GeoVirginia 2013

Williamsburg VA
September 30 - October 2

Lessons Learned in Geotechnical Engineering

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

Georgia Tech

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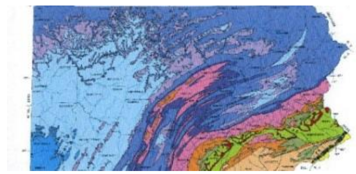
Georgia Institute of Technology

01 October 2013

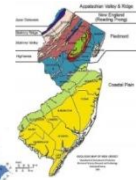
Surficial Extent of Appalachian Piedmont

Piedmont Geologic Province

PA



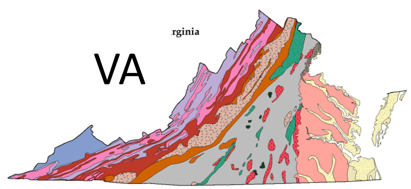
NJ



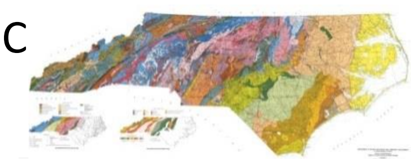
MD

DE

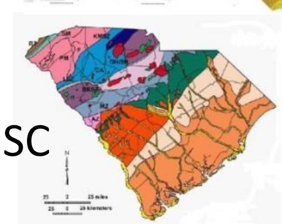
VA



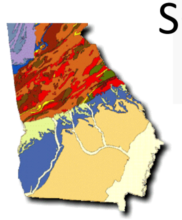
NC



SC

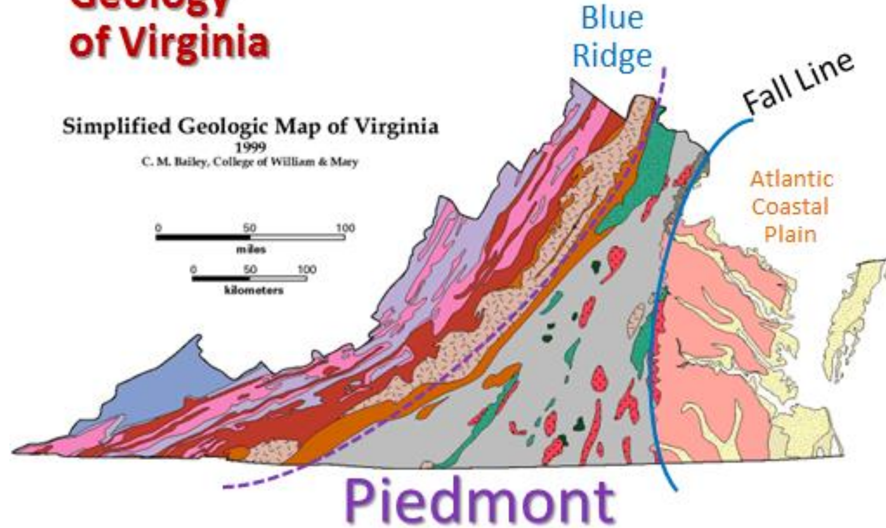


