Evaluating CPTu in sensitive Haney clay using a modified SCE-CSSM solution

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ABSTRACT
Results from piezocone tests in sensitive clay from Haney BC are interpreted using a modified analytical model based on spherical cavity expansion theory and critical state soil mechanics. The solution allows the evaluation of the undrained rigidity index which in turn provides the profiles of undrained shear strength and yield stress. The yield stress ratio is expressed in three separate formulations using net cone resistance, excess porewater pressure, and effective cone resistance. When compared together, this trio is useful in the identification of sensitive clays from insensitive clays.

RÉSUMÉ
Les résultats des tests de piézocône dans l'argile sensible de Haney BC sont interprétés en utilisant un modèle analytique légèrement modifié basé sur la théorie de l'expansion de la cavité sphérique et la mécanique des sols à l'état critique. La solution permet l'évaluation de l'indice de rigidité non drainé qui à son tour fournit les profils de la résistance au cisaillement non drainé et de la limite d'élasticité. Le rapport de contrainte d'écoulement est exprimé dans trois formulations distinctes en utilisant la résistance de cône net, la pression de l'eau interstitielle en excès et la résistance au cône efficace. Comparé entre eux, ce trio est utile pour identifier les argiles sensibles des argiles insensibles.

1 INTRODUCTION

The implementation of cone penetration tests (CPT), specifically piezocone tests (CPTu), in clays is an important task in geotechnical site characterization, as values of selected geoparameters are needed in the assessment of foundation bearing capacity, slope stability analyses, embankment consolidation, 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, and are thus prone to instability.

1.1 CPTu Readings

The piezocone penetration test provides three separate measurements with depth: (a) cone tip resistance, q_t; (b) sleeve friction, f_s; and (c) penetration porewater pressure at the shoulder, u_2. The penetrometer is pushed at a constant rate of 20 mm/s per ASTM D 5778 and data are recorded approximately at intervals of 1 or 2 s.

1.2 Soil Type

With the evaluation of production CPTu soundings in clays, the initial concern is in the proper identification of fine-grained soils which are sensitive. Since soil samples are not routinely obtained during CPTu, the determination of soil type is usually done via empirical charts that assign a soil behavioral type (SBT), such as those developed by Robertson (1990), Eslami & 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. (2016), Shahri et al. (2015), and Valsson (2016) in their studies. In this paper, an alternate means to screen the CPTu profiles for presence of sensitive clays is shown.

1.3 Geoparameter Evaluation

The full interpretation of CPTu readings depends upon the nature of the specific civil engineering project, yet often includes the evaluation of strength and stress history in sensitive and structured clays. This can be accomplished using empirical methods, correlation with lab testing programs, analytical models, and numerical simulations, such as finite elements.

In this paper, a closed-form modified analytical solution based on spherical cavity expansion (SCE) and critical state soil mechanics (CSSM) is used to interpret the undrained rigidity index ($I_R = G/s_u$), undrained shear strength (s_u), and yield stress ratio (YSR = σ_p'/σ_{vo}'), where σ_p' = preconsolidation stress or effective yield stress and σ_{vo}' = current effective overburden stress.

1.4 Haney Site, British Columbia

To illustrate the approach, results from CPTu soundings in sensitive Haney clay will be utilized for post-processing. A major landslide occurred in the Haney clay in 1880 (Greig 1985). The Haney site is 43 km east of Vancouver and underlain by marine, glaciomarine, and glacial sediments of the Fort Langley Formation.

Over the past century, the Haney clay has served as a quarry for providing mineral in the processing of brick and tile in commercial production. The clay has also been used in several laboratory testing programs conducted at the Univ. British Columbia (Byrne 1966; Vaid 1971; Zergoun 1982; Greig 1985). Lab index data on three test series of the Haney clay are given in Table 1, including natural water content (w_n), liquid limit (LL), and plasticity index (PI).

A representative CPTu-04 at the Haney site is shown in Figure 1. Of particular interest is the lower clay layer which is found to correspond to SBTn zone 1 (sensitive soils) and zone 3 (clay) at depths of about 10 to 20 m, as indicated by Figure 2.

