

# Profiling yield stresses and identification of soft organic clays using piezocone tests

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**Abstract.** The identification of soft organic clays by cone penetration tests is normally handled indirectly, using soil behavioral classification charts, since soil samples are not normally collected during the soundings. An alternate method is shown to be more reliable using three expressions for effective yield stress that depend on net cone resistance, excess porewater pressure, and effective cone resistance. Once identified as organic soils, a generalized procedure for assessing yield stress using a power law expression with net cone resistance is presented and applied to case studies from the USA, Sweden, and Brazil.

**Keywords.** Clays, Cone penetration, Organic clays, Piezocone, Preconsolidation, Stress history, Yield stress

## 1. Introduction

Cone penetration testing (CPT) with porewater pressure measurements, termed piezocone penetration tests (CPTu), offer an excellent means for continuous profiling of subsurface geostatigraphy and the evaluation of geoparameters in soils since at least three readings are measured with depth: cone tip resistance ( $q_t$ ), sleeve friction ( $f_s$ ), and penetration porewater pressures at the shoulder ( $u_2$ ).

An important initial step is the correct identification of soil type, since the selection of construction requirements, ground modification, and foundation type will depend upon the supporting medium. For CPT and CPTu, the soil classification is often assessed using charts that rely on the above-measured readings or using normalized parameters (i.e.,  $Q$ ,  $F$ , and  $B_q$ ), as discussed by Lunne, et al. [1], Robertson [2], and Mayne [3]. These soil behavioral charts (SBT) often correctly identify basic soil types such as clean sand, silt, and clay, however, in some instances involving more complex geomaterials, the charts can miss important situations. For instance, the presence of soft organic clays and peats is often missed by CPTu using the well recognized 9-zone SBT charts [4][5][6][7]. This is significant since soft organic soils are associated with issues of instability, high compressibility, exhibiting very low undrained shear strengths at high strain rates, excessive foundation settlements, biodegradation, and problems involving long-term creep. Herein, an alternate means of identifying soft organic soils via CPTu readings is offered.

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The in-situ yield stress ( $\sigma_p'$ ) or preconsolidation profile is a necessary input into the evaluation of foundation solutions and construction of embankments on soft ground. The benchmark profile of  $\sigma_p'$  is obtained from one-dimensional consolidation tests on undisturbed samples, either by incremental load oedometer or constant rate of strain (CRS) testing. Herein, an approach for evaluating  $\sigma_p'$  from CPTu in soft organic clays is presented and applied to several case studies. In normalized form, stress history is expressed as yield stress ratio ( $YSR = \sigma_p' / \sigma_{vo}'$ ), or overconsolidation ratio (OCR).

## 2. Profiling yield stresses in clays by CPTu

### 2.1 Simplified approach for inorganic and insensitive clays

A hybrid analytical model has been derived for evaluating the YSR from CPTu results in clays based on a combination of cavity expansion theory and critical state soil mechanics [8]. In a simplified form which applies to inorganic and non-structured clays of low-medium sensitivity, three first-order simplified expressions for evaluating the magnitude of yield stress in clays can be derived [9]:

$$\sigma_p' = 0.33 q_{net} = 0.33 (q_t - \sigma_{vo}') \quad (1)$$

$$\sigma_p' = 0.53 \Delta u_2 = 0.53 (u_2 - u_o) \quad (2)$$

$$\sigma_p' = 0.60 q_E = 0.60 (q_t - u_2) \quad (3)$$

An example using CPTu data in soft young inorganic and insensitive San Francisco Bay Mud reported by Pestana et al. [10] is shown in Figure 1. All 3 expressions agree with each other indicating  $\sigma_p'$  values of about 80 kPa at 7 m increasing to about 180 kPa at 24 m depth. These are compatible with reference CRS consolidation tests by Hunt et al. [11].

