Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0153

XVII European Conference on Soil Mechanics and Geotechnical Engineering
ECSMGE 2019 Reykjavik

Analytical CPTu model for sensitive clay at Tiller-Flotten site, Norway

Un modèle analytique CPTu pour l'argile sensible sur le site de Tiller-Flotten, Norvège

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ABSTRACT: A modified analytical cavity expansion-critical state model for sensitive clays is applied to piezocone results at the Tiller-Flotten Norwegian geotechnical research site to profile the undrained shear strength (s_u) and yield stress ratio (YSR) with depth. Input geoparameters include the value of effective friction angle in the normally-consolidated region (M_{c1}) and also for the structured region (M_{c2}) which associated to the measured cone resistance (q_t) and porewater pressure (u_2), respectively. The model directly provides the value of undrained rigidity index (I_R) that depends on the slope of (u_2-σ_{vo}) versus q_{net}. Results compare favorably with profiles of s_u and YSR obtained from laboratory triaxial and consolidation tests.

RÉSUMÉ: Un modèle modifié d'état critique d'expansion de la cavité analytique pour les argiles sensibles est appliqué aux résultats du piézocone sur le site de recherche géotechnique national de Tiller-Flotten en Norvège pour déterminer la résistance au cisaillement non drainée (s_u) ainsi que le taux de surconsolidation (YSR) avec la profondeur. Les paramètres d'entrée incluent la valeur de l'angle de friction effectif dans la région normalement consolidée (M_{c1}) et également pour la région structurelle (M_{c2}), qui est associée à la résistance du cône mesurée (q_t) et à la pression interstitielle (u_2), respectivement. Le modèle fournit directement la valeur de l'indice de rigidité (I_R) non drainé qui dépend de la pente de (u_2-σ_{vo}) par rapport à q_{net}. Les résultats se comparent favorablement aux profils de s_u et YSR obtenus à partir d'essais de laboratoire triaxiaux et de consolidation.

Keywords: clays, piezocone, shear strength, stress history, yield stress

1 INTRODUCTION

The use of piezocone penetration tests (CPTu) in clays is an initial and important task in geotechnical site characterization, as the interpreted magnitudes of various geoparameters are needed in the assessment and design of foundations, slope stability, embankments, excavations, and other civil engineering projects. Special considerations must be given for sensitive clays as these geomaterials can exhibit fragility, loss of strength, and strain softening, thereby prone to instability; and are more susceptible to sampling disturbance.

The CPTu collects at least three continuous readings with depth: (a) cone tip resistance (q_t);

(b) sleeve friction (f_s); and (c) penetration porewater pressures (u_2). The standard sounding is advanced at a rate of 20 mm/s and data are recorded approximately every 1 to 5 s.

1.1 CPTu in sensitive Tiller-Flotten clay

Norway has established five national test sites for the implementation of geotechnical research activities with each focusing on a specific soil type: sand, soft clay, silt, sensitive clay and permafrost (L'Heureux et al. 2017). The Tiller-Flotten site serves as the testing grounds for sensitive to quick clays. The clay content at the site ranges from 50-60% and the water content is around 45%. Details are provided by L'Heureux et al. (this volume).

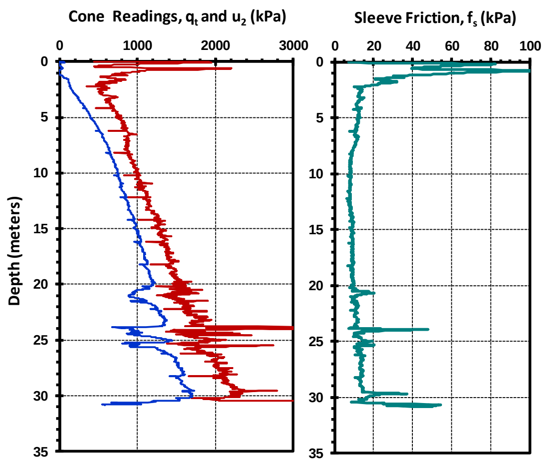

Figure 1. Representative piezocone sounding at the Tiller-Flotten test site

A representative piezocone sounding (CPTu No. TILC18) from the test site at Tiller-Flotten is presented in Figure 1. The uppermost 2.5 m of soil is interpreted as a dry/desiccated layer of stiff overconsolidated sandy clay. Beneath this crust, throughout the sounding depths up to 30 m lies a soft fine-grained soil. The clay is extremely sensitive to quick from approximately 7.5 m below the surface (sensitivity > 100).