Table 1. Index properties of Haney clay

Source	w_n (%)	LL (%)	PI (%)
Byrne (1966)	42	44	18
Vaid (1971)	41-44	46	20
Zergoun (1982)	63-73	89	54

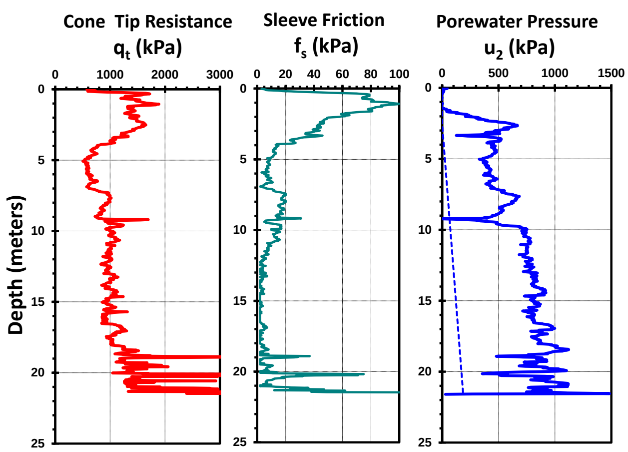

Figure 1. Representative piezocone sounding (CPTu-04) at the Haney site, BC

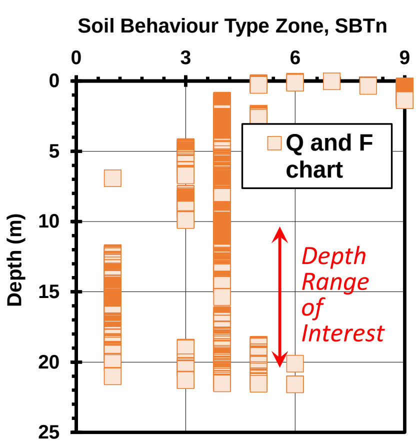

Figure 2. Profile of interpreted soil types at Haney site

2 PIEZOCONE EVALUATION OF STRESS HISTORY IN CLAYS

Results of CPTu soundings in clays have been used to interpret profiles of undrained shear strength and effective yield stress in clays, mainly via empirical correlations (e.g., Kulhawy & Mayne, 1990; Chen & Mayne 1996). For clays of Eastern Canada, including the structured and sensitive Champlain Sea clays or Leda clays, more geologic-specific relationships have been developed (Demers & Leroueil 2002). Similarly, for the 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 clays of low sensitivity was derived using a hybrid SCE-CSSM formulation (Mayne 1991; Burns & Mayne 1998). For structured and sensitive clays, a slightly modified SCE-CSSM solution has recently been presented by Agaiby & Mayne (2018) and applied to fit the CPTu results with available triaxial and consolidation data from the Canadian Test Site at Gloucester, Ontario.

2.1 Modified SCE-CSSM for CPTu in sensitive clays

In the recent 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 at peak strength (i.e., ϕ' at q_{max}) whereas M_{c2} is the value at maximum obliquity (i.e., ϕ' when ratio σ_1'/σ_3' max). For insensitive clays, the value of $\Lambda = 0.80$, while for clays that are structured and/or sensitive, the value of Λ is higher, specifically: $0.9 < \Lambda < 1$.

While Eq. [1] and [2] both depend on the I_R of the clay, Eq. [3] is independent of the I_R and obtained by combination of the first two formulations.

2.2 Simplified CPTu expressions for insensitive clays

For inorganic clays of low sensitivity, a simplification can be made to these equations by taking $M_{c1} = M_{c2} = 1.2$ (ϕ' =

30°), Λ = 1, and a default value of I_R = 100 (Mayne 2005). The reduced expressions become:

$$\sigma_p' \approx 0.33\ q_{net} \quad [4]$$

$$\sigma_p' \approx 0.53\ \Delta u_2 \quad [5]$$

$$\sigma_p' \approx 0.60\ (q_t - u_2) \quad [6]$$

Examples of the agreement of these approximations in "well-behaved" clays are shown for soft Brisbane clay in eastern Australia, soft Bothkennar clay in the UK, soft offshore clays at Troll East in the North Sea (Mayne 2008), and soft Burswood clay in western Australia (Mayne 2010).

When these expressions are applied to sensitive or structured clays, they show disagreement amongst each other. Figure 3 illustrates the results for Haney clay with clearly incompatible results for the three evaluated profiles of σ_p' in the lower sensitive clay layer.