GA

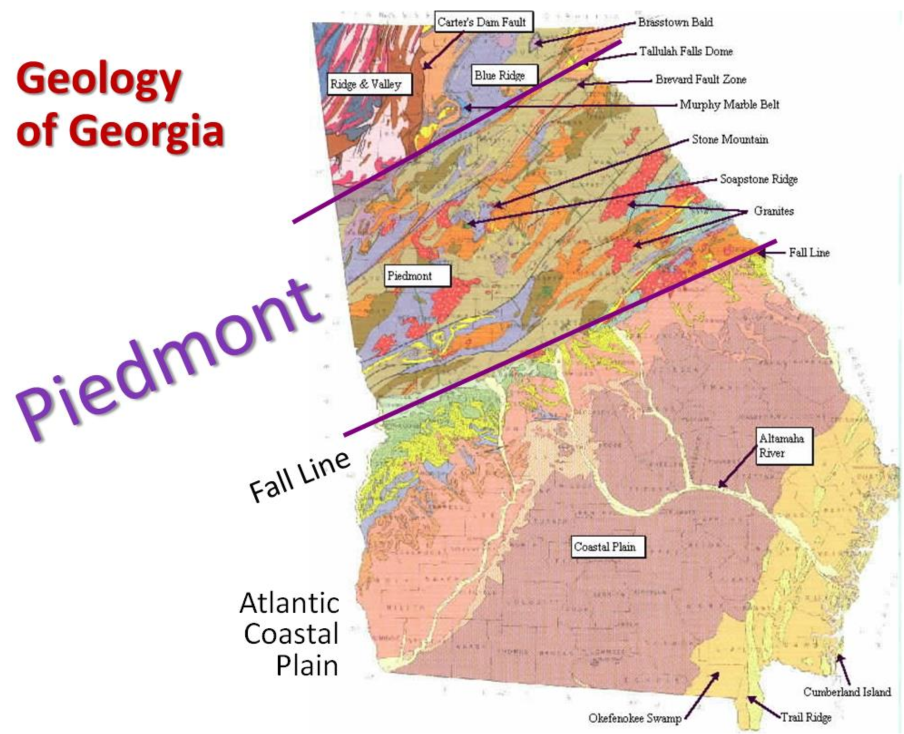


AL

Geology of Virginia

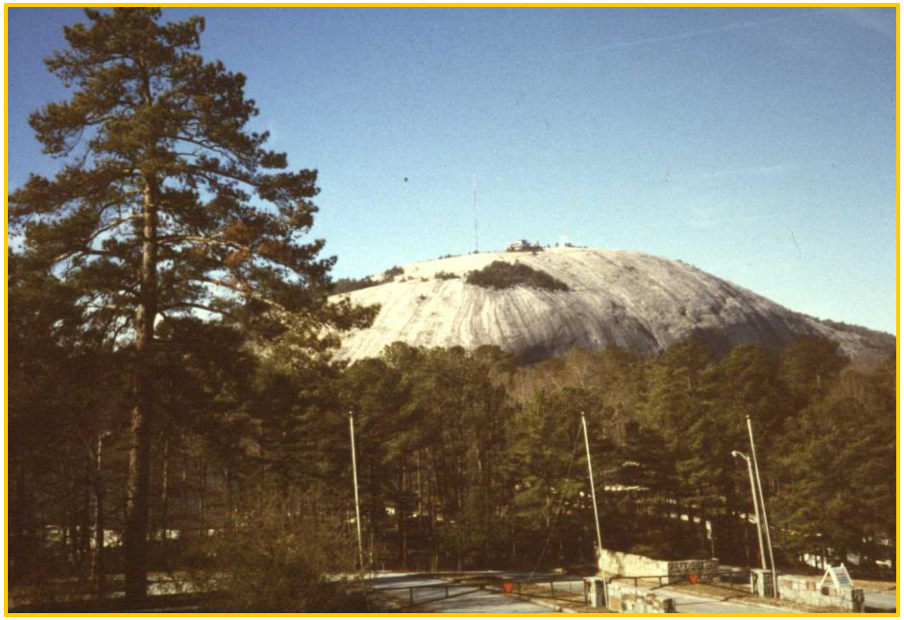


Geology of Georgia



Red Top Mountain

Stone Mountain



North Lake Lanier

"Georgia Red Clay"

Primary Rock Types by Geologic Origin

	Sedimentary Types		Metaphorphic		Igneous Types	
Grain Aspects	*Clastic*	*Carbonate*	*Foliated*	*Massive*	*Intrusive*	*Extrusive*
Coarse	Conglomerate Breccia	Limestone Conglomerate	Gneiss	Marble	Pegmatite Granite	Volcanic Breccia
Medium	Sandstone Siltsone	Limestone Chalk	Schist Phyllite	Quartzite	Diorite Diabase	Tuff
Fine-Grained	Shale Mudstone	Calcareous Mudstone	Slate	Amphi- bolite	Rhyotite	Basalt Obsidian