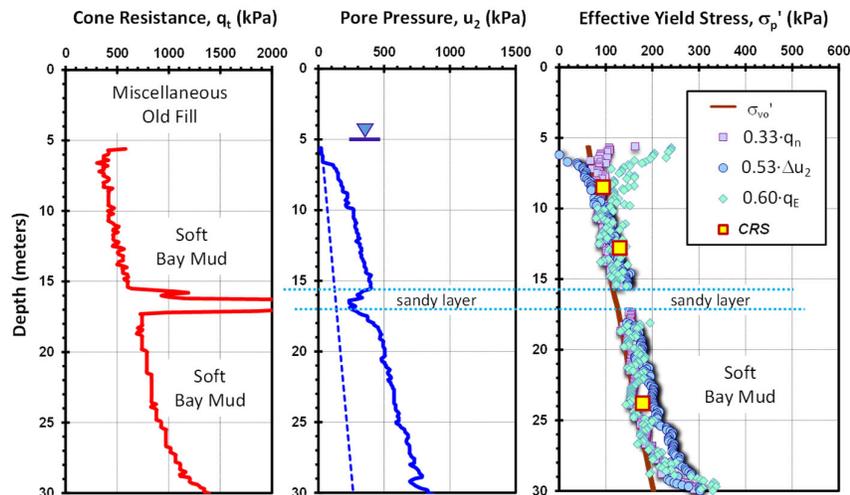


Figure 1. Piezocone sounding and yield stress in Bay Mud from CPTu expressions and lab CRS tests

## 2.2 Identification of organic clays

When the simplified approach is applied to organic clay deposits, the three expressions do not agree, thus serving as a warning sign and identification of such geomaterials. To illustrate, results from piezocone tests at Bolling Air Force Base in Washington D.C. are presented in Figure 2. The site is underlain by soft plastic alluvial organic clay and is very close to the Anacostia site reported by Mayne [12].

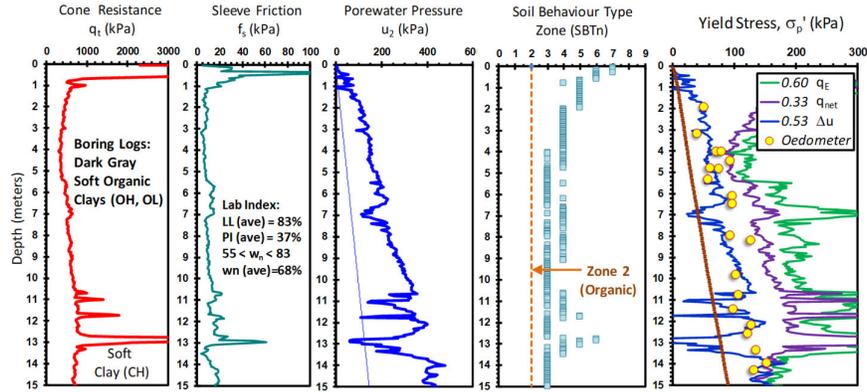


Figure 2. Piezocone sounding in organic clay at Bolling AFB, Washington, D.C.

The measured  $q_t$ ,  $f_s$ , and  $u_2$  are presented, along with the SBT soil types indicating primarily zone 3 “clays” and zone 4 “silt”, whereas these soils should fall in zone 2 (organic). Moreover, a recent study that collected CPTu data in 24 organic clays, only 1 site fell into the zone 2 grouping, as shown in Figure 3 [6]. Therefore, an independent means of establishing the presence of organic soils by CPTu would be helpful.

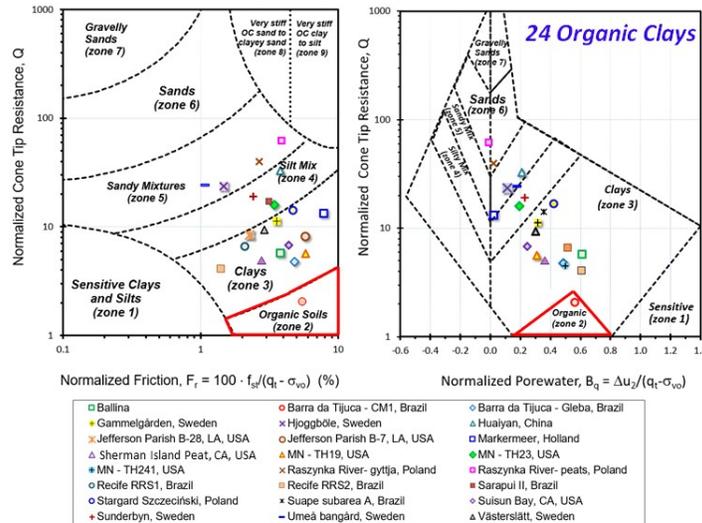


Figure 3. CPTu data from 24 organic clay deposits plotted on 9-zone soil behavioral type charts [6]

