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SITE CHARACTERIZATION OF PIEDMONT RESIDUAL SOILS AT THE NGES, OPELIKA, ALABAMA

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Abstract

The National Geotechnical Experimentation Site at Opelika, Alabama is underlain by residual silts and sands derived from the weathering of schist and gneiss of the Piedmont Geologic Province. Site characterization by in-situ tests has included an extensive series of cone and piezocone penetrometer soundings supplemented with standard penetration, flat plate dilatometer, pre-bored and full-displacement pressuremeter, and borehole shear. Geophysical surveys have been completed by crosshole, surface wave, and downhole tests. Complementary laboratory testing on split-barrel drive samples and continuous geoprobe samples have consisted of index, moisture, plasticity, gradation, & hydrometer analyses. Undisturbed tube samples have been subjected to triaxial, resonant column, permeability, and oedometer loading. Piedmont residual soils are unusual in that they exhibit behavioral facets characteristic of both clay and sand, thus creating a dichotomy in practice in selecting undrained versus drained soil parameters for analysis.

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Geologic Setting

Piedmont residuum serves as the foundation bearing soils for several major cities in the eastern United States, including Atlanta/GA, Columbia/SC, Charlotte/NC, Raleigh/NC, and Gaithersburg/MD, as well as western suburbs of Philadelphia/PA, Washington/DC, Wilmington/DE, Baltimore/MD, and Richmond/VA. Due to the importance of this geology with respect to geotechnical practice in the Atlantic region, the Opelika Test Site was established at the southern end of the Piedmont Province, as shown by Figure 1. The exposed surface extent of the Piedmont geologic province is 1200 kilometers long and up to 200 kilometers wide, appearing as a lenticular formation running parallel with the Atlantic Coast. At the Fall Line, the Piedmont actually dips easterly and underlies the extensive sediments of the Atlantic Coastal Plain. The name Piedmont means "foot of the mountains", reflecting a highly eroded geomorphological state since rolling terrain is the now the remnant of what once were mountains. The original Paleozoic rocks were primarily of metamorphic and igneous origin, including predominances of schist, gneiss, and granite, although localized regions contain slate, phyllite, greenstone, and diabase. The rocks of the Piedmont have decomposed mechanically and chemically inplace to form residuum and saprolite.

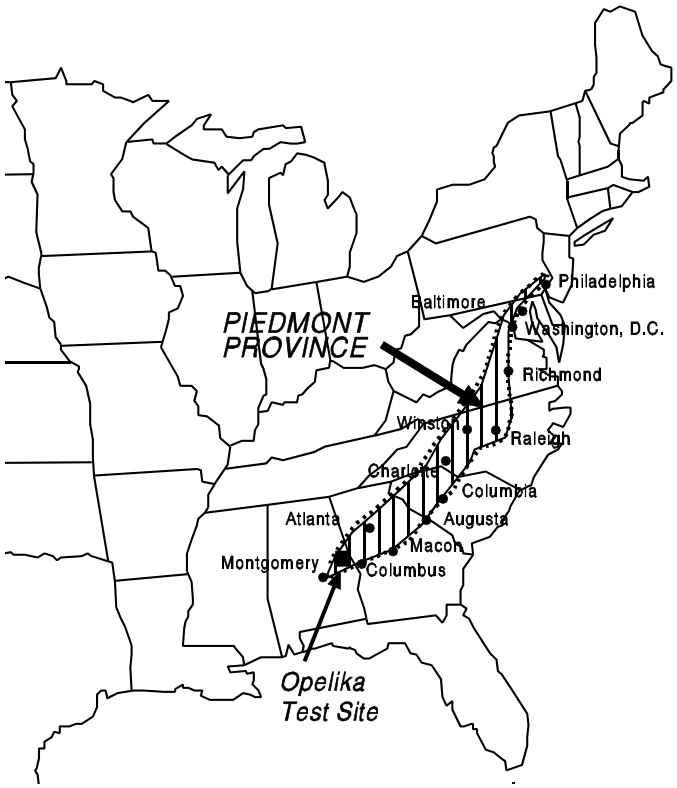

Figure 1. Surface Extent of Piedmont Geology and Opelika NGES Location.

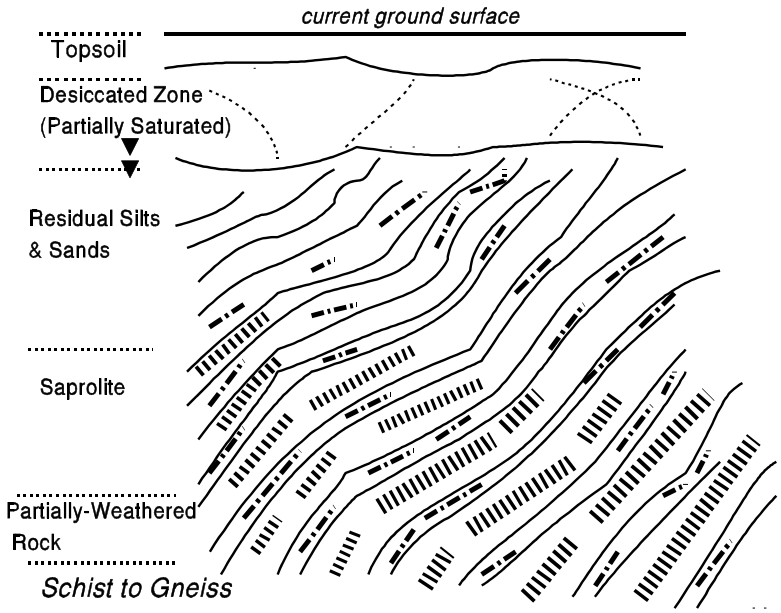

Figure 2. Weathering Profile in Residuum Derived From Piedmont Metamorphic Rock Types (modified after Sowers & Richardson, 1983).

Residual soils transition into a saprolite and disintegrated or partially-weathered rock with depth until refusal is encountered at the parent rock interface (Martin, 1977; Sowers & Richardson, 1983), as depicted in Figure 2. The Piedmont residual soils are not particularly well-categorized by the Unified Soil Classification System (USCS). The USCS was based on extensive testing and empirical understanding of more extensive and well-studied sedimentary deposits from marine, lacustrine, alluvial, fluvial, and glacial origins. The surface soils (< 1 m) may have severely weathered to fine-grained silt or clay, thus in the southern Piedmont it has been called "Georgia red clay" because of its agricultural relationships. However, the clay fraction of Piedmont soils is often small (< 10 %) and most index tests indicate nonplastic material, thus "red clay" is a misnomer.

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 alternate in random fashion, thus suggesting high variability over short distances. This is illusionary and due to the fact that the mean grain size of the Piedmont residuum is close to the opening size of the U.S. No. 200 Sieve (e.g., 0.075 mm). In fact, the 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. Due to differential weathering over horizontal distances, the residual soil overburden portion of the Piedmont can be thin (< 3 m) to over 50 meters thick.

Opelika Test Site

A national geotechnical experimentation site (NGES) was established near the small village community of Spring Villa, south of I-85 and east of Opelika, Alabama (Vinson, 1997). The site is contained within the southern Piedmont geology and located at the northeastern edge of the Opelika NGES property. The subsurface materials are composed of silty to sandy residual soils that grade eventually with depth into partially-weathered schist and gneiss. The water table lies about 2 to 3 m deep with the upper vadose zone above the phreatic surface appearing desiccated and crustal due to past groundwater fluctuations.

The Opelika NGES was established by the Alabama DOT as a 130-hectare tract (320 acres) for research projects related to bridge pier foundations and pavement subgrades. The original property consisted of forested rolling terrain. The site is managed by Auburn University and includes a deep soils site (discussed herein) at the south end of the property which is in use for full-scale load tests on deep foundations under axial and lateral static and dynamic loading. Ongoing research at the site includes construction of a racetrack for subgrade evaluations and performance of deep foundations in weathered rocks. 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 subsequently.

SPT and Index Results

A summary of standard penetration test (SPT) resistances from four soil test borings using hollow stem augers is presented in Figure 3a. Below a crustal zone evident in the upper 3 meters, the recorded N-values increase from about 8 blows/300 mm at z = 3 m to 14 blows/300 mm at the termination depths z = 15 m. Similar results with N-values increasing with depth were obtained at an earlier test site in Piedmont soils in Atlanta (Harris & Mayne, 1994).

