Case Studies Linking Foundation Performance and In-Situ Tests in the Appalachian Piedmont

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Surficial Extent of Appalachian Piedmont

Appalachian Piedmont Geologic Province

VA-MD-DC

GA-AL-SC-NC
Piedmont Geologic Province
# Primary Rock Types by Geologic Origin

<table>
<thead>
<tr>
<th>Grain Aspects</th>
<th>Sedimentary Types</th>
<th>Metaphorphic</th>
<th>Igneous Types</th>
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<td>Limestone</td>
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<td>Obsidian</td>
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**PIEDMONT**
<table>
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<tr>
<th>Era</th>
<th>Period</th>
<th>Epoch</th>
<th>Time Boundaries (Years Ago)</th>
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- **Geologic Time Scale**

Piedmont Granite

Piedmont Gneiss and Schist
Major Rock Formations in USA

Piedmont

Generalized Map of Major Formations of North America:
- Sedimentary rocks
- Igneous rocks
- Metamorphic rocks (with intrusive Plutonics)
- Plutonic rocks
Piedmont Subsurface Profile

"Georgia Red Clay" (CL - ML)

RESIDUUM (ML to SM)

SAPROLITE

Partially-Weathered Rock (PWR)

Intact Rock: Gneiss Schist, Granite
GT Load Test Site, West Campus

SPT N-values (bpf)

Depth (feet)

Piedmont Residuum:
Silty Fine Sand (SM)

PWR

GRANITIC GNEISS
In-Situ Testing in the Piedmont

- SPT = standard penetration testing
- PMT = pressuremeter testing
- DP = dynamic penetrometers
- percussive soundings (air-track)
- VST = vane shear testing
- DMT = flat plate dilatometer
- CPT = cone penetration testing
- CPTu = piezocone testing
- $V_s$ = shear wave velocity
- SCPTu = seismic piezocone
- SDMT = seismic dilatometer

Miller & Sowers (1967). Shear characteristics of Piedmont soils using rotating vanes
SCPTU in Piedmont residual silts
Winston-Salem, NC

- Depth (meters)
- Pressure (kPa)
- Material Index $I_D$
- Modulus $E_D$ (atm)
- Horiz. Index $K_D$

- $P_0$
- $P_1$

Clay Silt Sand
Fairfax Hospital, Northern Virginia (1984)
Case Study: Drilled shaft (L = 65' and d = 3') in Piedmont residuum
Axial Pile Influence Factors (Rigid Pile)

Poulos & Davis (1980) Solution vs. Randolph Solution

\[ W_t = \frac{P_t \cdot I_p}{d \cdot E_s} \]

Boundary Elements
- Closed Form $v = 0.5$
- Closed Form $v = 0.2$
- Closed Form $v = 0$
RIGID PILE RESPONSE
Length L and diameter d

Homogeneous Soil:
\( E_s = \) Elastic modulus
\( \nu' = \) Poisson's ratio

Ground Surface

Top Displacement, \( w_t \)
\[
 w_t = \frac{P_t \cdot I\rho}{d \cdot E_s}
\]

Randolph Solution

Side Load, \( P_s \)
\( = P_t - P_b \)

Load Transferred to Base:
\[
 \frac{P_b}{P_t} = \frac{I\rho}{1 - \nu^2}
\]

Base load
\( P_b = \) Base load
Fairfax Hospital, Northern Virginia

\[ E' \approx E_D \text{ (ave. 64 DMTs)} = 35 \text{ MPa} = 364 \text{ tsf} \]

\[ L = 65 \text{ feet and } d = 3 \text{ feet} \]

Ratio \( L/d = 21.7 \) gives \( I_p = 0.076 \)

\[ W_t = \frac{P_t \cdot I_p}{d \cdot E_s} \]
Buildings on Piedmont - Northern Virginia and Washington DC
DMT-SPT Correlation in Piedmont Residuum


$E_D = 22 \cdot \sigma_{\text{atm}} \cdot N_{60}^{0.82}$

Elastic Modulus, $E'$ (bars)

SPT N$_{60}$ value (bpf)
Foundation Systems in the Piedmont

- Spread footings
- Mat foundations
- Augercast pilings
- Drilled shafts
- Micropiles
- Driven pipe piles
- H-pilings
- Monotubes
- Step-taper piles
- Franki piles (PIFs)
First American Bank Mat

