Research article

CPTU identification of regular, sensitive, and organic clays towards evaluating preconsolidation stress profiles

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Abstract: Soil classification by piezocone penetration tests (CPTU) is mainly accomplished using empirical soil behavior charts (SBT). While commonly-used SBT methods work well to separate fine-grained soils from granular coarse-grained soils, in many instances, the groupings often fail to properly identify different categories of clays, specifically: (a) “regular” clays that are inorganic and insensitive, (b) sensitive and quick clays; and (c) organic soils. Herein, a simple means of screening and sorting these three clay types is shown using three analytical CPTU expressions for evaluating the preconsolidation stress profile from net cone resistance, excess porewater pressure, and effective cone resistance. A number of case studies are utilized to convey the methodology.

Keywords: clays; cone penetration; organic soils; piezocone; sensitive soils

1. Introduction

Cone penetration testing (CPT), particularly piezocone testing (CPTU), obtains detailed stratigraphic profiling of soil layers by collecting three distinct measurements with depth: (a) cone tip resistance, qt; (b) sleeve friction, fs; and (c) porewater pressure, u2, during the advancement of an electronic steel probe that is hydraulically pushed vertically at a constant rate of 20 mm/s. Since soil sampling is not normally conducted during cone penetration testing, different approaches are used for post-processing piezocone data to identify and classify soil type: (a) relating CPT readings to the logs of adjacent boreholes and recovered samples subjected to laboratory testing; (b) relying on rules-of-thumb; (c) using empirical soil behavioral type (SBT) charts; (d) adopting probabilistic methods [1].

The most common method of soil classification by CPTU employs empirical soil behavioral type
(SBT) charts which have been developed by various researchers such as Robertson [2], Lunne et al. [3], Eslami and Fellenius [4], Schneider et al. [5], and Jefferies & Been [6]. One of the most popular charts is comprised of 9 soil zones that relies on normalized piezocone parameters (termed SBTn), namely: (1) normalized cone resistance, \( Q = q_{\text{net}} / \sigma_{\text{vo}}' \), (2) normalized sleeve resistance, \( F(\%) = 100 \cdot f_s / q_{\text{net}} \), and (3) normalized porewater pressure, \( B_q = u_2 / q_{\text{net}} \), where \( q_{\text{net}} = q_t - \sigma_{\text{vo}} \), \( u_2 = u_2 - u_0 \), \( \sigma_{\text{vo}} = \) total overburden stress, \( u_0 = \) hydrostatic porewater pressure, and \( \sigma_{\text{vo}}' = \) effective vertical stress [3]. An update uses a modified form of \( Q \) that is termed \( Q_{\text{tn}} \) where the \( \sigma_{\text{vo}}' \) term has a power law format, as detailed by Robertson [7].

While all the charts include zones for sand, silt, and clay, the delineations by Eslami and Fellenius [4] do not include a zone specific for organic soils, while the method of Jefferies & Been [6] does include organic soils, but not a distinct region to identify sensitive soils. The SBTn charts generally work well in differentiating gravelly sands (zone 7) from clean sands (zone 6), sandy mixtures (zone 5), silts (zone 4), and clays (zone 3), as shown in Figure 1 for regular clays. However, clay soils that have a special nature, including sensitive clays (zone 1) and organic soils (zone 2), can be mis-classified as zone 3 (clays to clayey silts).

For sensitive and quick clays, several studies have indicated the shortcomings of SBTn charts in correctly assigning the appropriate zone 1 (e.g., [1,8–14]). Figure 1 illustrates a summary plot for a number of sensitive fine-grained soils, as compiled and reported by Agaiby [1], falling incorrectly in zones 3 and 4 instead of zone 1. This is important because sensitive clays are unstable, prone to landsliding, and susceptible to collapse.