The pore pressure gradient below the groundwater table is relatively low. This is attributed to drainage of coarser layers below the clay and towards the valley river called Nidelva. A piezometric profile of the in situ pore pressure conditions at Tiller-Flotten is shown in Figure 2.

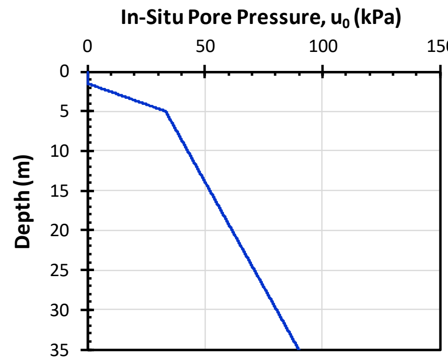

Figure 2. In-situ pore pressure at Tiller-Flotten

1.2 Soil type evaluation by CPT

With the evaluation of CPTu soundings in clays, the initial concern is in the proper identification of fine-grained soils which are sensitive (Sandven et al. 2016a). Since soil samples are not routinely obtained during CPTu, the evaluation of soil type is usually done via empirical charts that assign a soil behavioral type (SBT), as given by Robertson (1990), Lunne et al. (1997), Eslami and Fellenius (1997), and Schneider et al. (2012).

Despite the widespread use of these SBT charts, the proper identification of sensitive and structured clays is not always so successful, as noted by Sandven et al. (2016a), Shahri et al. (2015), and Valsson (2016).

For the CPTu data shown in Figure 1, the SBTn Q-F charts given by Robertson (2009) identify the upper 7.5 m of soils as zone 4 (silts) In the sensitive clay below 7.5 m depths, the SBTn Q-F system gives a mean value of CPT material index I_c = 3.01 with standard deviation S.D. = 0.12. Accordingly, most of these data should fall into zone 1 (sensitive soils). However, the breakdown sorting (n = 2334) by SBTn gives:

8% zone 1 (sensitive clays), 77% zone 3 (clays), and 15% zone 4 (silts). The Q-B_q chart was even less successful. Hence, in this paper, an alternate means to screen the CPTu profiles for presence of sensitive clays is presented.

2 EVALUATING GEOPARAMETERS OF CLAYS FROM CPTU

For clays, the results of CPTu soundings have been used to interpret profiles of undrained shear strength (s_u) and yield stress (σ_p'), mainly via generalized empirical correlations (Chen & Mayne 1996). For the sensitive Champlain Sea (Leda) clays of Eastern Canada, geologic-specific relationships have been developed (Demers & Leroueil 2002). Likewise, for the soft and sensitive clays of Norway, empirical trends have been established for application of CPTu data in geotechnical practice (Karlsrud et al. 2005).

An analytical model for CPTu interpretations in non-structured and inorganic clays of low sensitivity was derived using a hybrid spherical cavity expansion (SCE) and critical state soil mechanics (CSSM) formulation (Mayne 1991). For structured and sensitive clays, a slightly modified SCE-CSSM solution has recently been developed (Agaiby & Mayne 2018; Mayne et al. 2018), as discussed subsequently. This outputs values of rigidity index (I_R), undrained shear strength (s_u), and yield stress ratio (YSR = σ_p'/σ_{vo}').