A summary of mean grain size (D_{50}) from mechanical and hydrometer analyses is shown in Figure 3b. In certain specimens, the gradation tests were stopped at the percent fines content (No. 200 sieve), so that the D_{50} was not determined for several of the fine-grained samples. In any event, it can be seen that the mean grain size of the Piedmont soils is near the USCS cutoff of 0.075 mm (U.S. No. 200 sieve), thus borderline in its classification as sandy silt to silty sand. Companion lab tests gave a mean liquid limit of 46% and mean plasticity index of 8%, although a number of specimens were nonplastic (Brown & Vinson, 1998). Thus, the Piedmont residual soils are better described by dual symbols (SM-ML).

Geophysical Surveys

Crosshole and surface wave measurements were performed at the Opelika NGES to profile the shear wave velocity with depth. Two crosshole arrays were installed at

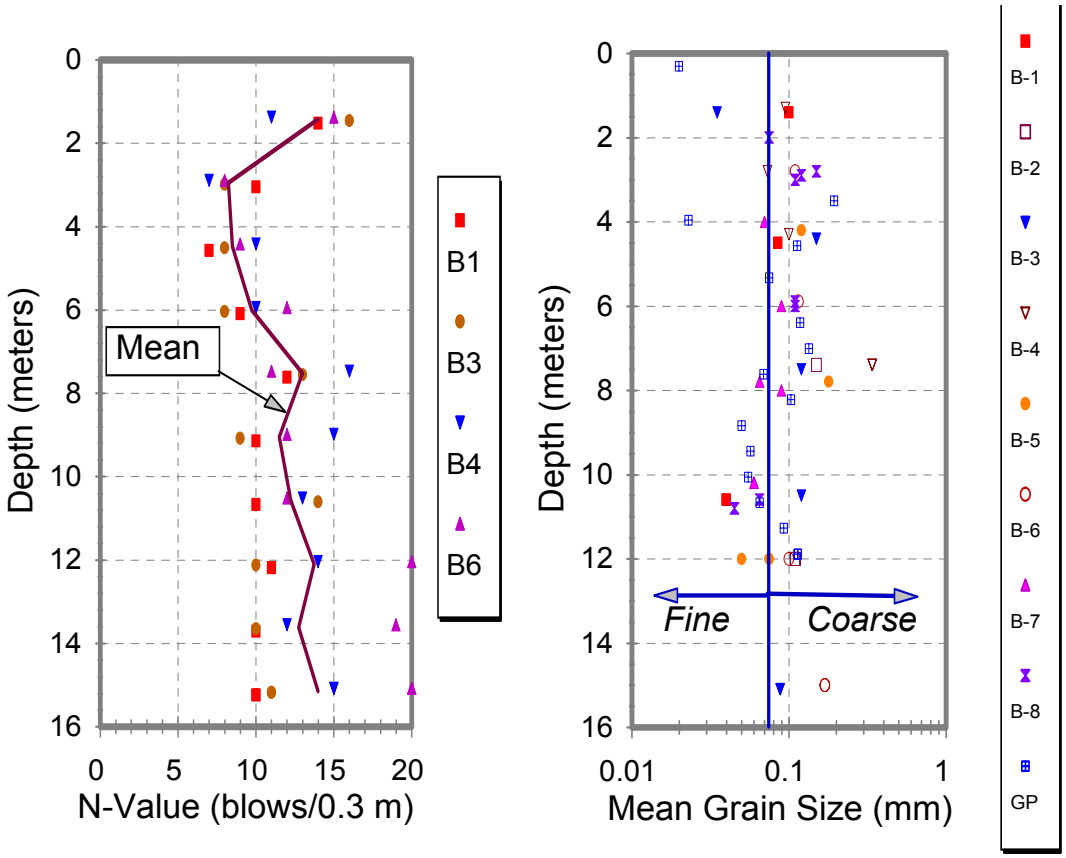

Figure 3. Summary Profiles of (a) SPT Resistances and (b) Mean Grain Sizes.

the site with each set comprised of three PVC-cased boreholes to 15 meters depth. The boreholes in each array were about 3 meters apart. The casing was grouted after placement using a cement-bentonite mixture and an inclinometer was used to determine the vertical alignment of each borehole (Brown & Vinson, 1998). A downhole hammer was used as a source in one outer borehole with receiver geophones placed at the same level in the middle and farthest borehole to allow both direct source-to-receiver, as well as interval receiver-receiver, determinations of shear wave velocity (V_s), per ASTM D-4428. Results from both crosshole series were similar (Kates, 1996) with the profile from one of the tests (CHT-2) presented in Figure 4. Generally, in the upper 11 meters at the NGES, the V_s is rather constant at 200± m/s.

The method of spectral analysis of surface waves (SASW) was performed using a two-channel HP-spectrum analyzer and paired set of geophones that was moved at the surface to obtain the dispersion curve at the site. Details of the test method, data collection, and inversion processing are given by Rix (1998). The measured surface waves (or Rayleigh waves) are a special type of shear wave that occurs because of the boundary condition formed by the plane of the ground surface. Results from the

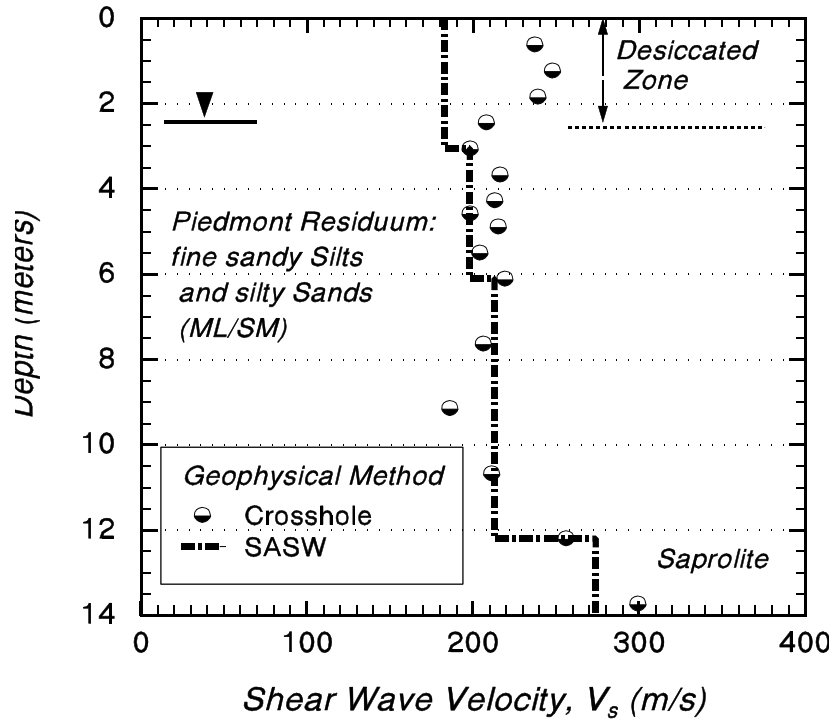

Figure 4. Results of Crosshole and Surface Wave Measurements at Opelika.

SASW are also presented in Figure 4 and show to be in general agreement with the crosshole tests below the desiccated region. Subsequently, results from downhole V_s measurements taken during seismic cone and seismic dilatometer tests are presented, as well as laboratory resonant column tests on recovered samples, with all tests indicating comparable results (Mayne, 1999).

Cone Penetration Tests

Several series of cone penetration tests (CPTs) have been conducted at the Opelika test site since 1995. The soundings have been advanced using a variety of penetrometers and cone rigs. Figure 5 shows one of four rigs used at the Opelika NGES, including: (a) 20-tonne Hogentogler truck, (b) 25-tonne Fugro truck, (c) 20-tonne track-mounted van den Berg rig; and (d) 6-tonne Geostar truck with twin earth anchors. The latter is operated by the In-Situ Testing research group at Georgia Tech. The soundings have been performed in general accordance with ASTM D 5778 guidelines using both 35.7- and 44-mm diameter penetrometers advanced at the standard rate of 20 mm/s, although accelerated rates have also been investigated (Finke, 1998). The various types of penetrometers (Fugro, Hogentoger, van den Berg, and Vertek) all provided readings of cone tip stress (q_c), sleeve friction (f_s), and

Figure 5. Cone Rig at the NGES, Opelika, AL

penetration porewater pressure (u) at regular depth intervals of 2 or 5 cm. In certain soundings, the vertical inclination of the penetrometer (i) was also monitored during penetration and specialized penetrometers provided other types of soil measurements (e.g., conductivity, dielectric, downhole seismic velocities).

Piezocone Tests

For the piezocone penetration tests (PCPT or CPTu), the investigations included penetration porewater pressure readings taken using porous filters located at either the mid-face (u_1) and/or shoulder (u_2) position (Finke, et al. 1999). In general, either a 50/50 mixture of glycerine and water, or else pure glycerine, was used to saturate the elements and cavities. Midface filters were made of porous plastic (Hogentogler) and ceramic (Fugro). Shoulder elements were made of porous plastic for all types.