A review of the CPTu data on different organic soils show that when the three expressions from equations (1), (2), and (3) are used, unmatched profiles occur in the following hierarchal order and the geomaterials can be identified as organic soils:

$$0.53 \Delta u_2 < 0.33 q_{net} < 0.60 q_E \quad (4)$$

### 2.3 Profiling yield stresses in organic clays

For the soft organic clays of Brazil [7] [13], it has been recommended to lower the coefficients of equations (1) and (3).

$$\sigma_p' = 0.125 q_{net} = 0.125 (q_t - \sigma_{vo}) \quad (5)$$

$$\sigma_p' = 0.154 q_E = 0.154 (q_t - u_2) \quad (6)$$

In another approach, for CPTu in a variety of soil types, an alternate solution retains the 0.33 coefficient of equation (1) and employs a power law algorithm in the form [14]:

$$\sigma_p' = 0.33 q_{net}^{m'} \quad (\text{units of kPa}) \quad (7)$$

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 4 shows the yield stresses  $\sigma_p'$  for various soil types plotted versus the net cone resistance. The corresponding expression in dimensionless terms is given by:

$$\sigma_p' = 0.33 q_{net}^{m'} (\sigma_{atm}/100)^{1-m'} \quad (8)$$

where  $\sigma_{atm}$  = reference pressure equal to 1 atmosphere  $\approx$  1 bar = 100 kPa.

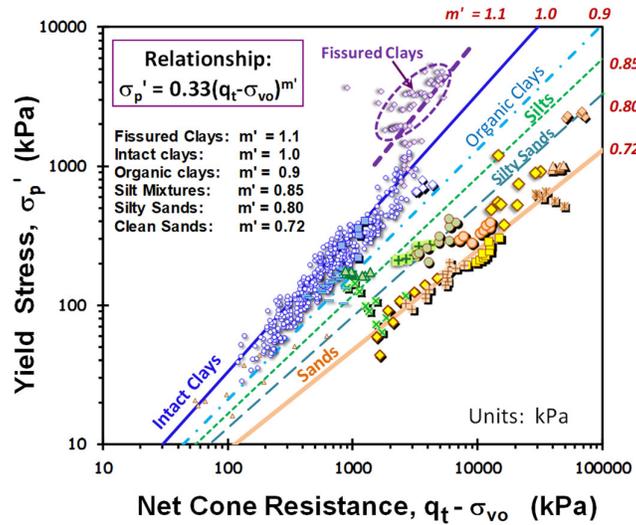


Figure 4. Generalized yield stress evaluation from CPT net cone resistance in soils [14]

### 3. Applications to organic clays

#### 3.1 Bolling AFB, Washington DC

Implementing the aforementioned approach to the CPTu data for the Bolling AFB site given in Figure 2, the hierarchal profiling expressed by equation (4) correctly identifies the soils as organic clays as presented in Figure 5. Applying equation (7 or 8) with  $m' = 0.9$  matches well with stress history results from oedometer tests for the soft organic clay.

