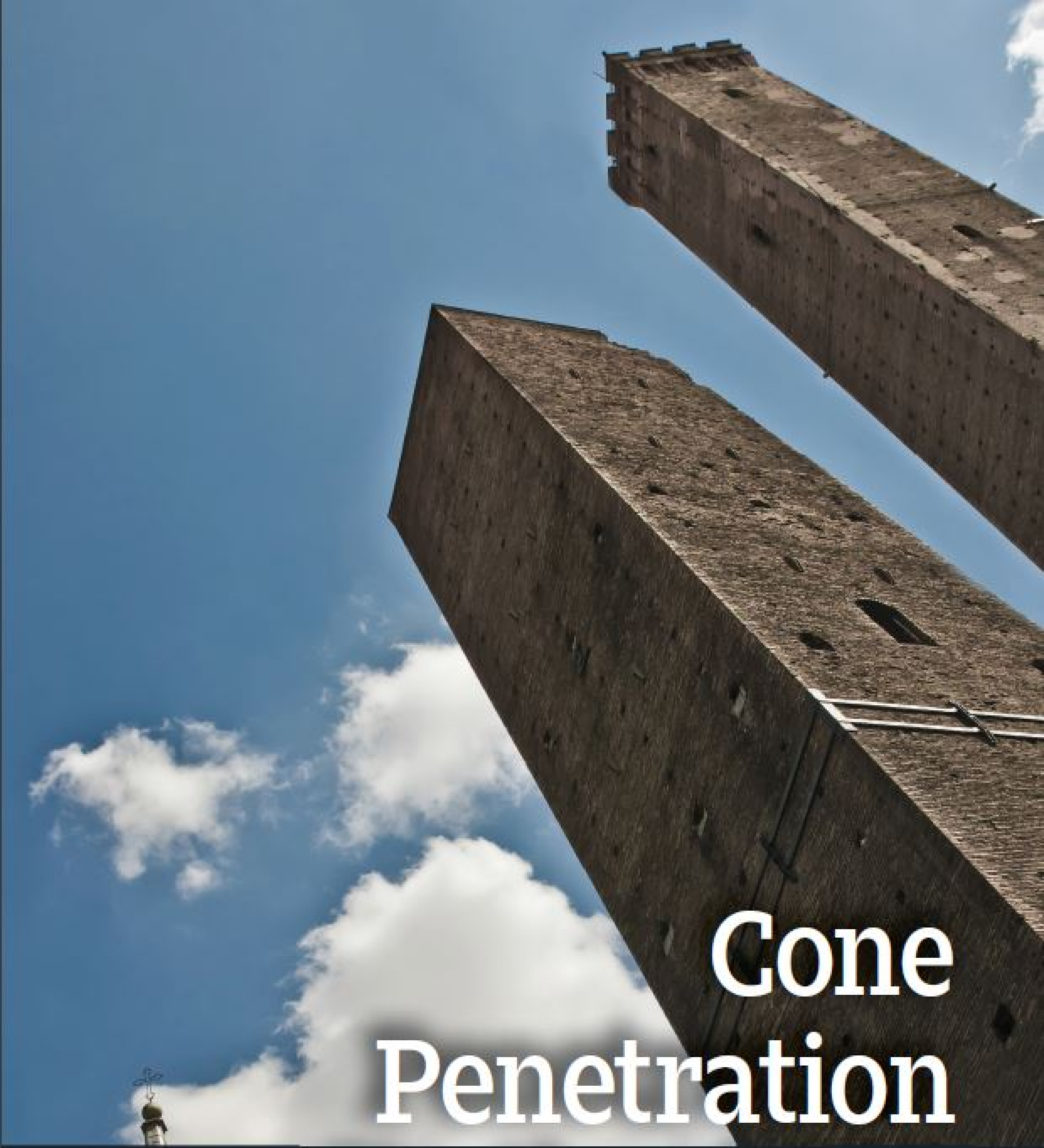

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CPTU evaluations in Appalachian Piedmont residual sandy silts

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ABSTRACT: Results from recent piezocone testing are compared with a statistical set of 22 prior CPTU soundings at the Opelika National Geotechnical Experimentation Site in Alabama. The site is underlain by residua comprised of fine sandy silts of the Appalachian Piedmont geologic province in the eastern USA. The cone resistance and sleeve friction from a 2016 CPTU compare well with the mean values from previous soundings while the porewater pressure readings are similar yet different because of a drop in the groundwater table from 2 m to 10 m over the period of study. Evaluations of the effective friction angle and yield stress from CPTU in residual soils are presented and compared with benchmark values obtained from laboratory triaxial and consolidation test results. Most interestingly, as the soil is intermediate with about 50-50 silt and sand, both undrained and drained penetration give more or less the same results.