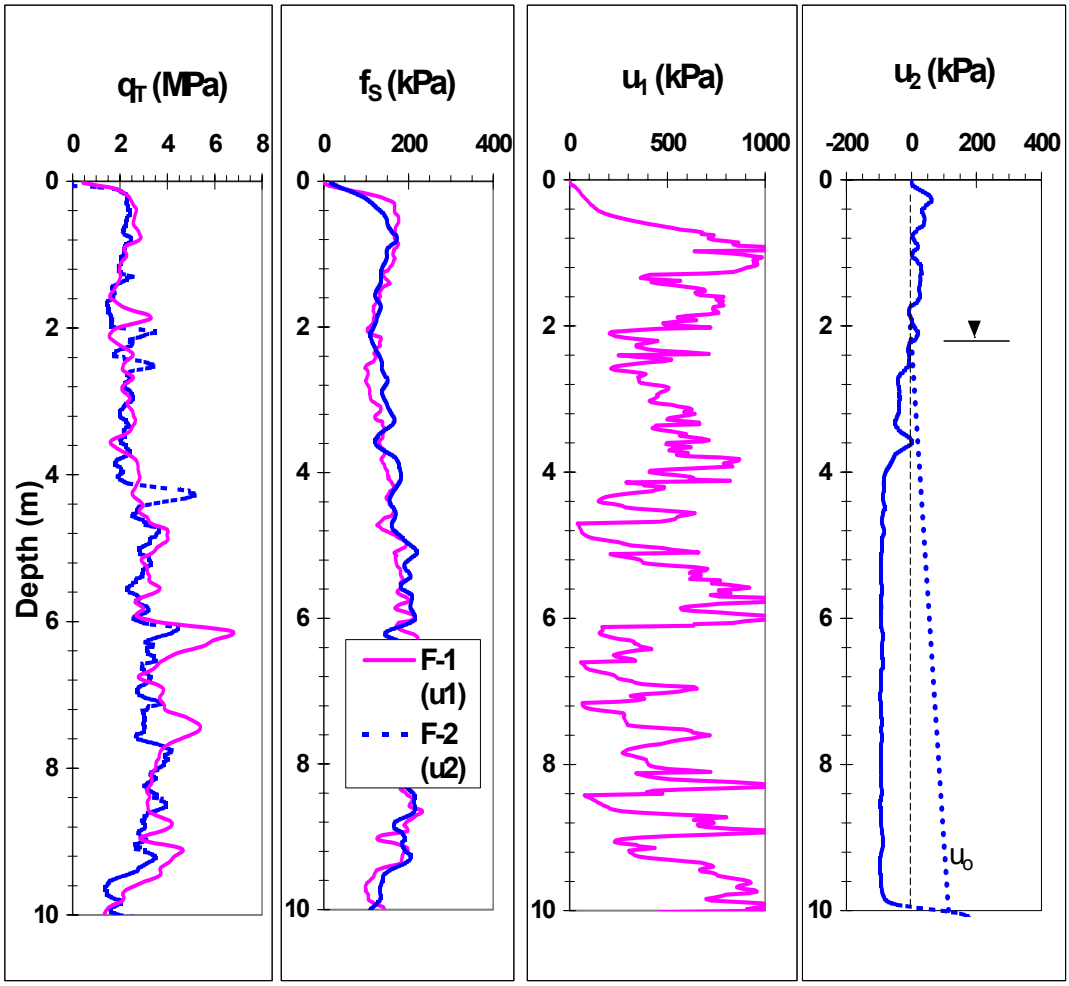

Figure 6. Piezocone Test Results from Two Sister Soundings Showing Both Midface (u_1) and Shoulder (u_2) Porous Filter Responses.

Results from a paired set of 15-cm^2 soundings side-by-side with the two types of pore pressure elements are shown in Figure 6. The tip stresses have been corrected as per recommended practice (Campanella & Robertson, 1988; Lunne, et al. 1997), although the correction from q_c to q_t is not significant in these residual soils (Finke, et al. 1999). The cone tip stresses measure about $2.5 < q_t < 3.5$ MPa in the upper 10 meters. Corresponding sleeve frictions are between $150 < f_s < 250$ 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 negative and near cavitation ($u_2 \approx -90$ kPa). This phenomenon of positive u_1 with negative u_2 response has been previously observed as characteristic of fissured overconsolidated clays (Mayne, et al. 1990; Lunne, et al. 1997).

The Piedmont residuum has relict features and qualities of the parent rock, including remnant bonding of the intact rock itself, as well as the discontinuities, jointing, cracks, and fissures of the rock mass (Sowers, 1994). It is postulated that,

since the midface u_1 filter lies within a zone of high compression located directly beneath the cone tip, this response is positive because it is dominated by the destructuration of the residual intact bonding of the original relict rock continuum. In contrast, the shoulder u_2 readings are negative because they reflect shear-induced pore pressures and remnant discontinuities within the matrix (St. John, et al. 1969). Thus, the u_1 readings reflect the destructuration of intact bonds and the u_2 readings are indicative of the fissures, fractures, and jointing of the original rock mass (Finke & Mayne, 1999).

In the vadose zone above the groundwater table, the penetration porewater pressures at midface have been observed to be either positive or "zero-ish", while at the shoulder, the values can be positive, zero, or negative. It is believed that these reflect the transient capillary conditions due to the current degree of partial or full saturation in the residual fine-grained soils which depends on the humidity, infiltration, and prior rainfall activities around the actual time of testing.

Porewater Pressure Dissipations

During selected piezocone soundings, a series of porewater pressure dissipation tests were performed to quantify the horizontal coefficient of consolidation and permeability characteristics. Figure 7 shows six sets of dissipation results obtained

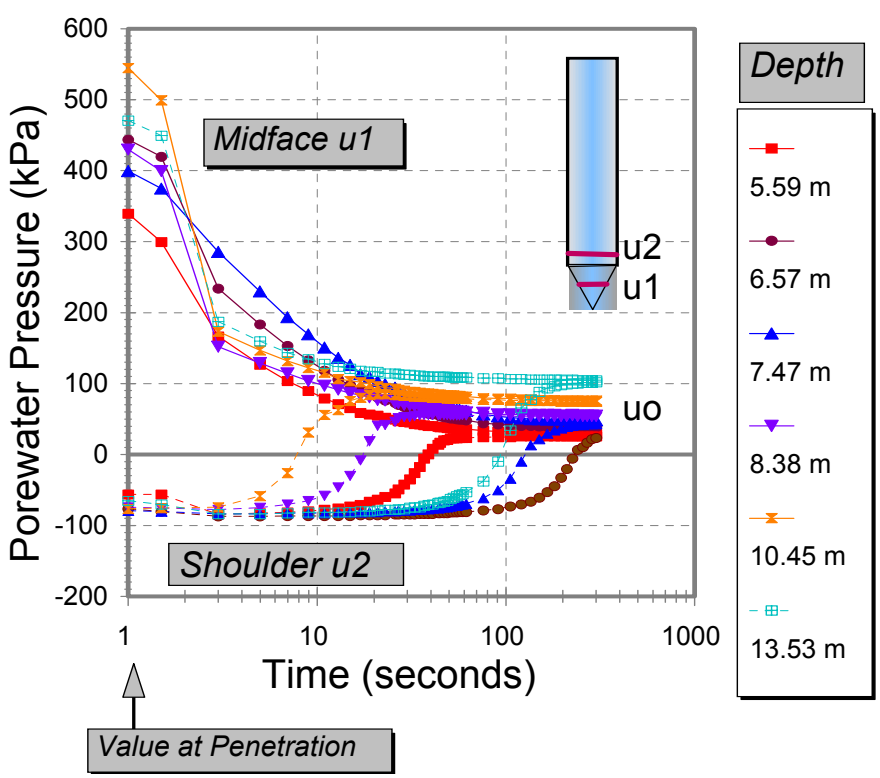

Figure 7. Representative Porewater Dissipations to Hydrostatic Conditions.

using a special 10-cm^2 dual-element penetrometer capable of monitoring u_1 and u_2 simultaneously. At depths ranging from 5.6 m to 13.5 m, separate paired records of pore pressure decay versus logarithm of time are shown. For reference, the associated values of u_1 and u_2 at the time of penetration are shown at t = 1 second. All dissipations reached hydrostatic values (u_0) and corresponded to the ambient unconfined water table at 3 m. Despite the vast differences in u_1 and u_2 readings taken during penetration, full dissipation to the same equilibrium value was achieved at each depth in only 0.5 to 2 minutes for both midface and shoulder elements. Figure 8 shows the initial values of penetration porewater pressures and final values at equilibrium, corresponding to hydrostatic conditions. The quick time for 100% decay indicates fairly high values of coefficient of consolidation ($c_h \approx 0.63$ cm^2/s) and hydraulic conductivity ($k \approx 1 \cdot 10^{-4}$ cm/s) for the silty to sandy Piedmont soils at Opelika (Finke, 1998).

