Site characterization of Piedmont residuum of North America

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ABSTRACT: The residual soils of the Piedmont geology of eastern North America consist of variable clayey to sandy silts and silty sands that have formed by the in-place weathering of schist, gneiss, and granites. Their behavior can vary from undrained to drained, as well as partially drained, depending upon the applied rate of loading, groundwater level, and capillarity. Results from in-situ and laboratory testing are presented to show the characteristics of these materials, in some cases reflecting a dichotomy with aspects of both stiff fissured clays and loose granular soils.

1 INTRODUCTION

1.1 *Geologic Setting*

The Piedmont geology underlies an important region along the eastern region of North America and its surficial exposure extends as a lenticular body approximately 1200 km long and 200 km wide from Alabama to Pennsylvania. Major cities within the Piedmont include Atlanta, Georgia; Columbia, South Carolina; Charlotte & Raleigh, North Carolina; Richmond,Virginia; Washington, DC; Baltimore, Maryland; Wilmington, Delaware; and Philadelphia, Pennsylvania. The physiographic region of the Piedmont is shown in Figure 1, indicating both its exposure and buried extent that underlies the more recent Atlantic coastal plain deposits.

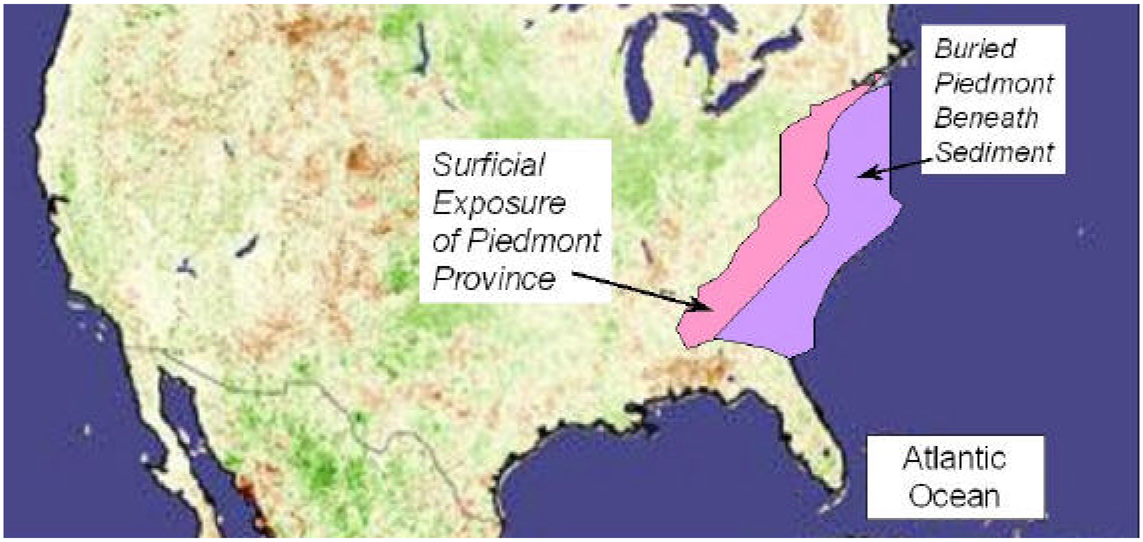

Figure 1. Surface and buried extent of the Piedmont in North America (Modified from www.nasa.gov).

The name *Piedmont* means "foot-of-the-mountains" that reflect remnants of an ancient mountain range that has since been extensively weathered, decomposed, and eroded to form rolling terrain and hillsides. The predominant metamorphic rocks are schist and gneiss with granitic intrusives of Z-time Precambrian age, although local occurrences of phyllite, slate, greenstone, diabase, quartzite, and soapstone are also found (Chew, 1993).

Variable weathering, temperature, drainage, and topography have reduced the rocks in-place to form overburden residual soils that range from clay topsoil to sandy silts and silty sands that grade with depth back into saprolite and partially-weathered rocks (Martin, 1977). The relict structure of the parent rock can be left within the derived soil materials with evidence of bonding or dissolved bond features, as well as cracks and fissures from the original fractured rock mass. The degree of weathering varies laterally and vertically such that rock may be encountered at depths of between 10 to 40 meters below ground surface, yet occasional rock outcrops and mountains up to 300 m high occur across the region. Often, there is concern in encountering rock along highway cuts, during foundation excavations, and utility construction. Foundations can range from shallow footings and mats to driven piles or drilled and bored piles, depending upon the consistency of the overburden soils and the depth to parent rock.

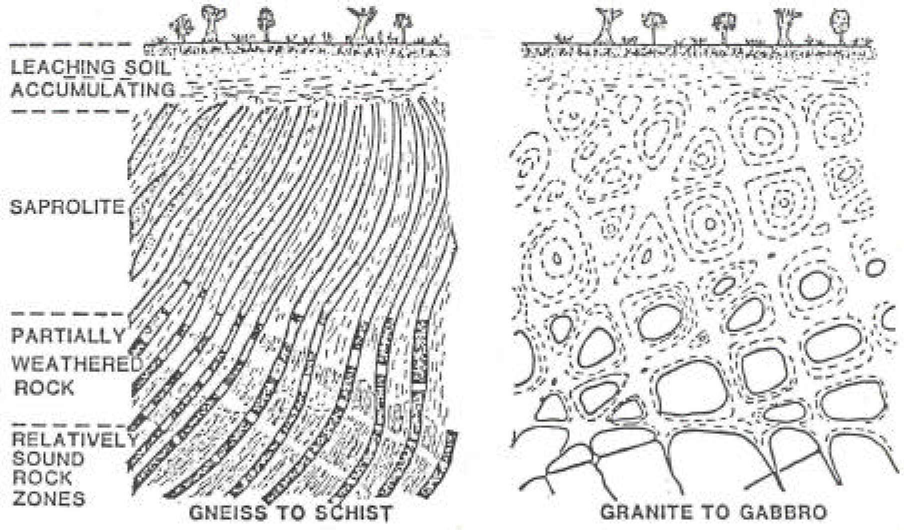

Figure 2. Weathering profile in residuum derived from Piedmont metamorphic and igneous rock types (after Sowers & Richardson, 1983).

Residual soils transition into a saprolite and disintegrated or partially-weathered rock with depth until refusal is encountered at the parent rock interface (Sowers & Richardson, 1983), as depicted in Figure 2. The very shallow surface soils ($z < 1$ m) may severely weather to fine-grained clay, thus in the southern Piedmont it has been called "Georgia red clay" by locals because of its farming use and red-tan color. However, the clay fraction of Piedmont soils is often small (generally 5 to 20 %), thus "clay" is a misnomer.

The Piedmont residual soils are not particularly well-categorized by the Unified Soil Classification System (USCS) that was developed from experiences with sediments. Using the USCS, a vertical profile in the Piedmont appears as if alternating strata of silty sands (SM) and sandy silts (ML) form the overburden. The strata seem to change in random fashion, thus suggesting high variability over short distances. This is illusionary due to the fact that the mean grain size of the Piedmont residuum is close to the 75-micron criterion that separates fine-grained from coarse-grained fractions (0.075 mm, or the No. 200 sieve size). In fact, the Piedmont residuum acts more as a dual soil type (SM-ML), exhibiting characteristics of both fine-grained soils (undrained) and coarse-grained soils (drained) when subject to loading.

1.2 *Opelika Test Site*

Test sites to characterize Piedmont residuum have been established in Georgia (Harris & Mayne, 1994), North Carolina (Borden, et al. 1996), and Alabama (Brown & Vinson, 1998). The Opelika national geotechnical experimentation site (NGES) is located near the village of Spring Villa, Alabama (Vinson & Brown, 1997) and provides the most comprehensive set of data todate. The site is located at the southern end of the Piedmont geology. The subsurface materials are composed of silty to sandy residual soils that grade eventually with depth into partially-weathered rock. Soil specimens have trace to some mica content. At the initial stages of testing at the NGES in 1995, the water table originally was encountered about 2 m deep. The vadose zone above the phreatic surface was desiccated and crustal due to past groundwater fluctuations. Later (circa 2000), however, the groundwater level dropped to 8 m or more due to drought conditions. As of May 2002, it has now risen to about 4.5 m.

The Opelika NGES is a 130-hectare tract for research projects related to bridge foundations and pavement subgrades. The original property consisted of forested rolling terrain. The site includes a deep soils site (discussed herein) that is used for full-scale load tests on deep foundations under axial & lateral static & dynamic loading. Research at the site also includes the evaluation of deep foundations in weathered rocks, since an outcrop of quartzite occurs at one end of the site. At the soil test portion of the NGES, a variety of laboratory and field tests have been performed to characterize the Piedmont residuum, as discussed in this paper.

2 LABORATORY TESTS

Various types of laboratory tests have been conducted on Piedmont residual soils to determine reference values for determining soil engineering parameters. Brief summaries of selected test results obtained from the Opelika test site are reviewed here.

