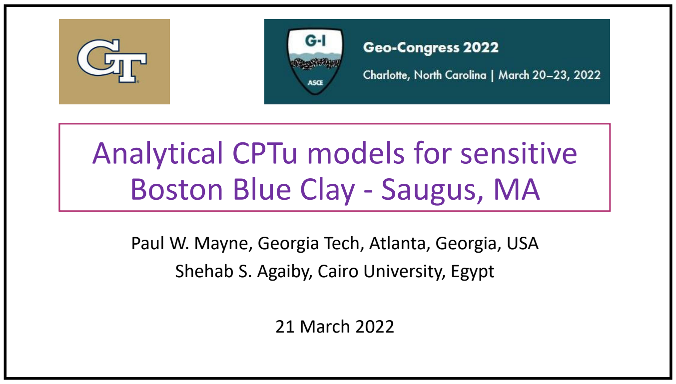
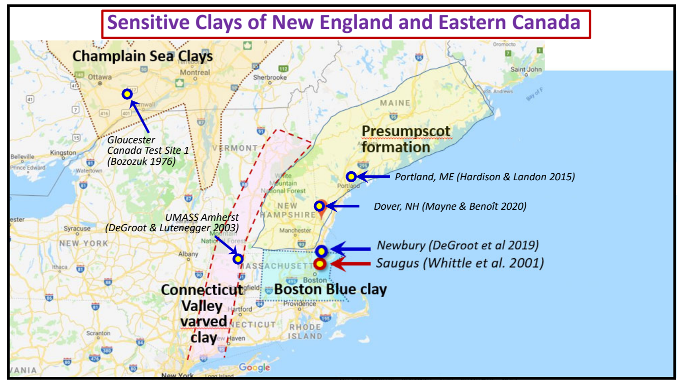
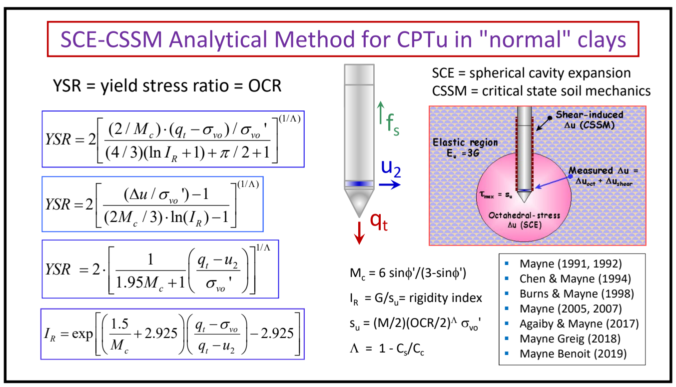
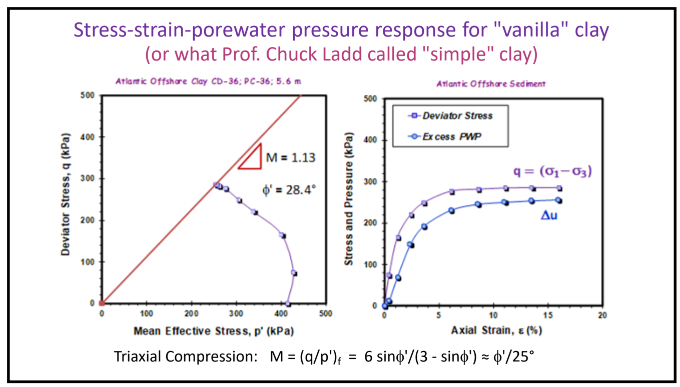
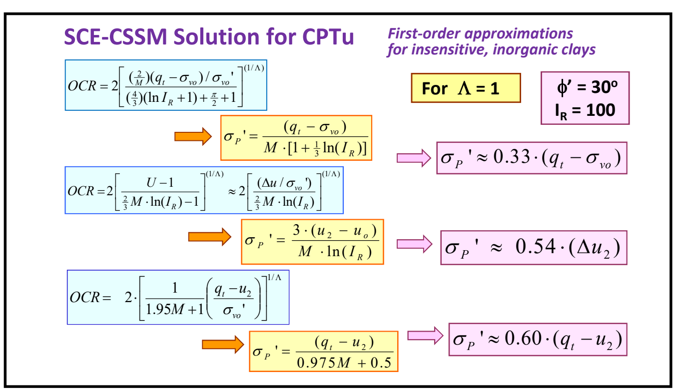
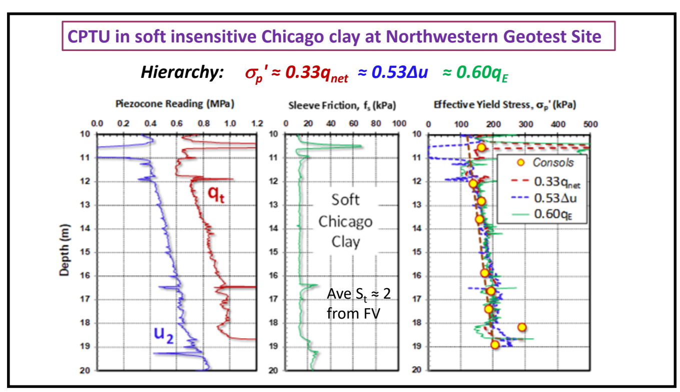

Geo-Congress 2022
Charlotte, North Carolina | March 20–23, 2022
Analytical CPTu models for sensitive Boston Blue Clay - Saugus, MA
Paul W. Mayne, Georgia Tech, Atlanta, Georgia, USA
Shehab S. Agaiby, Cairo University, Egypt
21 March 2022


Sensitive Clays of New England and Eastern Canada
Champlain Sea Clays
Gloucester Canada Test Site 1 (Bozozuk 1976)
Presumpscot formation
Portland, ME (Hardison & Landon 2015)
Dover, NH (Mayne & Benoît 2020)
UMASS Amherst (DeGroot & Lutenegger 2003)
Newbury (DeGroot et al 2019)
Saugus (Whittle et al. 2001)
Connecticut Valley varved clay
Boston Blue clay


SCE-CSSM Analytical Method for CPTu in "normal" clays
YSR = yield stress ratio = OCR
$YSR = 2\left[\frac{(2/M_c)\cdot(q_t-\sigma_{vo})/\sigma_{vo}'}{(4/3)(\ln I_R+1)+\pi/2+1}\right]^{(1/\Lambda)}$
$YSR = 2\left[\frac{(\Delta u/\sigma_{vo}')-1}{(2M_c/3)\cdot\ln(I_R)-1}\right]^{(1/\Lambda)}$
$YSR = 2\cdot\left[\frac{1}{1.95M_c+1}\left(\frac{q_t-u_2}{\sigma_{vo}'}\right)\right]^{1/\Lambda}$
$I_R = \exp\left[\left(\frac{1.5}{M_c}+2.925\right)\left(\frac{q_t-\sigma_{vo}}{q_t-u_2}\right)-2.925\right]$
f_s
u_2
q_t
SCE = spherical cavity expansion
CSSM = critical state soil mechanics
Shear-induced Δu (CSSM)
Elastic region $E_s = 3G$
Measured Δu = $\Delta u_{oct} + \Delta u_{shear}$
$\tau_{max} = s_u$
Octahedral-stress Δu (SCE)
$M_c = 6\sin\phi'/(3-\sin\phi')$
$I_R = G/s_u$ = rigidity index
$s_u = (M/2)(OCR/2)^{\Lambda}\,\sigma_{vo}'$
$\Lambda = 1 - C_s/C_c$
Mayne (1991, 1992)
Chen & Mayne (1994)
Burns & Mayne (1998)
Mayne (2005, 2007)
Agaiby & Mayne (2017)
Mayne Greig (2018)
Mayne Benoit (2019)

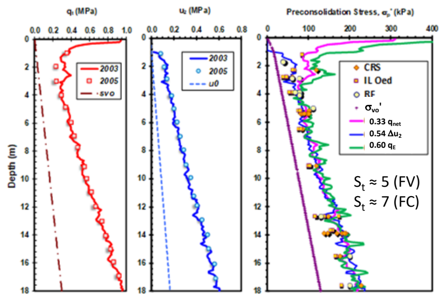

Stress-strain-porewater pressure response for "vanilla" clay
(or what Prof. Chuck Ladd called "simple" clay)
Atlantic Offshore Clay CD-36; PC-36; 5.6 m
Atlantic Offshore Sediment
M = 1.13
φ' = 28.4°
Deviator Stress, q (kPa)
Mean Effective Stress, p' (kPa)
Deviator Stress
Excess PWP
q = (σ1−σ3)
Δu
Stress and Pressure (kPa)
Axial Strain, ε (%)
Triaxial Compression: $M = (q/p')_f = 6\sin\phi'/(3-\sin\phi') \approx \phi'/25°$