2.1 Modified SCE-CSSM for CPTu in sensitive and structured clays

In these modified derivations, three separate algorithms relate the YSR to normalized CPTu parameters: $Q = q_{net}/\sigma_{vo}'$ and $U^* = \Delta u_2/\sigma_{vo}'$, where $q_{net} = q_t - \sigma_{vo}$ = net cone resistance and $\Delta u_2 = u_2 - u_0$ = excess porewater pressure. These are expressed by the following:

$$YSR = 2 \cdot \left[\frac{Q/M_{c1}}{0.667 \cdot \ln(I_R) + 1.95}\right]^{1/\Lambda} \quad (1)$$

$$YSR = 2 \cdot \left[\frac{U^* - 1}{0.667 \cdot M_{c2} \cdot \ln(I_R) - 1}\right]^{1/\Lambda} \quad (2)$$

$$YSR = 2 \cdot \left[\frac{Q - \frac{M_{c1}}{M_{c2}} \cdot (U^* - 1)}{1.95 \cdot M_{c1} + \frac{M_{c1}}{M_{c2}}}\right]^{1/\Lambda} \quad (3)$$

where $\Lambda = 1 - C_s/C_c$ = plastic volumetric strain potential, C_s = swelling index, C_c = virgin compression index, $I_R = G/s_u$ = rigidity index, $M_c = 6 \cdot \sin\phi'/(3 - \sin\phi')$ = frictional parameter in q-p' space. The value of M_{c1} is defined for the normally-consolidated region (i.e., destructured soil), whereas M_{c2} is the value for the intact structured soil from either CIUC or CAUC tests. Note that the condition: $M_{c1} \leq M_{c2}$ must be met.

For insensitive clays, a value of Λ = 0.70 to 80 is common, while for structured and sensitive clays, a higher value of Λ is appropriate, specifically: $0.9 < \Lambda < 1$ (Mayne 2008).

While equations (1) and (2) both depend on I_R, Equation (3) is independent of the I_R and obtained by combination of the first two expressions.

2.2 Simplified CPTu expressions for non-sensitive and inorganic clays

For inorganic clays of low sensitivity, a simplification can be made to these equations by taking $M_{c1} = M_{c2} = 1.2$ corresponding to $\phi' = 30°$, $\Lambda = 1$, and a default value of $I_R = 100$ (Agaiby & Mayne 2018). The reduced expressions become first-order expressions for yield stress:

$$\sigma_p' \approx 0.33\ q_{net} \quad (4)$$

$$\sigma_p' \approx 0.53\ \Delta u_2 \quad (5)$$

$$\sigma_p' \approx 0.60\ q_E = 0.60\ (q_t - u_2) \quad (6)$$

where q_E = effective cone resistance.

Examples of the agreement of these three approximate expressions in "well-behaved" soils are shown for soft to firm clays in Australia, Scotland, and the North Sea (Mayne 2008), and for the soft San Francisco Bay Mud (Mayne & Agaiby 2019).

2.2 Identification of sensitive clays by CPTu

When the simplified expressions are applied to sensitive or structured clays, however, they show disagreement amongst each other. Figure 3 illustrates the results for sensitive Tiller-Flotten clay with clearly incompatible results for the three evaluated σ_p' profiles in the lower sensitive clay layers below 7 m.

In sensitive clays, the observed hierarchy of the profiles is in the following order:

$$0.60\ q_E \ < \ 0.33\ q_{net} \ < \ 0.53\ \Delta u_2 \qquad (7)$$

A similar hierarchy is found in the sensitive Leda clay at Gloucester test site in Ontario, Canada (Agaiby & Mayne 2018); sensitive Haney clay of British Columbia (Mayne et al. 2018), sensitive Presumpscot clay of Maine (Hardison & Landon 2015), and the sensitive soft clay at Skatval, Norway (Paniagua et al. 2017).