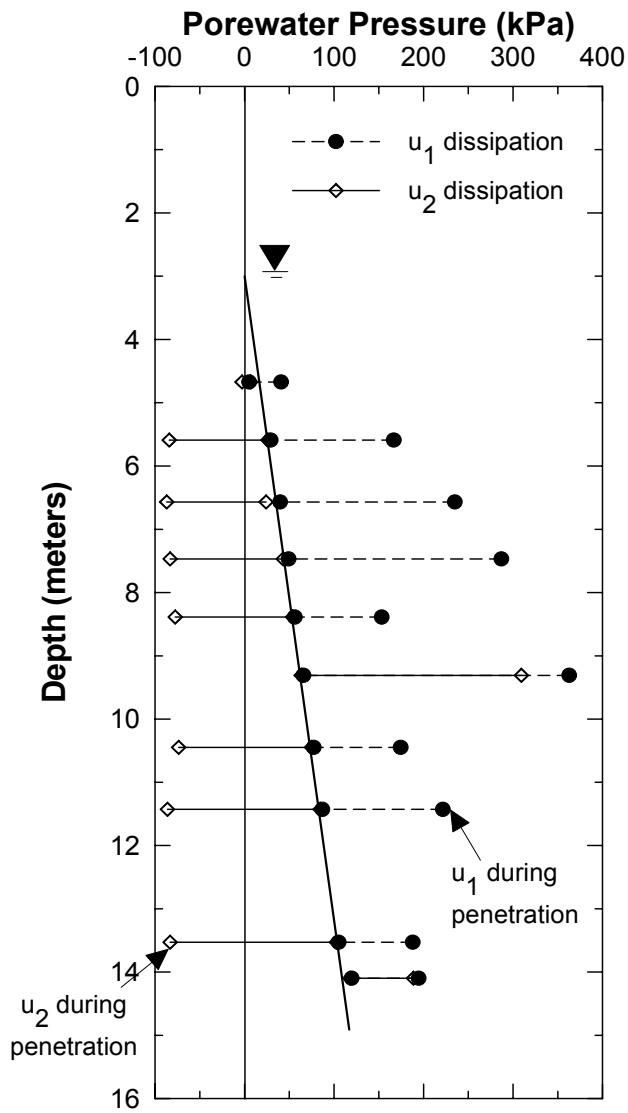

Figure 8. Summary of Initial and Final Porewater Pressures from Piezocones.

Seismic Cone Tests

Several CPTs have been performed at the Opelika NGES using a seismic penetrometer that includes a single horizontal geophone (velocity transducer) within the upper section of the probe. Using a horizontally-struck plank that is oriented parallel with the geophone axis, a vertically-propagating horizontally-polarized shear wave can be monitored at one-meter depth intervals, usually corresponding to the successive addition of cone rods. The source is usually located one to two meters from the axis of the vertical sounding. This downhole geophysical technique provides a pseudo-interval determination of V_s with depth (Campanella, 1994). Striking the plank from the left and then from the right produces two separate waves that are mirrored images. These can be superimposed to accentuate the arrival time of the shear wave on the oscilloscope screen and provide a better delineation during interpretation.

Figure 9 presents the results of a seismic piezocone penetration test (SCPTu) which conveniently provides four independent readings with depth from a single sounding (q_t, f_s, u_b, and V_s). The downhole V_s were relatively constant at 200 ± 50 m/s in the upper 12 meters and compare well with the values obtained from the aforementioned CHT and SASW surveys(Schneider et al. 1999).

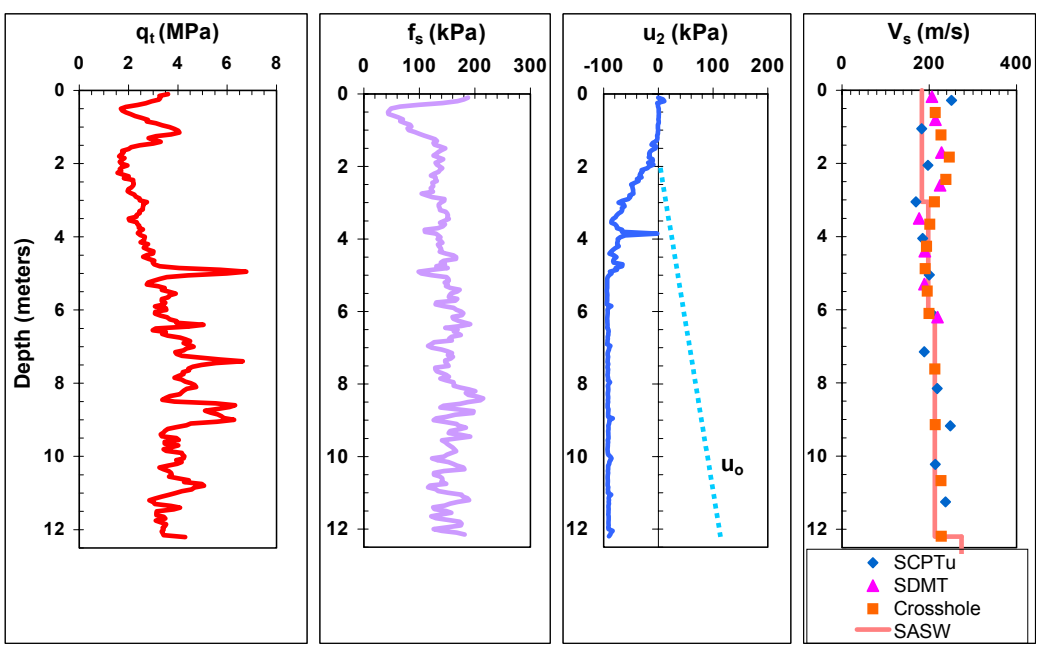

Figure 9. Representative Seismic Piezocone Sounding at Opelika, Alabama.

Flat Plate Dilatometer Tests

The flat plate dilatometer test (DMT) provides measurements of contact pressure (p_o) and expansion pressure (p_1) at regular intervals of either 20-cm or 30-cm with depth. These readings are used to evaluate the stratigraphy and strength properties of the soils. At Opelika, both the regular blade unit and a special modified system outfitted with a geophone in the rod coupler have been used (Martin & Mayne, 1998). Results from one regular DMT and two seismic dilatometer tests (SDMT) are given in Figure 10. The apparent crustal and desiccated zone is evident in the upper three meters in all three measurements (p_o, p_1, V_s). Beneath this, the readings are seen to increase slightly with depth. The shear wave data can be used to provide an initial stiffness, represented by the small-strain shear modulus, $G_0 = \rho(V_s)^2$, where ρ = total mass density of the soil. The DMT pressures can be used to evaluate the soil strength. Thus, it is possible to construct an entire stress-strain-strength curve at each depth from the results of the SDMT, as discussed elsewhere (Mayne, Schneider, & Martin, 1999).