PIEDMONT

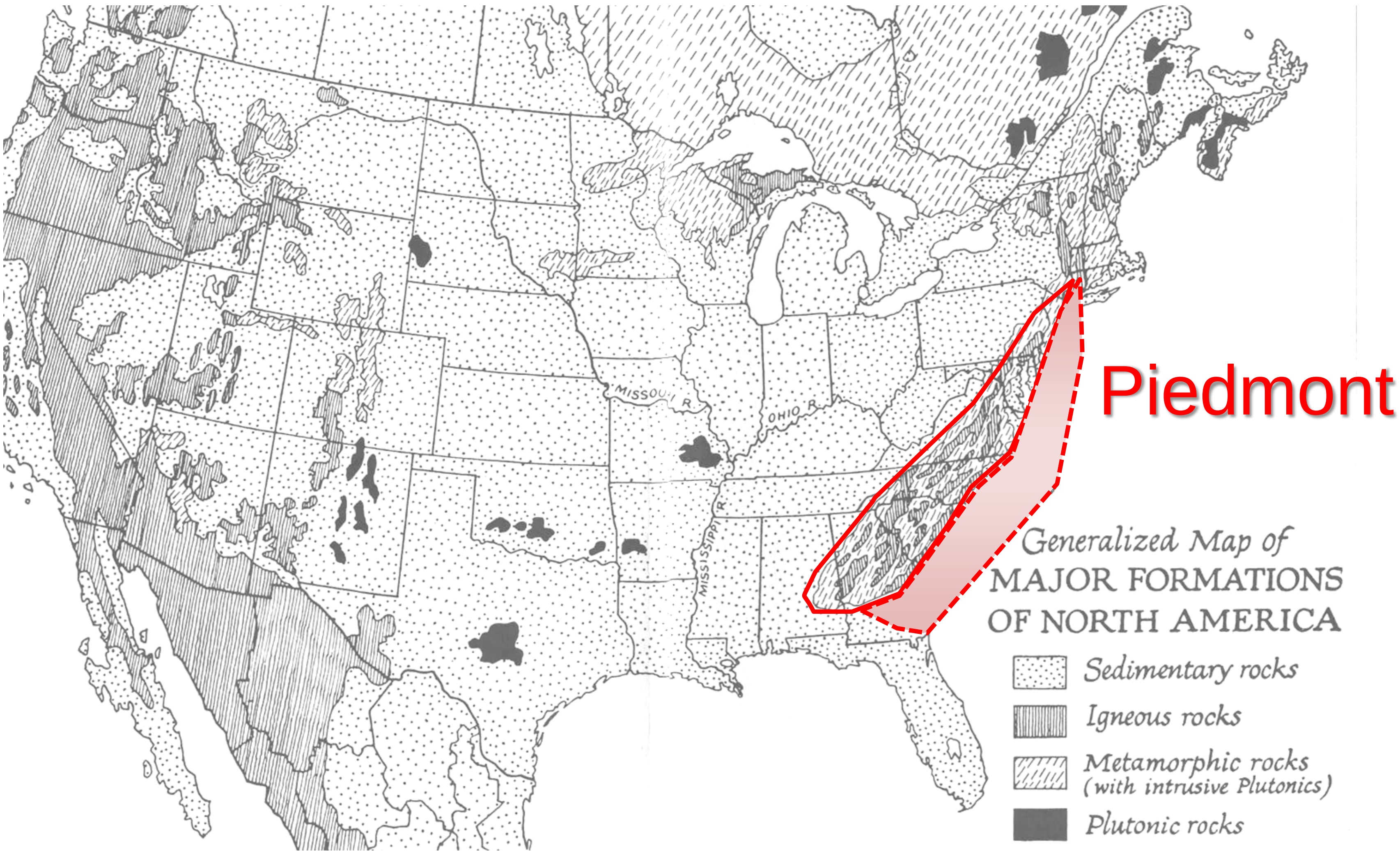
Geologic Time Scale

Era	Period	Epoch	Time Boundaries (Years Ago)
Cenozoic	Quaternary	Holocene - Recent	10,000
		Pleistocene	2 million
	Tertiary	Pliocene	5 million
		Miocene	26 million
		Oligocene	38 million
		Eocene	54 million
		Paleocene	65 million
Mesozoic	Cretaceous		130 million
	Jurassic		185 million
	Triassic		230 million
Paleozoic	Permian		265 million
	Carboniferous	Pennsylvanian	310 million
		Mississippian	355 million
	Devonian		413 million
	Silurian		425 million
	Ordovician		475 million
	Cambrian		570 million
Precambrian	Z-Age ≈ 1 billion years ago		3.9 billion
Earth Beginning			4.7 billion