A similar issue arises when the SBTn misplaces clays that should locate in zone 2 (organic soils) but instead classifies the soils as either zone 1 (sensitive), zone 3 (clays), or zone 4 (silts) as noted by several authors [1,15–21]. Figure 1 shows the Q-F and Q-B_q charts with representative CPTU data from 24 organic fine-grained soil sites, where only 1 or 2 of the organic clays are properly identified as zone 2 [1]. Again, the misdiagnosis can be important because organic clays are associated with high compressibility, large foundation, settlements, undrained and drained creep, and bio-degradation issues.

The same issues for CPTU in sensitive and organic clays arise when plotting these groups on alternate classification charts. Figure 2a illustrates the data on the Unicone Chart [22] where there is no zone provided for organic clays and several sensitive clays are misidentified. Moreover, the CPTU classification chart by Jefferies & Been [6] has no specific zone allocated for sensitive and structured clays, while it misses correctly classifying many of the organic clays, as presented in Figure 2b.

2. **Analytical CPTU solutions for clays**

Herein, an alternate means of identifying clay types by CPTU are grouped into three categories: (1) “regular” clays that are insensitive and inorganic; (2) sensitive clays; and (3) organic soils. This is accomplished using effective preconsolidation stress (\( \sigma_p' \)) profiles developed from the CPTU readings that are based on an analytical solution that evaluates overconsolidation ratio (OCR = \( \sigma_p' / \sigma_{\text{vo}}' \)) as functions of \( q_{\text{net}}, \Delta u_2, \) and \( q_{\text{E}} \). For regular clays and sensitive clays, a separate closed-form limit plasticity approach evaluates the effective friction angle characteristics of the clay.

Figure 1. A compilation of CPTU data from regular, sensitive, and organic clays using empirical SBTn charts: (a) $Q_{tn}$-$F_r$; (b) $Q_{tn}$-$B_q$ (after [1]).

Figure 2. Misidentification of sensitive and organic clays on: a) the Unicone Chart by Fellenius & Eslami [22]; and b) Jefferies & Been [6] classification chart.
2.1. SCE-CSSM solution

A hybrid formulation of spherical cavity expansion (SCE) and critical state soil mechanics (CSSM) expresses the overconsolidation ratio (OCR) of clays in three separate formulations using net cone tip resistance \( q_{\text{net}} = q_t - v_0 \), excess pore pressure \( u_2 = u_2 - u_0 \), and effective cone resistance \( q_E = q_t - u_2 \). Details of the solution for insensitive inorganic clays are given by Mayne [23], Chen & Mayne [24], and Burns & Mayne [25], whereas the application in sensitive and structured clays is provided by Agaiby & Mayne [26]; Mayne et al. [27, 28]; DiBuö et al. [29]; and Mayne & Benoit [14].

Three separate algorithms relate the OCR to normalized CPTU parameters: \( Q = q_{\text{net}} / v_0' \) and \( U = u_2 / v_0' \), where \( q_{\text{net}} = q_t - v_0 = \) net cone resistance and \( u_2 = u_2 - u_0 = \) excess porewater pressure. These are expressed by the following:

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

\[
\text{OCR} = 2 \cdot \frac{U^* - 1}{0.667 \cdot M_{c2} \cdot \ln(I_R) - 1}^{1/\Lambda} \tag{2}
\]

\[
\text{OCR} = 2 \cdot \frac{Q - M_{c1} / M_{c2} \cdot (U^* - 1)}{1.95 \cdot M_{c1} + M_{c1} / M_{c2}}^{1/\Lambda} \tag{3}
\]