2.1 *Index Parameters*

A summary of mean grain sizes (D_{50}) from mechanical and hydrometer analyses is shown in Figure 3. In certain specimens, the gradation tests were stopped at the percent fines content (No.

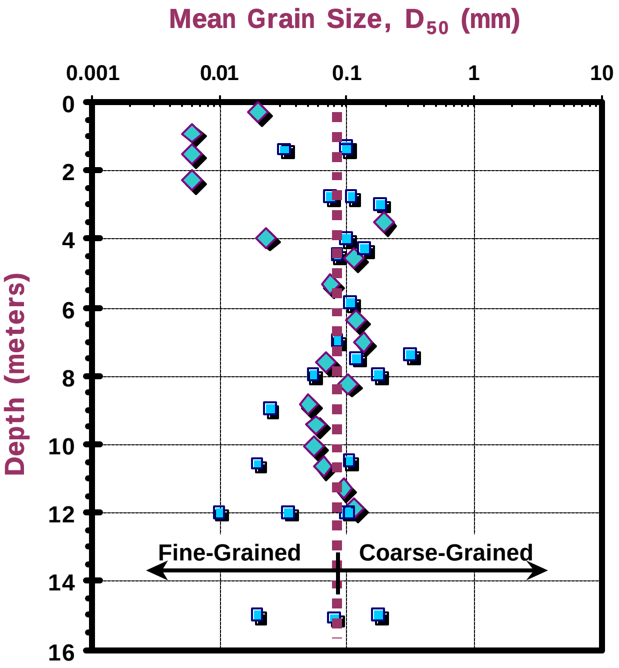

Figure 3. Summary of mean grain size and percent fines content from Opelika site.

200 sieve), so that the D_{50} was not determined for several of the fine- grained samples. It is notable that the mean grain size of the Piedmont soils is essentially at the USCS cutoff of 0.075 mm (US No. 200 sieve) at the Opelika NGES and therefore borderline in its classification as sandy silt to silty sand. Corresponding percent fines content (PF) generally vary between 40 to 60% for these materials. Similar results were determined in Piedmont soils at the Georgia Tech campus in Atlanta, Georgia, yet those profiles generally classified as very silty fine sand (SM) over a 22 m depth (Harris & Mayne, 1994; Mayne, 1999).

Atterberg tests on Opelika soils gave a mean liquid limit of 46% and mean plasticity index of 8%, although a number of specimens were nonplastic (Brown & Vinson, 1998). Figure 4 shows a summary plot of water contents relative to the plasticity indices. Because of the index values, the Piedmont residual soils are better described using dual symbols (SM-ML).

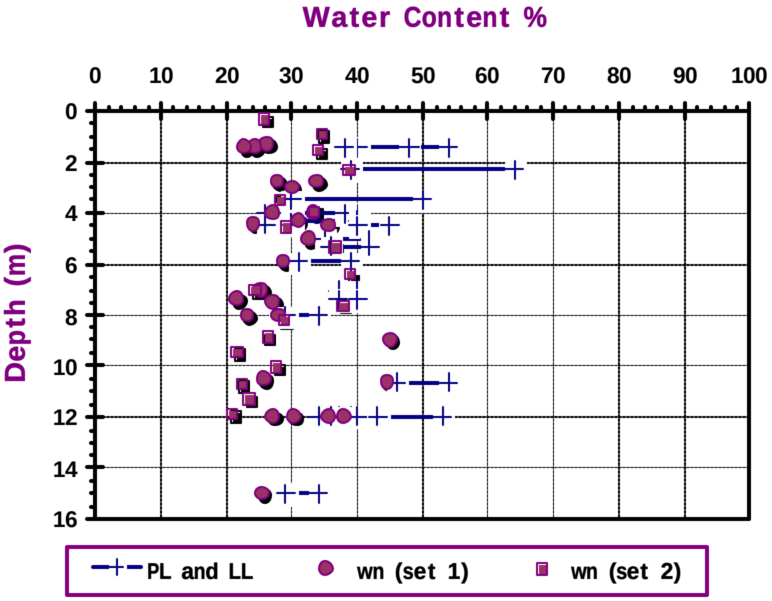

Figure 4. Summary of water contents and Atterberg limits in Piedmont soils from Opelika site.

2.2 *Consolidation Tests*

Representative results from one-dimensional consolidation tests on undisturbed Shelby tube samples from Opelika are presented in Figure 5 and indicate no clear yield on e-log σ_v' curves corresponding to an apparent preconsolidation stress (Wesley, 1994). Prior efforts at defining the preconsolidation stress in these materials have been attempted by Pavich & Obermeier (1985) who indicated Piedmont soils to be normally-consolidated. Wang & Borden (1996) showed the apparent overconsolidation ratio (AOCR) with 3 < AOCR < 4 for a site east of Raleigh/NC. At the Opelika site, Hoyos & Macari (1999) evaluated AOCRs decreasing from 4 to 1.1 in the upper 9 meters. Alternate plotting techniques to conventional e-log σ_v' curves can be utilized to help delineate apparent yielding, as discussed by Mayne (1989). Using energy per unit volume graphs and constrained modulus plots, Mayne & Harris (1993) concluded that the of Piedmont soils at the Georgia Tech site in downtown Atlanta have AOCRs ranging between 1.5 and 3 within the upper 15-m depths.

The residual soils of the Piedmont have likely weathered and de-bonded sufficiently from the parent rock such that no preconsolidation resides due to that original stress state and structure. However, groundwater fluctuations and desiccation have most certainly occurred during recent geologic times to result in overconsolidation effects and AOCRs of between 1.5 to 4.

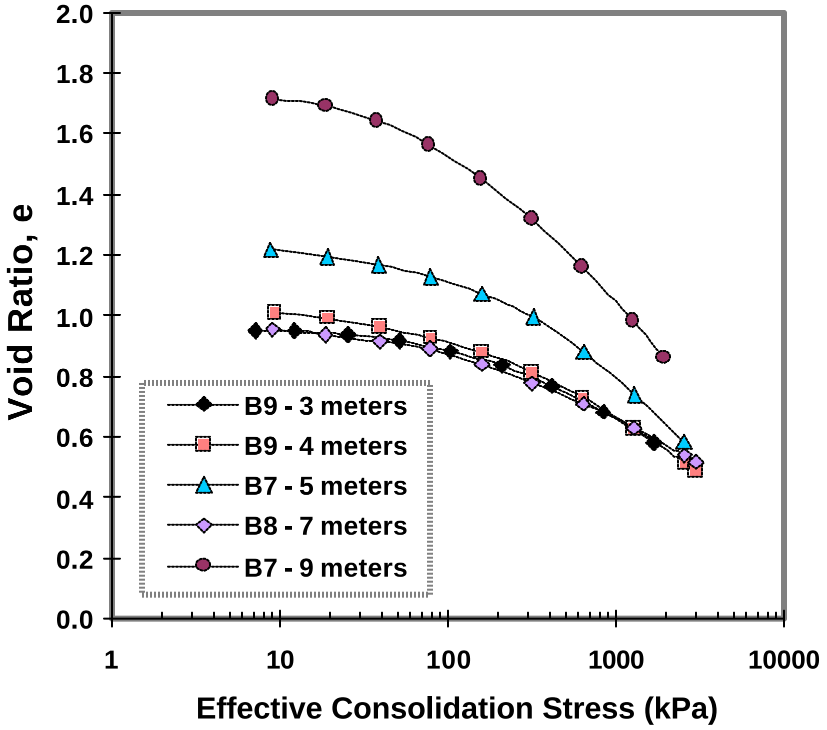

Figure 5. Representative consolidation results on undisturbed tube samples of Piedmont residuum.