SCE-CSSM Solution for CPTu
First-order approximations for insensitive, inorganic clays
For Λ = 1
φ' = 30°
$I_R = 100$
$OCR = 2\left[\frac{(\frac{2}{M})(q_t-\sigma_{vo})/\sigma_{vo}'}{(\frac{4}{3})(\ln I_R+1)+\frac{\pi}{2}+1}\right]^{(1/\Lambda)}$
$\sigma_p' = \frac{(q_t-\sigma_{vo})}{M\cdot[1+\frac{1}{3}\ln(I_R)]}$
$\sigma_p' \approx 0.33\cdot(q_t-\sigma_{vo})$
$OCR = 2\left[\frac{U-1}{\frac{2}{3}M\cdot\ln(I_R)-1}\right]^{(1/\Lambda)} \approx 2\left[\frac{(\Delta u/\sigma_{vo}')}{\frac{2}{3}M\cdot\ln(I_R)}\right]^{(1/\Lambda)}$
$\sigma_p' = \frac{3\cdot(u_2-u_o)}{M\cdot\ln(I_R)}$
$\sigma_p' \approx 0.54\cdot(\Delta u_2)$
$OCR = 2\cdot\left[\frac{1}{1.95M+1}\left(\frac{q_t-u_2}{\sigma_{vo}'}\right)\right]^{1/\Lambda}$
$\sigma_p' = \frac{(q_t-u_2)}{0.975M+0.5}$
$\sigma_p' \approx 0.60\cdot(q_t-u_2)$


CPTU in soft insensitive Chicago clay at Northwestern Geotest Site
Hierarchy: $\sigma_p' \approx 0.33q_{net} \approx 0.53\Delta u \approx 0.60q_E$
Piezocone Reading (MPa)
Sleeve Friction, f_s (kPa)
Effective Yield Stress, σ_p' (kPa)
Depth (m)
q_t
u_2
Soft Chicago Clay
Ave $S_t \approx 2$ from FV
Consols
$0.33q_{net}$
$0.53\Delta u$
$0.60q_E$

Bothkennar National Geotechnical Test Site - United Kingdom

(Hight et al, 2003; Powell and Lunne, 2005)

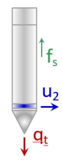


CPTu Parameters:

$q_{net} = q_t - \sigma_{vo}$

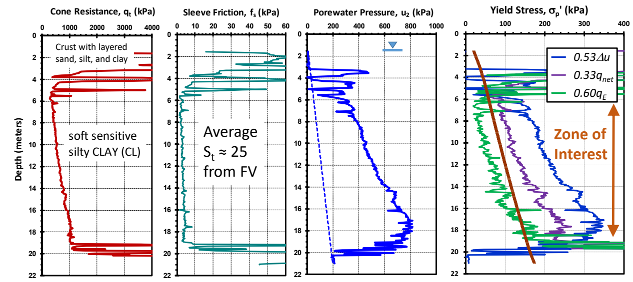
$\Delta u_2 = u_2 - u_0$

$q_E = q_t - u_2$



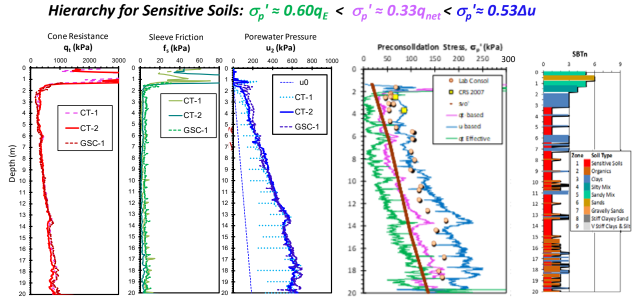
CPTU in soft sensitive clay at Dover NH (Mayne & Benoît 2020)

Hierarchy for Sensitive Soils: $\sigma_p' \approx 0.60q_E$ < $\sigma_p' \approx 0.33q_{net}$ < $\sigma_p' \approx 0.53\Delta u$



Canada Test Site 1 - Gloucester, Ontario (Agaiby & Mayne 2018)

Hierarchy for Sensitive Soils: $\sigma_p' \approx 0.60q_E$ < $\sigma_p' \approx 0.33q_{net}$ < $\sigma_p' \approx 0.53\Delta u$



CPTu method for screening of organic clays and sensitive/structured clays versus "normal" clays

- Normal or Well-Behaved Clays (generally OCRs < 3):

  Hierarchy: $\sigma_p' \approx 0.33q_{net} \approx 0.53\Delta u \approx 0.60q_E$

- Sensitive or Structured Clays (generally OCRs < 3):

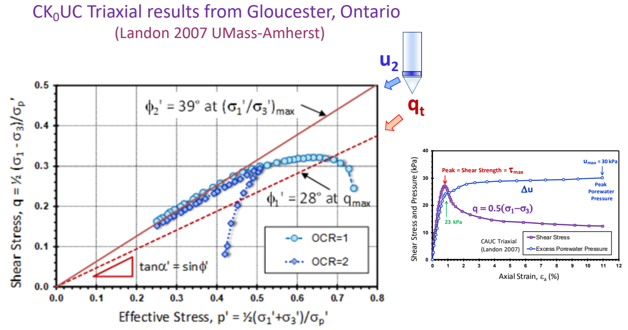
  Hierarchy: $\sigma_p' \approx 0.60q_E$ < $\sigma_p' \approx 0.33q_{net}$ < $\sigma_p' \approx 0.53\Delta u$

- Organic Clays (generally OCRs < 3):

  Hierarchy: $\sigma_p' \approx 0.53\Delta u$ < $\sigma_p' \approx 0.33q_{net}$ < $\sigma_p' \approx 0.60q_E$

CK_0UC Triaxial results from Gloucester, Ontario

(Landon 2007 UMass-Amherst)



SCE-CSSM Analytical Model for Sensitive Clays

$$YSR = 2\left[\frac{(q_t - \sigma_{vo})/\sigma_{vo}'}{M_{c1}\{\tfrac{2}{3}(\ln I_R + 1) + \tfrac{\pi}{4} + \tfrac{1}{2}\}}\right]^{(1/\Lambda)}$$

⇐ M_{c1} for $Q = (q_t - \sigma_{vo})/\sigma_{vo}'$; ϕ'_1 at q_{max}

$$YSR = 2\left[\frac{(\Delta u/\sigma_{vo}') - 1}{\tfrac{2}{3}M_{c2}\cdot\ln(I_R) - 1}\right]^{(1/\Lambda)}$$

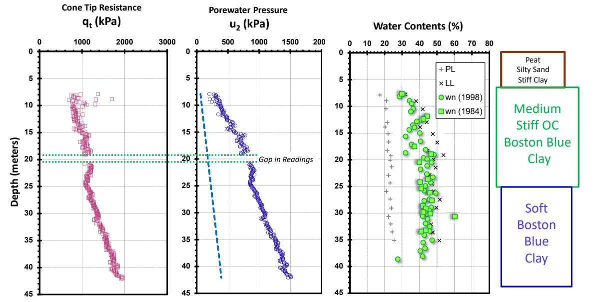
⇐ M_{c2} for $U = \Delta u_2/\sigma_{vo}'$; ϕ'_2 at $(\sigma_1'/\sigma_3')_{max}$

$$YSR = 2\cdot\left[\frac{Q_{t1} - (M_{c1}/M_{c2})[(\Delta u_2/\sigma_{vo}') - 1]}{1.95M_{c1} + (M_{c1}/M_{c2})}\right]^{1/\Lambda}$$

Triaxial Compression: $M_c = 6\sin\phi'/(3-\sin\phi')$

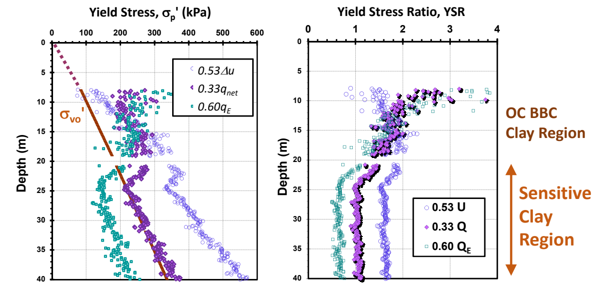
$$I_R = \exp\left[\frac{1.5 + 2.925M_{c1}\cdot a_q}{M_{c2} - M_{c1}\cdot a_q}\right] \quad where\ a_q = \frac{\Delta(u_2 - \sigma_{vo})}{\Delta(q_t - \sigma_{vo})}$$