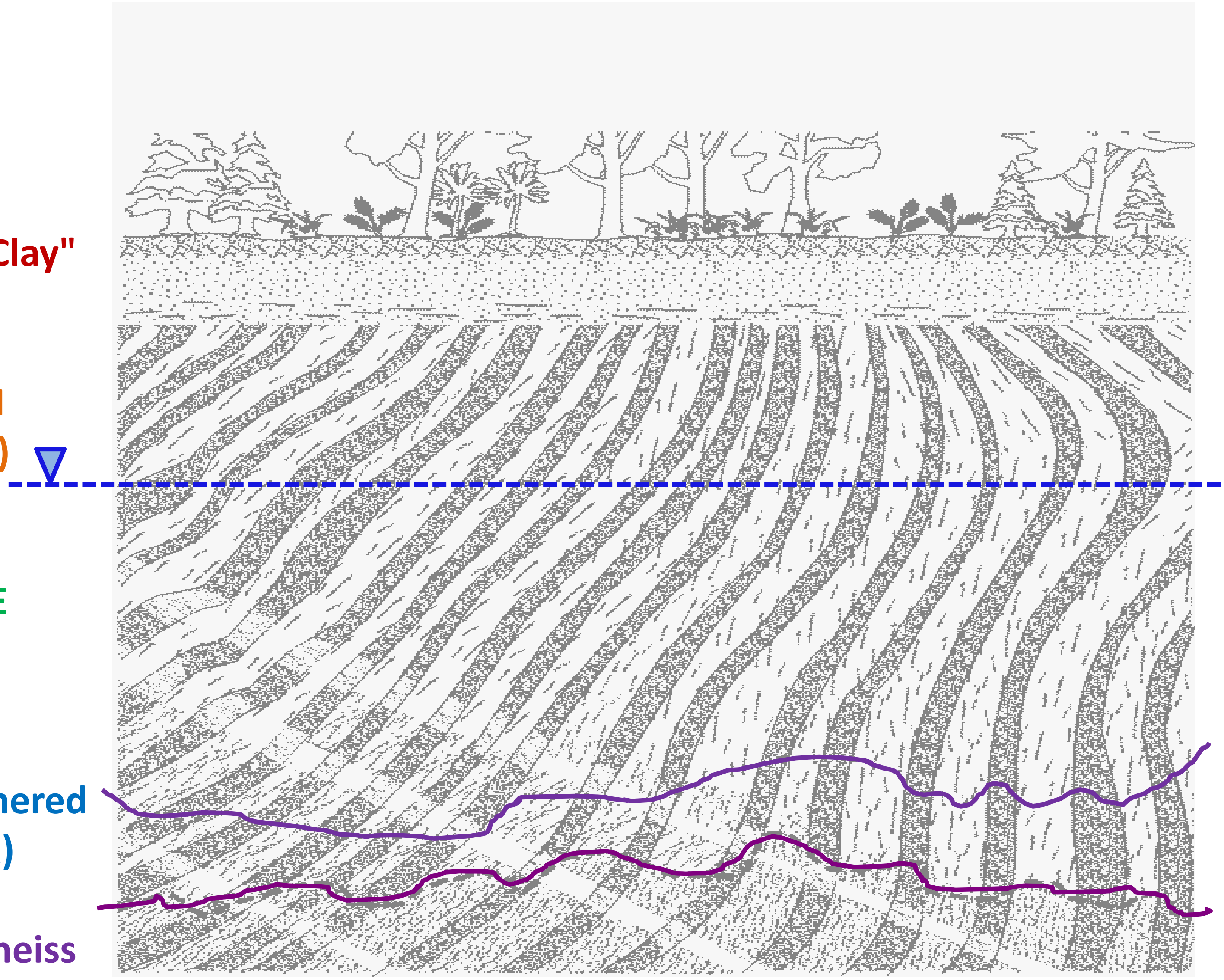
Piedmont Granite →

Piedmont Gneiss and Schist →

Major Rock Formations in USA



Piedmont Subsurface Profile



"Georgia Red Clay"
(CL - ML)