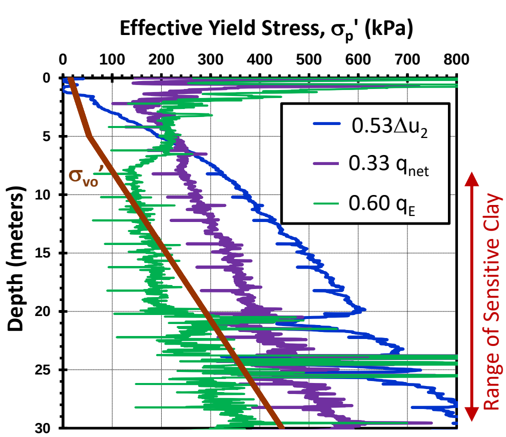

Figure 3. Simplified YSR algorithms applied to Tiller-Flotten showing disparities in the three expressions

2.2 Undrained rigidity index

The SCE-CSSM formulation also provides the direct assessment of undrained rigidity index:

$$I_R = exp\left[\frac{1.5+2.925 \cdot M_{c1} \cdot a_q}{M_{c2} - M_{c1} \cdot a_q}\right] \qquad (8)$$

where $a_q = \Delta u_\sigma / q_{net}$ and $\Delta u_\sigma = (u_2 - \sigma_{vo})$. The evaluation of a_q is determined as the slope of the graph of Δu_σ versus q_{net}, or alternatively by plotting (U*-1) versus Q. This is illustrated by Figure 4 which determines a value of $a_q = 0.703$ using the data from the continuous range of CPTu readings from depths of 8 to 18 m in the representative sounding at Tiller-Flotten.

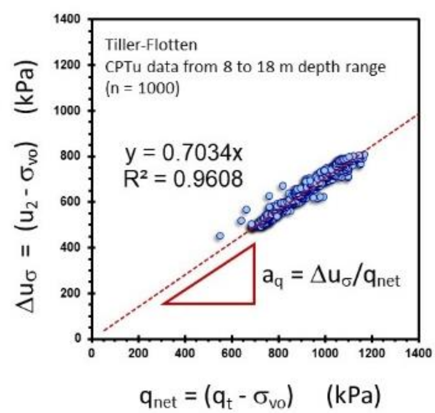

Figure 4. Slope parameter a_q for evaluating rigidity index in sensitive Tiller-Flotten clay

The above approaches for obtaining Δu_σ apply to clay deposits that are essentially submerged or have a shallow groundwater table (z_w < 2 m) since the slope parameter $a_q > 0$.

2.3 Undrained shear strength

For CPTu soundings in clay, the undrained shear strength is most often determined using the net cone resistance:

$$s_u = q_{net}/N_{kt} \qquad (9)$$

where N_{kt} = cone bearing factor. Karlsrud et al. (2005) correlates N_{kt} with OCR, plasticity and/or sensitivity. In the SCE-CSSM formulation, the Vesić (1977) expression for N_{kt} has been used for the CPTu which is given in terms of the undrained rigidity index:

$$N_{kt} = 4/3\ [\ln(I_R) + 1]\ +\ \pi/2 + 1 \tag{10}$$

Also, the derivation for YSR in terms of SCE-CSSM is based on a triaxial compression mode.

3 APPLICATION TO TILLER-FLOTTEN

The modified SCE-CSSM solutions will be applied to the CPTu at Tiller-Flotten site and compared with available laboratory triaxial and consolidation data.

3.1 *Triaxial test results*

Representativc results of effective stress paths from CAUC triaxial tests on undisturbed specimens of the structured highly sensitive clay at various depths are presented in Figure 5. From the effective stress paths, the magnitude of M_{c2} = 1.46 (ϕ' = 36°) can be assigned for the intact and structured region which agrees with the value reported by Agaiby & Mayne (2018) for Tiller data from Gylland et al (2013). A corresponding value of M_{c1} = 1.03 (ϕ' = 26°) is applicable for the normally-consolidated and destructured region as also pointed out by Thakur et al. (2018) on similar Norwegian clays.

3.2 *Rigidity index of Tiller-Flotten clay*

Using the M_{c1} = 1.03 and M_{c2} = 1.46 together with the slope parameter a_q = 0.703 from Figure 4 determines an undrained rigidity index I_R = 132 from equation (8). It is believed that this value of operational rigidity index corresponds with a failure state since 100% of all soil particles must be shoved aside when the full-displacement cone penetrometer is advanced. As such, the rigidity index can be considered as the reciprocal of the shear strain at failure (γ_s):

$$I_R\ =\ G/s_u\ =\ 1/\gamma_s \tag{11}$$

where $G = G_f$ = shear modulus defined at the peak strength.