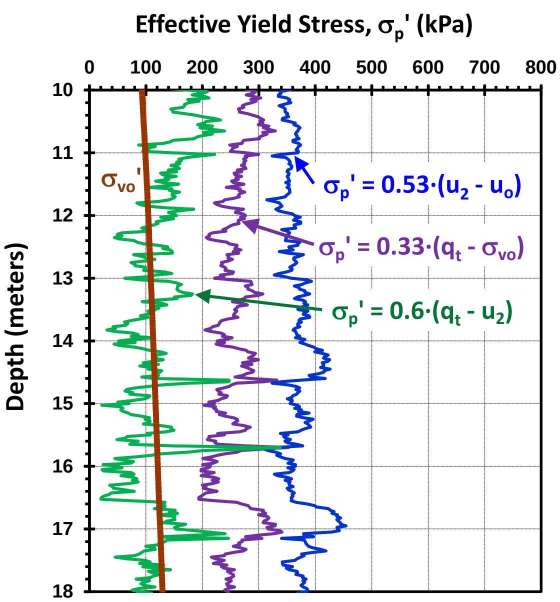

Figure 3. Simplified yield stress expressions applied to CPTu at Haney sensitive clay showing lack of agreement

2.3 Undrained Rigidity Index

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

$$I_R = exp\left[\frac{1.5+2.925 \cdot M_{c1} \cdot a_q}{M_{c2} - M_{c1} \cdot a_q}\right] \quad [7]$$

where a_q is found as the ratio of $\Delta u_\sigma = u_2 - \sigma_{vo}$ to net cone resistance, q_{net}. 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, as illustrated by Figure 4 which determines a value of a_q = 0.731 using the data from the Haney CPTu. Another means is to calculate this ratio with depth, as shown by Figure 5.

The above approaches to obtaining Δu_σ apply to clays that are essentially submerged or have a shallow groundwater table (z_w < 3 m) since the parameter should normally be a positive number; thus $u_2 > \sigma_{vo}$.

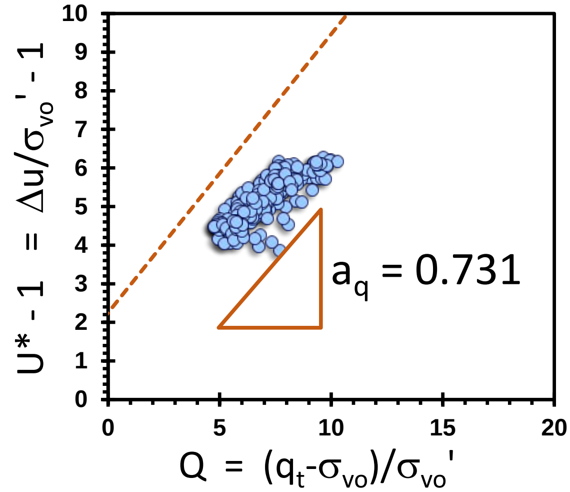

Figure 4. Procedure to evaluate slope parameter a_q from CPTu data at Haney clay site.

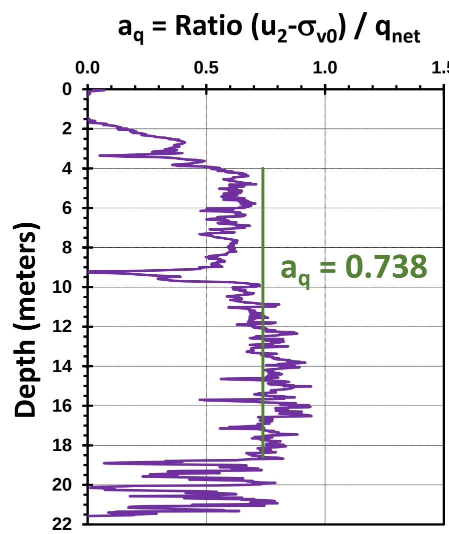

Figure 5. Alternate procedure to evaluate a_q parameter

3 APPLICATION TO HANEY CLAY

The modified SCE-CSSM formulations are applied to CPTu data from Haney clay using available lab triaxial, field vane, and results from one dimensional consolidation tests reported by Univ. of British Columbia.

3.1 Effective Friction Angle

Values of M_{c1} and M_{c2} are obtained from consolidated triaxial compression tests with pore pressure measurements. Results of CIUC and CAUC tests on

Haney clay are taken from Byrne (1966) and Vaid (1971), respectively, and shown in Figure 6. The value of M_{c1} = 0.88 (ϕ' = 22.5°) corresponds to the peak shear strength (q_{max} criterion) and M_{c2} = 1.30 (ϕ' = 32.3°) is associated with the maximum obliquity condition.

For triaxial testing of sensitive clays, peak strength is reached early followed by strain softening in the stress-strain response, whereas porewater pressures exhibit a maximum value at higher strains. Thus, the criterion of M_{c1} at q_{max} is associated with the cone tip resistance (q_t) and the latter criterion of M_{c2} at $(\sigma_1'/\sigma_3')_{max}$ is aligned with the CPTu measured porewater pressure (u_2).