1 INTRODUCTION

Since 70% of the Planet Earth is covered by oceans, most soils are formed originally as marine sediment. As a consequence, the majority of geotextbooks and research studies have focused on the interpretation of in-situ and laboratory tests involving water-borne deposits. It is estimated that approximately 5% of soils globally are found to be residual type, formed by the inplace disintegration and weathering of parent bedrock (USDA 2021), thus the evaluation of geoparameters in residua has been less well understood and quantified.

In this paper, results from piezocone penetration tests (CPTU) in residual sandy silts at a national test site in the southeastern USA are presented and interpreted. Of specific interest, the interpretation of effective stress parameters (c' and ϕ') and yield stress profile (σ_p') with depth provide the main focus.

When standard CPT soundings are performed at 20 mm/s, the results are considered *undrained* in clays, whereas in sands the response is taken as *drained* (Lunne et al. 1997). For silts, however, it is unclear whether the data are undrained or drained, or more likely in the regime of *partially-drained* behavior (DeJong, et al. 2012; Holmsgaard et. al. 2016; Blaker et al. 2019).

2 APPALACHIAN PIEDMONT RESIDUUM

The Appalachian Piedmont geologic province extends along the eastern USA ranging from Alabama to New Jersey, as shown in Figure 1. In addition to the surficial extent, the Piedmont lies beneath younger sediments of the Atlantic Coastal Plain deposits. Moreover, the Piedmont serves as an important source of crushed stone, aggregate, and sands from quarries, as well as provides the natural foundation bearing material for buildings, bridges, and highway pavements for major urbanized centers, including Atlanta/GA, Greenville/SC, Columbia/SC, Raleigh/NC, Charlotte/NC, Richmond/VA, Washington/DC, Baltimore/MD, and Philadelphia/PA.

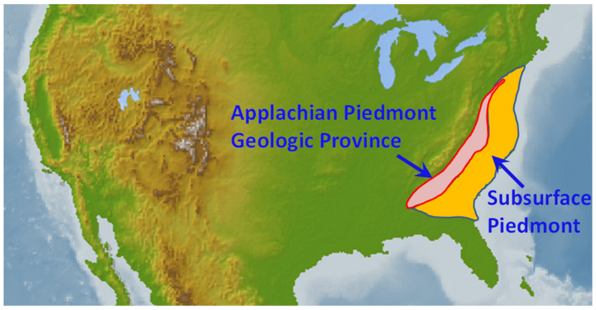

Figure 1. Extent of Appalachian Piedmont in eastern USA

Primary rock types include gneiss and schist of Precambrian Z-age that were later intruded by granitic rocks of Paleozoic age. Residual soils commonly form as very fine sandy silts (ML, MH) to very silty fine sands (SM) and a dual system (ML-SM) has been used in a modified form of the Unified Soil Classification System.

A generalized profile of the residual and saprolitic soil and rock types is presented in Figure 2. In the

