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Estimation of Undrained Shear Strength of Soil from CPTu Data

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ABSTRACT: The estimation of undrained shear strength (S_u) from Cone Penetration Test with pore pressure measurement (CPTu) for two sites was investigated in this research. The CPTu cone parameters: net cone resistance (q_t), excess pore pressure (Δ_u) and effective cone resistance (q_e) were used to estimate the S_u for the two sites and the values obtained were compared with the undrained shear strength in triaxial compression (S_{uc}) calculated from Anisotropically Consolidated Undrained Compression (CAUC) triaxial test results. For the clayey silt site, the undrained shear strength S_{uc} from the CAUC tests are higher compared to the values obtained from the CPTu, and the highest correlation was obtained from the effective cone resistance parameter q_e. For the quick clay test site, the S_{uc} value and S_u were relatively the same and showed stronger correlation as compared to the clayey silt site. The S_u measured from the cone parameter Δ_u had the highest correlation. It was concluded that q_e and Δ_u yields good correlation with the CAUC results for the clayey silt and quick clay test sites respectively as compared to the other con parameters.

KEYWORDS: CPTu, Undrained shear strength, CAUC, Cone parameters, Clayey silt, Quick clay.

I. INTRODUCTION

The in-situ undrained shear strength (S_u) is the shear strength of soil when it is loaded in an undrained condition, that is no drainage or dissipation of pore pressure. S_u can vary between different soil deposits or within the same deposit. The value of the undrained shear strength for a given soil depends on factors such as soil composition, stress history, and the test method used to determine the value (Mayne et al., 2009). There are different methods of measuring S_u, these include laboratory testing where soil samples are obtained from the field and tested in the laboratory. These samples may experience some level of disturbance during transportation there by changing the stress history and therefore results obtained may not give the accurate value of S_u. S_u is also determined through correlation of other soil parameters, this gives hypothetical values that may over predict or underestimate the S_u of the soil. Another method of measurement is by field testing, in this method, the S_u is measured in-situ there by capturing the soil fabric and stress history. There are several instruments used in field measurement but the Cone Penetration with pore pressure measurement (CPTu) also known as Piezocone has proven to be efficient and accurate. This research will focus on the use of CPTu to estimate undrained shear strength.

The CPTu is a repeatable and economical test, it gives information on soil type and stratigraphy. It also provides information about soil variability that cannot be matched with sampling and laboratory testing (Robertson, 2010). The CPTu is an electric piezometer probe that measures water pressure during penetration and pauses in penetration, it consists of a 60° cone with 10cm^2 base area and a 150cm^2 friction sleeve located above the cone. The filter for measurement of pore pressure can be located on the cone (u_1), behind the cone (u_2) or on the friction sleeve (u_3), but the preferred location is behind the cone (Lunne et al., 1997). *Figure 1* is a schematic diagram of the piezocone showing locations of the pore pressure filter positions.

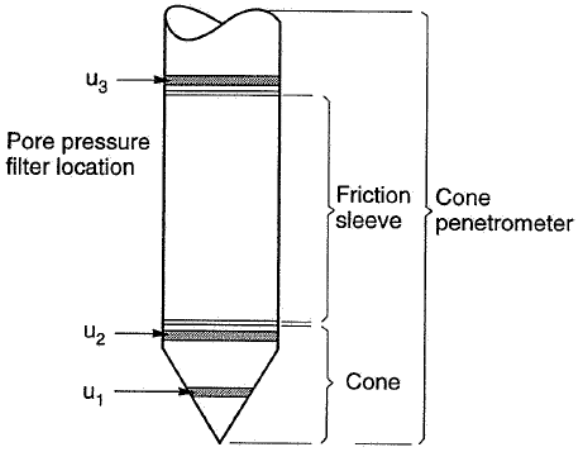

Figure 1: Cone penetrometer showing pore pressure location after Lunne et al. (1997).

A. *CPTu Correlations*

There are theoretical solutions and empirical approaches to evaluate S_u from CPTu data. The theoretical solutions include bearing capacity theory, cavity expansion theory, strain path theory, and numerical analysis from linear and non-linear stress-strain relationships. These theories show a relationship between S_u and q_c as indicated in Equation 1.

$$q_c = N_c S_u + \sigma_{vo} \qquad (1)$$

Where q_c is the cone resistance, N_c is the theoretical cone factor representing the bearing capacity factor and σ_{vo} is the in-situ total vertical stress.