CPTU in Boston Blue Clay, Saugus, MA
(Whittle et al. 2001)



CPTU screening for sensitive BBC at Saugus, MA

Hierarchy: $\sigma_p' \approx 0.60q_E$ < $\sigma_p' \approx 0.33q_{net}$ < $\sigma_p' \approx 0.53\Delta u$



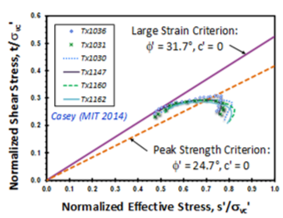
Rigidity Index from CPTU in Boston Blue Clay

$$I_R = \exp\left[\frac{1.5 + 2.925 M_{c1} \cdot a_q}{M_{c2} - M_{c1} \cdot a_q}\right] \quad where\ a_q = \frac{\Delta(u_2 - \sigma_{vo})}{\Delta(q_t - \sigma_{vo})}$$

Triaxial Compression:
$M_c = 6 \sin\phi'/(3 - \sin\phi')$

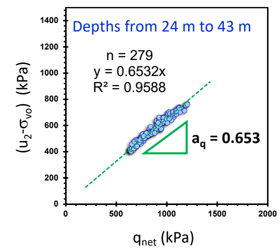
M_{c1} from ϕ' at q_{max}
M_{c2} from ϕ' at $(\sigma_1'/\sigma_3')_{max}$

ϕ' =	24.7	31.7
$\sin\phi'$ =	0.42	0.53
M =	0.97	1.27



Rigidity Index from CPTU in Boston Blue Clay

$$I_R = \exp\left[\frac{1.5 + 2.925 M_{c1} \cdot a_q}{M_{c2} - M_{c1} \cdot a_q}\right] \quad where\ a_q = \frac{\Delta(u_2 - \sigma_{vo})}{\Delta(q_t - \sigma_{vo})}$$



a_q =	0.653
M_{c1} =	0.97
M_{c2} =	1.27
I_R =	188.9
N_{kt} =	10.89

Undrained Strength of Boston Blue Clay, Saugus, MA

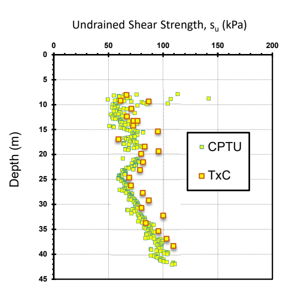
$$N_{kt} = \tfrac{4}{3} \cdot [\ln(I_R) + 1] + \tfrac{\pi}{2} + 1 = 10.9$$

$s_{uc} = q_{net}/N_{kt}$

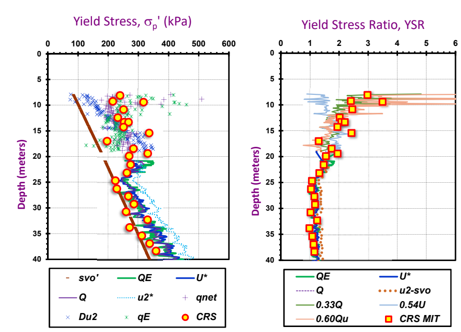
Vesic (1977) Solution

Rigidity Index:
I_R = 189

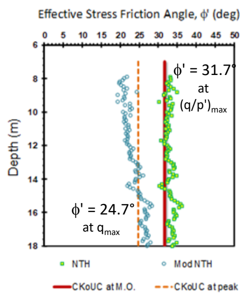
Cone Factor:
N_{kt} = 10.9



Yield Stress Profiles from CPTU in Boston Blue Clay

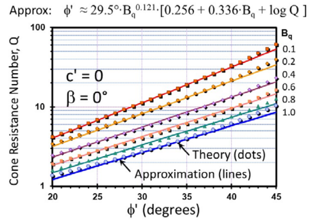


NTH Solution for Friction Angle from CPTU in Boston Blue Clay



Theory: $Q = \dfrac{\tan^2(45° + \phi'/2)\cdot\exp(\pi\cdot\tan\phi') - 1}{1 + 6\cdot\tan\phi'\cdot(1+\tan\phi')\cdot B_q}$

Approx: $\phi' \approx 29.5°\cdot B_q^{0.121}\cdot[0.256 + 0.336\cdot B_q + \log Q]$



Modified NTH Solution: Substitute Q' = Q/YSR^Λ

Simplified SCE-CSSM Solution for Monotonic Dissipation

Measured time for 50% consolidation: t_{50}

SCE-CSSM Solution: $c_{vh} = \dfrac{T'_{50}\cdot(a_c)^2\cdot(I_R)^{0.75}}{t_{50}}$

T_{50}' = 0.03 = time factor for 50% porewater dissipation

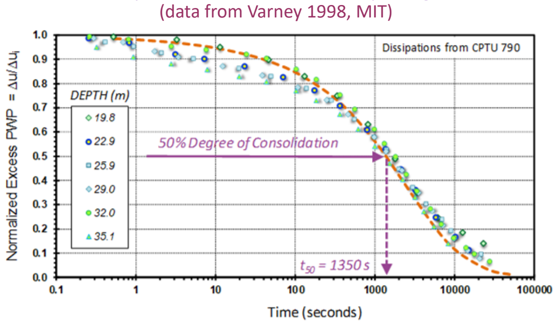
a_c = radius of penetrometer or probe or piling

I_R = G/s_u = undrained rigidity index of the clay from SCE-CSSM

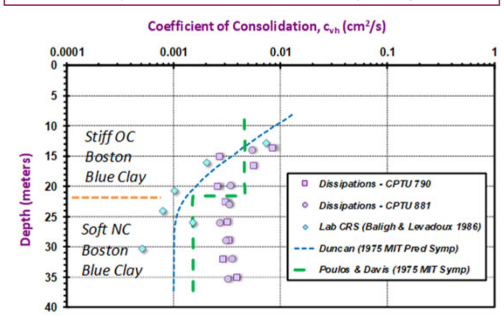
c_{vh} = coefficient of consolidation = $c_{vh} = \dfrac{k\cdot D'}{\gamma_w}$

CPTU Dissipations in Boston Blue Clay, Saugus, MA

(data from Varney 1998, MIT)



CPTU Dissipations in Boston Blue Clay, Saugus, MA



Sensitive Clay Sites Calibrated by NTH-SCE-CSSM Model

Site Name	*Location*	*Location*	*Reference*
Amherst Test Site	MA, USA	Conn Valley Varved Clay	DeGroot & Lutenegger (2005)
Boston Blue Clay	Saugus MA, USA	MIT research site	Whittle et al. (2001)
Dover-Newington	New Hampshire	Presumpscot Clay	Getcher & Benoit (2015)
Frastad	Sweden	soft quick clay	Lofroth et al. (2011, 2012)
Gloucester Test Site	Ontario, Canada	Leda Clay	Landon (2007); Agaiby & Mayne (2018)
Haney Clay	British Columbia	Sensitive clay (Landslide)	Mayne, Greig, & Agaiby (2018)
Lempaala	Finland	TUT research site	DiBuò et al (2018, 2020)
Masku	Finland	TUT research site	DiBuò et al (2018, 2020)
Paimio	Finland	TUT research site	DiBuò et al (2018, 2020)
Pernio T2	Finland	TUT research site	DiBuò et al (2018, 2020)
Portland (Falmouth)	Maine, USA	Presumpscot Clay	Hardison & Landon (2015)
Quyon Landslide	Quebec	Leda Clay (landslide)	Wang et al. (2015)
Saint Jude	Quebec	Sensitive clay (Landslide)	Locat et al. (2019)
Sipoo	Finland	TUT research site	DiBuò et al (2018, 2020)
Skatval	Norway	soft sensitive clay	Paniagua et al. (2017)
Tiller-Flotten Test Site	Norway	Trondheim	L'Heureux et al. (2019); Mayne et al. (2019)

Conclusions: CPTU in Boston Blue Clay, Saugus, MA

- All geoparameters from analytical models (no empirical correlations)
- NTH solutions for effective friction angle (drained & undrained strength)
  - ϕ'_{qmax} from original NTH
  - ϕ'_{MO} from modified NTH
- Hybrid SCE-CSSM model for CPTU in Clays:
  - $I_R = G/s_u$ = undrained rigidity index (imply G_f and γ_f)
  - s_u = undrained shear strength (triaxial compression)
  - YSR = yield stress ratio from Q, U, and Q_E
  - c_v = coefficient of consolidation from CPTU dissipations (imply k)