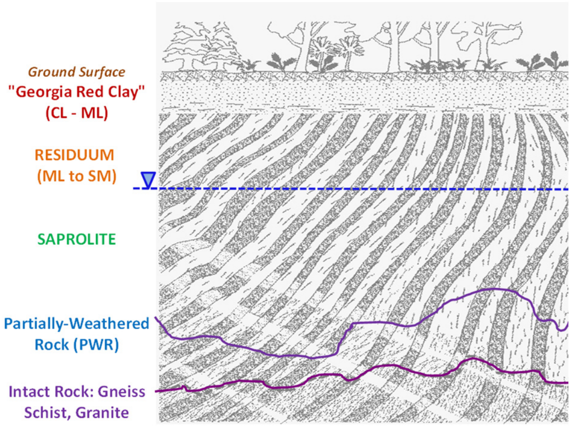

Figure 2. Generalized soil-rock profile in Piedmont geology

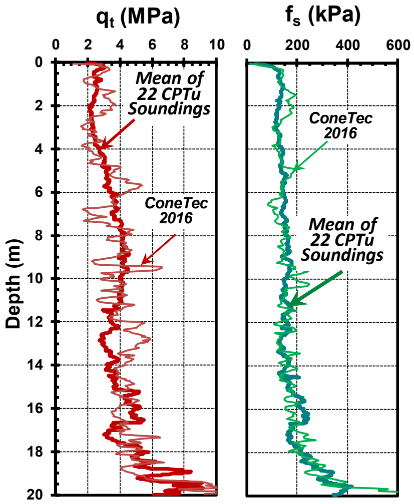

Figure 3. Comparison of mean q_t and f_s profiles from 22 CPTU series (2009 vintage) with 2016 sounding at Opelika test site

southern Piedmont, saprolitic residuum is called *partially-weathered rock* (PWR) when the standard penetration test (SPT) values exceed 100 blows per foot (bpf), whereas in the northern Piedmont, the term *decomposed rock* is used and defined when SPT values exceed 60 bpf.

2.1 *Opelika test site, Alabama*

Some three decades ago, six national geotest sites were established with federal funding in the continental USA (Benoît & Lutenegger 2000).

The Opelika test site in Alabama is situated in the Piedmont geology and serves as research grounds for laboratory, in-situ, geophysical, and full-scale foundation studies (Vinson & Brown 1997; Mayne et al. 2000; Mayne & Brown 2003; Anderson et al. 2019). The site is approximately 150 hectare, owned by the Alabama Dept. of Transportation, and managed by Auburn University.

2.2 *CPTU soundings at Opelika NGES*

During the period from around 1995 to approximately 2000, many CPTU soundings were conducted at the Opelika NGES by several research groups and commercial testing firms (Mayne & Brown 2003). A statistical summary of some 22 CPTUs at the site are reported by Mayne et al. (2009), as shown by Figure 3. At the time of those series of soundings, the groundwater table was generally found to be around 2 to 3 m deep (Anderson et al. 2019).

In 2016, two new CPTUs were conducted by ConeTec Group as part of a new research program on energy piles (Atalay 2019). Results from one of these soundings is superimposed on the q_t and f_s profiles in Figure 3, showing very good overall agreement in these profiles in magnitudes while also displaying some local variations within the residual soil profile due to differential weathering.

Penetration porewater pressures at the shoulder position (u_2) in the Piedmont residuum is often negative below the groundwater table (Finke et al. 2001), as evident in Figure 4. The 2016 CPTU reading is also shown and differs in that the water table was considerably lower ($z_w \approx 10$ m), as detailed by Anderson et al. (2019).

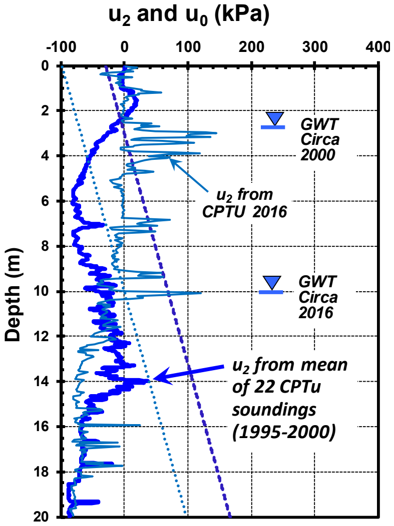

Figure 4. CPTU porewater pressure readings in fine sandy silt at Opelika test site.

2.3 *Groundwater effect on CPTU*

The depth to groundwater governs the equilibrium porewater pressure (u_0) and may affect the CPTU readings. Of interest here too is that the soils may be either dry, partially- or fully-saturated due to capillarity, since partially saturated soils may occur in the vadose zone between the ground surface and groundwater.

In some reported studies involving groundwater tables and partially saturated soils, the CPTU readings can show differences at seasonal changes due to matrix suction, partial or full capillarity, desiccation, and rainfall (e.g., Lehane et al. 2004; Huffman et al. 2015; Giaceti et al. 2019). In fact, for CPT in residual clayey sands derived from sandstone, Giaceti et al. (2019) showed changes in q_t and f_s in the upper 4 m while less differences at greater depths. Lehane et al. (2004)

had two test areas at the same site, one with euclalyptus trees and one in an open area. The CPTU soundings in the open area did not show seasonal changes, while those in the treed area did. Huffman showed some seasonal changes in CPTU readings at a silty site in Oregon.