Bank Tower:
Total Q = 73,400 ksi
Bearing Elev = +495 feet msl
Mat Thickness, t = 4.5 ft
Applied Stress: q = 3.47 ksf
Wachovia/Wells Fargo
Tysons Corner, VA
Settlements: GSU Dormitory, Atlanta

www.geoengineer.org

10" mat settlements

DMT $\text{E}_D = 85$ tsf

**Dormitory B Settlement Contours**

- 100 mm
- 120 mm
- 140 mm
- 160 mm
- 180 mm
- 200 mm
- 220 mm
- 240 mm

**Reinforced Concrete Mat Foundation:** $c = 105$ m; $d = 18.3$ m, thickness $t = 1.07$ m

**Center Deflection:**

$$\rho_c = \frac{q \cdot d \cdot I_H (1 - v^2)}{E_s}$$

**Finite Layer Thickness, $h/d$**

- Harr (1966) Approximation

**Distance (meters)**

- SW-NE Diagonal
- NW-SE Diagonal
- DMT Calculated ($h = 12$ m)
- DMT Calculated ($h = 18$ m)
- DMT Calculated ($h = 24$ m)
Load Tests

- End-bearing drilled shaft: $d = 0.76$ m, $L = 19.2$ m
- Friction-type drilled shaft: $d = 0.76$ m, $L = 16.9$ m
- Deep plate load test: $d = 0.61$ m, $z = 16.9$ m
GT End-Bearing Shaft C1: $d = 2.5'$ by $L = 70'$

Axial Load Transfer Distribution

Axial Load, $Q$ (tons)

Depth (feet)

Base

Vibrating Wire Strain Gages
Elastic Continuum Response - GT Shaft C1

Axial Load, $Q$ (kN)

Top Deflection, $w_t$ (mm)

$Q_{total} = Q_s + Q_b$

Pred. $Q_s$

Pred. $Q_b$

Meas. Total

Meas. Shaft

Meas. Base

Using DMT $E_D$ Modulus in Elastic Solution
Elastic Continuum Response - Shaft C2

Using DMT $E_D$ Modulus in Elastic Solution

$Q_{total} = Q_s + Q_b$

Predicted $Q_s$

Predicted $Q_b$

Measured Total

Measured Shaft

Measured Base
Cone Penetration Tests (CPT) at GT West Campus

![Graph showing q_t (MPa), f_s (kPa), and FR = f_s/q_t (%) versus depth. Continuous Readings at 20 mm/s.](image)
CPT

- Current Phase Transformer
- Cross Product Team
- Cellular Paging Teleservice
- Chest Percussion Therapy
- Crisis Planning Team
- Consumer Protection Trends
- Computer Placement Test
- Current Procedural Terminology
- Cost Per Treatment
- Choroid Plexus Tumor
- Cardiopulmonary Physical Therapy
- Corrugated Plastic Tubing
- Cumulative Price Threshold
- Cell Preparation Tube
- Central Payment Tool
- Certified Proctology Technologist
- Cockpit Procedures Trainer
- Cone Penetration Test
- Color Picture Tube
- Critical Pitting Temperature
- Certified Phlebotomy Technician
- Control Power Transformer
- Cost Production Team
- Channel Product Table
- Conditional Probability Table
- Command Post Terminal
Piezocone Response in the Piedmont

Cone Tip Resistance $q_t$ (MPa)

Sleeve Friction $f_s$ (kPa)

Porewater Pressure $u_2$ (kPa)

Porewater Pressure $u_1$ (kPa)

Height of Capillarity
CPTu in Piedmont PWR- Atlanta, GA

- q_T (MPa)
- f_s (MPa)
- u_2 (MPa)

Depth (m)

SPT
N60
23
34
71
Residuum: silty fine sand

Saprolite (hard fine sandy silt)

Partially-Weathered Rock (gneiss)
SCPTU in Piedmont residual silts
Winston-Salem, NC
Geotechnics 2013 in the Piedmont

More Measurements

is

More Better

Mas Mejor
Seismic Piezocone (SCPTu)
Piedmont silts in Marietta, GA
Tip Resistance
$q_T$ (MPa)

Sleeve Friction
$f_s$ (kPa)

Porewater Pressure
$u_2$ (kPa)

Shear Wave Velocity
$V_s$ (m/s)

Depth (m)

Shear Wave Velocity
$V_s$ (m/s)
Piezo-Dissipation in Piedmont Residuum

- u₁ dissipations
- u₂ dissipations
- u₀

Porewater Pressure (kPa)

Time (seconds)