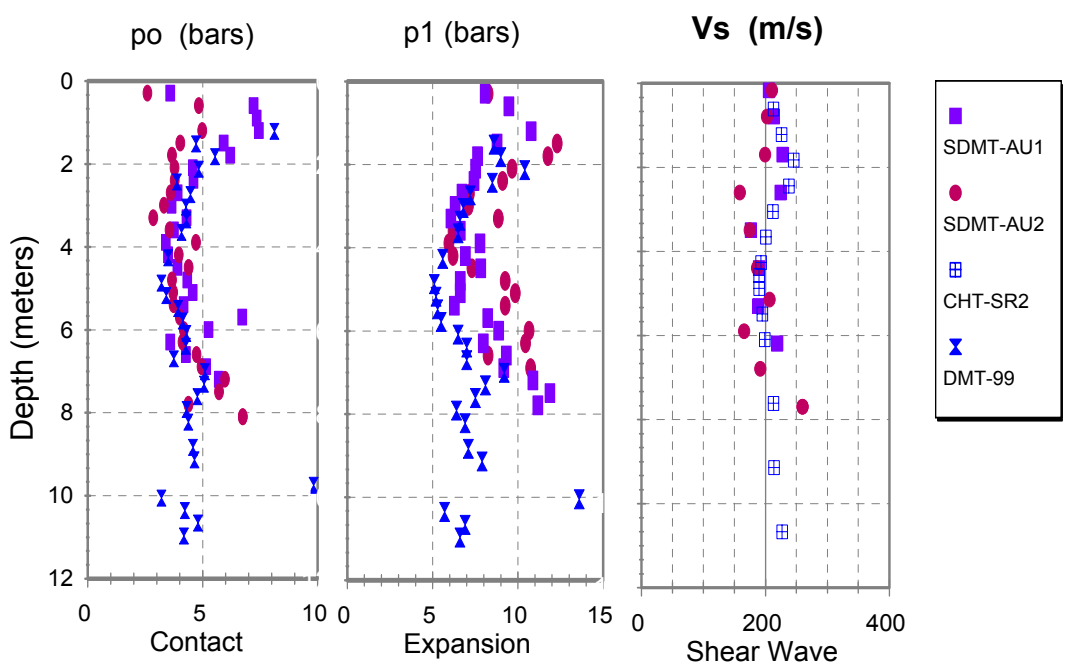

Figure 10. Results from Seismic Flat Plate Dilatometer Tests at Opelika NGES.

Dissipation tests can also be performed using the flat plate dilatometer (Lutenegger, 1988). A special series of DMT dissipations tests have been carried out at Opelika using the A-readings (unpublished). The latter indicate the A-readings decay to about 90% of their penetration value after 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.

Pressuremeter Tests

Menard pre-bored type pressuremeter tests (PMT) were conducted at the NGES using a monocell "Texam"-type probe. The hole was pre-formed by first pushing a 71-mm diameter thin-walled Shelby tube sample at the bottom of the borehole, prior to placement of the pressuremeter. A total of 16 PMTs were completed (Brown & Vinson, 1998). Sample results for the expansion pressure versus measured volume curves are given in Figure 11 from two boreholes at two test depths. Details on the assessment of total horizontal stress (P_o), elastic modulus (E_{pmt}), strength, and limit pressure (P_L) are discussed in Vinson (1997).

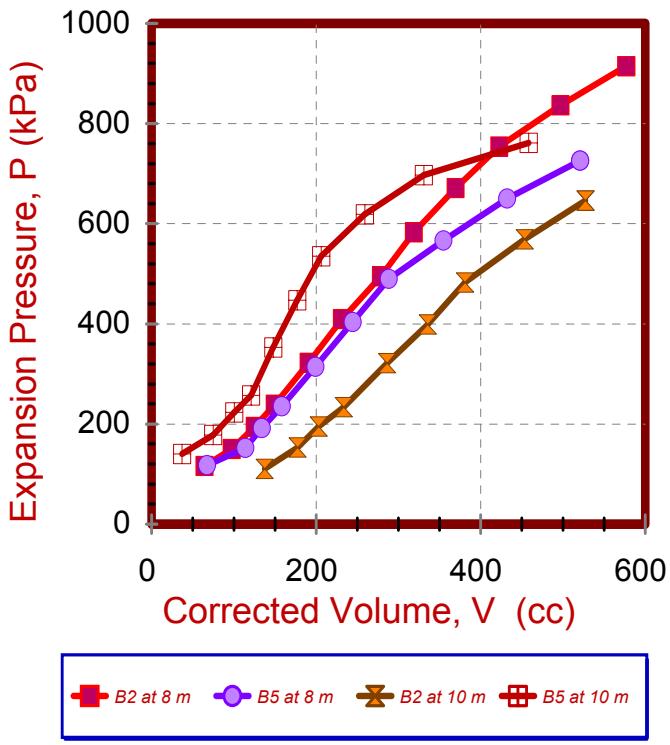

Figure 11. Representative Results from Pre-Bored Type Pressuremeter Tests.

Full-displacement type pressuremeter tests (FDPMT) were also conducted at Opelika using a 35.7-mm diameter Pencel probe having a 60˚ apexed-tip at its front end. This probe is pushed directly into place, thus an assessment of in-situ lateral stress state is not obtainable. However, the test is considerably quicker than regular PMTs that took two days to complete, compared with a total of 29 FDPMTs which were completed in only 6 hours work. Selected results at three test depths are shown in Figure 12, including an unload-reload cycle to better define some pseudo-elastic stiffness of the Piedmont residual soils.

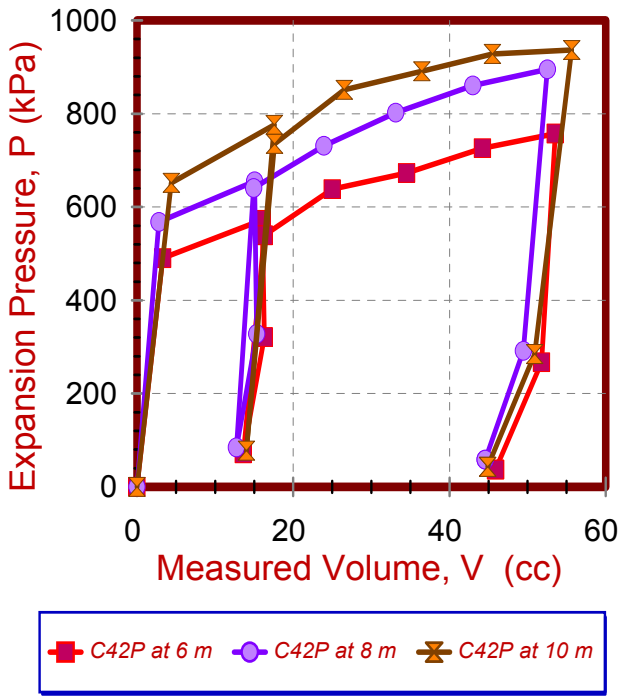

Figure 12. Representative Data from Full-Displacement Pressuremeter Tests.

Figure 13. Conducting CPTs using anchored rig at Opelika, Alabama

Borehole Shear Tests

Iowa borehole shear (IBS) tests were performed downhole in selected soil test borings using a stage-loading procedure. Details are given elsewhere (Vinson & Brown, 1997). These IBS results showed considerable variations in the derived Mohr-Coulomb strength parameters.

Laboratory Testing Program

In addition to drive samples, thin-walled Shelby tube samples were readily obtainable in the Piedmont residual silts and sands. At the Opelika NGES, several sets of tube samples have been retrieved and subjected to a varied assortment of tests, including: unit weight determinations, one-dimensional consolidation, permeability, drained & undrained triaxial shear, and resonant column.

Oedometer Series

The e-log σ_v' curves derived from one-dimensional consolidation tests on Piedmont soils do not show a clear yield point (see Figure 14), thus it is difficult to assign any reputable value of preconsolidation stress, or corresponding overconsolidation ratio (OCR) to these materials (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. Mayne & Harris (1993) suggested the apparent overconsolidation ratios (AOCR) of Piedmont silty sands were between 1.5 and 2.5 within the upper 15 m in downtown Atlanta/GA, while Wang & Borden (1996) showed 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.

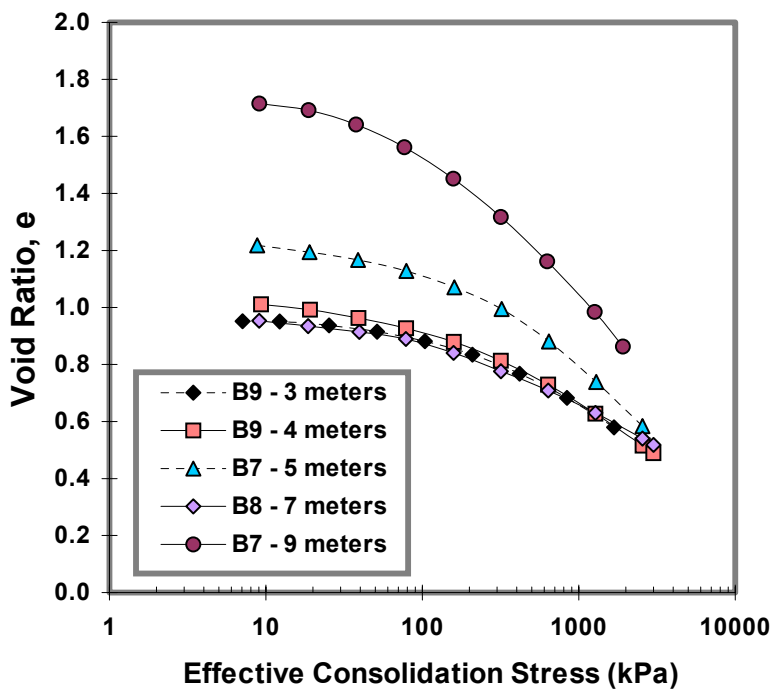

Figure 14. Oedometer Test Data From Piedmont Residuum.