However, the q_t and f_s profiles at Opelika do not show significant differences in the 2000 and 2016 profiles of cone and sleeve resistances, despite the large changes in groundwater levels.

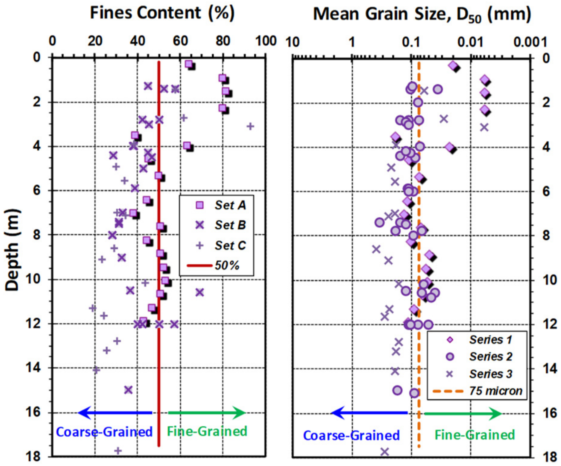

Figure 5. Fines content and mean grain size at Opelika

3 GEOCHARACTERIZATION OF PIEDMONT

In this section, selected CPTU interpretations in Piedmont residuum at Opelika will be compared with laboratory results.

3.1 *Laboratory testing of residuum*

An extensive set of drive samples and undisturbed tube samples were collected for laboratory testing. The lab program included: index testing, grain size, one-dimensional consolidation, triaxial compression, resonant column, direct shear, and permeability (Vinson & Brown 1997).

Results from mechanical analyses using sieves of recovered samples are presented in Figure 5. The measured fines content (FC) and mean grain size (D_{50}) are shown with depth to 16 m. It is evident that the soil particle sizes are at the threshold demarcation between fine-grained soils and coarse-grained soils, i.e. $D_{50} = 0.075$ mm corresponding to the US No. 200 sieve.

The fines content has a mean value FC = 44 % (n = 63), thus the dual symbol ML-SM is seen appropriate for the fine sandy silts to silty fine sands. Average liquid limits and plasticity indices were 46% and 8%, respectively, although many specimens test as nonplastic (Mayne & Brown 2003). Natural water contents typically range between 20 and 40% in the upper 16 m, yet specifically for the earlier set of data, the mean $w_n = 29.9 \pm 6.2$ % (n = 26) that dropped to $w_n = 25.7 \pm 7.0$% (n = 37) in 2016, presumably due to the groundwater drop.

Due to the closure of a nearby marble quarry some 4 km from the site in 2014, the groundwater has now begun a recovery toward its former regime (Anderson et al. 2019).

3.2 *Yield stress profiles in Piedmont residuum*

Consolidation tests on undisturbed samples from the site are reported by Hoyos & Macari (1999). Figure 6 shows the interpreted profile of yield stress (σ_p') and yield stress ratio (YSR = σ_p'/σ_{vo}') from this test series. Assuming that full capillarity occurs in the overburden, a drop in the groundwater table to 20 m and subsequent rise to a depth of 3 m could explain the apparent preconsolidation stress caused by changes in effective stress at the Opelika site (Mayne 2013).

For CPTU, a generalized first-order evaluation of σ_p' is made from (Mayne et al. 2009):

$$\sigma_p' = 0.33\ q_{net}^{m'} \qquad \text{[units of kPa]} \qquad (1)$$

where m' is an exponent that varies with soil type: m' = 1.0 (clays), 0.9 (organic soils), 0.85 (silts), 0.80 (silty sands), and 0.72 (clean quartzitic sands). For the fine sandy silts of the Piedmont geology, a value of 0.83 has been found suitable (Mayne 2013). The profile agrees well with the values from one-dimensional consolidation tests, as evident from Figure 6. The value of m' has also been related to mean grain size (D_{50}), fines content (FC), and material index (I_c), as detailed by Agaiby & Mayne (2019).