The empirical correlation is done by three methods which involve estimation of S_u from CPTu cone parameters. These methods are discussed below and will be used in this research.

Method 1: estimation of S_u from the net cone resistance (q_t), this is the most common and reliable method of estimating S_u from CPTu results (Mayne et al. 2019) as given in equation 2.

$$S_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \qquad (2)$$

Where q_t is the net cone resistance and N_{kt} is an empirical cone factor.

The choice of N_{kt} can be made based on theoretical, experimental, and statistical correlations. For CPTu in soft to firm clays N_{kt} of 12 is recommended (Lunne et al., 2005; Mayne and Peuchen, 2018). However, Karlsrud et al. (2005) had lower cone factor within the ranges 7.5 to 11.5 for several sensitive Norwegian clays. Also, N_{kt} of 10.5 was reported for soft sensitive clay in Québec (Wang et al., 2015). Generally, N_{kt} value of 15 is used for estimating the S_u value of intact clay.

Method 2: estimation of S_u from excess pore pressure (Δ_u), the relationship between excess pore pressure and S_u is given by the equation.

$$S_u = \frac{\Delta_u}{N_{\Delta u}} = \frac{u_2 - u_0}{N_{\Delta u}} \qquad (3)$$

Where $N_{\Delta u}$ is the empirical cone factor, u_0 is the in-situ pore water pressure. Based on cavity expansion theory, $N_{\Delta u}$ vary between 2 and 20. However, it has also been found to vary between 4 and 10 (Karlsrud et al., 1996; Hong et al., 2010).

Method 3: estimation of S_u from the effective cone resistance (q_e), this is the difference between the corrected cone tip resistance q_t and the pore pressure u_2 measured behind the cone (Lunne et al., 1997) as shown in the equation:

$$S_u = \frac{q_e}{N_{ke}} = \frac{q_t - u_2}{N_{ke}} \qquad (4)$$

Where N_{ke} is the empirical cone factor representing the effective cone resistance. N_{ke} value vary between 1 to 13 (Lunne et al., 1997) and 16±3 (Kim et al., 2009).

Previous studies have shown that soil specific parameters such as plasticity, soil type, and over consolidation ratio (OCR) can affect S_u value. Research by Bol et al. (2019) to determine S_u from q_c, q_t and q_e for fine grained fluvial sediments using the Robertson and Wride (1998) soil behavior index chart showed that S_u estimated for soil with the same behaviour type index had similar values as those measured in the laboratory. Similarly, Karlsurd et al. (2005) in their research on CPTu correlation of Norwegian marine clays using the cone factors Δ_u, q_t and q_e found that the OCR and plasticity index has a great effect on the S_u, his study showed that Δ_u gives a consistent and good correlation with S_{uc} from CAUC for very soft to sensitive clays. Also, Kim et al. (2009) in their research on estimating S_u for marine clays in Korea from CPTu results using q_t and q_e, found that the use of q_e is more effective with reduced uncertainty as it does not require any experimental process of soil sampling and laboratory testing. Significant research is yet to be done on the determination of S_u from all three cone parameters. This research will focus on using the three existing methods to estimate S_u from the cone parameters and then compare the values obtained to the undrained shear strength in triaxial compression (S_{uc}) calculated from Anisotropically Consolidated Undrained Compression (CAUC) triaxial tests to determine the method that best estimates S_u for a clayey silt and sensitive to quick clay soil type.

II. METHODOLOGY

CPTu and CAUC triaxial tests data for two test sites obtained from the datamap website were used for this research. Datamap is an open access web-based application where geotechnical database comprising of field and laboratory tests data are made publicly available: https://www.geocalcs.com/datamap (Doherty et al., 2018). The datamap website contains the Norwegian Geotest Sites (NGTS) data and the Australian National Field-testing Facility (NFTF) data. NGTS has established five national test sites for geotechnical research with each site focusing on a certain soil type (L'Heureux et al., 2017) these five test sites are shown in *Figure 2*. The Halden site is the testing ground for clayey silts and the Tiller-Flotten site in Trondheim is for sensitive to quick clays. These sites are further discussed below.

Figure 2: Location of the NGTS test sites after Narainsamy and Jacobsz (2022).