where \( \Lambda = 1 - C/C_v = \) plastic volumetric strain potential, \( C_s = \) swelling index, \( C_v = \) virgin compression index, \( I_R = G/s_u = \) undrained rigidity index, \( M = 6 \cdot \sin \phi' / (3 - \sin \phi') = \) frictional parameter in \( q-p' \) space. The value of \( M_{c1} \) is defined at peak strength (i.e., \( \phi' \) at \( q_{\text{max}} \)) whereas \( M_{c2} \) is the value defined at large strains which occurs at maximum obliquity (i.e., \( \phi' \) when the ratio \( [\sigma_1']/[\sigma_3'] \) max). For insensitive clays, the value of \( \phi' \) at \( q_{\text{max}} \) is equal to \( \phi' \) at \( (\sigma_1'/\sigma_3')_{\text{max}} \), and thus \( M_c = M_{c1} = M_{c2} \). For insensitive clays, the value of \( \Lambda = 0.80 \), whereas for sensitive clays, a value of \( \Lambda \approx 1.0 \) is more suitable.

While equations (1) and (2) both depend on the \( I_R \) of the clay, Equation (3) is independent of the \( I_R \) and is obtained by combination of the first two formulations. The rigidity index is thus given directly from [30]:

\[
I_R = \exp \left[ \frac{1.5 + 2.925 \cdot M_{c1} \cdot a_q}{M_{c2} - M_{c1} \cdot a_q} \right] \tag{4}
\]

where \( a_q = (U - 1)/Q = (u_2 - \sigma_{vo}) / (q_t - \sigma_{vo}) \). The parameter \( a_q \) can be determined as a single value for any clay layer or uniform clay deposit by taking the slope of a plot of the parameter \( (U - 1) \) versus \( Q \), or alternatively taken as the slope of \( (u_2 - \sigma_{vo}) \) versus \( (q_t - \sigma_{vo}) \). Using regression analyses, slightly different slope values for \( a_q \) are obtained.

2.2. NTH solution for \( \phi' \) from CPTU

In the event that laboratory-measured values from triaxial compression tests are not available, the effective friction angle can be evaluated using an effective stress limit plasticity solution for undrained penetration developed by Senneset et al. [31] and Sandven et al. [10,11] at the
Norwegian University of Science and Technology (NTNU), formerly NTH. For soft to firm clays, it can be adopted that effective cohesion intercept $c^* = 0$, where an approximate expression is given by Mayne [32,33]:

$$\phi' = 29.5 \cdot B_q^{0.121} \left[ 0.256 + 0.336 \cdot B_q + \log Q \right]$$  \hspace{1cm} (5)

which is valid for the following parametric ranges: $20^\circ \leq \phi' \leq 45^\circ$ and $0.1 \leq B_q \leq 1.0$ and OCRs $< 2.5$. Additional details for NC and OC insensitive clays are provided by Ouyang & Mayne [34,35], while $\phi'$ from CPTU in sensitive clays is addressed by Mayne et al. [28], DiBuo et al. [29], and Mayne & Benoît [14].

2.3. Simplified approach for insensitive and inorganic clays

A series of simplifications can be made for insensitive inorganic clays, or “regular” and “normal” clays. For one, equation (2) can be approximated by:

$$OCR \approx 2 \cdot \left[ \frac{U}{0.667 \cdot M_c \cdot \ln(I_R)} \right]^{1/\Lambda}$$  \hspace{1cm} (6)

As noted previously for regular clays which are inorganic and insensitive, the values $M_c = M_{c1} = M_{c2}$, therefore equation (3) reduces to:

$$OCR = 2 \cdot \left[ \frac{1}{1.95 M_c + 1} \left( \frac{q_t - u_2}{\sigma_{vo}} \right) \right]^{1/\Lambda}$$  \hspace{1cm} (7)

For a first-order estimate of $\sigma_p'$ in regular clays, further simplifications are achieved by: (a) setting the exponent $\Lambda = 1$ to reduce the power law format to linear equations; (b) adopting a characteristic effective friction angle of clay $\phi' = 30^\circ$ ($M_c = 1.2$), and (c) using a default value of $I_R = 100$ [33,36]. The reduced expressions become simple linear trends:

$$\sigma_p' \approx 0.33 \cdot q_{net} = 0.33 \cdot (q_t - \sigma_{vo})$$  \hspace{1cm} (8)

$$\sigma_p' \approx 0.53 \cdot \Delta u_2 = 0.53 \cdot (u_2 - u_o)$$  \hspace{1cm} (9)

$$\sigma_p' \approx 0.60 \cdot q_E = 0.60 \cdot (q_t - u_2)$$  \hspace{1cm} (10)