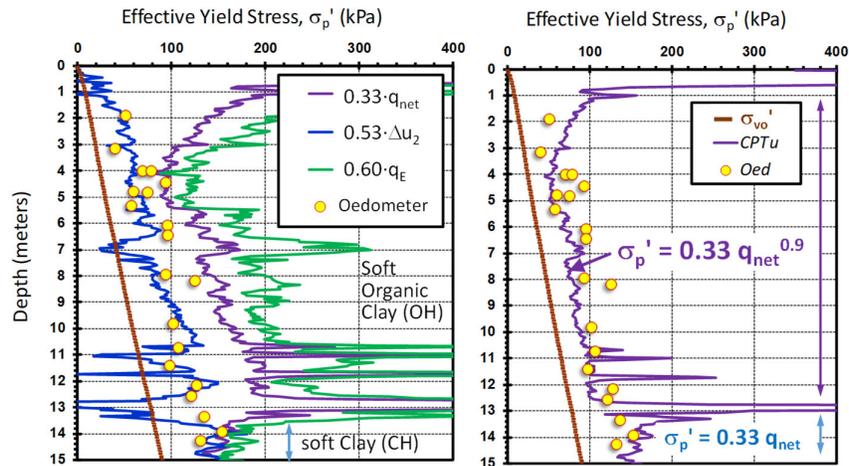


Figure 5. Post-processed CPTu results with consolidation data in soft organic clay in Washington D.C.

#### 3.2 Sarapuí II, Brazil

A research test site on soft organic clay has been established in the bay around Rio de Janeiro, Brazil [15]. Here, an extensive series of laboratory index measurements and mechanical tests for strength, compressibility, and stress history have been carried out with complementary series of in-situ tests including soil borings with samples, CPTu, flat plate dilatometer, and vane shear testing.

Results from the CPTu post-processing using the 9-zone SBT charts clearly show that the organic clay layers are not properly recognized [16], instead classifying the soil types as zone 3 (clay) and zone 4 (silt).

A representative CPTu sounding from the Sarapuí II site is shown in Figure 6 with corresponding profiles of  $q_t$ ,  $f_s$ , and  $u_2$  with depth. Post-processing the results per equation (4) shows confirmation of the hierarchal order with the estimation of preconsolidation stresses given by:  $0.53 \Delta u_2 < 0.33 q_{net} < 0.60 q_E$  and this properly identifies these soils as organic clays. The final right column of Figure 6 shows a good match of the CPTu-evaluated yield stress in agreement with the results from laboratory consolidation tests with  $m' \approx 0.9$ .

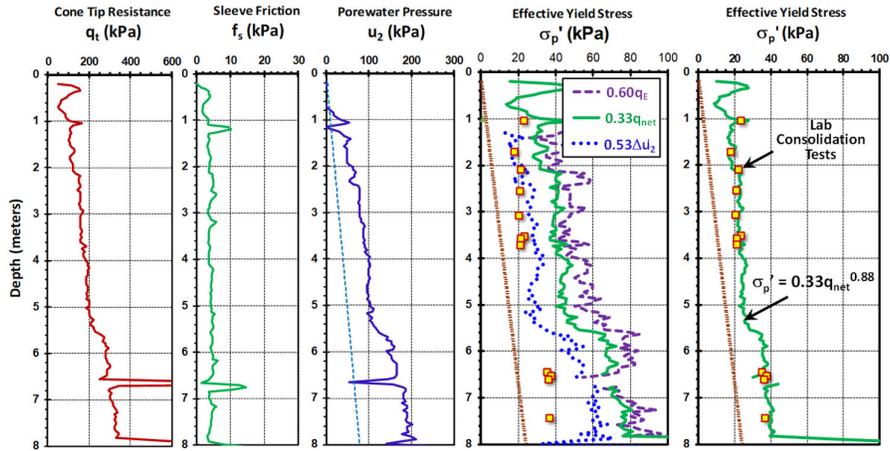


Figure 6. CPTu and yield stress profiles in soft organic clay at Sarapu II, Brazil

### 3.3 Gammelgarden, Sweden

The occurrence of organic clays in Sweden is well known and appreciated. Results of CPTu at the Gammelgarden site and affiliated lab testing on the organic clays are reported by Larsson et al. [17]. Figure 7a, 7b, and 7c present the profiles of  $q_t$ ,  $f_s$ , and  $u_2$  from a representative CPTu advanced at the site. As seen in Figure 3, the CPTu data place into the zone 3 (clays) for both the Q-F and Q-B<sub>q</sub> plots of the SBTn charts, whereas in contrast, the laboratory organic contents and soil descriptions clearly indicate these sulfide clays are actually organic in content. Unfortunately, the CPTu data do not fall within zone 2 region, as they should. Using the aforementioned screening approach, Figure 7d shows that the three simplified expressions do not agree with each other and fail to match the  $\sigma_p'$  profile from consolidation tests. Finally, the recommended power law equation with  $m' \approx 0.9$  shows reasonable matching with the CRS tests.