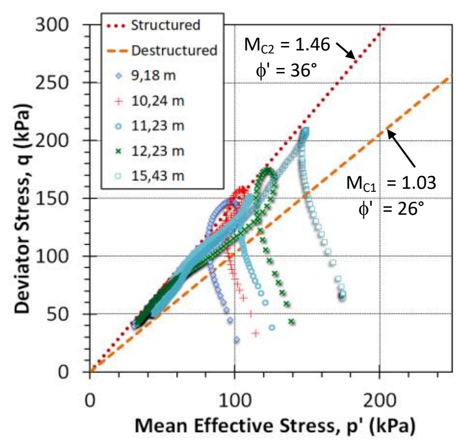

Figure 5. Results from CAUC triaxial tests at the site

3.3 *Yield stress ratio profile*

Adopting a characteristic value Λ = 0.95 for the sensitive clay, the three profiles for YSR can be generated using equations (1), (2), and (3) with the normalized cone resistance Q, porewater pressure parameter U*, and frictional values of M_{c1} and M_{c2}.

As evident in Figure 6, the three yield stress profiles agree for depths > 7 m. Results from benchmark values of σ_p' obtained one-dimensional CRS consolidation tests on undisturbed samples confirm the magnitudes are valid and increase with depth from 300 to 450 kPa.

The corresponding normalized YSR profiles are presented in Figure 7. The YSR ≈ 3 at depth of 8 m and decreases to about YSR ≈ 1.5 at 20 m.

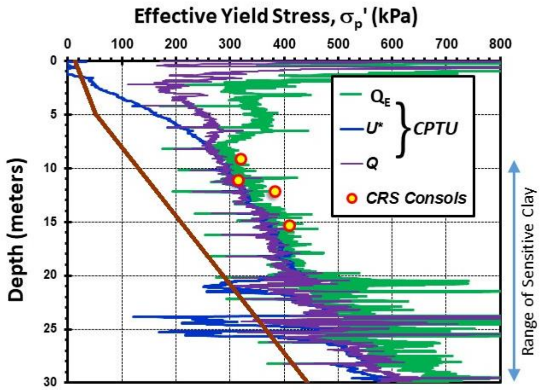

Figure 6. Modified SCE-CSSM profiles of yield stress at Tiller-Flotten

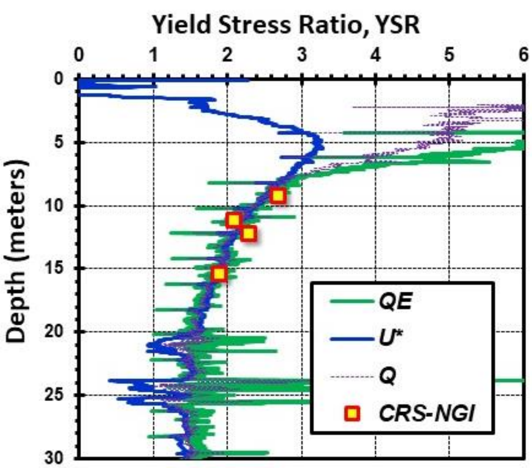

Figure 7. Modified SCE-CSSM profiles of yield stress ratio (YSR) at Tiller-Flotten

3.4 *Undrained strength profile*

Using the derived $I_R = 132$ for the Tiller-Flotten clay, equation (10) determines a cone factor $N_{kt} = 10.4$ for the site. Using this in the standard equation (9) provides the triaxial profile for s_{uc} ranging from 50 to 100 kPa in the depth range of 8 to 20 m, as shown in Figure 8. Results from 7 CAUC triaxial tests confirm the reasonableness of the derived strength profile in the soft sensitive to quick clay.