Table 1 lists several selected examples of regular or normal clays that have been subjected to both field CPTU and drilling with soil sampling operations. Laboratory testing was performed on recovered samples using standard classification methods and one-dimensional consolidation. Illustrative examples of CPTU soundings in four regular clays are presented in Figure 3 showing their three readings with depth: $q_t, f_s, \text{and } u_2$. Applying equations (8), (9), and (10) to the piezocone soundings, Figure 4 shows the good comparison matching of $OCR = \sigma_p'/\sigma_{vo}$ profiles from the CPTU with reference values from laboratory consolidometer testing on undisturbed samples. For the presented cases listed in Table 1, all three OCR expressions from the CPTU agree with each other and are verified with lab benchmark values obtained from consolidation testing, thereby indicating the signature of regular clays.
Table 1. Select CPTU database of “Regular” clays that are inorganic and insensitive.

<table>
<thead>
<tr>
<th>Clay Site</th>
<th>Location</th>
<th>OCR Reference Measurement Method***</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsøy soft clay, Historic NTS*</td>
<td>Norway</td>
<td>IL</td>
<td>[37,38,39]</td>
</tr>
<tr>
<td>Busan soft clay*</td>
<td>South Korea</td>
<td>IL</td>
<td>[40,41]</td>
</tr>
<tr>
<td>Ballina soft clay NTS*</td>
<td>Australia</td>
<td>CRS</td>
<td>[42,43,44]</td>
</tr>
<tr>
<td>Bothkennar soft clay NTS*</td>
<td>United Kingdom</td>
<td>CRS, IL, RF</td>
<td>[45]</td>
</tr>
<tr>
<td>Chicago soft clay, NTS*</td>
<td>NWU**, Illinois, USA</td>
<td>IL</td>
<td>[21]</td>
</tr>
<tr>
<td>San Francisco, soft Bay Mud</td>
<td>California, USA</td>
<td>CRS</td>
<td>[20]</td>
</tr>
<tr>
<td>Lower Troll East soft clay</td>
<td>North Sea</td>
<td>IL</td>
<td>[46]</td>
</tr>
<tr>
<td>Port of Brisbane, soft clay</td>
<td>Australia</td>
<td>IL</td>
<td>[46]</td>
</tr>
</tbody>
</table>

Notes: * NTS = national test site and presented in current study; ** NWU = Northwestern University; *** IL = Incremental load oedometer tests; RF = Restricted flow consolidation tests; CRS = Constant Rate of Strain consolidation tests.

3. Piezocone screening of sensitive clays

A selected group of 8 sensitive clays that have been field tested by CPTU has been compiled and listed in Table 2. The sources of data and information are given here, along with the calibrated values of $\phi_1'$ and $\phi_2'$ using the modified SCE-CSSM formulations. Figures 5 and 6 present the CPTU soundings for these sensitive clays.

Initially, the set of simplified expressions for OCR from CPTU are applied to these eight clays, with the results shown in Figures 7 and 8. The stress history estimates using equations (8), (9), and (10) clearly show mismatching of the OCR profiles amongst each other and evident disagreement when compared to lab reference values from consolidation tests. Moreover, a consistent hierarchy can be observed which gives the signature identification of sensitive clays:

$$0.60 \, q_E < 0.33 \, q_{net} < 0.53 \, \Delta u_2$$

(11)

Additional screening of sensitive clays verifies this approach and hierarchy of the $q_{net}$, $\Delta u_2$, and $q_E$ equations, as documented for the following: Gloucester NTS, Ontario [26], Haney sensitive clay, BC [27], sensitive Tiller-Flotten clay, Norway [28], and sensitive Presumpscot clay in NH [14].
Figure 3. Piezocone soundings for “regular” clays that are insensitive and inorganic: a) Onsøy, Norway; b) Busan, Korea; c) Ballina, Australia; and d) Bothkennar, UK.