2.3 *Triaxial Testing*

A representative series of isotropically-consolidated undrained triaxial compression (CIUC) tests with porewater pressure measurements on samples from Opelika, Alabama are shown in Figure 6. Shelby tube samples (ASTM D 1587) were taken from test depths of 8 to 15 m. The results appear quite similar to those presented by Mayne & Harris (1994) for natural residuum in Atlanta, Georgia. Earlier results on Piedmont soils (Sowers & Richardson, 1983) indicated c' = 0

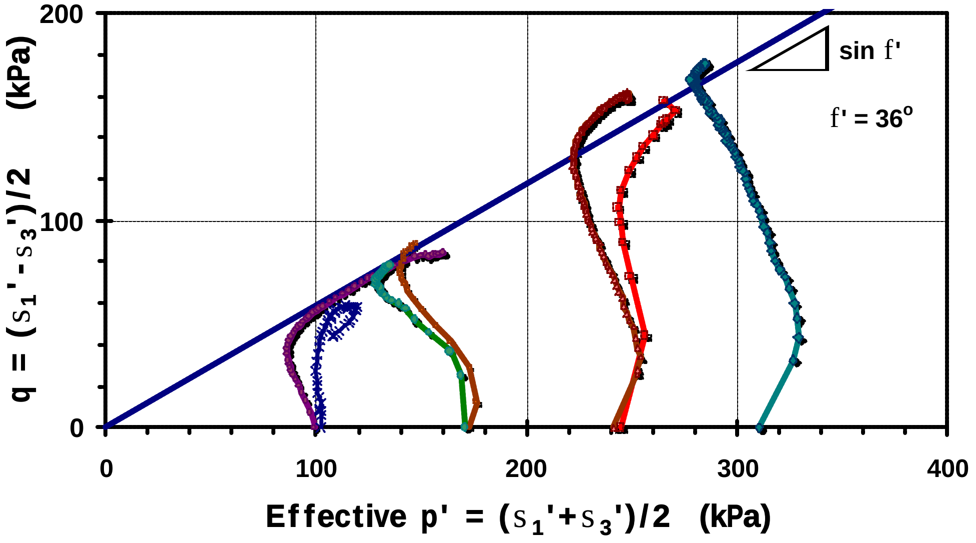

Figure 6. Effective stress paths for CIUC tests on Piedmont residuum from Opelika site.

and effective stress friction angles of $\phi' = 32^o$, yet these tests were generally performed on compacted samples and saturated during consolidation and backpressuring stages. A full summary of the effective stress envelopes at the Opelika site has shown $c' = 0$ and $\phi' = 35.3^o$ (Mayne, et al. 2000).

An advantage of CIUC tests is that both total stress and effective stress parameters are assessed from the same specimen. Figure 7 provides a total stress interpretation of the triaxial results in terms of the undrained shear strength (s_u) versus the effective confining stress (σ_c'). The σ_c' values were taken at 0.5, 1.0, and 1.5 times σ_{vo}'. Also shown are the scattered results from unconsolidated undrained (UU) tests on specimens from the site. While no discernable trend is evident in the UU tests, the CIUC tests show increased s_u with increased confining stress level (Figure 7). Regression analyses on 22 tests ($r^2 = 0.79$) indicate a normalized undrained shear strength to overburden ratio of $s_u/\sigma_{vo}' = 0.65$, which roughly corresponds to an apparent OCR of between 1.5 to 2.5 for natural clay materials (Mayne, 1988).

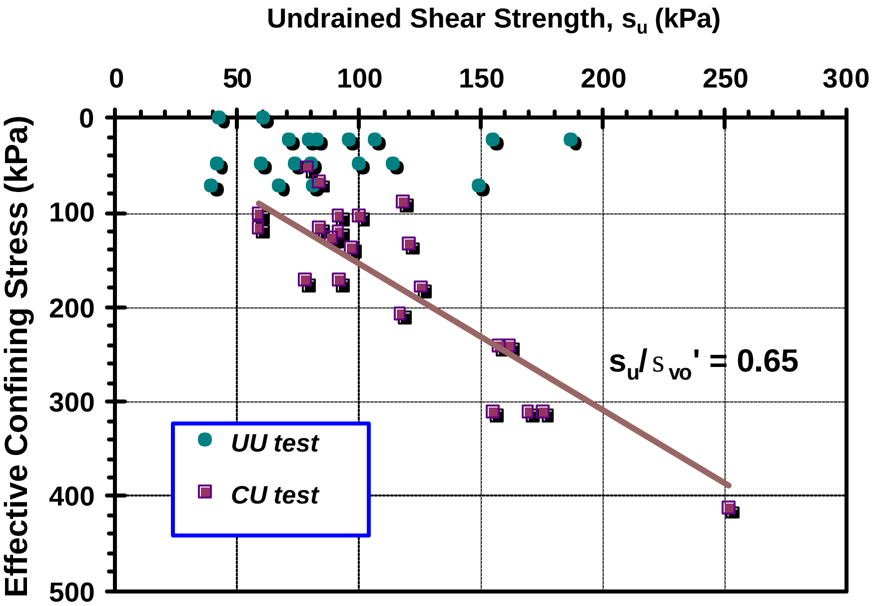

Figure 7. Summary of undrained shear strengths from UU and CIUC triaxial test series.

2.4 *Other Lab Tests*

Other types of laboratory tests on undisturbed samples of Piedmont residuum have been reported, but are not presented here. These include permeability testing (Finke, et al. 1999), direct shear testing (Vinson, 1997), resonant column (Borden, et al. 1996; Hoyos & Macari, 1999; Schneider, et al., 1999), as well as cubical triaxial test series on saturated and partially-saturated specimens (Hoyos, 1998).

3 IN-SITU FIELD TESTS

A variety of in-situ probes, penetration tests, and geophysical methods have been conducted to characterize the residuum at Opelika. Selected results are presented in the following sections.

3.1 *Shear Wave Measurements*

Crosshole, downhole, and surface wave measurements have been obtained at Opelika with relatively consistent results among all methods. Full results are discussed in Schneider, et al. (1999). Two separate crosshole arrays have been established at the site with each set comprised of three plastic-cased boreholes to 15-m depths and situated about 3 meters apart. The casing was grouted in-place and an inclinometer used to determine vertical alignment. A downhole hammer was used as a source in one outer borehole with receiver geophones placed at the same level in remaining two boreholes to allow direct source-to-receiver, as well as interval receiver-receiver, determinations of shear wave velocity (V_s), per ASTM D-4428. Downhole V_s measurements were taken during seismic cone tests (SCPTu) using the procedure outlined by Campanella (1994). Downhole velocities were also obtained using seismic dilatometer tests (SDMT) at Opelika (Martin & Mayne, 1998). Good agreement between the crosshole tests (CHT S1-R2) series, three sets of SCPTu (Soundings 04, OPEIJT2, and OPEL I2), and one SDMT (No. AU-1) is seen in Figure 8.

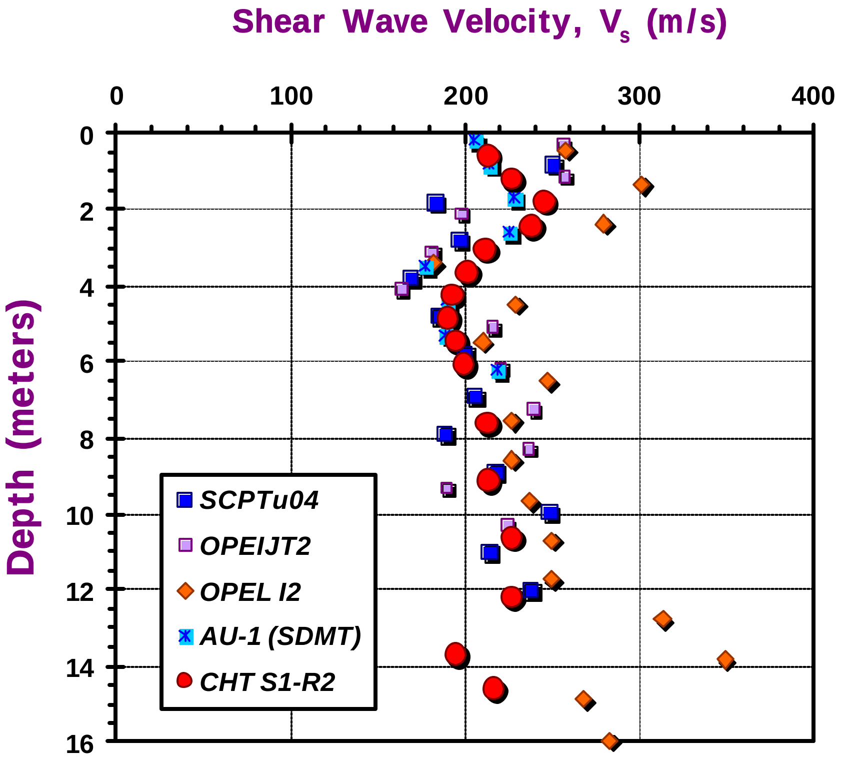

Figure 8. Derived shear wave velocity profiles from crosshole and downhole tests.

3.2 *Cone Penetration Tests*

Several types of cone penetration tests (CPTs) have been conducted at the Opelika test site using 35.7- and 44-mm diameter penetrometers and general procedures per ASTM D 5778. The soundings have been advanced at the standard rate of 20 mm/s, although accelerated rates have also been investigated (Finke, et al. 2001). Tests have been made using different penetrometers, including: Fugro, Hogentoger, van den Berg, Geotech AB, Envi, and Vertek. All these provided readings of cone tip stress (q_c), sleeve friction (f_s), and penetration porewater pressure (u) at regular depth intervals of between 1 to 5 cm. In select soundings, specialized penetrometers provided measurements of dual porewater pressures, conductivity, dielectric, or downhole seismic velocity, as well as dissipation of porewater pressures.