5.59 m
6.57 m
7.47 m
8.38 m
10.45 m
13.53 m

500
400
300
200
100
0
-100
1 10 100 1000

u₁
u₂
u₀
SCPTù at Atlanta Airport Runway 5

Five Independent Readings of Soil Behavior: $q_t$, $f_s$, $u_b$, $t_{50}$, $V_s$
Equivalent Elastic Modulus for Static Loading

\[ E_{\text{max}} = 2G_{\text{max}}(1+\nu) \]

\[ G_{\text{max}} = \rho_t V_s^2 \]

\[ \rho_t = \frac{\gamma_t}{g} \]
Algorithm: \( G/G_0 = 1 - (q/q_{\text{max}})^g \)

\[ g = 0.2 \ 0.3 \ 0.4 \ 0.5 \text{ = exponent} \]

Resonant Column, Torsional Shear, and Triaxial Data

Mobilized Strength, \( q/q_{\text{max}} = 1/FS \)
Randolph Compressible Pile

\[ I_p = x_1/x_3 \]

\[ x_1 = 4 \cdot (1+v) \left[ 1 + \frac{1}{\pi \lambda} \cdot \frac{8}{1-v} \cdot \eta \cdot \tanh(\mu L) \cdot L \right] \]

\[ x_2 = \frac{4}{1-v} \cdot \frac{\eta}{\xi} \cdot \frac{1}{\cosh(\mu L)} \]

\[ x_3 = \frac{4}{1-v} \cdot \frac{\eta}{\xi} + \frac{4\pi \rho_E}{\zeta} \cdot \tanh(\mu L) \cdot L \cdot \frac{d}{d} \]

The proportion of load transferred from the top to base:

\[ P_b/P_t = x_2/x_3 \]

The proportion of load carried in side shear is:

\[ P_s/P_t = 1 - P_b/P_t \]

The displacement at the pile toe/base is given by:

\[ w_b = w_t / \cosh(\mu L) \]

\[ \eta = d_b/d = \text{eta factor} \quad \text{(Note: } d_b = \text{base diameter, so that } \eta = 1 \text{ for straight shaft piles)} \]

\[ \xi = E_{sL}/E_b = \text{xi factor} \quad \text{(Note: } \xi = 1 \text{ for floating pile; } \xi < 1 \text{ for end-bearing pile)} \]

\[ \rho_E = E_{sm}/E_{sL} = \text{rho term. The parameter can be evaluated from: } \rho_E = \frac{1}{2}(1+E_{so}/E_{sL}). \]

\[ \lambda = 2 \cdot (1+v) \cdot E_p/E_{sL} = \text{lambda factor} \]

\[ \zeta = \ln\{[0.25 + (2.5 \cdot \rho_E \cdot (1-v) - 0.25) \cdot \xi] (2 \cdot L/d)\} = \text{zeta factor} \]

\[ \mu L = 2 \cdot (2/\zeta \cdot \lambda)^{0.5} \cdot (L/d) = \text{mu factor} \]
LAB TESTING
- Grain size
- Hydrometer
- Plasticity indices
- Unit weights
- Triaxial shear (CIUC, CIDC)
- Direct shear, UU, and UC
- Fixed wall permeameter
- Flex-wall permeability
- Resonant column tests
- One-dim consolidation

IN-SITU TESTING and GEOPHYSICS
- Standard penetration tests (SPT)
- Full-displacement pressuremeter (FDPMT)
- Menard pre-bored pressuremeter (PMT)
- Flat plate dilatometer tests (DMT)
- Cone penetration tests (CPT)
- Piezocone tests with dissipations (CPTû)
- Seismic dilatometer tests (SDMT)
- Dual element piezocones (CPTu1u2)
- Resistivity cones (RCPTu)
- Seismic piezocones (SCPTu)
- Dielectric cones (DCPTu)
- Borehole shear tests (IBST)
- Geophysical crosshole tests (CHT)
- Spectral analysis of surface waves (SASW)
- Torque measurements following SPT
- Penetration rate effects studies
- Frequent interval Vs profiling
- Surface resistivity surveys

FULL-SCALE LOAD TESTS
- Drilled shaft foundations
- Axial tests on drilled shafts
- Lateral tests on drilled shafts
- Time and construction effects studies
- Driven pipe piles at varied rates
- De Waal piles
- Lateral loading testing of pile groups
- Shafts with self-compacting concrete
Opelika NGES in the Piedmont

Applied Load, Q (kN)

Displacement, s (mm)

Q (total)

4 Drilled Shafts

\( d = 0.91 \text{ m} \)
\( L = 11.0 \text{ m} \)

Q shaft

Q base
Load Test at I-85 Bridge, Coweta County, GA

GDOT Drilled
Shaft Load Test:

D = 0.91 m
L = 20.1 m

Load Test
Directed by
Mike O'Neill
SCPTu at I-85 Bridge, Newnan, GA
Drilled Shaft Response, Coweta County, GA

Axial Load, $Q$ (kN)

Displacement, $w_t$ (mm)

$Q_{total} = Q_s + Q_b$

Pred. $Q_s$

Pred. $Q_b$

Meas. Total

Meas. Shaft

Meas. Base
HERBERT, ONCE UPON A TIME YOU WERE THE ROCK OF MY WORLD. THEN YOU BECAME THE STONE IN MY SHOE... NOW YOU'RE THE SAND IN MY SANDWICH. GOODBYE.