Figure 4. Simplified OCR expressions for regular clays from CPTU along with lab reference values from consolidation tests for: a) Onsøy; b) Busan; c) Ballina; and d) Bothkennar.
Table 2. Select CPTU database of sensitive clays used for case study applications.

<table>
<thead>
<tr>
<th>Clay Site</th>
<th>Location</th>
<th>OCR Method</th>
<th>$\phi_1$ at peak strength</th>
<th>$\phi_2$ at maximum obliquity</th>
<th>Undrained Rigidity Index, $I_R$</th>
<th>A</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dover, NH*</td>
<td>USA</td>
<td>IL</td>
<td>28.7</td>
<td>36.7</td>
<td>260</td>
<td>0.9</td>
<td>[14,47]</td>
</tr>
<tr>
<td>Saint Jude, QC*</td>
<td>Canada</td>
<td>IL</td>
<td>29.0</td>
<td>30.0</td>
<td>200</td>
<td>0.95</td>
<td>[48,49,50]</td>
</tr>
<tr>
<td>Skatval*</td>
<td>Norway</td>
<td>CRS</td>
<td>23.0</td>
<td>31.0</td>
<td>123</td>
<td>1.0</td>
<td>[51]</td>
</tr>
<tr>
<td>Perniö*</td>
<td>Finland</td>
<td>CRS</td>
<td>30.0</td>
<td>33.4</td>
<td>140</td>
<td>1.0</td>
<td>[29,52,53]</td>
</tr>
<tr>
<td>Quyon, QC*</td>
<td>Canada</td>
<td>NA</td>
<td>26.0</td>
<td>34.0</td>
<td>151</td>
<td>0.95</td>
<td>[54,55]</td>
</tr>
<tr>
<td>Slomarka*</td>
<td>Norway</td>
<td>IL</td>
<td>22.0</td>
<td>34.0</td>
<td>100</td>
<td>0.95</td>
<td>[51]</td>
</tr>
<tr>
<td>St. Hilaire, QC*</td>
<td>Canada</td>
<td>IL</td>
<td>28.0</td>
<td>32.0</td>
<td>200</td>
<td>0.95</td>
<td>[56,57]</td>
</tr>
<tr>
<td>Dragvoll*</td>
<td>Norway</td>
<td>IL, CRS</td>
<td>31.0</td>
<td>38.0</td>
<td>279</td>
<td>1.0</td>
<td>[10,11,58,59]</td>
</tr>
<tr>
<td>Tiller-Flotten</td>
<td>Norway</td>
<td>CRS</td>
<td>26.0</td>
<td>36.0</td>
<td>132</td>
<td>0.95</td>
<td>[28]</td>
</tr>
<tr>
<td>Haney, BC</td>
<td>Canada</td>
<td>IL</td>
<td>22.5</td>
<td>32.3</td>
<td>181</td>
<td>0.95</td>
<td>[27]</td>
</tr>
<tr>
<td>Skatval</td>
<td>Norway</td>
<td>CRS</td>
<td>23.0</td>
<td>31.0</td>
<td>124</td>
<td>1.0</td>
<td>[51]</td>
</tr>
<tr>
<td>Koa</td>
<td>Norway</td>
<td>CRS</td>
<td>28.0</td>
<td>41.0</td>
<td>67</td>
<td>1.0</td>
<td>[51]</td>
</tr>
<tr>
<td>Lempaala</td>
<td>Finland</td>
<td>CRS</td>
<td>NA</td>
<td>NA</td>
<td>88</td>
<td>1.0</td>
<td>[29]</td>
</tr>
<tr>
<td>Masku</td>
<td>Finland</td>
<td>CRS</td>
<td>30.0</td>
<td>36.9</td>
<td>124</td>
<td>1.0</td>
<td>[29]</td>
</tr>
<tr>
<td>Paimio</td>
<td>Finland</td>
<td>CRS</td>
<td>27.5</td>
<td>33.7</td>
<td>138</td>
<td>1.0</td>
<td>[29]</td>
</tr>
<tr>
<td>Sipoo</td>
<td>Finland</td>
<td>CRS</td>
<td>25.4</td>
<td>33.7</td>
<td>332</td>
<td>1.0</td>
<td>[29]</td>
</tr>
</tbody>
</table>