Piezocone tests (CPTu) obtained penetration porewater pressure readings taken either at the mid-face (u_1) and/or shoulder (u_2) position (Finke, et al. 1999). Either a 50/50 mixture of glycerine-water, or pure glycerine, was used to saturate the elements and cone cavities for most soundings. Midface filters were either made of porous plastic or ceramic, while shoulder elements were of porous plastic or sintered steel. The Envi memocone uses a greased slot.

Results from a paired set of 15-cm^2 Fugro soundings conducted side-by-side with two types of pore pressure elements are shown in Figure 9. The ambient groundwater at this time was 3 m deep. The cone tip stresses measure about $2.5 < q_t < 3.5$ MPa in the upper 10 meters. Corresponding sleeve frictions are between $150 < f_s < 220$ kPa. For penetration porewater pressures, dramatically different responses are evident with the midface readings high and positive ($400 < u_1 < 800$ kPa) and the shoulder element readings generally negative and near cavitation ($u_2 = -90$ kPa), yet saturation was always maintained. Similar results have been found with other commercial penetrometers. The phenomenon of positive u_1 readings with negative u_2 response has been previously observed in fissured overconsolidated clays (Mayne, et al. 1990; Lunne, et al. 1997). The Piedmont residuum has relict features of the parent rock, including remnant bonds from the intact rock, as well as the discontinuities and cracks of the rock mass (Sowers, 1994). The midface u_1 response is positive because it is dominated by the destructuration of the residual intact bonding of the original rock continuum. In contrast, the shoulder u_2 readings are negative because they reflect shear-induced porewater pressures and remnant rock discontinuities within the matrix (St. John, et al., 1969). Negative u_2 readings have been recorded at the shoulder position at many other locations in the Piedmont geology in Georgia and North Carolina (e.g., Finke, et al., 1999; Mayne & Schneider, 2001).

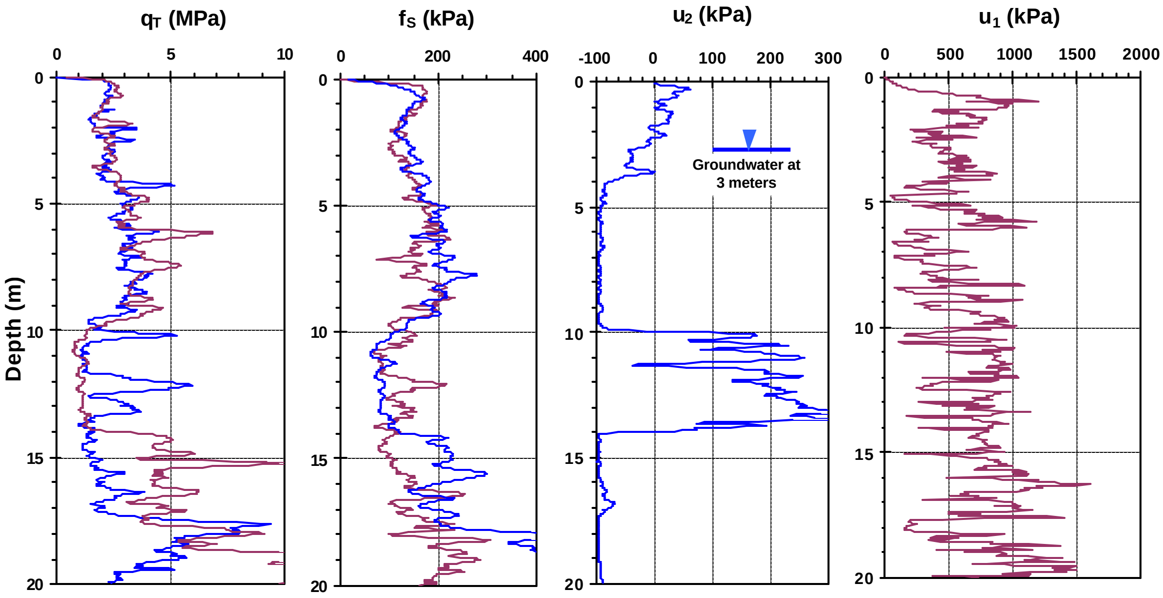

Figure 9. Paired set of Fugro soundings with midface u_1 and shoulder u_2 porewater pressures at Opelika.

For type 2 piezocones at Opelika, an anomaly occurs repeatedly with positive u_2 porewater pressures recorded in a layer below 8 m. The thickness and depth of this layer varies from sounding to sounding and remains a mystery. The layer occurs at depths between 8 to 15 m with apparent thicknesses of 1 to 5 m. Recent sampling at the site encountered some localized zones rich in mica and kaolinite content, thus perhaps the normal matrix of constituents of the Piedmont (quartz, mica, feldspar, and kaolinite) may have a localized "ore deposit" of mica-kaolin.

In the vadose zone above the groundwater table, the penetration porewater pressures at midface have been observed to be either positive or near zero, while at the shoulder, the values can be positive, zero, or negative. It is believed the variances reflect the transient capillary conditions due to the current degree of saturation, partial or full, in the residual fine-grained soils and depends on the humidity, infiltration, and prior rainfall activities around the actual time of testing. Thus, the importance and relevance of unsaturated soil mechanics in these residual silty soils can be appreciated, yet not implemented and well-studied in this geology.

During selected piezocone soundings, porewater pressure dissipation tests were performed to evaluate the horizontal coefficienst of consolidation and permeability characteristics (Finke & Mayne, 1999). Tests were performed using separate soundings with either type 1 or 2 filter element positions, or else a special dual-element piezocone with both u_1 and u_2 readings taken simultaneously (see Figure 10). All dissipations reached hydrostatic values (u_0) corresponding to the ambient unconfined water table at 3 m (time of testing). Despite the contrasts in positive u_1 and negative u_2 readings taken during penetration, full dissipation to the same equilibrium u_0 value was achieved at each depth in only 0.5 to 2 minutes for both elements. The relatively quick time for full decay indicates fairly high values of coefficient of consolidation ($c_h \approx 0.6$ cm^2/s) and hydraulic conductivity ($k \approx 1 \cdot 10^{-4}$ cm/s) for the silty to sandy Piedmont soils at Opelika (Finke, et al., 2001). Similar rates of dissipation have been observed at other test locations in the Piedmont (e.g., Mayne & Schneider, 2001).

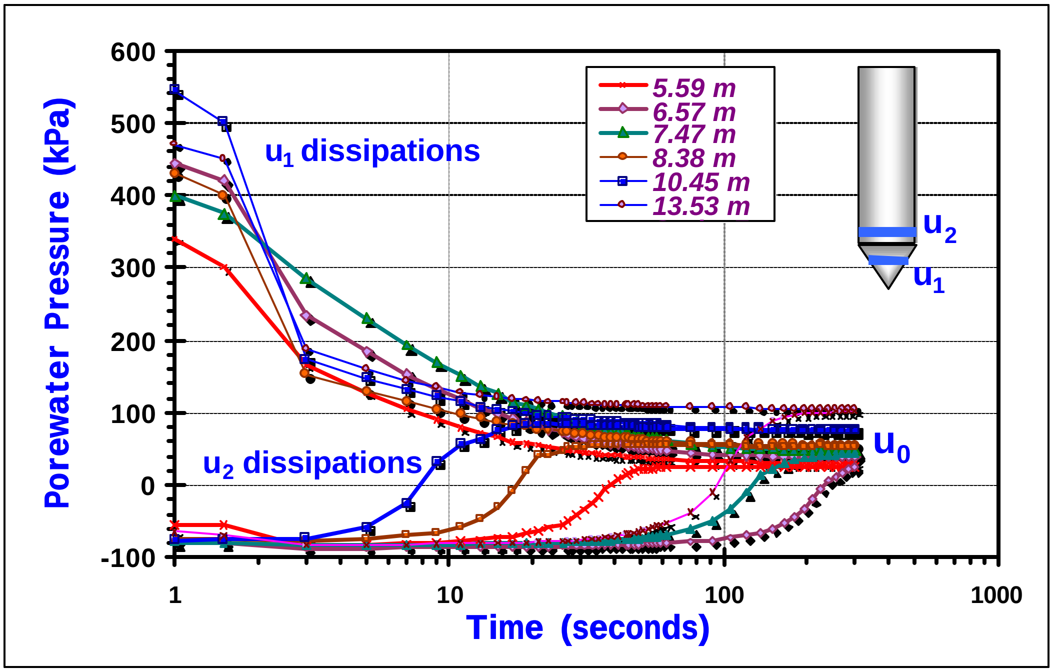

Figure 10. Summary of dissipation results from dual-element piezocone in residuum at Opelika.