With the corresponding values of M_{c1}, M_{c2}, and a_q, the operational value of rigidity index for Haney clay is I_R = 181.

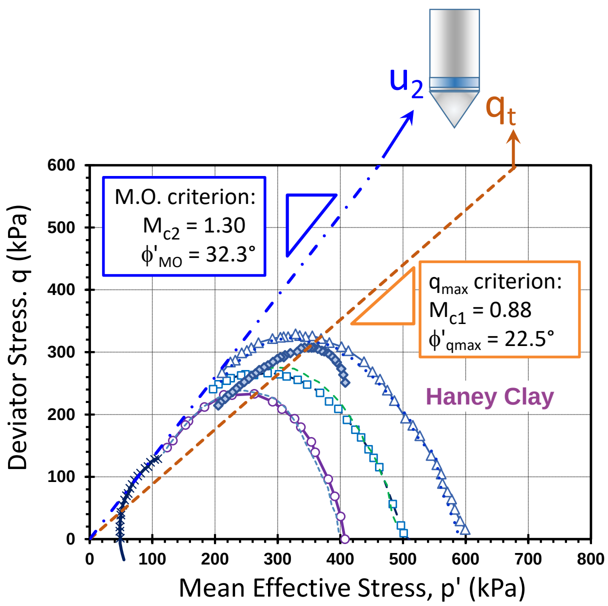

Figure 6. Triaxial results on Haney clay reported by UBC

3.2 Yield Stress Profiles in Haney Clay

Using the three expressions for YSR in sensitive and structured clays given by Eqns [1], [2], and [3], Figure 7 shows the CPTu evaluations of effective yield stress for Haney clay for I_R = 181, M_{c1} = 0.88, M_{c2} = 1.30, and Λ = 0.95. Here, all 3 CPTu profiles agree well with each other, thus supportive of the geoparameter values that were selected.

The CPTu profiles are also consistent and in general agreement with laboratory one-dimensional consolidation tests performed on block samples taken at the site. Summary results from several different laboratory consolidation series performed at Univ. of British Columbia (UBC) are given in Table 2. In these references, only a single value of preconsolidation or effective yield stress was reported for the Haney clay, as listed. The intermediate value from Zergoun (1982) is shown in Figure 7 and presented as a constant value with depth.

Table 2 also includes clay fraction (CF) and sensitivity, as measured by unconfined compression (UC) tests (S_t). Probably UC tests are not the best means to ascertain S_t in clays, since they are adversely affected by sample disturbance and stress relief (Abouhajar et al. 2010). Field vane data reported by Greig (1985) indicate 4 < S_t < 12.

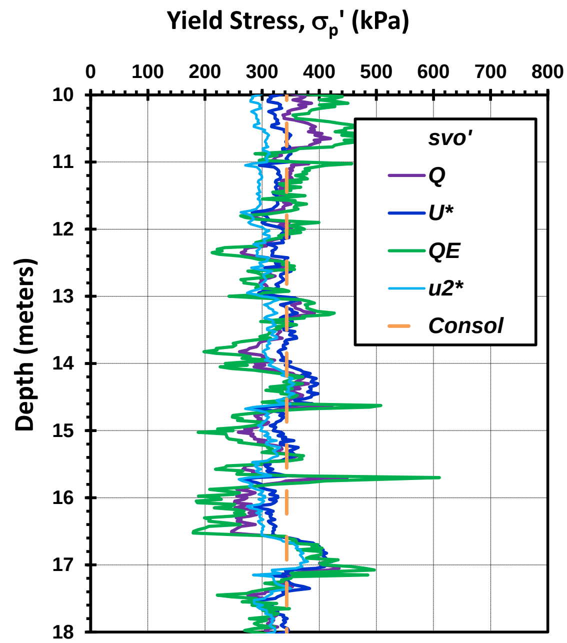

Figure 7. The 3 modified SCE-CSSM expressions applied to CPTu data for Haney sensitive clay site showing agreement with each other and with yield stress from consolidation tests reported by Zergoun (1982)

Table 2. Effective yield stresses from consolidation tests

Source	CF	S_t	σ_p' (kPa)
Byrne (1966)	46	12	275
Vaid (1971)	46	6-10	392
Zergoun (1982)	85	6-10	343

3.3 Vane Shear Tests

Two series of field vane shear tests (VST) at Haney are reported by Greig (1985). The vane strengths (s_{uv}) results are presented in Figure 8. With regard to CPTu, the undrained shear strength of clays is most often determined using the net cone resistance:

$$s_u = q_{net}/N_{kt} \quad [8]$$

where N_{kt} = cone bearing factor. In the SCE-CSSM formulation, the Vesić (1977) expression for N_{kt} is used and is given in terms of the undrained rigidity index:

$$N_{kt} = 4/3\,[\ln(I_R) + 1] + \pi/2 + 1 \quad [9]$$

For the value of I_R = 181, the operational value for Haney gives N_{kt} = 10.8. This compares well with the s_{uv} profiles from VST, as shown in Figure 8.