Since these geomaterials have formed inplace from the debonding of the underlying parent rock, the mechanism is one that is opposite of the traditional maximum applied prestressing associated with increased overburden and subsequent erosion or glaciation (e.g. loading-unloading). The Piedmont soils are very old and it is likely that any any preconsolidation effects can likely be attributed to more recent desiccation and groundwater fluctuations that have occurred since the primary debonding events. Expected OCRs due to these latter mechanisms are in the range of 1.5 to 4.

Triaxial Shear Tests

A series of isotropically-consolidated undrained and drained triaxial shear tests were conducted to define the strength and stiffness parameters of the Piedmont residuum at the NGES (Brown & Vinson, 1998). Figure 15 shows the corresponding stress paths in terms of the parameters $q = ½(\sigma_1 + \sigma_3)$ and $p' = ½(\sigma_1' - \sigma_3')$, as well as the interpreted Mohr-Coulomb parameters ($c' = 17$ kPa; $\phi' = 31^\circ$). The majority of tests were CIUC type and overall showed little excess porewater pressure development. No clear trend of contractive nor dilative behavior was observed for the Opelika soils, as noted previously for Piedmont soils in Atlanta (Mayne & Harris, 1993). If the effective cohesion intercept is taken to be negligible ($c' = 0$), then Figure 16 shows the alternative interpretation for the stress path points at failure in MIT q-p' space ($\phi' = 35.3^\circ$).

Figure 15. Laboratory Equipment for Consolidated Triaxial Tests

Corresponding total stress parameters can also be defined for the Piedmont soils. Results from laboratory UU and CIUC tests determined an average $s_u = 92$ kPa within the upper 15 m. Comparisons with values from SPT, DMT, CPT, and PMT

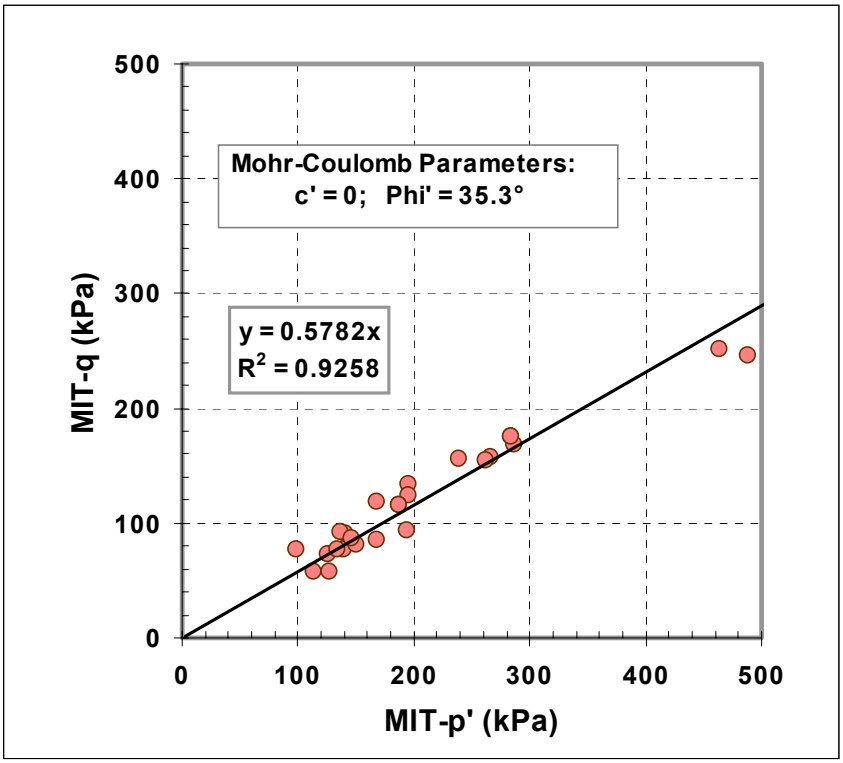

Figure 16. Frictional Envelope of Piedmont Residual Soils at Opelika.

are discussed elsewhere (Vinson & Brown, 1997). Interestingly, a fairly high value for the cone bearing factor of $N_{KT} = 36$ was required to match the CPT results with the laboratory data, whereas commonly adopted values for intact clays are often taken in the range: $8 < N_{KT} < 16$ for compression type loading modes (Lunne, et al. 1997).

Permeability

A very limited number of falling head permeability tests have been conducted on tube samples (Finke, 1998). These tests indicated representative values of coefficient of hydraulic conductivity ($k \approx 1 \cdot 10^{-4}$ cm/s) for the sandy silts to fine sandy silts of the Piedmont geology at Opelika.

Resonant Column

A total of 12 resonant column specimens (142-mm height; 72-mm diameter solid cylinders) were tested under isotropic consolidation using a Stokoe device. The specimens were recovered and trimmed from 10 Shelby tubes retrieved at Opelika NGES. The specimens corresponded to residual soil formations (SM and ML) at depths ranging from 3 m to 10 m. Details are presented in Schneider et al. (1999) and Hoyos & Macari (1999).

Two samples per depth were tested in the resonant column device for validation of test results. Each specimen was tested at five different levels of confinement corresponding to 0.5, 1, 2, 4, and 8 times the effective overburden stress. This range of confining pressures was selected to reflect states of stress below, near, and above the in-situ stress state. Figure 17 presents the summary of small-strain shear moduli (G_{max} or G_0) versus effective confining stress (σ_c'). Both axes are made dimensionless by dividing by a reference pressure equal to one atmosphere (p_a = 1 bar ≈ 100 kPa ≈ 1 tsf).

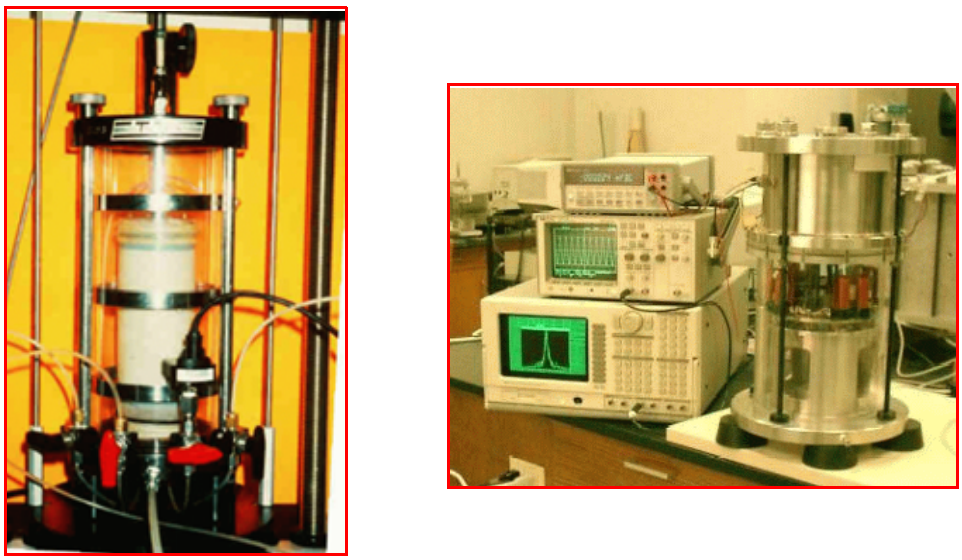

Figure 17. Laboratory Resonant Column Test Setup for Obtaining Small-Strain Shear Modulus (G_{max}) of Piedmont Residual Soils from Opelika AL.

Discussion

A comparison of the strength and stiffness parameters from the various in-situ and lab tests has been made and presented by Brown & Vinson (1998). Since shear modulus (G) is highly dependent on level of shear strain, Figure 18 indicates a very wide variation in measured values, from as low as 2 MPa for the initial loading curve of a Menard PMT to as high as 120 MPa for the small-strain value obtained in field geophysical surveys. Intermediate values of G are obtained with the flat DMT, lab triaxial, and unload-reload cycles applied during the full-displacement type PMT.