A. *Halden Test Site*

The Halden geotechnical test site is located approximately 120 km south of Oslo in Norway. The site is composed of 10 to 12 m thick deposit of fjord marine low plasticity clayey silt (Blaker et al., 2019). The clayey silts are normally consolidated, and the water table is located 2 m below the surface. The silts have a bulk unit weight of 19 kN/m3 and are split into two sub-profiles as shown in Figure 5: Unit II which extends from 5 to12 m below surface and Unit III which extends from 12 to 16 m below surface. Units II and III are regarded as the same material with the same geologic origin and were separated based on the results from the indicator tests which indicated that the silt becomes sandier in the lower Unit III. CPTu tests were conducted on the site as well as CAUC triaxial tests conducted on high quality Sherbrooke block samples obtained from boreholes adjacent to the CPTu tests locations. A total of 9 triaxial tests and 5 CPTu tests were assessed, results from the CAUC triaxial tests are shown in *Figure 3*. Except for the sample obtained at 9 m depth from borehole 1(B01_9m) which showed strain softening behaviour, all the other samples showed strain hardening behaviour.

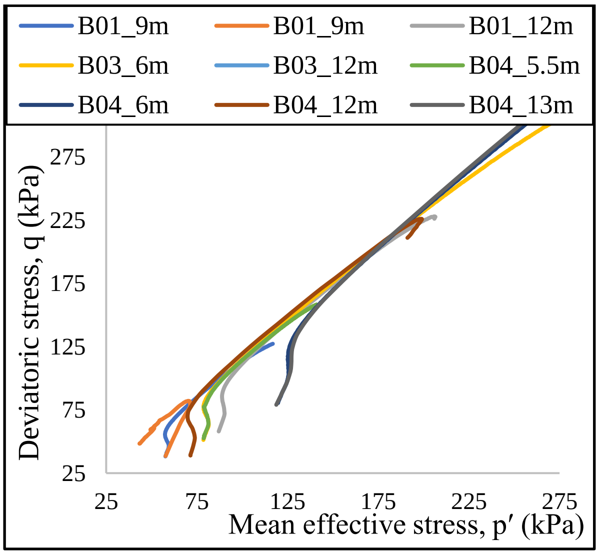

Figure 3: CAUC Triaxial test result on the Sherbrooke samples from Halden test site.

B. *Tiller-Flotten Test Site*

The Tiller-Flotten geotechnical test site consists of 50 m thick marine deposit of sensitive clay, due to the glacial history of the area the clay is over consolidated with OCR of 1.5 and 3.0 and a bulk unit weight of 18 kN/m^3 (L’Heureux et al., 2019). The location of the water table is between 1 and 2 m below ground level. The clays are split into two sub-profiles as shown in Figure 6: Unit IIA extends from 2 to 7.5 m below surface and comprises clay of medium sensitivity and Unit IIB extends from depths greater than 7.5 m and comprises clay of extreme sensitivity. CPTu field testing was conducted and CAUC triaxial tests were conducted on high quality Sherbrooke block samples obtained from boreholes adjacent to the CPTu test locations. A total of 10 triaxial tests and 5 CPTu tests were obtained, results from the CAUC triaxial tests shown in *Figure 4*, indicate stain softening which is expected of a sensitive clay.

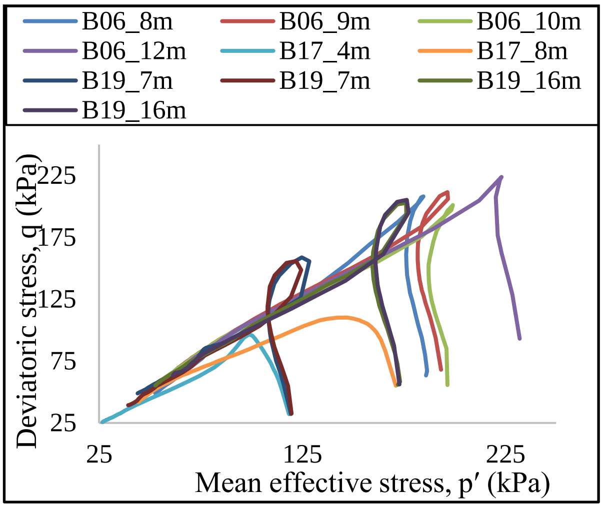

Figure 4: CAUC Triaxial test result on the Sherbrooke samples for the Tiller-Flotten test site.