Note: * = Presented in current study; NA = not available; IL = Incremental load oedometer tests; CRS = Constant Rate of Strain test.

Figure 5. Piezocone soundings for sensitive and structured clays: a) Dover, NH; b) Saint Jude, QC; c) Skatval, Norway; and d) Perniö, Finland.
Figure 6. Piezocone soundings for sensitive and structured clays: a) Quyon, QC; b) Slomarka, Norway; c) Saint Hilaire, QC; and d) Dragvoll, Norway.

Figure 7. Simplified OCR expressions for CPTU in sensitive clays along with lab reference values from consolidation tests for: a) Dover; b) Saint Jude; c) Skatval; and d) Perniö.
Figure 8. Simplified OCR expressions for CPTU in sensitive clays along with lab reference values from consolidation tests for: a) Quyon; b) Slomarka; c) Saint Hilaire; and d) Dragvoll clays.

To assess the OCR from CPTU in sensitive clays, equations (1), (2), and (3) are utilized with corresponding $M_{c1}$ and $M_{c2}$ that can be obtained from the original NTH expression [34] and modified NTH expression [35], respectively. Results from laboratory triaxial compression tests also confirm and validate these values. Appropriate values of $\phi_1'$, $\phi_2'$, and $\Lambda$ for the 8 sensitive clays are listed in Table 2 and applied to the CPTU results for OCR profiles in Figures 9 and 10. The agreement with the three CPTU equations is good as well as reasonable and comparable to the reference OCR profiles obtained from one-dimensional consolidation tests.

Figure 9. Modified SCE-CSSM solution for OCR in sensitive clays along with lab reference values from consolidation tests for: a) Dover; b) Saint Jude; c) Skatval; and d) Perniö.
Figure 10. Modified SCE-CSSM solution for OCR in sensitive clays along with lab reference values from consolidation tests for: a) Quyon; b) Slomarka; c) Saint Hilaire; and d) Dragvoll clays.

4. Piezocone screening in organic clays

Organic soils are often associated with high compressibility and low shear strength. Moreover, organic clays commonly exhibit problems in construction, foundation performance, and stability of embankments, excavations, and slopes [60]. Therefore, it is very important to be able to identify these geomaterials when CPTU soundings encounter soft organic clays, organic silts, peats, muskeg, gytta, and sulfide clays [61,62].

A review of CPTU data on a variety of different organic clays and soils show that when the three expressions from equations (8), (9), and (10) are used, a set of unmatched OCR profiles occur in the following hierarchal order [20]:

\[ 0.53 \Delta u_2 < 0.33 q_{\text{net}} < 0.60 q_E \]  

(12)

Therefore, equation (12) serves as the CPTU signature that is characteristic of organic fine-grained soils. To illustrate this, eight well-documented organic clay and peaty sites are summarized in Table 3. Full piezocone soundings for these sites are presented in Figures 11 and 12.
Table 3. Select CPTU database of organic clays used for case study applications.