Several CPTs have been performed at the Opelika NGES using penetrometers outfitted with geophones to measure downhole shear wave velocities. Vertically-propagating horizontally-polarized shear waves are monitored at one-meter depth intervals and a surface seismic source is located about one meter from the axis of the sounding. This downhole technique provides a pseudo-interval determination of V_s with depth (Campanella, 1994). Figure 11 presents the full results of a seismic piezocone penetration test (SCPTu) that conveniently provides five independent readings with depth from a single sounding (q_t, f_s, u_b, t_{50}, and V_s). The downhole V_s compare well with crosshole values, as well as spectral analysis of surface waves (SASW), as presented elsewhere (Schneider, et al., 1999).

Inadvertent dissipations are shown in the sounding presented in Figure 11 where the 1-m rod breaks show the negative u_2 readings approaching the hydrostatic u_0 values. For this sounding, full dissipation was not achieved as only 15 to 20 seconds were allocated before resuming the hydraulic pushing. Note the anomalous layer with positive u_2 readings at 8.2 to 9 m depth for this sounding location where it appears thin relative to the zone shown in Figure 9.

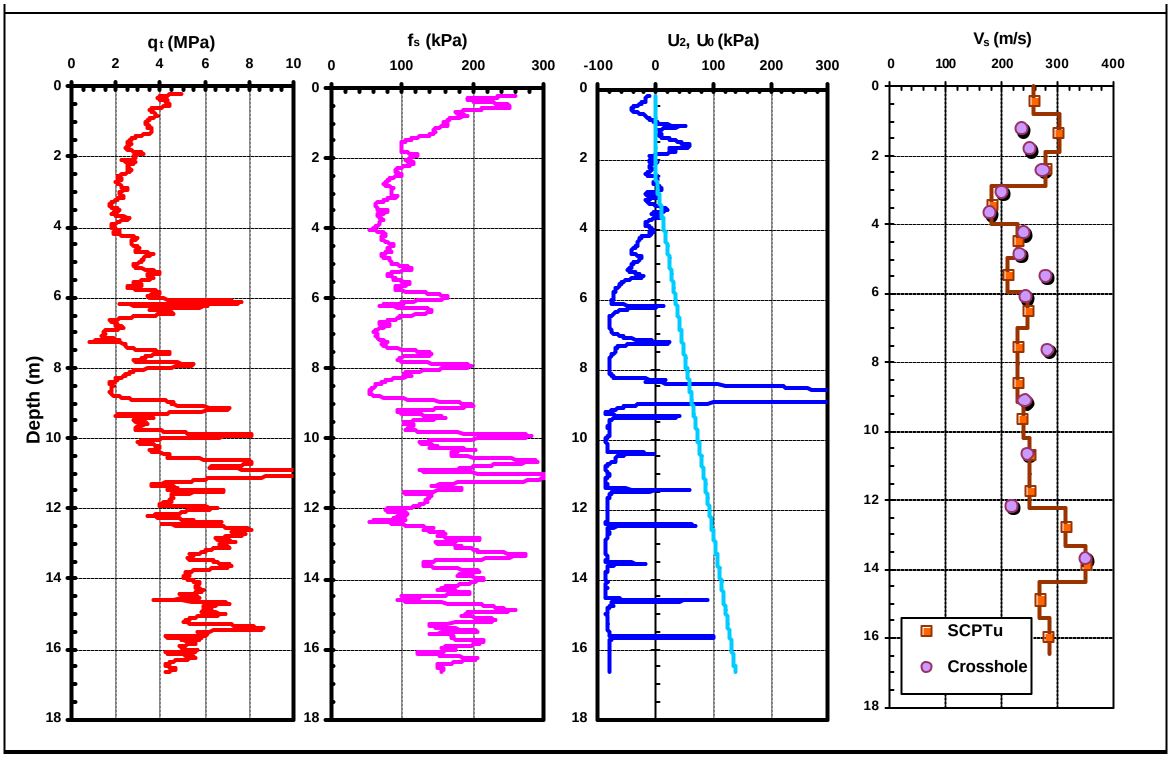

Figure 11. Seismic piezocone sounding with dissipation phases at Opelika test site, Alabama.

3.3 *Flat Plate Dilatometer Tests*

The flat plate dilatometer test (DMT) obtains paired measurements of contact pressure (p_0) and expansion pressure (p_1) in soils at regular intervals of 20-cm (or alternate 30-cm) with depth. Results from a DMT sounding at the NGES are given in Figure 12. The readings are used to calculate three parameters (I_D = material index, E_D = dilatometer modulus, and K_D = horizontal

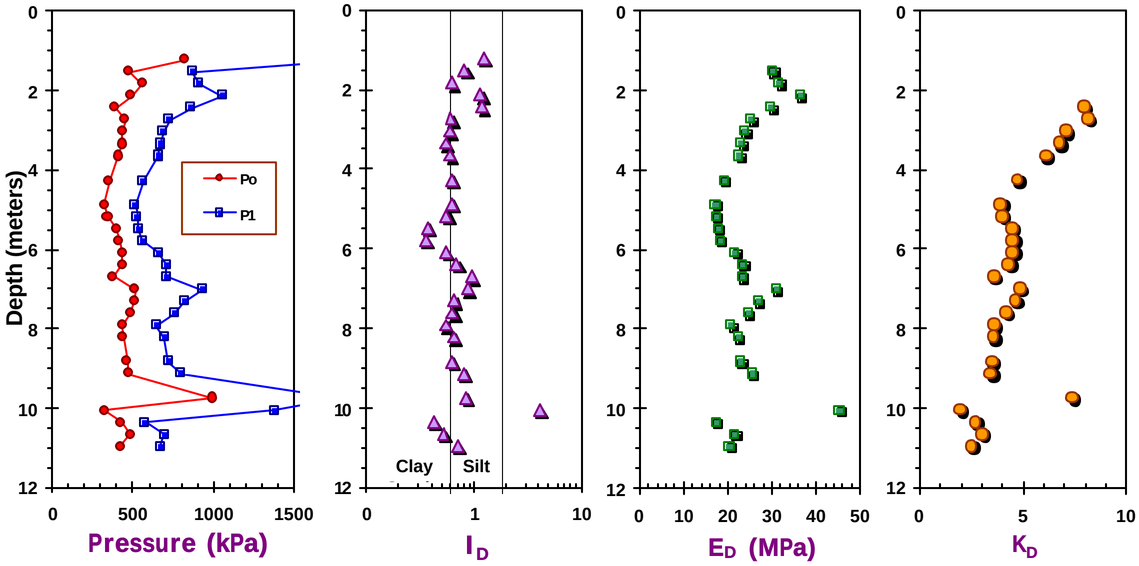

Figure 12. Results from a representative flat dilatometer sounding in Piedmont silts at Opelika.

stress index) which can be used to evaluate the geostratigraphy, strength, and stiffness parameters (Marchetti, 1997). The material index indicates that the soil behavior is silt-like and therefore in agreement with the grain size distributions. In the Piedmont, the dilatometer modulus has been found to correspond to an approximate drained elastic modulus (E') at working load levels for evaluating deflections of shallow and deep foundations (Mayne & Frost, 1988; Mayne, et al., 1999b).

Dissipation tests can also be performed using the flat plate dilatometer (Lutenegger, 1988; Marchetti, 1997). A special series of DMT dissipations tests have been carried out at Opelika using the p_0-readings, as shown in Figure 13. The latter indicate the A-readings decay to about 80 to 90% of their penetration value after 1 to 2 minutes. A separate series of DMTs has been performed whereby the A and B readings were recorded 2-minutes after the blade was installed.

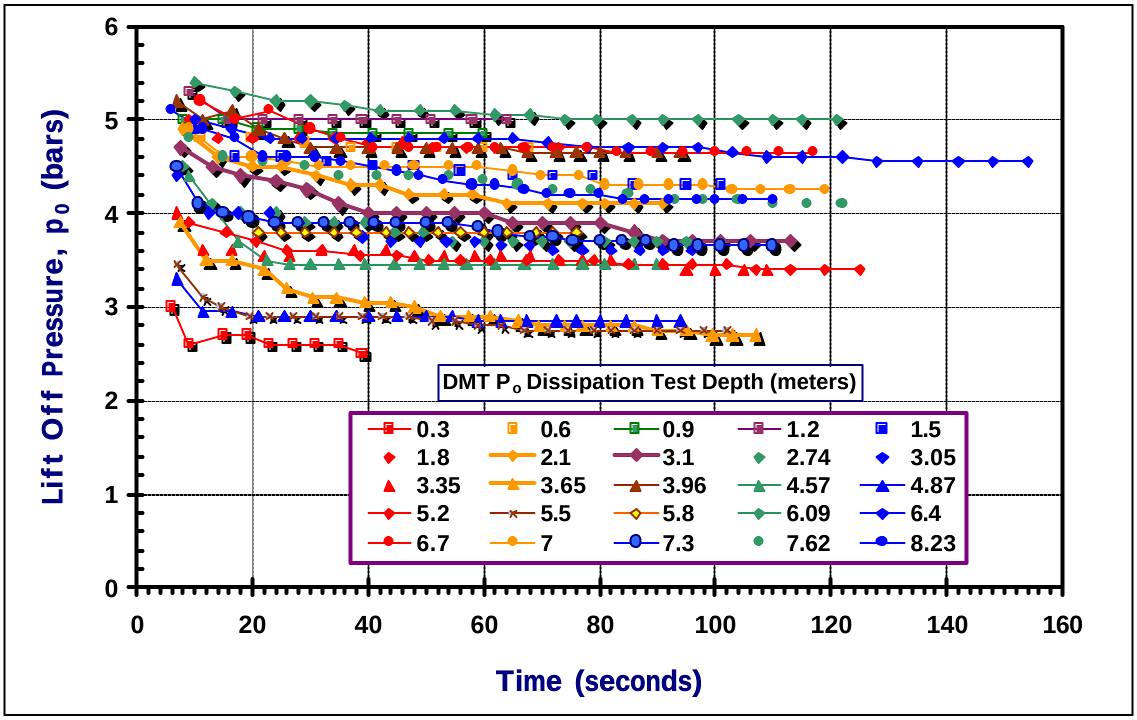

Figure 13. Dissipation of p_0 readings in special DMT tests conducted in Piedmont residuum.