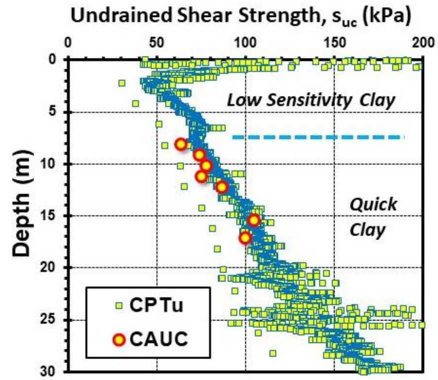

Figure 8. Undrained strength profile from CPTu and CAUC triaxial tests at Tiller-Flotten

4 EFFECTIVE FRICTION ANGLE

An effective stress limit plasticity solution developed at the Norwegian University of Science & Technology (NTNU) permits the evaluation of the effective stress friction angle (ϕ') of clays from CPTu measurements (Senneset et al. 1989). For the case where effective cohesion intercept c' = 0, an approximate expression is given by (Mayne 2007):

$$\phi' = 29.5°B_q^{0.121}\,[0.256+0.335B_q+\log N_{mc}] \quad (12)$$

For NC clays, $N_{mc} = Q$ = cone resistance number and the following parametric ranges are maintained: $0.1 \le B_q \le 1.2$ and $20° \le \phi' \le 40°$.

For OC clays, a modified N_{mc} is obtained by normalizing the net cone resistance by the equivalent effective stress (σ_e'), as discussed by Sandven et al. (2016b). The magnitude of σ_e' is determined from the soil stress history (Schofield & Wroth 1968; Mayne et al. 2009):

$$\sigma_e' = (\sigma_{vo}')^{1-\Lambda}\cdot(\sigma_p')^{\Lambda} = \sigma_{vo}'\cdot YSR^{\Lambda} \quad (13)$$

Since $N_{mc} = q_{net}/\sigma_e'$, for the case of NC soils with YSR = 1, the value of N_{mc} is simply $Q = q_{net}/\sigma_{vo}'$.

For the CPTu results at Tiller-Flotten, both the original and modified NTNU solutions have been applied, as presented in Figure 9. Of particular interest is that the original solution using σ_{vo}' appears to correspond to the friction angle for structured clay (ϕ'_2 = 36°) while the modified solution more or less is compatible with the value for destructured clay (ϕ'_1 = 26°). Values of ϕ' from the CAUC triaxial test series on structured clay (Figure 5) are also shown. Thus, on a preliminary basis, the aforementioned methodology provides most of the required input parameters for a successful assesment of M_{c1}, M_{c2}, YSR, I_R, and s_u in sensitive clays.

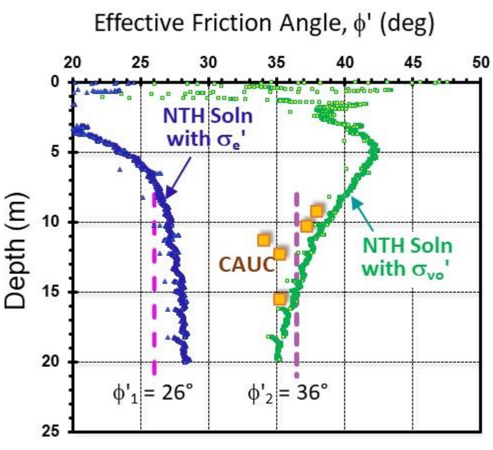

Figure 9. Effective friction angles from original and modified NTNU solutions compared with model input parameters and CAUC triaxials from Tiller-Flotten

5 CONCLUSIONS

A modified SCE-CSSM solution has been developed for evaluating rigidity index (I_R), undrained shear strength (s_u), and yield stress ratio (YSR) profiles from piezocone soundings in sensitive to structured soft clays. Shear strength corresponds to the triaxial compression mode. The derivations use normalized cone resistance and porewater pressure parameters with the effective frictional characteristics of clays taken at both structured and destructured states. The methodology is applied to sensitive clay at Tiller-Flotten, Norway in good agreement with lab CRS and CAUC results. In addition, a NTNU solution for assessing effective friction angle of clays can be implemented.

5 ACKNOWLEDGMENTS

The first author thanks ConeTec Group of Richmond BC for supporting our in-situ research activities. The authors would also like to acknowledge the Research Council of Norway (RCN) for funding the Norwegian GeoTest site Project (Project No. 245650/F50).

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