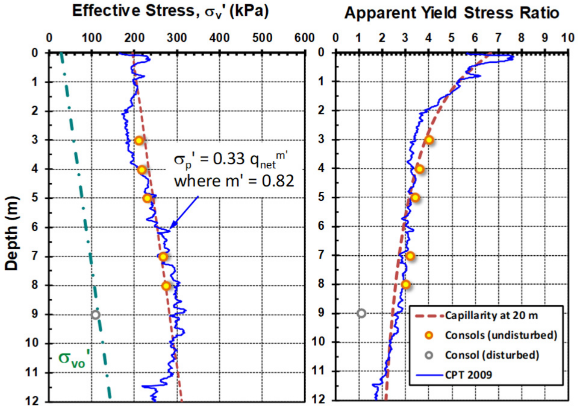

Figure 6. Yield stress and YSR at Opelika test site

3.3 *Triaxial friction angle of Piedmont soils*

A total of 23 triaxial compression tests were performed on tube samples taken from the site (Vinson & Brown 1997; Brown & Vinson 1998). A summary of these tests is presented in Figure 7 giving an overall effective stress envelope represented by the Mohr-Coulomb parameters: c' = 0 and $\phi' = 35.5°$.

At each sample depth, several CIUC type triaxials were conducted where the confining stresses were applied either at the in-situ overburden, or approximately half or about double the effective overburden.

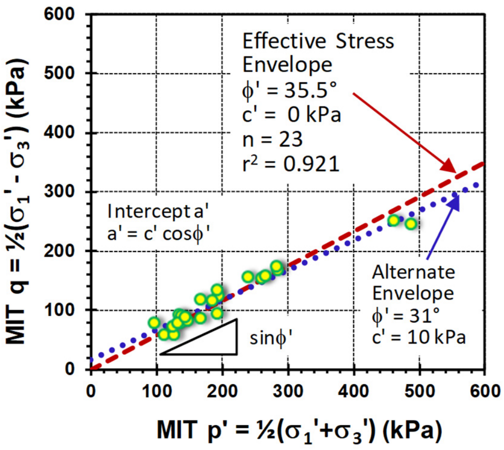

Figure 7. Summary triaxial tests at Opelika test site

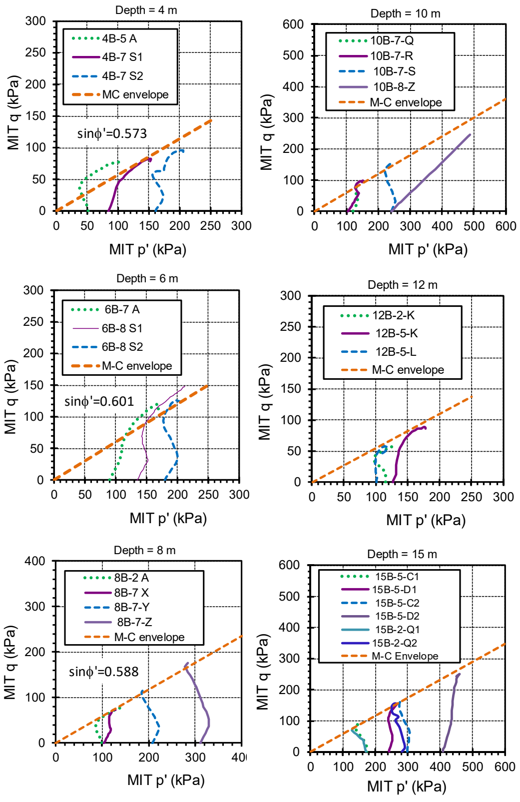

Figure 8. Triaxial results for various depths at Opelika

Consequently, an evaluation of the secant effective friction angle at six depths is made in Figure 8. Values of ϕ' ranged from 33.5° to 37.1°.

4 CPTU EVALUATION OF FRICTION ANGLE

For CPTU in silts, it is not initially clear whether the evaluation should be drained, undrained, or intermediate, such as partially-drained (DeJong et al. 2012; Holmsgaard et al. 2016; Bihs et al. 2018). This is a major conundrum for CPTU interpretation in Piedmont fine sandy silts.