3.4 *Additional In-Situ Tests*

Other field and in-situ tests have been conducted in the Piedmont residuum at the Opelika test site, including pre-bored pressuremeter tests, full-displacement pressuremeter tests, geoprobe-type continuous sampling, borehole shear tests, conductivity soundings, SPTs with torque measurements, seismic flat dilatometer tests, impulse torsional shear tests, and dielectric readings. Some of these results are reported elsewhere (e.g., Brown & Vinson, 1998; Mayne, et al., 1999a, 2000), whereas certain of these studies are still underway. In addition, full-scale load tests on driven and drilled pile foundations under static, statnamic, axial, and lateral loading have been performed during ongoing research studies by Auburn University and the Alabama Department of Transportation.

4 SOIL BEHAVIORAL CLASSIFICATION

In that the Piedmont soils are "non-textbook" geomaterials, they exhibit some unusual characteristics in their behavior, notably interpretations involving total stress strength parameters and effective stress strength parameters from in-situ tests (Mayne, et al., 2000). Results from the same set of CPT, DMT, and standard penetration tests (SPT) can be evaluated to give reasonable undrained shear strengths (s_u), as well as reasonable effective stress friction angles (ϕ').

The proximity of the mean grain size to the 75-micron border between fine-grained and coarse-grained soils causes USCS designations within the same boring or sounding to apparently fluctuate between ML and SM classifications, even though no significant changes in soil type actually occur. For the CPT, no samples are obtained, therefore soil behavioral classification systems have been developed (e.g., Robertson, 1990). As with the USCS, similar contradictions are found in the soil behavioral systems, as shown below.

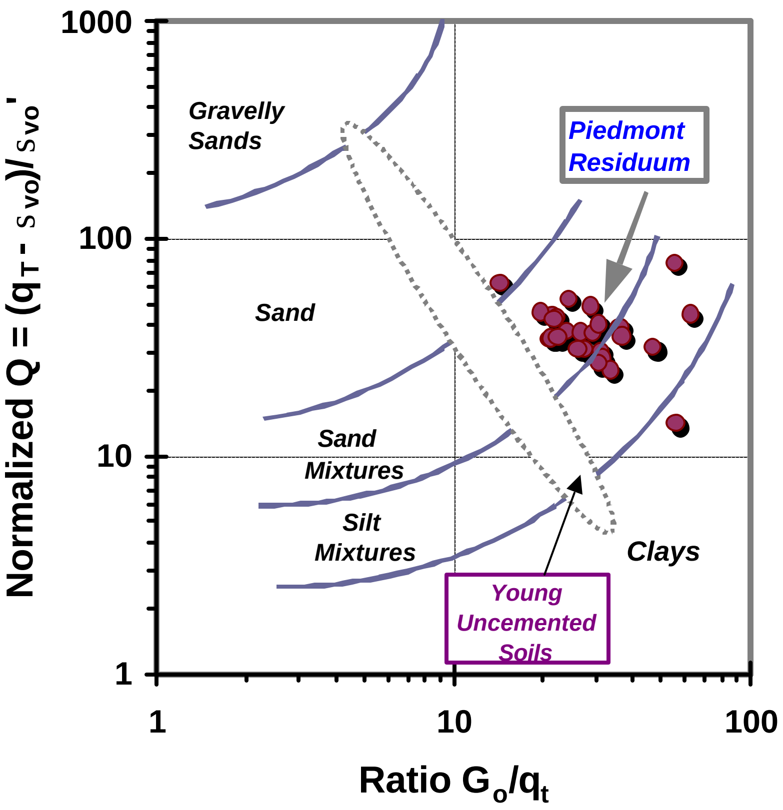

Figure 14. Interpreted soil behavioral type of Piedmont residuum from SCPTU results (chart from Lunne, Robertson, & Powell, 1997).

Using the results of seismic piezocone tests from Piedmont residual soils at Opelika, a graph of normalized cone tip resistance, $Q = (q_t-\sigma_{vo})/\sigma_{vo}'$, versus the small-strain shear modulus normalized to cone tip stress, G_{max}/q_t, is presented in Figure 14. Based on this chart, the Piedmont residuum categorizes as a sand to silt mixture. In contrast, Figure 15 presents the same SCPTU data in terms of a clay database where the small strain stiffness is plotted directly with net cone resistance. The database has been presented earlier by Mayne & Rix (1993) and includes a variety of natural clays from worldwide sources. Here, the Piedmont residuum appears in concert with stiff fissured clays.

The fissures in the residual soil are believed to reflect the relict discontinuities of the original fractured rock formation (Finke & Mayne, 1999). Prior studies by St. John, et al. (1969)

discussed the occurence of fissures and slickensided features in Piedmont soils. In addition, the measurement of positive u_1 and negative u_2 pressures at the shoulder position are characteristic of stiff fissured clays (Mayne, et al., 1990; Lunne, et al., 1997). The very fast dissipation records observed in these residual materials, however, are not indicative of clay materials (e.g., Burns & Mayne, 1998).

Interestingly, the material index (I_D) from flat dilatometer tests consistently gives values that are characteristic of silty materials ($0.6 < I_D < 1.8$) when performed in Piedmont residuum, as shown previously in Figure 12 for Opelika as well as other sites (e.g., Harris & Mayne, 1994; Wang & Borden, 1996).

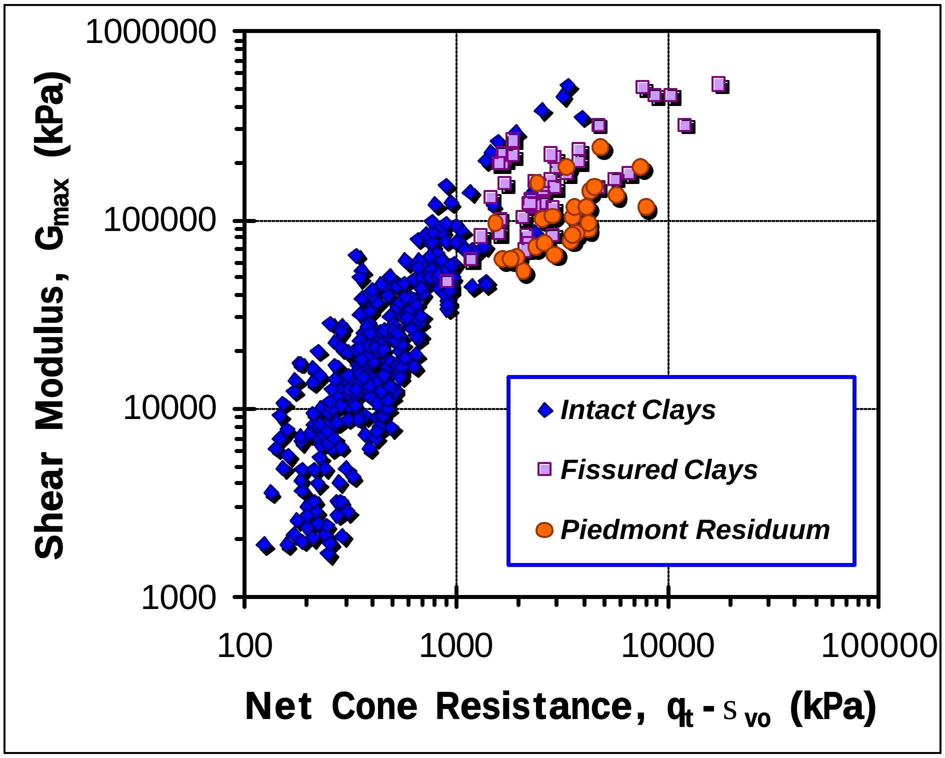

Figure 15. Comparison of SCPTU data in Piedmont residuum with intact and fissured natural clays.