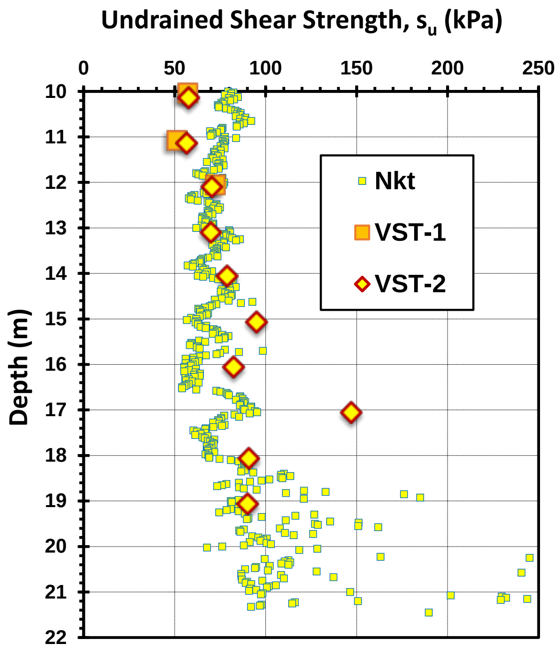

Figure 8. Profiles of undrained shear strength from CPTu and VST at Haney site (VST data from Greig 1985).

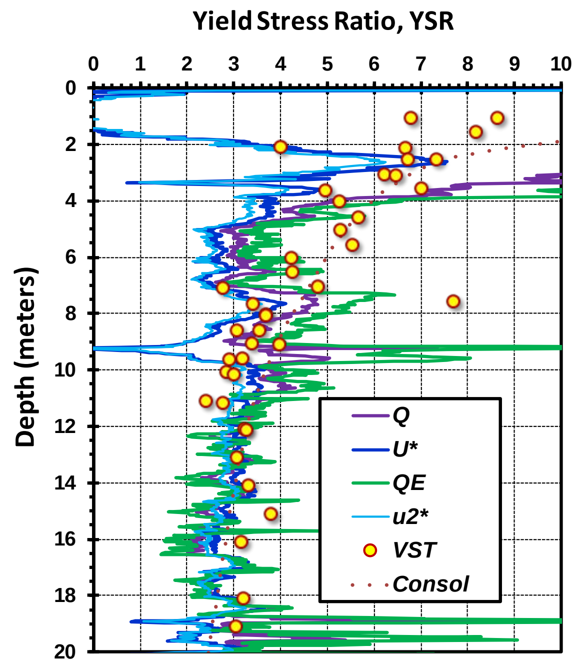

Figure 9. Profiles of yield stress ratio from VST, CPTu, and consolidation tests in sensitive clay at Haney, BC

As noted by Greig (1985), the VST can also be used to ascertain the profile of OCR in clays. In this case, the empirical expression reported by Mayne & Mitchell (1988) has been employed:

$$\sigma_p' = 22 \cdot s_{uv}/\sqrt{PI} \qquad [10]$$

Using a value of PI = 18 reported by Greig (1985), the corresponding profiles of YSR with depth from the vane tests and piezocones are presented in Figure 9. These show the YSR decreasing from 9 near the surface to about 3 at depths of 20 m. Also shown is the YSR profile by adopting a constant yield stress σ_p' = 343 kPa from the aforementioned one-dimensional consolidation tests reported by Zergoun (1982), as listed in Table 2. All three independent methods (VST, CPTu, lab consolidation) are compatible.

4 CONCLUSIONS

Results of piezocone tests in sensitive clay at Haney, BC are utilized in a modified analytical solution to obtain the rigidity index, undrained shear strength, and effective yield stress profile with depth. Input effective stress parameters include the q-p' friction parameter M_{c1} defined at q_{max} which corresponds to the measured cone tip resistance (q_t) and M_{c2} at maximum obliquity or large strains which is associated with the maximum measured porewater pressure (u_2) during cone penetration. The CPTu profiles of YSR compare well with independent results from laboratory one-dimensional consolidation tests and field vane shear tests performed at the site.

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