Analytical CPTU solutions applied to Boston Blue Clay

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Paul W. Mayne, Ph.D., P.E., Life M. ASCE[2]

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ABSTRACT

Representative piezocone penetration test (CPTU) soundings along with dissipation tests in structured Boston Blue clay (BBC) at the famous Saugus Station 246 site (Whittle 2001) are used for a complete geo-characterization where strength, stress history, and flow parameters are interpreted using closed-form analytical solutions. The test site is underlain by an upper overconsolidated (OC) clay layer over a lower structured and sensitive normally consolidated (NC) layer. A modified hybrid spherical cavity expansion – critical state soil mechanics (SCE-CSSM) framework is utilized to obtain the operational rigidity index (I_R), effective yield stress (σ_p'), and undrained shear strength (s_{uTC}) for the upper OC layer and lower NC structured layer, whereas the coefficient of consolidation (c_{vh}) is evaluated using the piezo-dissipation results. The interpreted profiles of σ_p', I_R, s_{uTC}, and c_{vh} from CPTU soundings agree well with results from laboratory consolidation and triaxial testing.

INTRODUCTION

Sensitive and structured clays are characterized by their special mechanical and physical engineering properties, where upon remolding, significant disturbance can result in a severe loss of shear strength and collapse. Hence, more detailed analyses are needed in the understanding of the stress-strain-strength behavior of such clays and in quantifying their stress history.

For marine deposits, sensitive clays consist of fine-grained geomaterials that were originally sedimented in salt-water environments but later leached by exposure to freshwater aquifers. They commonly exist in Canada, Norway, Sweden, and Labrador (L'Heureux et al., 2014), as well as in the New England area of the USA (Lutenegger 2015). Other types of structured clay deposits can occur due to environments that contain chemical constituents in groundwater regimes that result in soil characteristics rendering them unstable or collapsible (Locat et al., 2003).

CLAY STRESS HISTORY

The stress history of clays is commonly represented by a preconsolidation stress, or yield stress (σ_p'), that can be defined as the maximum effective overburden stress experienced by the soil during its stress history. The yield stress ratio (YSR = σ_p'/σ_{vo}') is the normalized and dimensionless form, where σ_{vo}' is the current effective vertical stress.

The most basic and conventional means to determine the preconsolidation stress is from the results of laboratory one-dimensional consolidation testing performed on undisturbed samples using an oedometer or consolidometer (ASTM D 2435) or automated constant rate of strain (CRS) device (ASTM D 4186). Laboratory-based techniques are associated with many issues such as sampling disturbance and handling, stress relief with possible swelling, change in effective stress, specimen trimming method, load application duration, secondary consolidation consideration, temperature, salt concentration in pore fluid, lack of proper saturation, specimen slenderness, and capacity of loading frame (Germaine and Germaine, 2009).

The independent evaluation of σ_p' from field test data can assist in validating lab measurements, as well as fill in the information between sampling depths. Usage of cone penetration tests (CPT) and piezocone tests (CPTU) for quantifying σ_p' in various clay deposits has been promoted by Konrad & Law (1987), Mayne (1991), Chen & Mayne (1994; 1996), Demers & Leroueil (2002), Larsson & Åhnberg (2005), Robertson (2009), and others.

Specifically of interest herein is the analytical solution developed by Mayne (1991) that relates YSR to CPTu parameters using a set of algorithms developed from spherical cavity expansion (SCE) and critical state soil mechanics (CSSM) since that same approach was extended to allow interpretations of flow parameters (c_{vh} and k) from piezodissipation tests (Burns & Mayne 1998). While these solutions are applicable to clays, silty clays, and clayey silts of low sensitivity, it became evident that structured and sensitive clays require a slightly modified SCE-CSSM hybrid model to address their evaluation of stress history, as well as associated piezocone dissipation testing, as discussed in Agaiby (2018); Mayne et al. (2018; 2019); Di Buò et al. (2019); Mayne & Benoît (2020), and Agaiby et al. (2021).

ORIGINAL SCE-CSSM SOLUTION

Chen and Mayne (1994) detailed the derivation of a hybrid formulation of spherical cavity expansion and critical state soil mechanics (SCE-CSSM) to express the cone tip resistance (q_t) and porewater pressure (u_2) using closed-form equations as follows:

$$q_t = \sigma_{vo} + [(4/3) \cdot (\ln I_R + 1) + \pi/2 + 1] \cdot (M/2) \cdot (YSR/2)^{\Lambda} \cdot \sigma_{vo}' \quad [1]$$

$$u_2 = u_o + [(2/3) \cdot (\ln I_R) \cdot (M) \cdot (YSR/2)^{\Lambda} \cdot \sigma_{vo}'] + [1 - (YSR/2)^{\Lambda}] \cdot \sigma_{vo}' \quad [2]$$

where M = (6 sinϕ')/(3-sinϕ') = slope of the frictional envelope for triaxial compression in q-p' space, $\Lambda = (1 - C_s / C_c)$ = plastic volumetric strain potential, C_s = swelling index, C_c = virgin compression index, I_R = rigidity index = G/s_u, and OCR = σ_p'/σ_{vo}'. Typically, the value of $\Lambda \approx 0.8$ for most insensitive clays while $\Lambda \approx 1.0$ for sensitive and structured clays.

The hybrid SCE-CSSM model can be rearranged to determine the yield stress ratio (YSR) of the clay in three separate formulations using net cone tip resistance ($q_{net} = q_t - \sigma_{vo}$), excess porewater pressure ($\Delta u = u_2 - u_0$), and effective cone resistance ($q_{eff} = q_t - u_2$):

$$YSR = 2 \cdot \left[\frac{(2/M) \cdot (q_t - \sigma_{vo})/\sigma_{vo}'}{(4/3) \cdot (\ln I_R + 1) + \pi/2 + 1}\right]^{(1/\Lambda)} \quad [3]$$

$$YSR = 2 \cdot \left[\frac{(\Delta u/\sigma_{vo}') - 1}{(2/3) \cdot M \cdot \ln(I_R) - 1}\right]^{(1/\Lambda)} \quad [4]$$

$$YSR = 2 \cdot \left[\frac{1}{1.95 \cdot M + 1}\left(\frac{q_t - u_2}{\sigma_{vo}'}\right)\right]^{(1/\Lambda)} \quad [5]$$

Measured excess porewater pressures by the penetrometer have two components: octahedral and shear induced. For soft to firm clays with YSRs < 2, the shear induced component of is small (< 20%) of the total u_2 reading (Baligh 1986; Mayne 1991; Burns & Mayne 1998). Thus, it can be omitted for all practical purposes to give a slightly simpler form:

$$YSR = 2 \cdot \left[\frac{(\Delta u/\sigma_{vo}')}{(2/3) \cdot M \cdot ln(I_R)}\right]^{(1/\Lambda)} \quad [6]$$

A set of stepped down versions of the equations can be developed to determine the stress history (σ_p') by assuming $\Lambda = 1$ so that the power law formats become linear equations for yield stress. Further approximations can be obtained by adopting characteristics values $\phi' = 30°$and I_R = 100 (Mayne, 2005) as follows:

$$\sigma_p' \approx 0.33 \cdot (q_t - \sigma_{vo}) \quad [7]$$

$$\sigma_p' \approx 0.54 \cdot (u_2 - u_o) \quad [8]$$

$$\sigma_p' \approx 0.60 \cdot (q_t - u_2) \quad [9]$$

Combining equations [3] and [4], the value of the rigidity index can be obtained as:

$$I_R = exp\left(\frac{1.5 + 2.925 \cdot M \cdot a_q}{M \cdot (1 - a_q)}\right) \quad [10]$$

where $a_q = (U^* - 1)/Q = (u_2 - \sigma_{vo})/(q_t - \sigma_{vo})$. Hence, a_q can be determined as a single value for any 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.

BBC AT SAUGUS STATION 246 SITE

Figure 1 presents the profiles from a representative CPTu sounding performed in the well-documented BBC at the MIT test site in Saugus, MA, as reported by Whittle et al. (2001). The conducted field investigation aimed to obtain porewater pressure readings for piezocone devices for penetration and dissipation phases and calibrating them numerically. Two tapered piezoprobes and two conventional piezocones were utilized. Figure 1 presents the measured profiles of cone resistance (q_t) and penetration porewater pressure (u_2) with depth. Piezocone testing was conducted using a type 2 piezocone penetrometer where the porewater pressures were measured at the shoulder location, in accordance with ASTM D 5778 procedures.