5 APPARENT OVERCONSOLIDATION

Existence of a quasi-preconsolidation effect in Piedmont residuum has been a debated issue, as noted in Section 2.2. The fact that Piedmont residual silty soils do not exhibit a clear yielding in consolidation tests may be partially attributed to inadequate sampling techniques, as standard thin-walled Shelby tubes are used exclusively throughout the Piedmont region. Despite the fact that Piedmont soils are easily retained in tubes, specimens may still undergo significant disturbance and stress release upon extrusion from tubes in the laboratory because of the high fine sand fraction and/or presence of mica minerals. Perhaps an improved sampling program using Laval and/or Sherbrooke-type, or NGI-type samplers, would avail higher quality specimens in oedometer tests and clearer definitions of yield stresses. The question could also be partially resolved by a series of stress-path triaxial tests to define the existence of either an isotropic or anisotropic yield surface in q-p' space, as proposed by Leroueil & Vaughan (1990).

At the Opelika site, series of consolidation tests on samples were interpreted with apparent overconsolidation ratios (AOCR) in the range 1.1 < AOCR < 4.0 (Hoyos & Macari, 1999). Slightly higher AOCRs of 3 to 4 are reported in Piedmont soils of North Carolina (Wang & Borden, 1996). Notably, it is plausible to interpret yield stresses that do not actually exist in soils

(Graham, et al. 1982), therefore alternate and indirect means to assess the apparent preconsolidation stress state were explored.

If the Piedmont residuum indeed behaves as a stiff clay, then an empirical estimate of the preconsolidation stress from cone penetration tests can be made (Kulhawy & Mayne, 1990; Chen & Mayne, 1996; Demers & Leroueil, 2002):

$$OCR = 0.32 \left(\frac{q_t - s_{vo}}{s_{vo}'} \right) \qquad [1]$$

The corresponding profile of AOCR (= σ_p'/σ_{vo}') derived at the Opelika site is presented in Figure 16 and clearly shows a severe overprediction, relative to values interpreted from oedometer tests. In fact, the normalized cone resistance, $Q = (q_t - \sigma_{vo}')/\sigma_{vo}'$, is well outside the range expected at these low OCRs (Powell, et al., 1988).

In contrast, if the Piedmont soils are analyzed as if sand-like, an empirical expression derived from CPTs conducted in calibration chambers on clean, uncemented, unaged quartz sands gives (Mayne, 1995; Lunne et al., 1997; Mayne, 2001):

$$OCR = \left[\frac{1.33 \cdot q_t^{0.22}}{K_{oNC} \cdot (s_{vo}')^{0.31}} \right]^{\frac{1}{(a-0.27)}} \qquad [2]$$

where the q_t = cone resistance (MPa) and σ_{vo}' = effective overburden (kPa). The parameter α can be taken as $\alpha = (1 - K_{oNC}) \approx \sin\phi'$ for a first approximation (Mayne, 2001). Generally, Figure 16 indicates a consistent underprediction of the AOCR, relative to the interpreted consolidation test values. Neither assessment of AOCR by cone tip stress is appropriate.

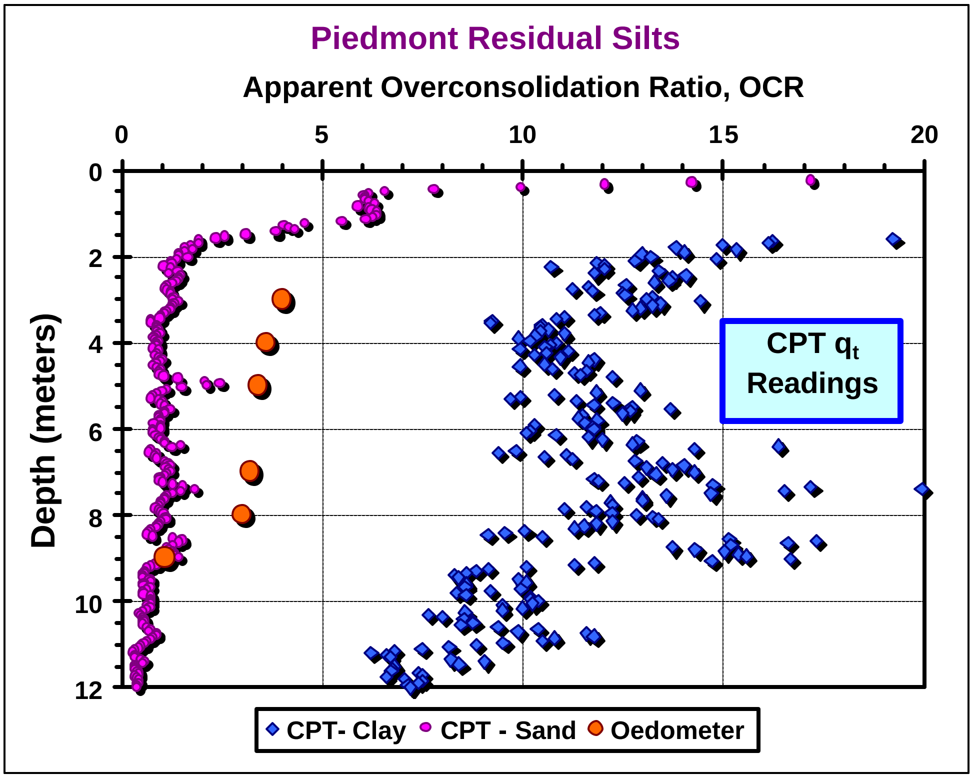

Figure 16. CPT interpretations of apparent OCR in Piedmont residual silts compared with oedometer.

The flat-plate dilatometer (DMT) has been used relatively successfully for estimating the degree of preconsolidation of natural soils. The original expression for clays is (Marchetti, 1980):

$$\mathrm{OCR} \;=\; (0.5\,K_D)^{1.47} \qquad [3]$$

where $K_D = (p_o-u_o)/\sigma_{vo}'$ = lateral stress index. Results from two DMT soundings (Nos. SV99 and AU-1) at the site are given in Figure 17 and show reasonable agreement with the AOCR profiles from the laboratory one-dimensional consolidation tests. Also shown are lower AOCR values from an alternate approach based on analysis of a larger database of natural clays within a simple theoretical framework (Mayne & Bachus, 1989; Mayne, 1995):

$$\mathrm{OCR} \;=\; 0.509\,K_D \qquad [4]$$

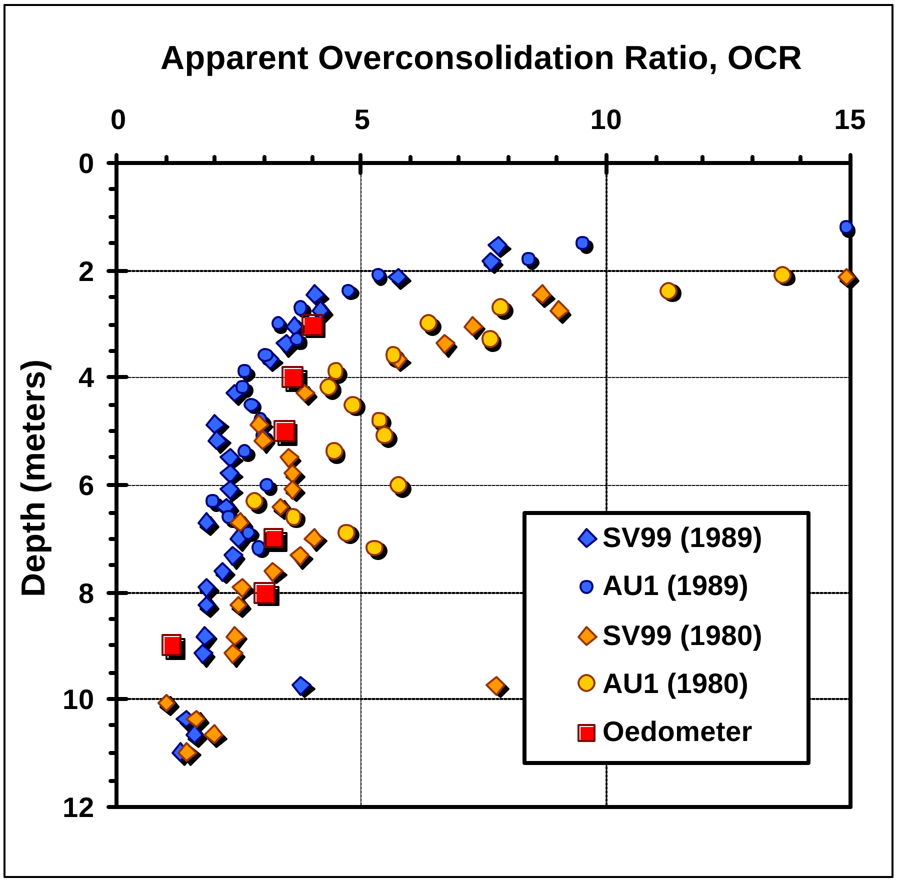

Figure 17. DMT-estimated OCRs in comparison with limited oedometer results.