Rock → Stone → Sand = Formation of Residuum
Class “A” Prediction of Axial Pile Response
Jackson County, Georgia

Turbine Foundations,
Plant Dahlberg Power Station
Southern Companies

- \( G_{\text{max}} \) from SCPTu for dynamically-loaded block foundations
- Switched to driven 273 mm diameter closed-ended steel pipe piles: \( 8 < L < 18 \text{ m} \).
- CPT \( q_t, f_s \text{ and } u_2 \) used for axial capacity and \( V_s \) for initial stiffness.

Courtesy Marty Meeks
Seismic Piezocone Sounding, Jackson County, GA

- \( q_t \) (MPa)
- \( f_s \) (kPa)
- \( u_2 \) (kPa)
- \( V_s \) (m/sec)
Axial Pile Response from SCPTu, Jackson County, GA

Driven Steel Pipe Pile No. P22 (L = 9.45 m)

Axial Load, Q (kN)

Deflection, w (mm)

Predicted by SCPTu in Advance

Measured
Axial Pile Response from SCPTu, Jackson County, GA

Driven Steel Pipe Pile No. P33 (L = 17.8 m)

Axial Load, Q (kN)

Deflection, w (mm)

Predicted in advance from SCPTU data

Measured from Load Test

Predicted in advance from SCPTU data

Measured from Load Test
Pile Load Tests

Dead Weight
www.hindu.com

Reaction Frame
www2.dot.ca.gov

Statnamic Load Test
www.statnamic europe.com

Osterberg Cell
www.fhwa.dot.gov
GDOT O-Cell Load Test for Viaduct at CNN

**Constructed Dimensions of Drilled Shaft**

- **Stage 1 O-cell**
  - Partially-Weathered Rock (PWR)
  - $d = 1.44$ m

- **Stage 2 O-cell**
  - Residual Soils (ML/SM)
  - $d = 1.59$ m

- **Total depth**
  - 2.9 m
  - 11.8 m
  - 6.2 m

*Images of construction equipment and buildings.*
GT Seismic Piezocone Sounding (SCPTu)  
GDOT - International Blvd. 

Notes: Electronic data lost from 15.70 m to 16.70 m due to computer malfunction.
**Class A Prediction - GDOT Bridge at CNN**

**GDOT International Blvd. at CNN**

Axial Load, $Q$ (MN)

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<th>Axial Load, $Q$ (MN)</th>
<th>Top Deflection, $w_t$ (mm)</th>
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- **LoadTest**
- **Elastic Continuum Solution with SCPTu data input**

**Qt Predicted**
- **O-cell top down**
- **O-cell Creep Limit**
O-cell load tests in Piedmont rocks

Drilled shafts - Lawrenceville, GA (2011)
**O-Cell Elastic Solution**

**Rigid pile shaft under upward loading**

\[
\frac{P_1}{G_{s1} r_1 w_1} = \frac{2\pi}{\zeta_1} \cdot \frac{L_1}{r_0} 
\]

**Rigid pile or plate under compression loading**

\[
\frac{P_2}{G_{s2} r_2 w_2} = \frac{4}{(1-\nu)\zeta} + \frac{2\pi}{\zeta_2} \cdot \frac{L_2}{r_0} 
\]

- **P** = applied force
- **L** = pile length
- **r_o** = pile radius
- **E_p** = pile modulus
- **G_s** = soil side shear modulus
- **G_{sL}** = soil-pile stiffness ratio
- **G_{s2}** = soil modulus below pile base/toe
- **G_{sb}** = soil modulus below pile base/toe
- **w** = pile displacement
- **I** = \(\frac{E_p}{G_{sL}}\)
- **\(\zeta\)** = \(G_{s2}/G_{sb}\) (Note: floating pile: \(\zeta = 1\))
- **\(\zeta_1\)** = soil zone of influence
- **\(\zeta_2\)** = soil zone of influence
- **\(\nu\)** = Poisson's ratio of soil
- **\(r_m\)** = magic radius
**O-cell tests - ADSC/ASCE Lawrenceville, GA**