Boston Blue Clay (BBC) is a marine deposit that has had many environmental and geologic processes that have resulted in a sensitive clay structure (DeGroot et al. 2019). Based on comprehensive laboratory testing at the Saugus site reported by Ladd et al. (1994), the mean index readings in the clay layers include natural water content, w_n = 40%, liquid limit, LL = 45%, plasticity index, PI = 23%, unit weight, $\gamma_t = 1.8$ kN/m^3, and specific gravity of solids of 2.81, thus classified as low-plasticity marine clay per the Unified Soils Classification System (ASTM D 2487). Moreover, vane shear testing (VST) data by Ladd et al. (1980) show sensitivity (S_t) values up to 7 for the lower clay layer and the liquidity index (LI) values for the lower clay layer are greater than 1 which is indicative or suggestive of sensitive clays. Stress history and compressibility data was investigated extensively using CRS consolidation tests by Varney (1998); where the data (as presented in upcoming figures) showed that the lower clay layers at depths greater than 24.5m are normally-consolidated (NC) to very lightly overconsolidated (LOC) with YSR values ranging from 1.0 to 1.2; whereas the upper clay layers are stiff and moderately overconsolidated (OC).

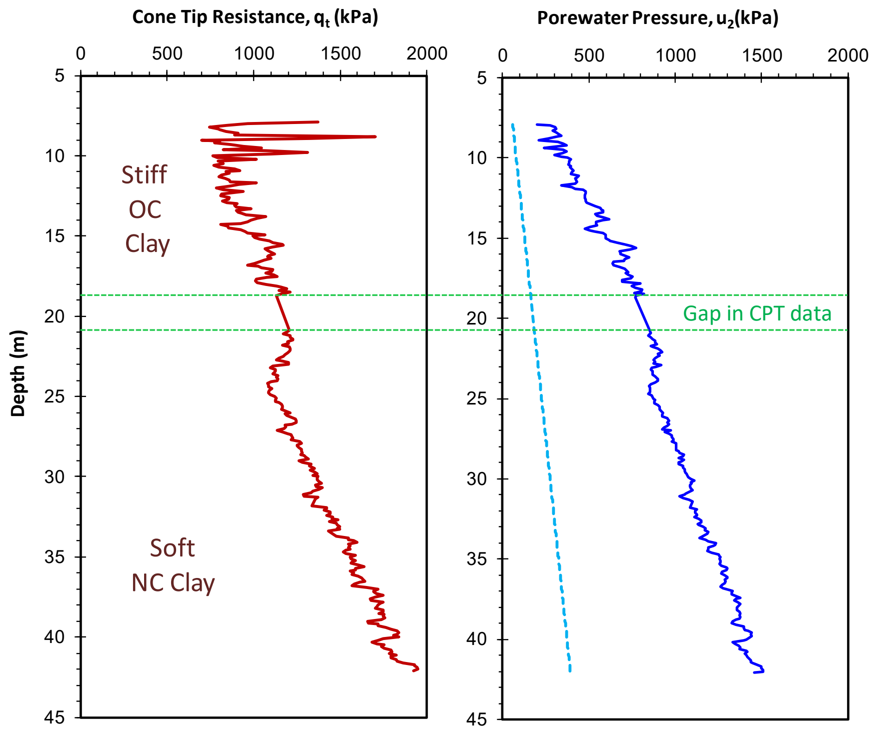

Figure 1. Piezocone sounding for BBC Saugus Station 246 test site, MA: (a) cone tip resistance, q_t; (b) porewater pressure, u_2. (Whittle et al., 2001)

As an initial attempt to estimate the stress history profiles, the entire site is considered as insensitive inorganic well-behaved clay, whereby using the simplified SCE-CSSM solutions presented in Equations [7] to [9], one can estimate the stress history profile for BBC Saugus test site as presented in Figure 2. However, from the three obtained profiles, it can be noticed that the simplified solution only works for the upper stiff overconsolidated clay layer above depths of about 20 meters where the estimated profiles agree well with the reference CRS data by Varney (1998). Accordingly, site-specific values for the input parameters are needed for the lower sensitive soft normally consolidated clay layer which include the effective friction angle (ϕ'), rigidity index (I_R), and plastic potential (Λ), along with the main measurements of the piezocone (q_t and u_2).

MODIFIED SCE-CSSM SOLUTION

Applications of the modified SCE-CSSM solutions in sensitive and structured clays is provided by Agaiby & Mayne (2018), Mayne et al. (2018, 2019), DiBuö et al. (2019), and Mayne & Benoît (2020). Three separate algorithms relate the YSR to normalized CPTU parameters: $Q = q_{net}/\sigma_{vo}'$ and $U = \Delta u_2/\sigma_{vo}'$. Note that the common porewater parameter $B_q = \Delta u_2/q_{net} = U/Q$.

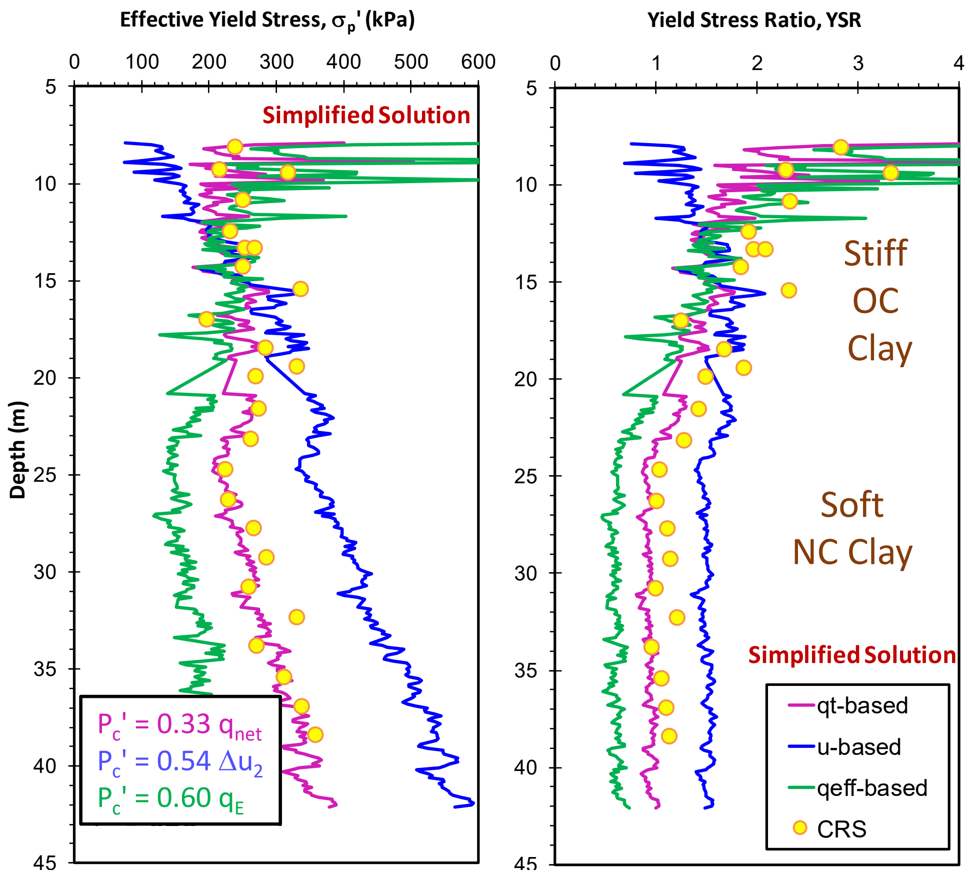

Figure 2. Incompatible profiles of effective yield stress and YSR from the simplified CPTU solutions indicating sensitive clay for BBC Saugus test site

The YSR profiles are expressed by the following:

$$YSR = 2 \cdot \left[\frac{Q/M_{c1}}{0.667 \cdot \ln(I_R) + 1.95}\right]^{1/\Lambda} \quad [11]$$

$$YSR = 2 \cdot \left[\frac{U^* - 1}{0.667 \cdot M_{c2} \cdot \ln(I_R) - 1}\right]^{1/\Lambda} \quad [12]$$

$$YSR = 2 \cdot \left[\frac{Q - \frac{M_{c1}}{M_{c2}}(U^* - 1)}{1.95 \cdot M_{c1} + \frac{M_{c1}}{M_{c2}}}\right]^{1/\Lambda} \quad [13]$$

where the value of M_{c1} is defined at peak strength (i.e., ϕ' at q_{max}) and M_{c2} is the value defined at large strains which occurs at maximum obliquity (i.e., ϕ' when the ratio $[\sigma_1'/\sigma_3']_{max}$). For insensitive clays, the value of ϕ' at q_{max} is equal to ϕ' at $(\sigma_1'/\sigma_3')_{max}$, and thus $M_c = M_{c1} = M_{c2}$. For insensitive clays, the value of $\Lambda \approx 0.8$, whereas for sensitive clays, a value of $\Lambda \approx 0.9$ to 1.0 is more suitable.