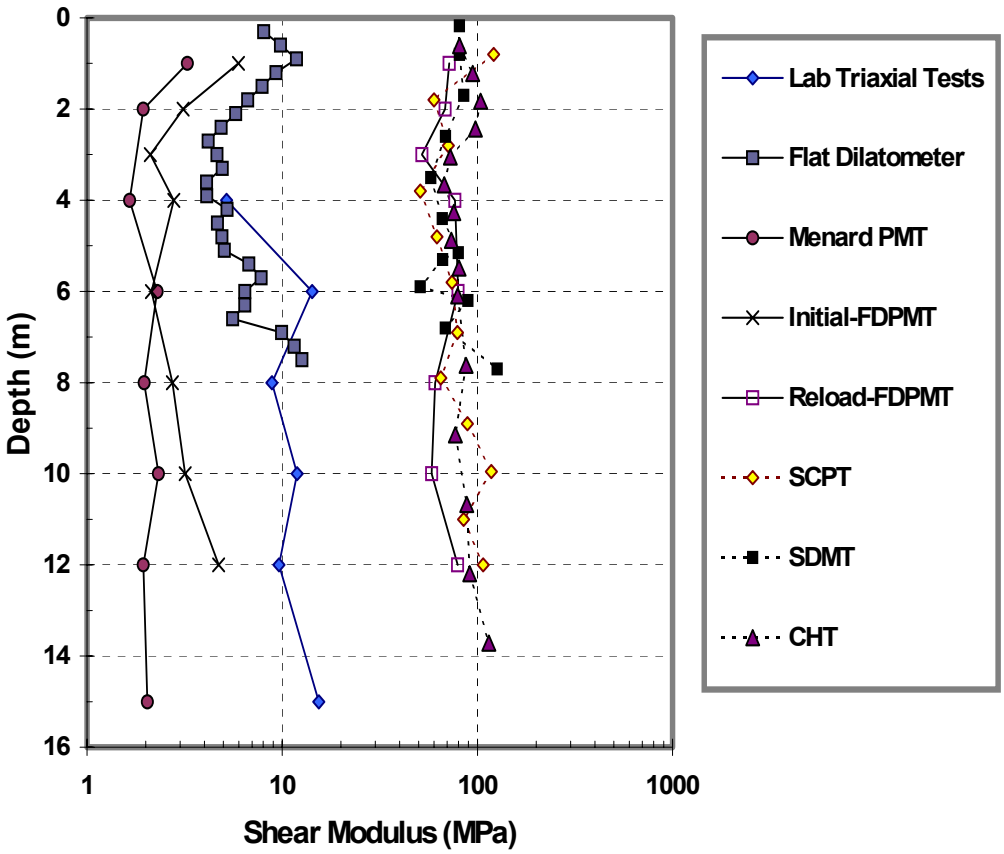

Figure 18. Soil Stiffnesses from Various Tests at Opelika in Terms of Shear Modulus (G) at Different Strain Levels. Note: Modulus E = 2G(1+ν).

An interesting dichotomy occurs in the evaluation of total stress versus effective stress parameters at Opelika. Although excess porewater pressures occur during penetration, the interpretation of SPT, CPT, and PMT by conventional analyses seem to provide reasonable values of effective stress friction angle (ϕ'), thus supporting the favor of interpreted drained behavior in these residual soils. Figure 19 illustrates the utilization of the SPT method (Schmertmann, 1975), CPT data (Kulhawy & Mayne, 1990), and recent DMT approach by Marchetti (1997). The SPT N-values were taken from borings numbered B1, B3, and B4 (see prior Figure 3). For the comparison presented herein, the cone tip resistance (q_t) from CPT sounding number CPT42 (previously reported by Mayne, 1999) and the value of horizontal stress index (K_D) from DMT-99 (Fig. 10) were used. As seen in Figure 19, the interpreted ϕ' from these three in-situ penetration tests give comparable values to the $\phi' = 35^\circ$ (assuming c' = 0) obtained from the triaxial series (prior Fig. 16). The CPT approach by Robertson & Campanella (1983) gave ϕ' values about 1° higher at shallow depths and -1° lower at deeper depths. In addition, the interpreted values of effective stress friction angles for the full-displacement and prebored PMT data are $30^\circ < \phi' < 33^\circ$ (Vinson & Brown, 1997).

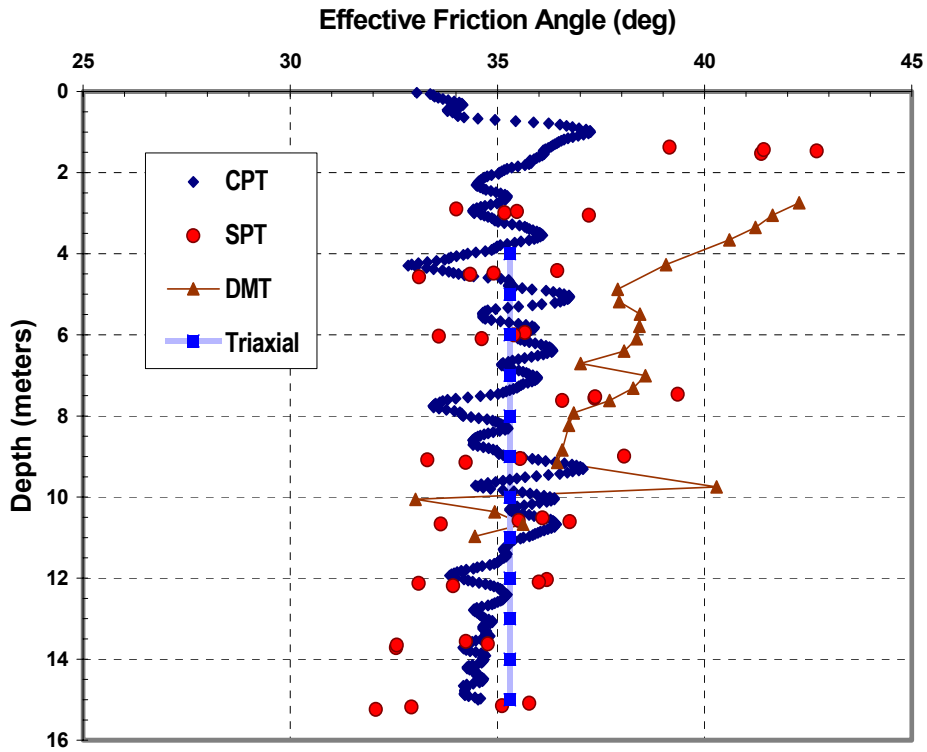

Figure 19. Interpreted Effective Stress Strength Parameters at Opelika NGES.

In contrast, a total stress interpretation of in-situ data suggests that the Piedmont residuum acts as a stiff fissured clay. Evidence for this is three-fold: (1) penetration porewater pressure response; (2) backcalculated cone bearing factor; (3) shear wave data; as explained subsequently.

Reviews of piezocone data worldwide have showed that the unusual combination of penetration porewater pressures (positive u_1 yet negative u_2) occur in stiff fissured geomaterials (Mayne, Kulhawy, & Kay, 1990; Lunne, Robertson, & Powell, 1997). Examples include the fissured clays in London (Brent Cross), Gault clay (Madingley), and Beaumont formation (Texas). The positive u_1 readings are likely indicative of destructuration of the relict bonding of the parent intact rock, yet the negative u_2 readings reflect the remnant cracks, fissures, and discontinuities of the former rock mass (Finke, et al. 1999). Both facets are still represented within the residual soil matrix. Mapped evidence of pre-existing cracks, fissures, and slickenslides in the Piedmont has been documented previously (St. John, et al. 1969; Sowers & Richardson, 1983).

Because of the relict presence of fissures & cracks, the operational undrained strength is less than that of a comparable intact "clay". Thus, prior work has shown that backcalculated N_{kT} factors for fissured materials are on the order of 25 to 30+ (Marsland & Powell, 1988; Powell & Quarterman, 1988), thus in agreement with the

values obtained by Brown & Vinson (1998). It is important to cite the specific mode of undrained shear under consideration (i.e., triaxial, simple shear, plane strain) and direction of loading (i.e., compression vs. extension), as the undrained shear strength (s_u) depends significantly on these facets, as well as the effects of strain rate, anisotropic stress state, and other factors (Kulhawy & Mayne, 1990).

Figure 20 shows the undrained shear strengths (s_{uTC}) for triaxial compression loading from reference laboratory CIUC tests compared with in-situ interpretations based on the CPT using a bearing factor N_{kt} = 35 (Lunne, et al. 1997), SPT (Stroud, 1988), and DMT with N_c = 7 (Roque, et al. 1988). The overall average s_{uTC} from UU and CIUC tests is 92 kPa at the Opelika site. The triaxial data shown herein are only CIUC results performed at the current effective vertical overburden stresses. Surprisingly, the same SPT, CPT, and DMT data were used to generate both the total stress parameters (Fig. 20) and effective stress parameters (Fig. 19), thus illustrating the hermaphroditic strength characteristics of the Piedmont residuum.