The raw CPTu data obtained from the Database was processed using version 3.6.2.6 of the CPeT-IT software package developed by Geologismiki (Narainsamay and Jacobsz, 2022). Based on the soil behaviour index *Ic* as proposed by Robertson and Wride (1998) and the pore pressure ratio *Bq*, The CPTu data was evaluated in terms of undrained hydraulic conditions as most of the probing through the test sites was undrained. The interpreted CPT data for the Halden and Tiller-Flotten test sites are shown in *Figure 5 and 6 respectively.*

The cone factors used for the CPTu analysis were obtained from previous literature on the two sites. A cone factor N_{kt} of 15 was used for the Halden test site (Blaker 2020), N_{kt} =10.4 was used for Tiller-Flotten site (Mayne et al., 2019) and $N_{\Delta u}$ of 8 (Karlsurd et al., 2005) and N_{ke} of 9 was used to analyse both sites.

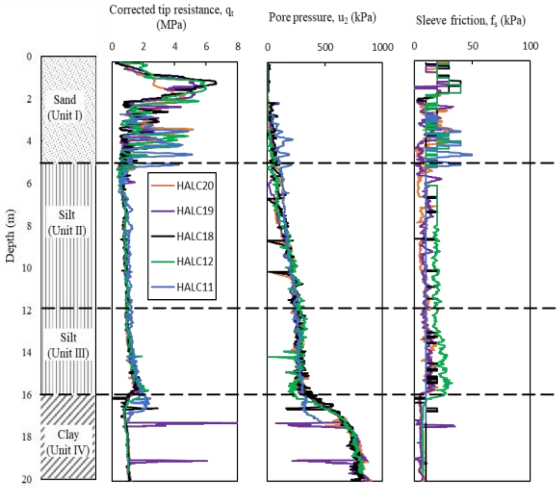

Figure 5: Soil classification and CPTu data for the Halden silt site (after Blaker et al., 2019)

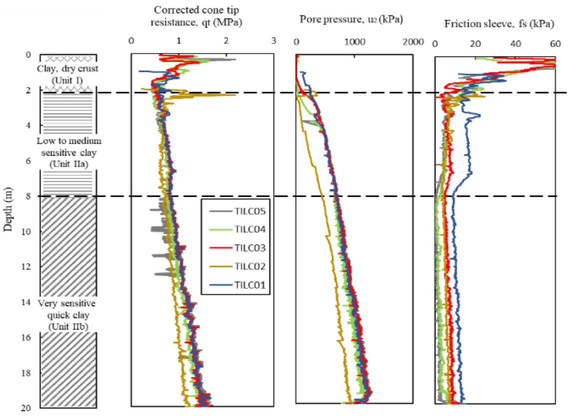

Figure 6: Soil classification and CPT data for the Tiller-Flotten quick clay site (after L’Heureux et al., 2019)

III.RESULTS

The CAUC triaxial tests were conducted on samples taken at various depths adjacent to CPTu probing points. The laboratory result was used as the benchmark against which the S_u computed from the CPTu were compared to determine which of the three empirical correlation method produced values that were closely matched to the triaxial test results at the various depths. The S_{uc} derived from CAUC laboratory test and S_u estimated from CPTu cone parameters using the three methods is plotted with depth in *Figure 7 and 8* for the Halden test site and Tiller-Flotten test site respectively. The CPTu results produced lower values of undrained shear strength for the Halden test site as seen in *Figure 7* compared to laboratory results. The S_{uc} value for the Halden test site range from 48-127 kPa, while S_u from CPTu are of the range 35-70 kPa, 8-35 kPa and 40-100 kPa obtained using method 1, 2 and 3 respectively as shown in *Figure 7a, b, and c.*

Figure 8 show similar shear strength values for both CAUC and CPTu results for the Tiller-Flotten test site. The S_{uc} value for the Tiller-Flotten test site range from 40-70 kPa, while S_u from CPTu are of the range 50-85 kPa, 50-100 kPa and 15-40 kPa obtained using method 1, 2 and 3 respectively as shown in *Figure 8a, b, and c*.