While equations [11] and [12] both depend on the I_R of the clay, Equation [13] is independent of the I_R and is obtained by combination of the first two formulations. The rigidity index is thus given directly from:

$$I_R = exp\left[\frac{1.5 + 2.925 \cdot M_{c1} \cdot a_q}{M_{c2} - M_{c1} \cdot a_q}\right] \quad [14]$$

After obtaining an operational value for the rigidity index using the derived solution, I_R can be directly used to evaluate the undrained shear strength of the clay under study using a cone bearing factor (N_{kt}) with the net cone tip resistance, where undrained shear strength is obtained from:

$$s_{uc} \quad = \quad \frac{q_{net}}{N_{kt}} \qquad [15]$$

From spherical cavity expansion theory, the cone bearing factor (N_{kt}) is expressed solely in terms of the rigidity index (Vesić 1977):

$$N_{kt} = [(4/3) \cdot (ln\, I_R + 1) + \pi/2 + 1] \qquad [16]$$

APPLICATION TO BBC

Using the results from K_0 consolidated triaxial compression (CK_0UC) tests reported by Casey (2014), a summary of the effective stress paths in q-p' space are presented in Figure 3. These show the mobilized effective stress friction angles at two definitions: (a) value at peak stress (q_{max}) and (b) value at maximum obliquity $(\sigma_1'/\sigma_3')_{max}$. In fact, it has been common to report effective friction angles mobilized at both maximum stress and maximum obliquity for triaxial conditions (e.g., Koutsoftas & Ladd, 1985; Berre 2014).

In an analogous concept for the piezocone, the measured cone resistance (q_t) corresponds to the peak friction angle ϕ'at q_{max} while the measured porewater pressure (u_2) relate to the value taken at larger strains, corresponding to maximum obliquity, or ϕ'_{MO}. For BBC Saugus test, the corresponding values are ϕ' at $q_{max} = 24.7°$ and $\phi'_{MO} = 31.7°$.

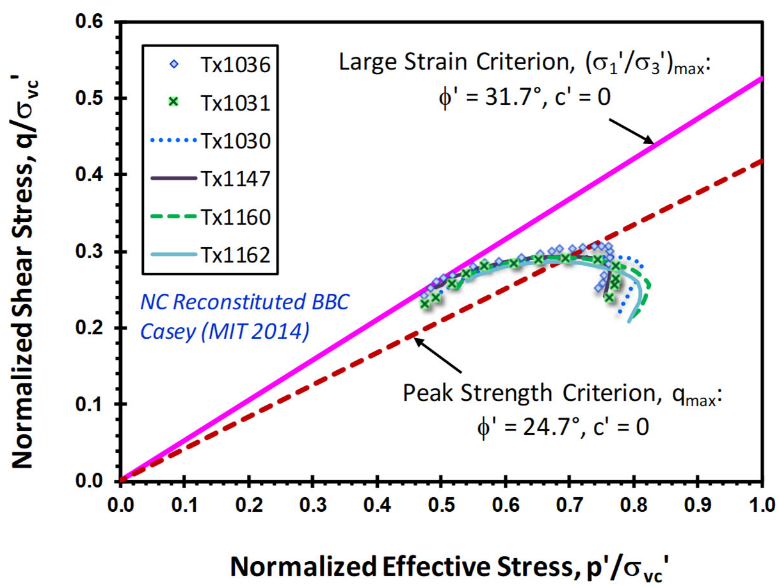

Figure 3. Normalized triaxial stress paths for reconstituted BBC indicating mobilized friction angles: (1) ϕ_1' at q_{max} and (b) ϕ_2' at maximum obliquity (data from Casey 2014)

As for the undrained rigidity index for Saugus test site, Figure 4 presents a plot of $(u_2\text{-}\sigma_{vo})$ plotted versus net cone tip resistance for the lower sensitive normally consolidated clay layer extending from 24 to 34 m: with a corresponding slope value of 0.6443. Using the slope value with the values of mobilized effective friction angle at q_{max}: $\phi_1' = 24°$ and at $(\sigma_1'/\sigma_3')_{max}$: $\phi_2' = 32°$ and applying equation [14], the corresponding rigidity index value (I_R) is 170.

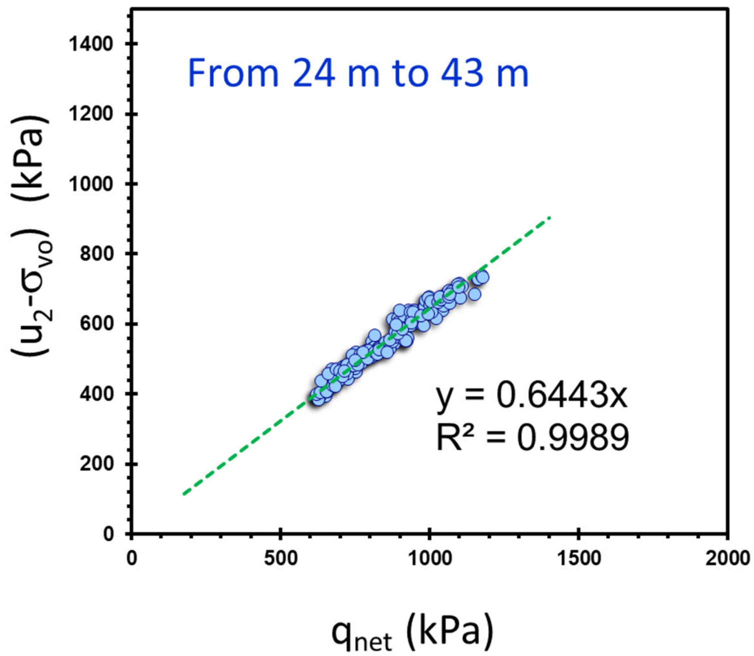

Figure 4. Plot to obtain slope parameter a_q from CPTU data for BBC Saugus test site

The obtained I_R value is used to obtain cone bearing factor (N_{kt}) as per equation [16] for evaluating the undrained shear strength (s_u). Using the determined I_R = 170, the corresponding N_{kt} value is 10.75. Laboratory reference values for s_u in CKoUC mode are obtained from the SHANSEP (Stress History And Normalized Soil Engineering Parameters) approach developed at MIT which is expressed as a normalized undrained shear strength:

$$s_u/\sigma_{vo}' = S \cdot YSR^m \qquad [17]$$

where the coefficient S and exponent m can be found using SHANSEP, as detailed by Ladd (1991) and Ladd & DeGroot (2003). The value of $S = (s_u/\sigma_{vo}')_{NC}$ is found experimentally by extensive laboratory testing with companion series of plane strain compression (PSC), simple shear (SS), and plane strain extension (PSE) tests on the soils at varied YSRs, or by series of triaxial compression (TC), simple shear (DSS), and triaxial extension (TE) tests. Representative S values as suggested by Ladd (1991) are 0.30 for TC, 0.21 for DSS, and 0.15 for TE. The exponent m can be determined experimentally and has been generally found to be on the order of 0.8 ± 0.1. For BBC, S = 0.31 and m ≈ 0.9.

Values of YSR from the CRS consolidation series were used to provide values of s_u at various depths as measured by Varney (1998). It is evident that the CPTU profile of s_u provides an excellent agreement with the triaxial compression laboratory measured s_u reference values as presented in Figure 5. Moreover, field vane data as reported by Ladd et al. (1980) is added for reference and comparison, where a fair agreement is shown for the upper OC clay layer.