**Application of Randolph Elastic Solution**

**Test Shaft 1 in Rock**

- Applied Load, $Q$ (tons)
- Displacement, $w$ (inches)

- Upper Segment
- Base Response
- Elastic Pred Upward
- Elastic Down Pred

- $E' = 3500$ tsf

**Test Shaft 2 in PWR**

- Applied Load, $Q$ (tons)
- Displacement, $w$ (inches)

- Upper Segment
- Base Response
- Elastic Pred Upward
- Elastic Down Pred

- $E' = 1050$ tsf
Recommendations to Geotechnical Practice

Site Characterization in the Piedmont
NON-INVASIVE GEOPHYSICS
(Resistivity, Radar, Conductivity)
Direct Push Borehole Methods

**Continuous Push Sampling**

- Steel mandrel with inner plastic lining ($d = 35$ to $70$ mm)
- Hydraulic and/or percussive push in 3-m strokes

**Sonic Drilling**

- Vibrations at resonant frequency of drill pipe
- Fast and continuous sampling of soil and rock

www.geoprobe.com  www.ams-samplers.com  boartlongyear.com
## Calibration of SPT Energy - Auto Hammers

<table>
<thead>
<tr>
<th>Manufacturer Type</th>
<th>ID No.</th>
<th>Mean Energy Ratio (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diedrich D-120</td>
<td>ID 26</td>
<td>46</td>
<td>UDOT</td>
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<td>Diedrich D-50</td>
<td>321870551</td>
<td>56</td>
<td>GRL</td>
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<td>CME 850</td>
<td>ID 21</td>
<td>62.7</td>
<td>UDOT</td>
</tr>
<tr>
<td>BK-81 w/ AW-J rods</td>
<td>B2</td>
<td>68.6</td>
<td>ASCE</td>
</tr>
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<td>Mobile B-80</td>
<td>ID 18</td>
<td>70.4</td>
<td>UDOT</td>
</tr>
<tr>
<td>SK w/ CME hammer</td>
<td>B6</td>
<td>72.9</td>
<td>ASCE</td>
</tr>
<tr>
<td>Diedrich D50</td>
<td>UF5</td>
<td>76</td>
<td>UF</td>
</tr>
<tr>
<td>CME 55</td>
<td>UF2</td>
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<td>CME 850</td>
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<td>79</td>
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<td>CME 45</td>
<td>UF1</td>
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<td>UF</td>
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<td>CME 85</td>
<td>UF4</td>
<td>81.2</td>
<td>UF</td>
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<tr>
<td>CME 75 w/ AW-J rods</td>
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<td>81.4</td>
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<tr>
<td>CME 75</td>
<td>UF3</td>
<td>83.1</td>
<td>UF</td>
</tr>
<tr>
<td>CME 750</td>
<td>ID 4</td>
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<tr>
<td>Mobile B-57</td>
<td>DR-35</td>
<td>93</td>
<td>GRL</td>
</tr>
<tr>
<td>CME 75 rig</td>
<td>ID 10</td>
<td>94.6</td>
<td>UDOT</td>
</tr>
</tbody>
</table>

*Factor of 2.1*
O-cell load tests in Piedmont rocks
Drilled shafts - Lawrenceville, GA (2011)

Figure 7 % RQD from Rock Cores
Methods for Rating Rock Masses

- Core Recovery (CR)
- Rock Quality Designation (RQD); Deere et al. (1966)
- Rock Mass Rating (RMR); Bieniawski (1976, 1989)
- Q-System by NGI; Barton et al. (1976, 1991)
- Geological Strength Index (GSI); Hoek (1995, 2009)

Rock Mass Rating (RMR)

- Uniaxial Compressive Strength, $q_u$
- Rock Quality Designation (RQD)
- Spacing of Joints
- Condition of joints and/or infilling
- Groundwater conditions
Shear Wave Velocity Profile in Piedmont
VC Summer Power Station, South Carolina

Intact Rock

CR = 98 - 100%
RQD = 97 - 100%

Vs = 10,100 fps = 3078 m/s

q_u = 25 ksi = 170 MPa

γ_t = 180 pcf = 28 kN/m³

Vs from suspension logging in boreholes
Beyond conventional SPT and PMT, showed advent and value of DMT, CPT, + SCPTu, SDMT

Elastic continuum solution for pile foundations

- Static top down loading
- Bi-directional O-cell load tests

Fundamental soil stiffness: \( G_{\text{max}} = \rho V_s^2 \)

Presented case studies in Piedmont

Use of Rock Mass Rating (RMR)

Recommended more use of geophysics for site characterization, particularly \( V_s \) profiling
thanks