4.1 *CPTU evaluation of ϕ' in sands*

At the standard rate of 20 mm/s, CPTU in clean sands is considered drained response. Various methods for evaluating ϕ' from CPTU in sands are available (Ching et al. 2017) including an approach from Robertson & Campanella (1983):

$$\phi' = \arctan[0.1 + 0.38\cdot\log_{10}(q_t/\sigma_{vo}')] \qquad (2)$$

A method based on corrected CPT chamber tests from Kulhawy & Mayne (1990):

$$\phi' = 17.6° + 11.0°\cdot\log_{10}[(q_t/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm})^{0.5}] \qquad (3)$$

where $\sigma_{atm} \approx 1$ bar = 100 kPa. A modified form of this is given by Robertson & Cabal (2015):

$$\phi' = 17.6° + 11.0°\cdot\log_{10}(Q_{tn}) \qquad (4)$$

where $Q_{tn} = (q_{net}/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm})^n$ is a normalized net cone tip resistance that has a variable exponent that ranges from about 1 in clays to 0.75 in silts to around 0.5 in sands.

For the Opelika CPTU, the various normalized cone resistance parameters (q_t/σ_{vo}', q_{t1}, Q, Q_{tn}) are shown in Figure 9a. It can be stated that these profiles are quite similar.

In fact, a recent study of 27 sands and silty sands that were sampled undisturbed using special freezing methods and/or gel samplers confirmed the relationships given by both (3) and (4) by comparison with laboratory triaxial compression tests (n = 63) and field CPTU (Uzielli & Mayne 2019).

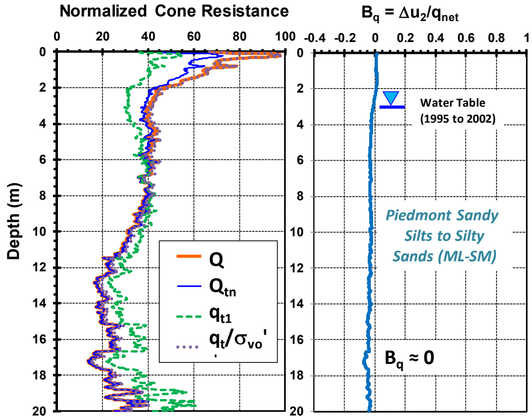

Figure 9. Normalized CPTU parameters at Opelika: (a) cone resistance; (b) porewater pressure ratio.

4.2 *CPTU evaluation of ϕ' in clays*

At the standard CPTU rate of 20 mm/s in clays, response is taken to be undrained, corresponding to no volumetric strains (DeJong et al. 2012). Clays are identified when the CPT index $I_c \geq 2.95$ (Robertson & Cabal 2015). In consideration of clayey silts, a value of $I_c > 2.6$ is often taken to be "undrained" response.

A limit plasticity solution developed at the Trondheim Institute of Technology (NTH) for CPTU evaluation of ϕ' under undrained conditions is available from Senneset et al. (1989) that relates Q to ϕ' and B_q:

$$Q = \frac{\tan^2(45° + \phi'/2)\cdot\exp(\pi\cdot\tan\phi') - 1}{1 + 6\cdot\tan\phi'(1+\tan\phi')\cdot B_q} \qquad (5)$$

An approximation for ϕ' is expressed directly as a function of Q and B_q for the following ranges: $0.05 \le B_q < 1.0$ and $18° < \phi' < 45°$ (Mayne 2007):

$$\phi' = 29.5° \cdot B_q^{0.121} \cdot [0.256 + 0.336 \cdot B_q + \log_{10} Q] \qquad (6)$$

In fact, data on over 105 different clays tested under both triaxial compression and CPTU have been calibrated to show they give comparable ϕ' values (Ouyang & Mayne 2018).

4.3 *CPTU evaluation of ϕ' in fissured geomaterials*

For the case where $B_q < +0.05$, eqn (6) is not valid and results from CPTUs at Opelika show $B_q \approx 0$, in fact, technically the B_q values are negative and average around -0.02 to -0.05, as evidenced by Figure 9b. Negative porewater pressures are often recorded in fissured geomaterials, such as stiff overconsolidated clays (Mayne et al. 1990), but also observed in residual soils (Schneider et al. 2001; Finke et al. 2001).