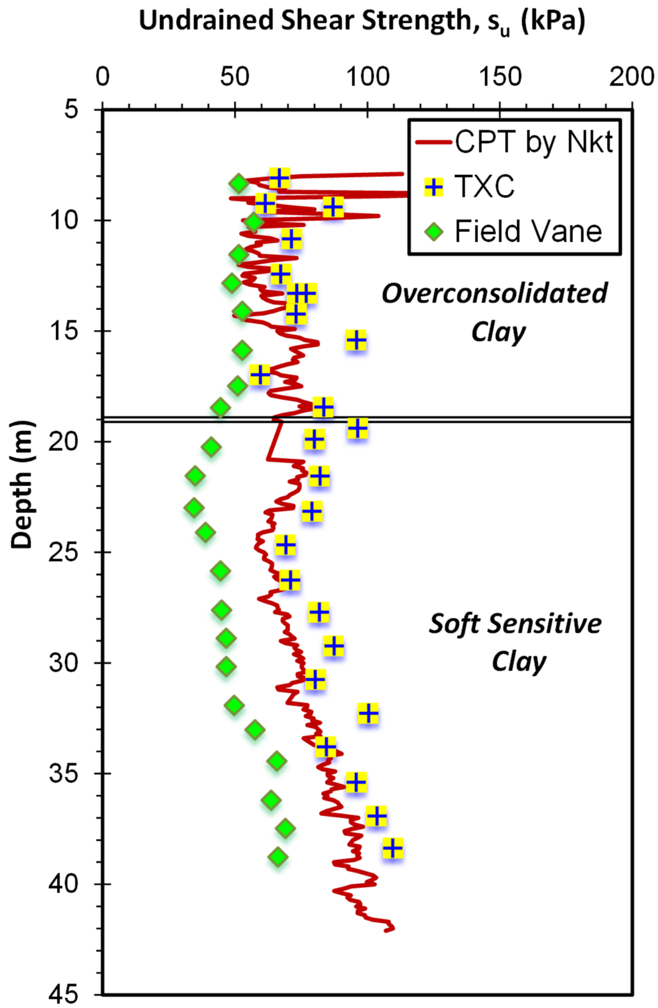

Figure 5. Undrained shear strength profile using the CPTU bearing factor in comparison with laboratory CK_0UC triaxial and field vane data

For the yield stress profiles in BBC, application of equations [11], [12], and [13] to the results of piezocone sounding with an operational rigidity index value of $I_R = 170$ and mobilized effective friction angle values at q_{max} ($\phi_1' = 24°$) and at $(\sigma_1'/\sigma_3')_{max}$ ($\phi_2' = 32°$), an improved stress history evaluation is obtained as presented in Figure 6 for the lower sensitive normally consolidated clay layer only. Here, in the soft clay below 19 m, the three expressions for YSR profiles all agree with each other and also compare quite well with the values from laboratory CRS consolidation tests.

Notably, however, in the OC region of clay above depths of 19 m, the YSR profiles do not agree. To resolve this issue, both the simplified approach and modified solutions can be used to derive YSR profiles for the full profile of OC and NC BBC at Saugus.

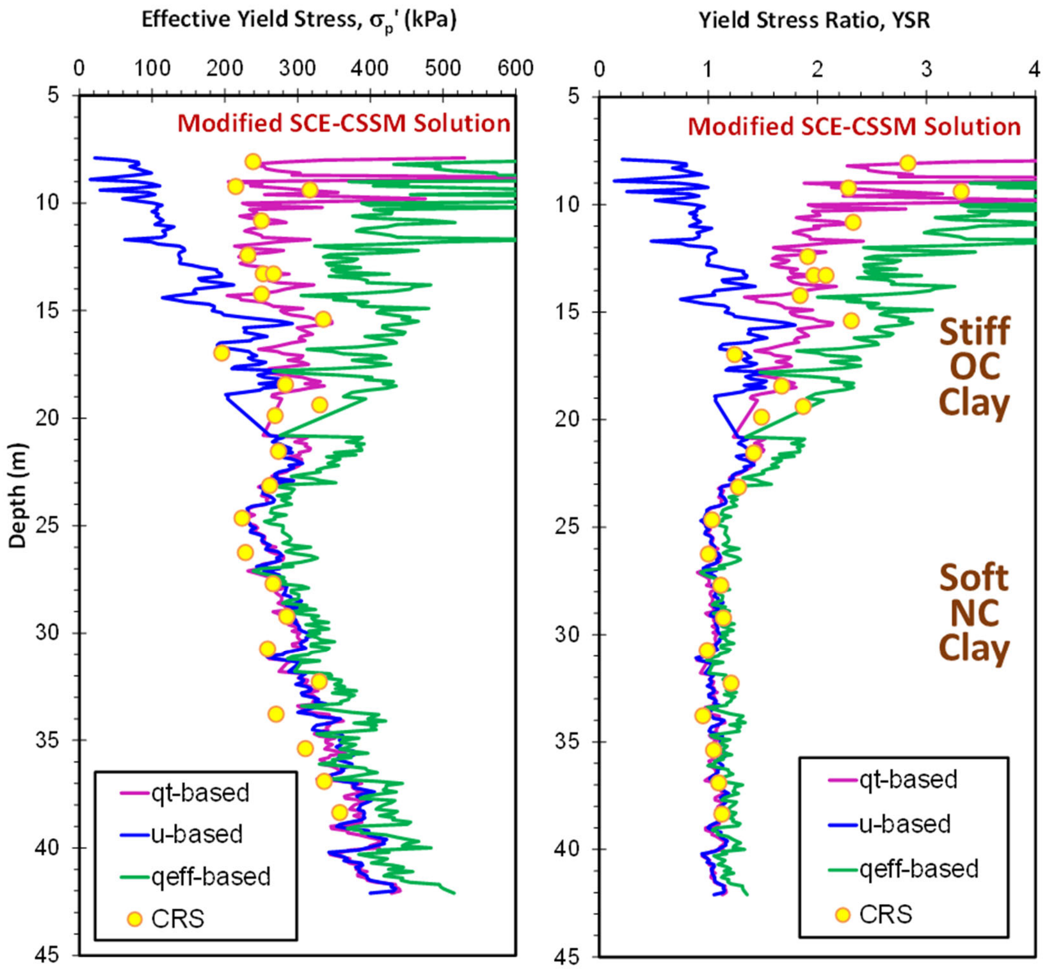

Figure 6. Profiles from modified SCE-CSSM solution and laboratory consolidation tests: (a) effective preconsolidation stress, and (b) YSR (CRS data from Varney, 1998)

By combining both solutions, the simplified original SCE-CSSM for the upper OC clay layer and the modified hybrid SCE-CSSM for the lower sensitive NC clay layer are used to evaluate YSR. As presented in Figure 7, good agreement is observed when compared with reference laboratory measured values of σ_p' and YSR profiles reported by Varney (1998)

FLOW PROPERTIES FROM PIEZODISSIPATION TESTS

The results of piezocone dissipation tests can be used to evaluate the permeability and the coefficient of consolidation of fine-grained soils (Jamiolkowski et al. 1985; Baligh & Levadoux 1986; Whittle et al. 2001). As the piezocone penetrates the ground, transient excess porewater pressures are generated around the probe. When the penetration is halted, the measured u_2 readings decay over time until eventually reaching the hydrostatic porewater pressure value (u_0) which is the equilibrium condition (Varney 1998).