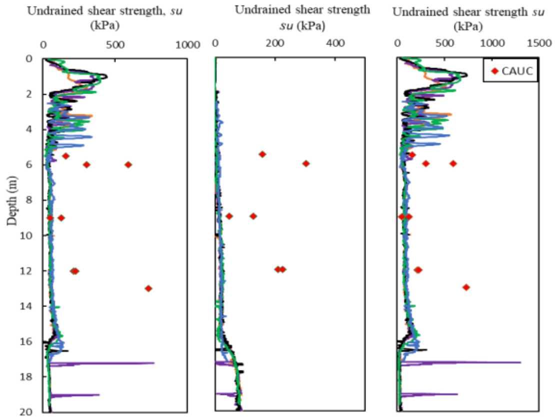

Figure 7: Undrained strength profile from CPTu and CAUC triaxial tests at Halden test site: (a) Method 1: S_u from q_t (b) Method 2: S_u from Δ_u (c) Method 3: S_u from q_e

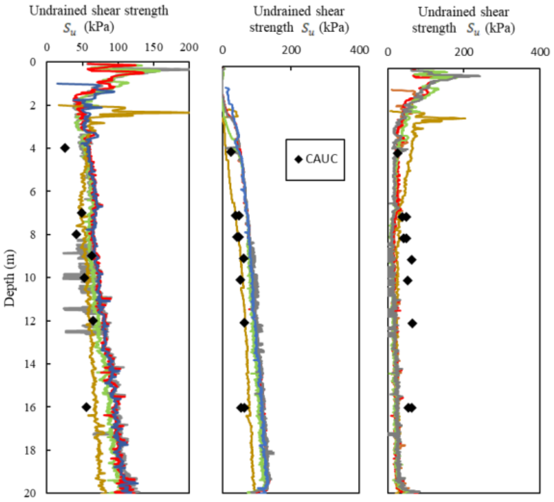

Figure 8: Undrained strength profile from CPTu and CAUC triaxial tests at Tiller-Flotten: (a) Method 1: S_u from q_t (b)Method 2: S_u from Δ_u (c)Method 3: S_u from q_e.

IV.DISCUSSION OF RESULTS

When silty soils are sheared, they exhibit dilative behaviour and high values of undrained shear strength (Robertson, 2012), this behaviour can be seen in the CAUC test result shown in *Figure 3* for the Halden test site. The plot indicate that the soil increases in strength at high strains, therefore the end of the test value was assumed to be the undrained shear strength. The CPTu results also estimates high S_u values but these values plot significantly lower than the results from triaxial test. The S_u estimated from each of the empirical methods and S_{uc} from the CAUC was plotted with depth as seen in Figure 7a,7b and 7c. Method 2 shows low values of S_u and no correlation with CAUC results as the CAUC points do not align with the CPTu graph. The low values from the CPTu could be the effect of the cone factor used. On the contrary, Method 1 and 3 have a better correlation to the S_{uc} values as seen in *Figure 7a and 7c*, where these methods estimated higher values of S_u and has more CAUC points on the CPTu graph. The S_u values agree with values obtained by Blaker et al. (2019) for the Halden test site. Amongst the three empirical methods used, Method 3 has a better correlation with the CAUC result as proposed by Kim et al. (2009) that the use of q_e is more effective with reduced uncertainty.

The contractive behaviour of the Tiller-Flotten site from the CAUC result in *Figure 4* indicate that the soil is brittle at high strains. The S_u values obtained from CPTu tests are in close range with vales measured from triaxial tests. As seen in Figure 8, CAUC results plot nicely on the CPTu data estimated from Method 2 using cone parameter Δ_u, followed by Method 1 and 3 from cone parameter q_t and q_e respectively. The S_u values obtained agree with values obtained by Mayen et al. (2019) for the Tiller-Flotten teat site. Figure 8b shows S_u estimated using Method 2 gives a good correlation with the S_{uc} measured from CAUC test, this agrees with Karlsurd et al, (2005) that the S_u estimated from Δ_u is more reliable for very soft to sensitive clays as it gives a consistent and good correlation with CAUC values (Remai, 2013; Karlsurd et al., 2005; Robertson 2012).

V. CONCLUSION

For estimation of undrained shear strength from CPTu cone parameters using the three methods, it is seen that the Method 3 which uses the cone parameter q_e best estimates the undrained shear strength for the clayey silt site, while the Method 2 which uses excess pore pressure Δ_u better estimates the undrained shear strength for very soft to sensitive clays. More research needs to be done in the determination of S_u for clayey silts and silty soils, as there is a gap in literature for these soils providing a limited range for choice of cone factor.

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