Additional dichotomies exist. The negative porewater pressures at the shoulder cone position are indicative of very stiff overconsolidated clays (e.g., Powell, et al., 1988; Lunne, et al., 1997). Correlative trends (Mayne, et al., 1990; Larsson & Mulabdif, 1991) based on normalized excess porewater pressures ($\Delta u_2/\sigma_{vo}'$) suggest AOCRs > 15. These are in rough agreement with the aforementioned normalized Q values. On the other hand, the measured excess positive midface porewater pressures can be used to interpret the degree of preconsolidation in clay soils (Larsson & Mulabdif, 1991; Chen & Mayne, 1996):

$$OCR \approx 0.47 \cdot \left(\frac{\Delta u_1}{s_{vo}'} \right) \qquad [5]$$

The mean porewater pressures of four CPTu$_1$ piezocone soundings at Opelika have been used with [5] to derive a profile of AOCR (Figure 18), with surprisingly good agreement with the oedometer values. Use of the shear wave velocity (V_s in m/s) to profile preconsolidation stress (σ_p' in kPa) in natural intact clays may be made (Mayne, Robertson, & Lunne, 1998):

$$\sigma_p' = 0.106\ (V_s)^{1.47} \qquad [6]$$

The shear wave values from crosshole tests (CHT) are also shown in Figure 18 and tend to confirm the low AOCRs in the range of 1.5 to 4 at the site. Notably, however, data on overconsolidated and fissured clays also exhibit somewhat low shear wave velocities (e.g., Butcher & Powell, 1995), thus the interpretation by [6] may be fortuitous.

Some additional confirmation on the interpreted lightly overconsolidated state is afforded by the series of isotropically-consolidated undrained triaxial compression tests (CIUC). An apparent overconsolidation ratio can be calculated using an inverted Cam-clay or SHANSEP form (e.g., Mayne, 1988), again with reasonable agreement with the oedometer results.

While erosional processes have undoubtably caused the present landscape in the Piedmont, considerable time has passed for complete debonding and loss of any preconsolidation effects due to this mechanism. More likely, a combination of groundwater fluctuations and desiccation in the partially-saturated zone have caused the current low OCR profiles. Assuming a past drop in the groundwater level to 20 m beneath current grade gives a profile compatible with the consolidation results, as depicted in Figure 19.

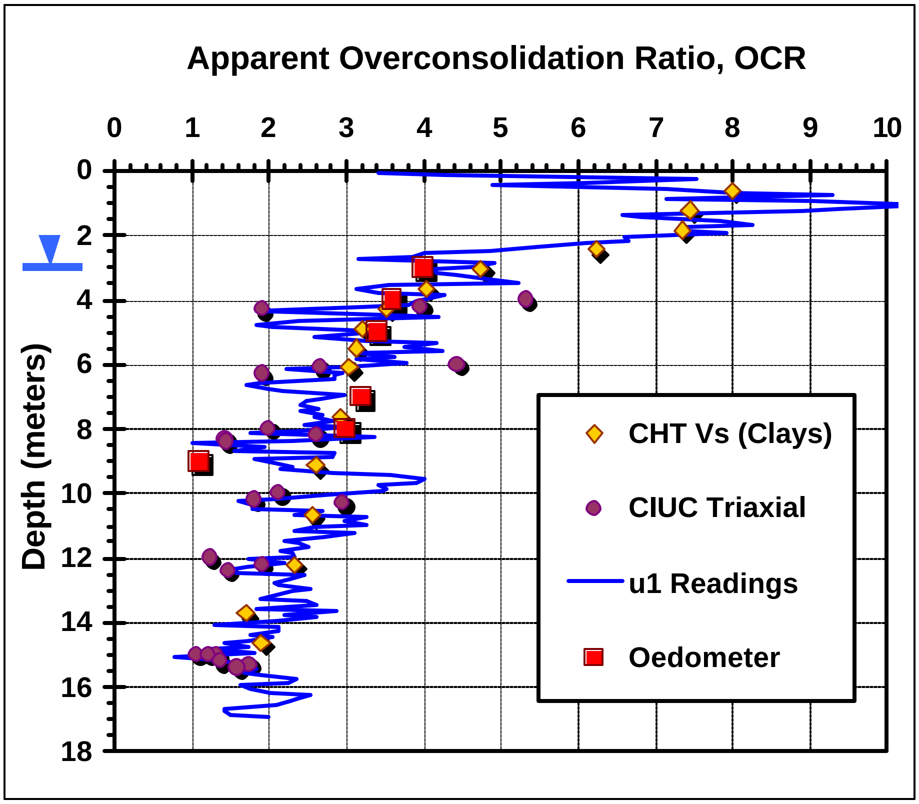

Figure 18. Derived AOCRs in residuum from midface porewater pressures, crosshole, and triaxial data.

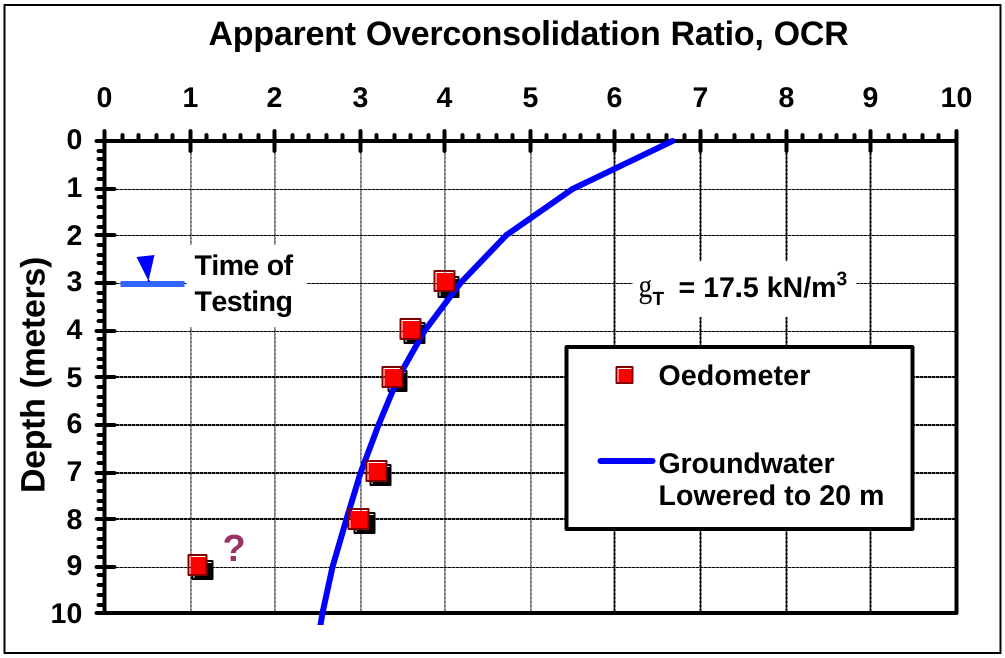

Figure 19. Calculated OCR due to groundwater level fluctuations at the Opelika site.

6 SUMMARY

Results from laboratory and in-situ testing on Piedmont residuum from eastern North America have been presented to illustrate characteristics on a "non-textbook" geomaterial. The Piedmont residual soils are comprised of fine sandy silts to silty fine sands, derived predominantly from the inplace weathering of gneiss and schist. Selected results from the national experimentation test site at Opelika, Alabama are presented from laboratory test series (index, triaxial, consolidation) and in-situ test programs (piezocone, flat dilatometer, shear wave measurements). Difficulties are found in the use of the conventional Unified Soil Classification System since the mean grain size varies about the 0.075-mm demarcation between fine-grained and coarse-grained soils (US No. 200 sieve). Soil behavioral classifications based on seismic cone data show discrepancies with one system implying sand-silt mixture, another system suggesting the residuum acting as stiff fissured clay. Contradictions occur in the interpretation of the stress history, with lab oedometer and triaxial tests indicating the residual silts are apparently lightly overconsolidated (1 < AOCRs < 4) with supporting trends given by midface CPT porewater pressures (u_1), flat dilatometer tests, and shear wave correlations. In contrast, measured cone tip stresses (q_t) and shoulder porewater pressures (u_2) implicate soil behavior that is characteristic of stiff fissured clay with high AOCRs > 10. Therefore, caution must be exercised in using empirical correlations in non-textbook geomaterials. Findings should be verified by standard test methods and laboratory calibration is warranted in assessing realistic soil parameters & properties for design.

7 ACKNOWLEDGMENTS

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