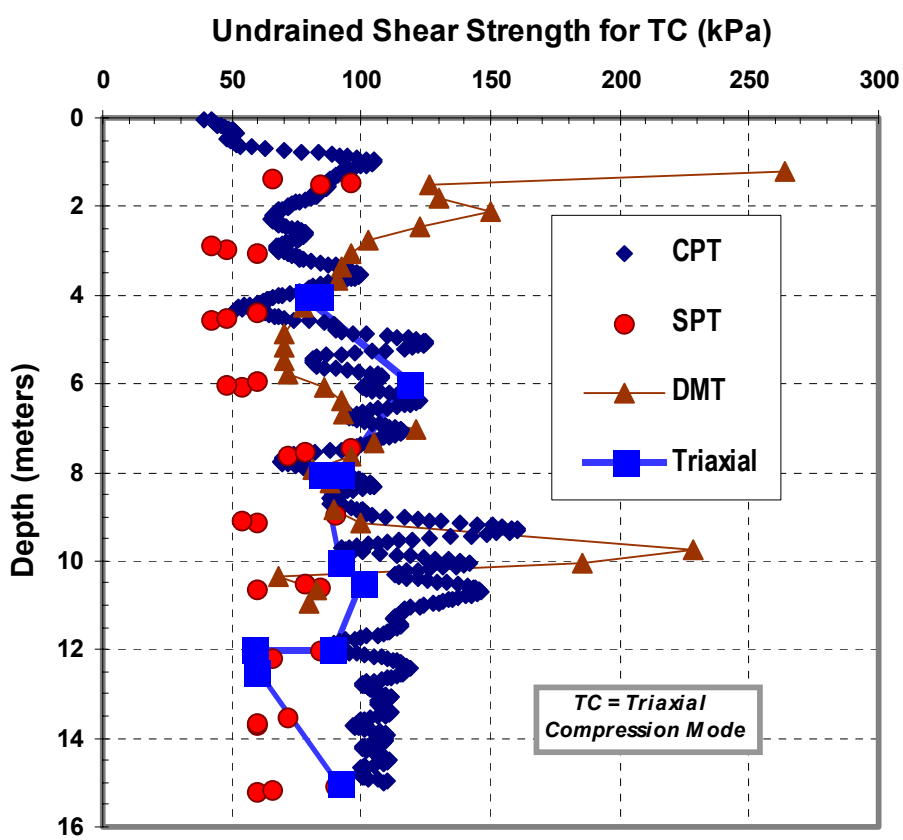

Figure 20. Interpreted Undrained Shear Strengths at Opelika NGES.

Interrelationships between small-strain G_0 and penetration resistance q_T have been formulated for different soil types, including clean quartz sands (Baldi, et al. 1989), clays (Mayne & Rix, 1993), as well as a full range of soil types (Lunne, et al. (1997). Here too, a dichotomy occurs in that the use of the seismic piezocone data (taken from Fig. 9) presented in terms of normalized cone tip resistance [$Q = (q_t - \sigma_{vo})/\sigma_{vo}'$] versus the ratio G_0/q_t plots within the region of "sand mixtures" grading to "silt mixtures", as shown by Figure 21. This gives an apparent reasonable classification according to soil type by gradation and is consistent with the aforementioned dual ML/SM nomenclature. However, when the same data are put in terms of the clay database (Figure 22) and presented directly as G_0 vs. q_t, the results suggest that the Piedmont soils are behaving analogous to stiff fissured clays.

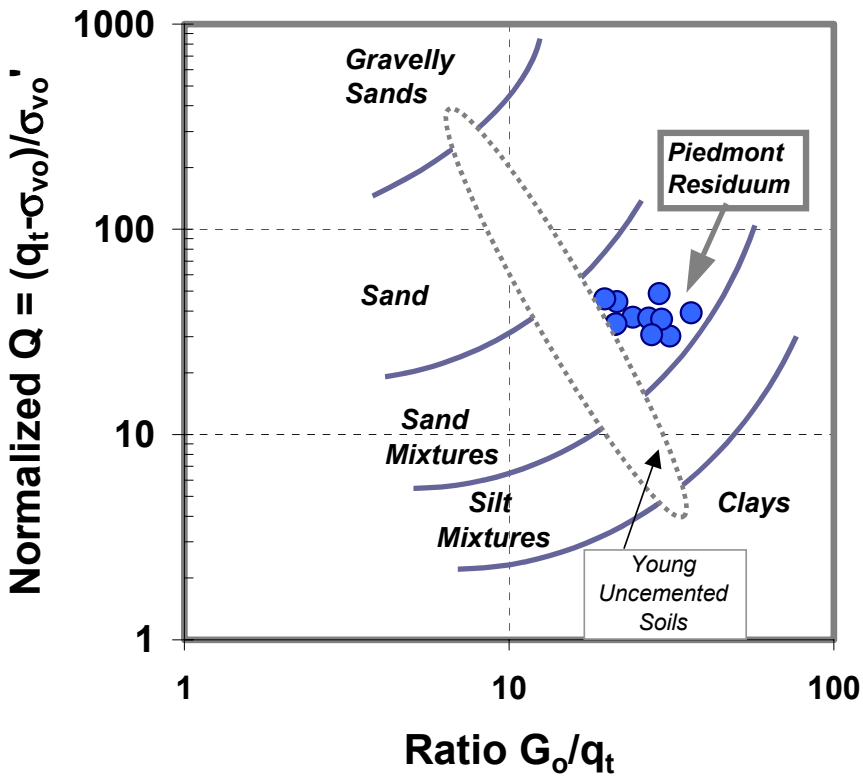

Figure 21. Normalized Cone Tip Stress Q vs. Ratio G_0/q_t from SCPTu Sounding. (Soil Behavioral Classification System given in Lunne, et al. 1997).

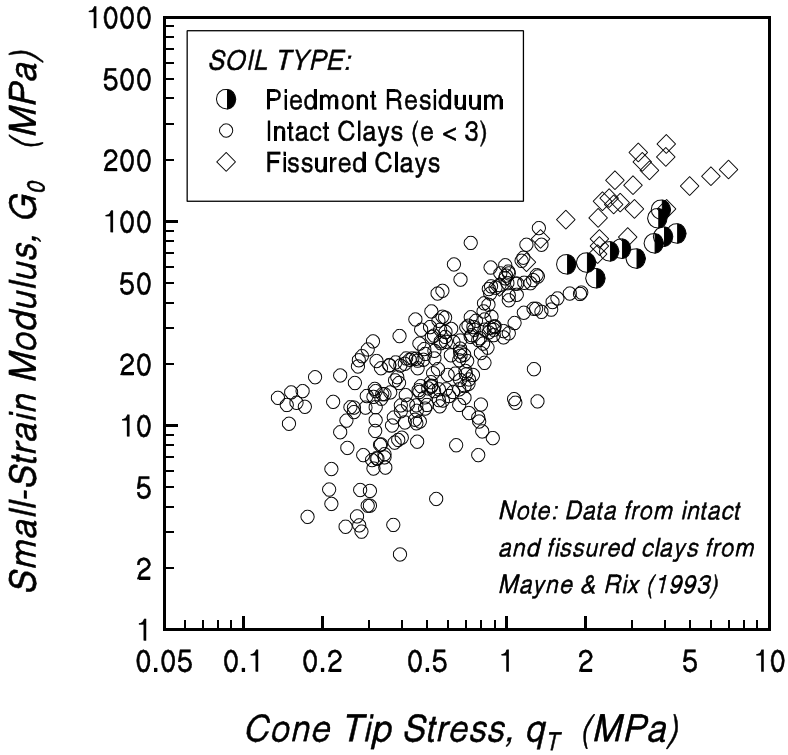

Figure 22. Small-Strain Stiffness (G_0) versus Cone Tip Stress (q_t) in Intact to Fissured Clay Geomaterials, including Piedmont SCPTu Data.

Conclusions

A geotechnical characterization program has been directed at the improved understanding of Piedmont residual soils which are comprised of fine sandy silts and silty fine sands derived from weathered gneiss and schist. At the Opelika NGES in southeastern Alabama, several series of in-situ field penetration tests (SPT, CPT, PCPT, SCPT, DMT, SDMT, FDPMT), borehole tests (PMT, IBS), and geophysical techniques (CHT, DHT, SASW) have been performed and complemented by series of laboratory tests (index, triaxial, consolidation, resonant column). Piedmont soils are unusual in that they exhibit behavioral features which are characteristic of both sand and clay.

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