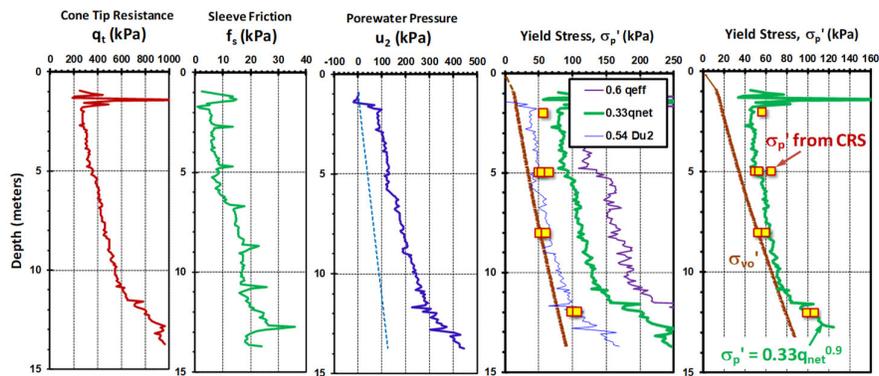


Figure 7. CPTu and yield stress profiles in soft organic sulfide clays at Gammelgarden, Sweden

### 3.4 Saint Paul, Minnesota

A research test site established by the Minnesota Department of Transportation is located just under I-35 and north of St. Paul, MN. The site is underlain by a layer of fill which overlies organic peats and clays, as confirmed by soil borings, laboratory testing, and in-situ CPTu soundings [18].

A representative CPTu at the Saint Paul site is presented in Figure 8 with profiles of  $q_t$ ,  $f_s$ , and  $u_2$  with depth. Post-processing shows evidence of the noted hierarchy and confirmation of organic soils. The final column shows the comparison of CPTu-estimated and laboratory reference values of  $\sigma_p'$  with depth at the site.

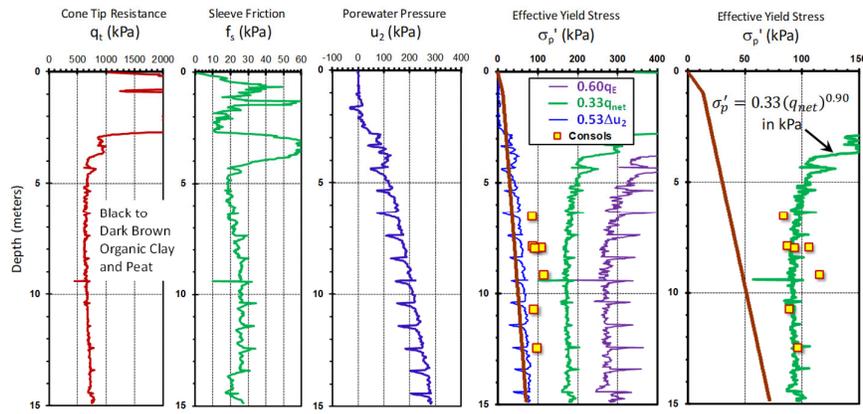


Figure 8. CPTu and yield stress profiles in soft peat at St. Paul, Minnesota

## 4. Conclusions

For CPTu soundings in "regular" or "normal" soft to firm clays that are inorganic and insensitivity, a first order estimate of yield stress is found from:

$$\sigma_p' \approx 0.53 \Delta u_2 \approx 0.33 q_{net} \approx 0.60 q_E$$

When applying this approach to organic soils, a hierarchal sorting shows:

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

This can be helpful in identifying the presence of soft organic clays and peats, especially since there are cases where soil behavioral charts do not correctly diagnose these types of geomaterials, instead often classifying them as clays or silts.

Once properly recognized, the yield stress of organic clays can be estimated from:

$$\sigma_p' \approx 0.33 q_{net}^{0.9}$$

Several examples from various organic clay sites tested by laboratory methods and field CPTu soundings are presented to show the validity of the approach.

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