<table>
<thead>
<tr>
<th>Clay Site</th>
<th>Location</th>
<th>OCR Method</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarapuí II soft organic clay*</td>
<td>Brazil</td>
<td>IL</td>
<td>[20,63]</td>
</tr>
<tr>
<td>Gammelgarden soft organic clay*</td>
<td>Sweden</td>
<td>IL, CRS</td>
<td>[20,64]</td>
</tr>
<tr>
<td>Nichollet soft peat*</td>
<td>MN, USA</td>
<td>IL</td>
<td>[65,66]</td>
</tr>
<tr>
<td>Belfast organic silty “sleech”*</td>
<td>Ireland</td>
<td>IL</td>
<td>[67,68]</td>
</tr>
<tr>
<td>Roback soft organic clay*</td>
<td>Sweden</td>
<td>IL</td>
<td>[69]</td>
</tr>
<tr>
<td>Suisun Bay soft organic clay*</td>
<td>CA, USA</td>
<td>IL</td>
<td>[70]</td>
</tr>
<tr>
<td>Bolling AFB soft organic clay*</td>
<td>Washington, DC, USA</td>
<td>IL</td>
<td>[20,71]</td>
</tr>
<tr>
<td>Lampen soft organic clay*</td>
<td>Sweden</td>
<td>CRS</td>
<td>[72,73]</td>
</tr>
<tr>
<td>Soft peat, Toronto Portlands</td>
<td>ON, Canada</td>
<td>na</td>
<td>[21]</td>
</tr>
<tr>
<td>Soft peat, Sherman Island</td>
<td>CA, USA</td>
<td>CRS, IL</td>
<td>[21]</td>
</tr>
<tr>
<td>Soft peat, Green Lake</td>
<td>MN, USA</td>
<td>IL</td>
<td>[21]</td>
</tr>
<tr>
<td>Soft peat, St. Paul</td>
<td>MN, USA</td>
<td>IL</td>
<td>[20]</td>
</tr>
</tbody>
</table>

Notes: * = Presented in current study; IL = Incremental load oedometer tests; CRS = Constant Rate of Strain consolidation tests; na = not available.

Figure 11. Piezocone soundings for organic soils located at: a) Sarapuí II, Brazil; b) Gammelgarden, Sweden; c) Nichollet, Minnesota; and d) Belfast, Ireland.
Figure 12. Piezocone soundings for organic soils at: a) Roback, Sweden; b) Suisun Bay, California; c) Bolling AFB, Washington, DC; and d) Lampen, Sweden.

When the CPTU screening approach is applied to the investigated organic soil deposits as presented in Figures 13 and 14, the three profiles from the expressions do not agree, thus serving as a warning sign and identification of organic geomaterials. These profiles show clear disagreement when compared to lab reference values from consolidation tests. Note that the hierarchical behavior aforementioned by Equation (12) is evident.

Figure 13. Simplified OCR expressions for CPTU in organic soils along with lab reference values from consolidation tests at: a) Sarapuí II; b) Gammelgarden; c) Nichollet; and d) Belfast clays.
4.1. Preconsolidation stress of organic clays from CPTU

For evaluating the preconsolidation stress of soft organic soils by CPTU, it has been recommended to lower the coefficients of equations (8), (9), and (10). This could be justified because organic clays and peats exhibit rather high friction angles ($\phi' > 40^\circ$) when compared to regular clays [60,61]. By use of a higher friction angle (e.g., $M_c > 1.2$) in equations (1), (2), (3), and (7), the resulting set of simplified equations (8), (9), and (10) would consequently have smaller coefficients for $q_{net}$, $\Delta u_2$, and $q_E$.

