value and applying it to one of the CPT/DMT pairs shows good agreement (Figure 5c). These alluvial deposits appear to behave as expected and $N_{kt} = 15$ is likely to be appropriate for these soils as a general value.

4.4   Volcanic Tuff/Ash

Figure 4(d) shows some scatter but the average again appears to be around $N_{kt} = 15$ for this data set (three CPT/DMT pairs). Using $N_{kt} = 15$, shows good reasonable agreement between CPT and DMT derived s_u values on the depth plot in Figure 5(d). This value ($N_{kt} = 15$) appears to work well for this particular data set, but the same value may not be applicable for all volcanic clays in Auckland. There is likely to be a large amount of variability in this material and so caution should be taken when assigning a N_{kt} value in these soils. Site specific correlation may be required. It should also be noted that the DMT s_u correlations using the standard Marchetti (1980) correlations based on SHANSEP may not be applicable for these soils. Another reference test may be required for a site specific correlation.

4.5   Waitemata and Waipapa Group Residual Soils

There are 7 data sets in the Waitemata Group but only one in the Greywacke residual soils. Both these geological units show a similar trend in the DMT s_u vs. q_{net} plots on Figures 4(e) and 4(f) with N_{kt} tending to the higher end, averaging between 20 and 25. There is considerable scatter in the Waitemata Group soils, most of which may be attributable to the natural variation and layered nature of the material. A depth plot of the Waitemata Group materials in shown on Figure 5(e) showing DMT derived s_u values with those derived from CPT using an $N_{kt} = 25$. This seems high and may be a reflection of the DMT derived s_u values possibly not being applicable to these residual soils. Further research will be required to establish the DMT-s_u correlations in these soils.
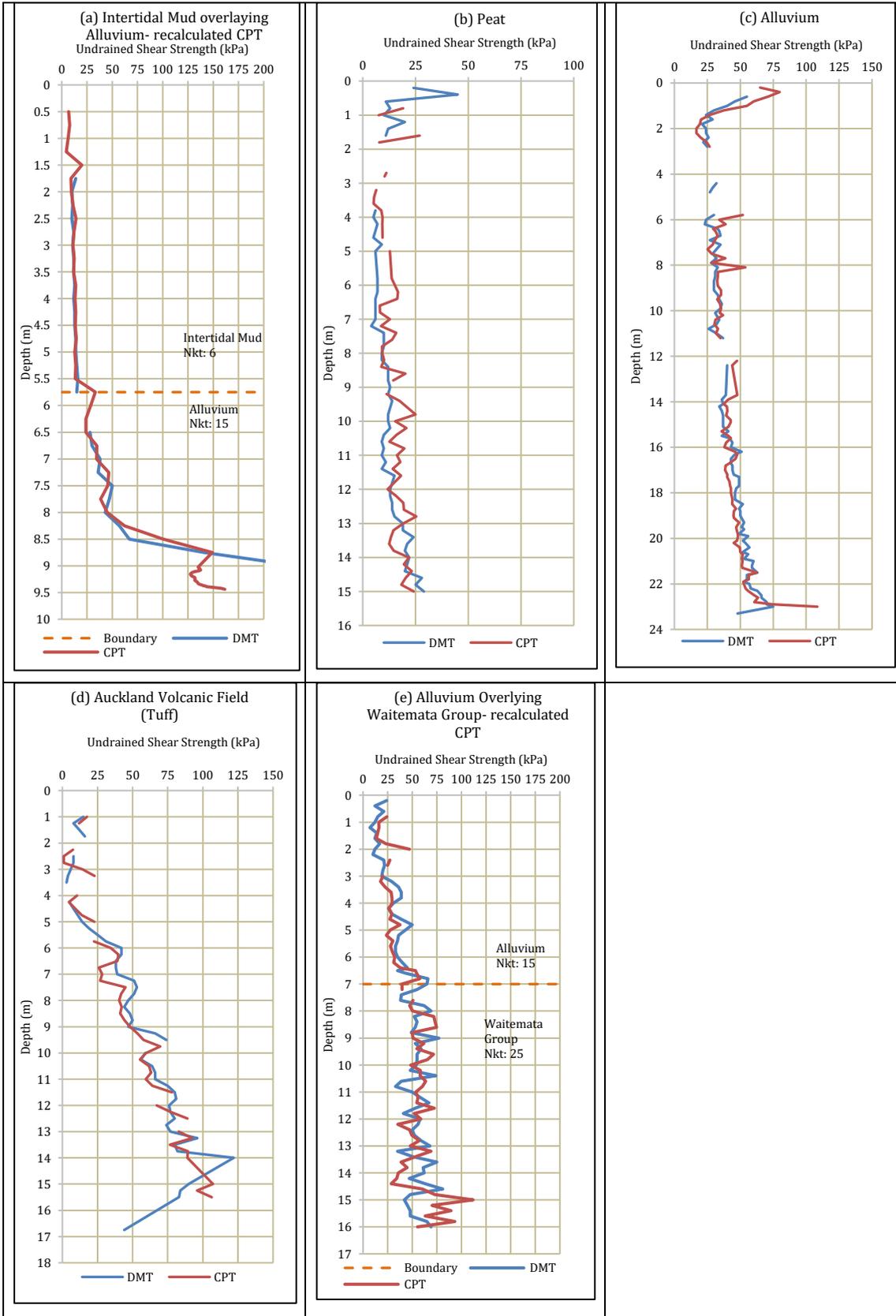
Figure 5: Depth plots of DMT and CPT derived s_u values

5 CONCLUSIONS

The undrained shear strength, s_u, derived from side-by-side CPT and DMT tests over a range of Auckland clays have been compared to determine typical N_{kt} values for the various geological units. In this approach, the DMT is used as the reference test to which the CPT is compared. It appears that a N_{kt} value of 15 is a good fit in general for the Alluvial clays. In this study, $N_{kt} = 15$ also appears to work well for amorphous peats and volcanic soils, however, caution should be applied in these materials and site-specific correlation is advised. In marine intertidal muds, an $N_{kt} = 6$ appears to be applicable, but will be dependent on the normalised pore pressure. Good pore pressure response, u_2, in the CPT test is important to allow a more comprehensive assessment of s_u in soft clays. In the residual Waitemata Group soils, N_{kt} values appear high (around 25) using the approach of this paper. It is possible that the standard DMT-s_u correlations may not be applicable in these soils. Until correlations have been developed, site-specific correlation with another reference test is suggested to determine N_{kt} in these residual soils.

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