From a measurement viewpoint, Campanella & Robertson (1988) showed the u_2 readings in a stiff clay were either slightly negative or slightly positive depending on the specific filter element, and thus u_2 can be affected by the thickness, width, and actual location of the porous element. Furthermore, studies by DeJong et al. (2007) show that type of fluid (water, oil, glycerine, silicone), its viscosity, and degree of saturation play a role in porewater pressure measurements during CPTU. Of final note, the NTH solution cannot handle negative B_q (Sandven 1990).

As such, a value of $B_q = 0$ is assumed at Opelika for CPTU at standard rates of 20 mm/s. An approximation for (5) when $B_q = 0$ can be expressed (Ouyang & Mayne 2019):

$$\phi' = 8.18° \cdot \ln_e (2.13 \cdot Q) \qquad (7)$$

4.4 *Effective ϕ' from I_c relationship*

Using the database on 27 undisturbed sands and silty sands, a relationship was also found between ϕ' and CPT material index, I_c (Mayne 2020):

$$\phi' = 53.0° - 6.9° \cdot I_c \qquad (8)$$

for values of $I_c \le 2.6$.

The profile of I_c at Opelika is presented in Figure 10 showing the intermediate geomaterial more or less follows the threshold value of $I_c = 2.60$ to 11 m depth.

4.5 *CPTU evaluation of ϕ' in Piedmont silts*

The above 4 drained equations [i.e., (2), (3), and (4)] one undrained method [i.e., eqn (7)], and CPT index expression [i.e., eqn (8)] are all applied to the mean CPTU data at Opelika, as shown in Figure 11. Interestingly, all 5 methods approximately agree with each other. Moreover, all CPT expressions agree well and provide comparable profiles to the effective friction angles obtained from the lab triaxial compression test series. This likely only occurs for this very silty fine sand to very sandy silt because of its high fines content (average FC = 44%) and material index at the undrained-drained border of $I_c = 2.60$, since the mean value of index $I_c \approx 2.7$ for this site.

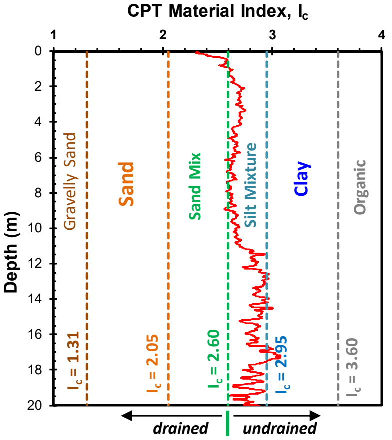

Figure 10. Profile of CPT material index at Opelika

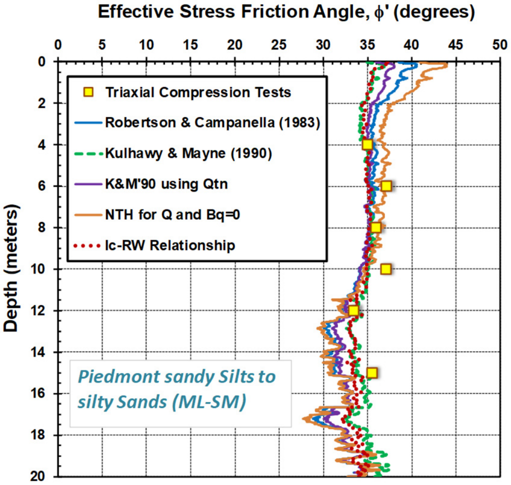

Figure 11. Profile of effective friction angle from five CPTU expressions in comparison with triaxial results on natural Opelika sand-silt mixture.

5 CONCLUSIONS

Interpretation of CPTU in residual soils is complicated by their mixed constituency of clay, silt, sand, and rock particles, as well as considerations of partially drained, fully-drained, and undrained behavior, particularly at the standard rate of 20 mm/s. Nevertheless, success was shown for CPTU in residual silts and sands (ML-SM) at the Opelika national test site, located within the Appalachian Piedmont geologic province in eastern USA. Specifically, a means to profile the yield stress ratio (YSR) from a generalized approach that uses net cone resistance and an exponent m' = 0.82. Moreover, a surprising agreement is found in the assessment of effective friction angle ϕ' by use of both drained and undrained CPTU equations that compare well with series of triaxial compression tests.

6 ACKNOWLEDGMENTS

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