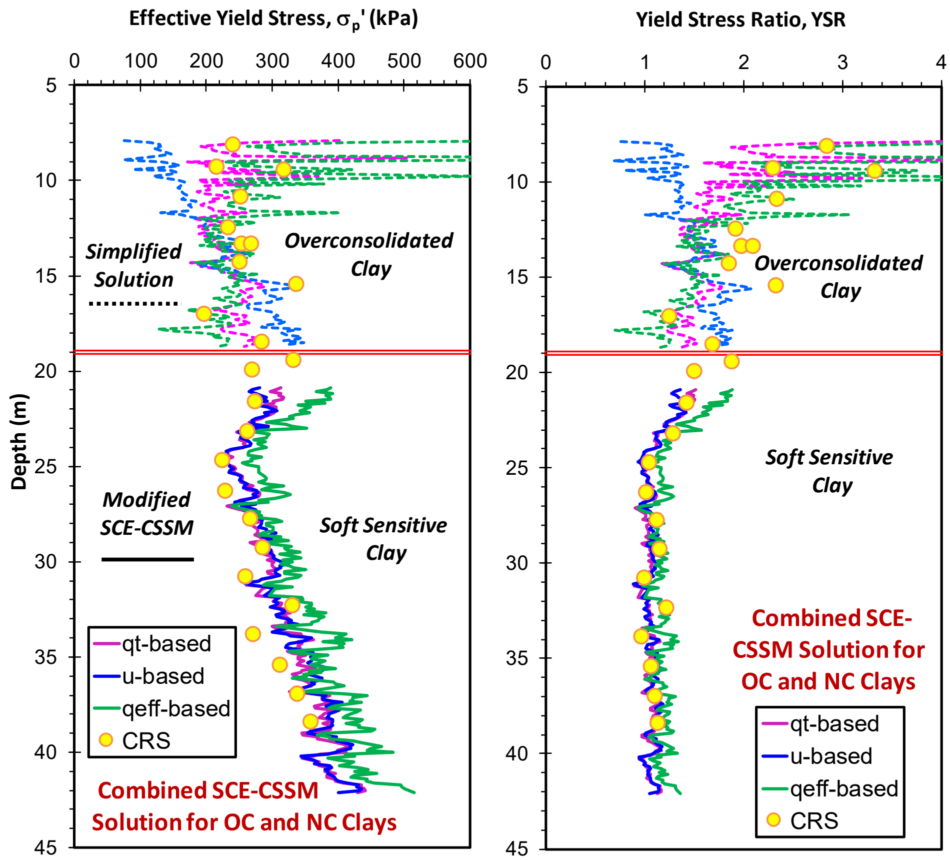

Figure 7. Profiles from combined SCE-CSSM solution for OC and NC clay at BBC Saugus test site: (a) effective preconsolidation stress, and (b) YSR (CRS data from Varney,1998)

While several procedures are available (e.g., Robertson et al. 1992; Chai et al. 2012), the original SCE-CSSM approach is detailed by Burns & Mayne (1998a, 1998b) and can be used here without alterations since the solution depends solely on the porewater pressures and input parameters. In this case, simply the higher mobilized ϕ_2' value is used for evaluating the excess porewater pressure responses. The generated excess porewater pressures that are measured are the sum of octahedral plus shear-induced components, which can be computed as:

$$\Delta u_{2\,i} \;=\; (\Delta u_{oct})_i \;+\; (\Delta u_{shear})_i \qquad [18]$$

where the octahedral component is represented by spherical cavity expansion that extends the plastic zone out into the surrounding ground (i.e., D/d ratio) and the shear-induced part occurs at the soil-structure interface as the steel of the penetrometer rubs against the clay soil (thin shear zone) and represented by CSSM. The initial values are determined from:

$$(\Delta u_{oct})_i \;=\; (2\cdot M_{c2}/3)\,(YSR/2)^{\Lambda}\cdot \ln(I_R)\cdot \sigma_{vo}' \qquad [19]$$

$$(\Delta u_{shear})_i \;=\; [1 - (YSR/2)^{\Lambda}]\cdot \sigma_{vo}' \qquad [20]$$

These two components dissipate at different rates because they are separate phenomena. Coupled flow is unwarranted and not applicable here. Hence, porewater pressure can be evaluated at any time (t) using the following algorithm (Mayne 2001):

$$(\Delta u_2)_t = \frac{(\Delta u_{oct})_i}{1+50\cdot T'} + \frac{(\Delta u_{shear})_i}{1+5000\cdot T'} \quad [21]$$

where the modified time factor (T') is given by:

$$T' = \frac{c_{vh}\cdot t}{a_c\cdot {I_R}^{0.75}} \quad [22]$$

where t = elapsed time after stopping penetration and ac = piezocone radius.

For normally consolidated (NC) to lightly overconsolidated (LOC) clays with monotonic dissipations and YSRs < 3, a simplified solution for the evaluation of c_{vh} can be expressed (Agaiby & Mayne 2018b):

$$c_{vh} = \frac{T'_{50}\cdot(a_c)^2\cdot(I_R)^{0.75}}{t_{50}} \quad [23]$$

where T'_{50} is the time factor for 50% consolidation and is equal to 0.028, a_c is the radius of the piezocone, and I_R = undrained rigidity index. This solution is obtained for the special analytical case when shear-induced porewater pressures are zero (i.e., YSR = 2).

To apply the simplified approach to the BBC Saugus test site, t_{50} values are obtained from a study at MIT by Varney (1998). A piezocone radius of a_c = 1.785 cm for the 10 cm^2 cone and operational rigidity index value of I_R = 170 are utilized in [23].

Figure 8 presents the results of the coefficient of consolidation obtained using the simplified SCE-CSSM solution along independent supporting lab and field data, where a good agreement is seen between the reference tests and piezo-dissipation interpretations.

CONCLUSIONS

For sensitive and structured clays, an acknowledged strain incompatibility occurs during triaxial compression, such that the deviator stress ($\sigma_1 - \sigma_3$) reaches a peak strength at low strains whereas excess porewater pressures are maximized later at much higher strains. Thus, the effective strengths at these points can be implemented to represent these phenomena. This stress-strain and porewater pressure behavior is witnessed within different sensitive and/or structured clays under study: BBC at Saugus Test Site in Massachusetts.

A slightly modified SCE-CSSM solution is presented that incorporates the following definitions of mobilized effective stress friction angles (ϕ'): (1) maximum deviatoric stress (ϕ'_{qmax}) and (2) maximum obliquity (ϕ'_{MO}). In concert with field CPTU soundings, these correspond to the measured cone tip resistances (q_t) and penetration porewater pressures (u_2), respectively. The derivation provides three formulations for clay stress history for evaluating YSR from CPTu, all of which agree well with the benchmark laboratory consolidation testing. Corresponding profiles of preconsolidation stress in the lower sensitive normally consolidated clay layer are obtained from the modified CPTU solutions, whereas the original SCE-CSSM framework with its simplified approximate expressions works for the upper overconsolidated insensitive clay layer. The modified approach provides a methodology to obtain operational rigidity index (I_R) where the proposed method gives a very good agreement with lab-measured undrained shear strength values using corresponding cone bearing factors.

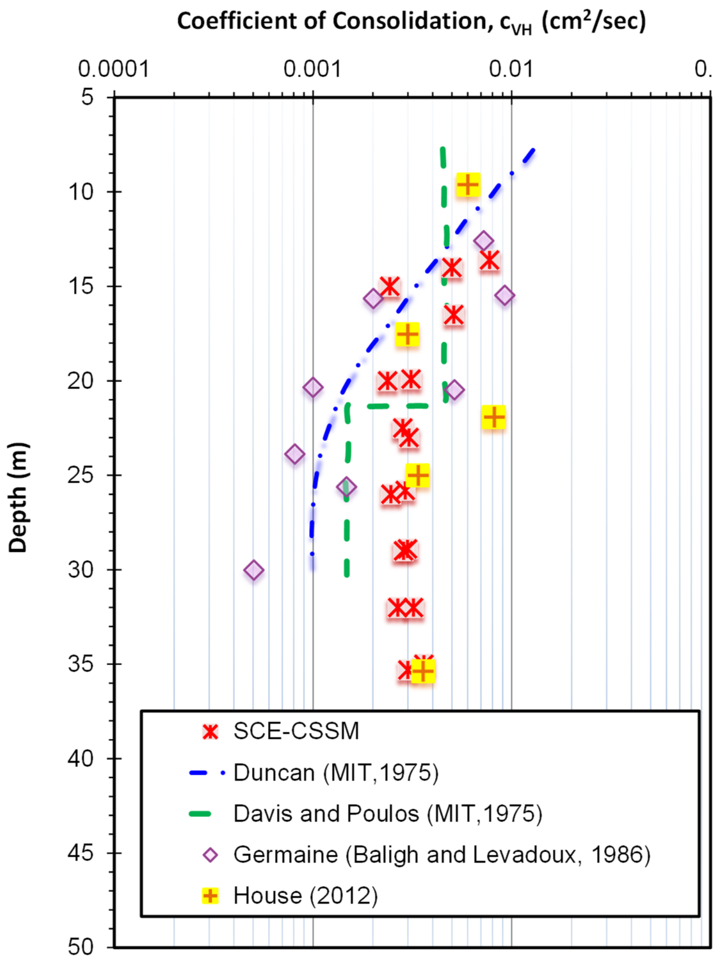

Figure 8. Comparison of predicted and measured profiles of coefficient of consolidation with depth at BBC Saugus test site

In addition, a simplified approach based on the hybrid SCE-CSSM framework is used to interpret flow parameters from piezodissipation tests taken in the sensitive lower BBC layer at Saugus test site, specifically to directly evaluate the profiles of coefficient of consolidation (c_{vh}) that fairly agree with independent laboratory and field measured reference values.

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