For instance, for the soft organic clays of Brazil, modified expressions have been developed [16,74]:

$$\sigma_p' = 0.125 \, q_{net} \quad (13)$$

$$\sigma_p' = 0.154 \, q_E \quad (14)$$

In another approach, for CPTU in a variety of soil types, a generalized solution retains the 0.33 coefficient of equation (8) and employs a power law algorithm in the form [75,76]:

$$\sigma_p' = 0.33 \, q_{net}^m' \quad \text{(units of kPa)} \quad (15a)$$

where the exponent $m'$ depends upon the soil behavioral type ($= 1.0$ intact inorganic clays; 0.90 organic clays; 0.85 silt mixtures; 0.80 silty sands; and 0.72 clean quartz-silica sands). Figure 15 shows the preconsolidation stresses $\sigma_p'$ for various soil types plotted versus the net cone resistance. The corresponding expression in dimensionless terms is given by:

$$\sigma_p' = 0.33 \, q_{net}^m' \left(\sigma_{atm}/100\right)^{-m'} \quad (15b)$$
where $\sigma_{\text{atm}}$ = reference pressure equal to 1 atmosphere = 1 bar = 100 kPa.

By adopting equation (15) with exponent $m' = 0.90$, the estimated preconsolidation profiles match well with the stress history results from one-dimensional consolidation tests for the 8 case studies involving soft organic clays and peats, as shown in Figures 16 and 17.

**Figure 15.** General relationship for preconsolidation stress of soils and CPT net cone resistance in different geomaterials (adapted after Agaiby and Mayne [76]).

**Figure 16.** CPTU profiles for preconsolidation stress in organic soils along with lab reference values from consolidation tests for: a) Sarapuí II; b) Gammelgarden; c) Nichollet; and d) Belfast.
Figure 17. CPTU profiles for preconsolidation stress in organic soils along with lab reference values from consolidation tests for: a) Roback; b) Suisun Bay; c) Bolling AFB; and d) Lampen.

5. Conclusions

The identification of regular clays that are insensitive and inorganic from organic clays and sensitive or quick clays using CPTU is normally handled via empirical soil behavioral classification charts that sometimes miss the mark. As an alternate screening method for separating these three clay categories, a preconsolidation stress approach can be utilized which is based in a hybrid formulation of spherical cavity expansion theory and critical state soil mechanics (SCE-CSSM).

For CPTU soundings in “regular” or “normal” soft to firm clays that are inorganic and insensitive, a first order estimate of preconsolidation stresses is found from:

\[ \sigma_p' \approx 0.53 \Delta u_2 \approx 0.33 q_{\text{net}} \approx 0.60 q_E. \]

When applying this approach to sensitive, quick, and structured clays, a hierarchal sorting shows: 0.60 q_E < 0.33 q_{\text{net}} < 0.53 \Delta u_2.

where the three corresponding profiles of \( \sigma_p' \) and OCR do not agree. Once identified properly, a modified SCE-CSSM solution is used to obtain the undrained rigidity index (I_R) based on the normalized cone tip resistance (\( Q = q_{\text{net}}/\sigma_{vo}' \)) and porewater pressure readings (\( U = \Delta u_2/\sigma_{vo}' \)). The modified solution utilizes the effective stress friction angle (\( \phi' \)) defined at: (i) peak stress (\( \phi_{q_{\text{max}}}' \)) and (ii) maximum obliquity (\( \phi_{MO}' \)). These can be obtained from the NTH limit plasticity solution. The derived expressions provide three formulations for clay stress history that relate the OCR to CPTU in terms of net resistance (\( q_t - \sigma_{vo} \)), excess porewater pressures (\( u_2 - u_0 \)), and effective cone resistance (\( q_t - u_2 \)), all of which agree well with the benchmark laboratory consolidation testing and corresponding profiles of preconsolidation stress at the site.

In contrast, when the simplified SCE-CSSM approach is applied to organic soils, a reversed hierarchal sorting shows: 0.53 \( \Delta u_2 < 0.33 q_{\text{net}} < 0.60 q_E \).

Once properly recognized, the preconsolidation stress of organic clays can be evaluated from a power law expression with net cone resistance.
Several case study examples from regular clays, sensitive clays, and organic soils that have been tested both in the laboratory (e.g., index parameters, plasticity, sensitivity, organic content, consolidation, triaxial) and by field CPTU soundings are presented in the paper to show the validity of the hierarchal approach.

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Conflict of interest

The authors declare no conflict of interest.

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