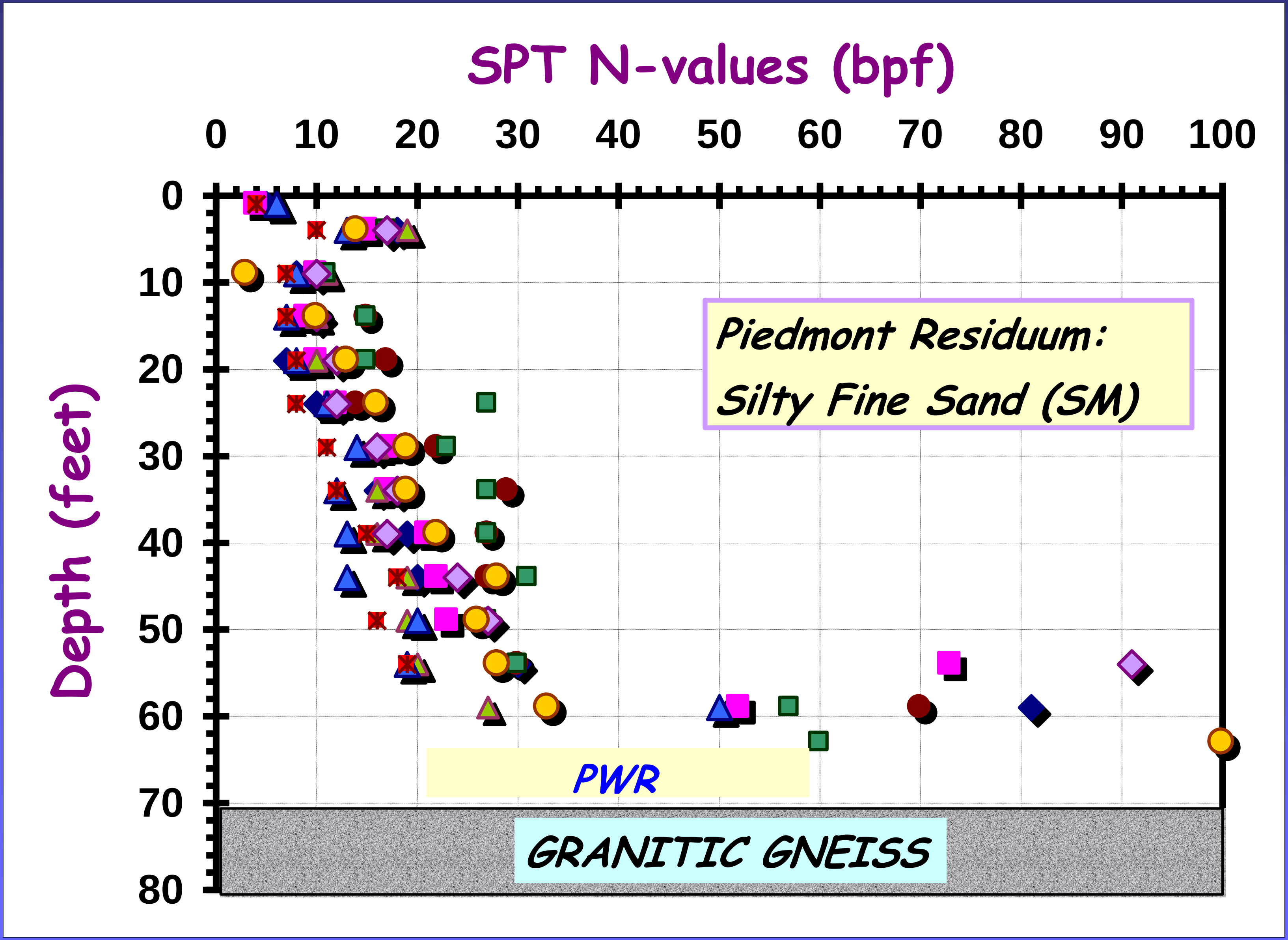
RESIDUUM
(ML to SM)

SAPROLITE

Partially-Weathered
Rock (PWR)

Intact Rock: Gneiss
Schist, Granite

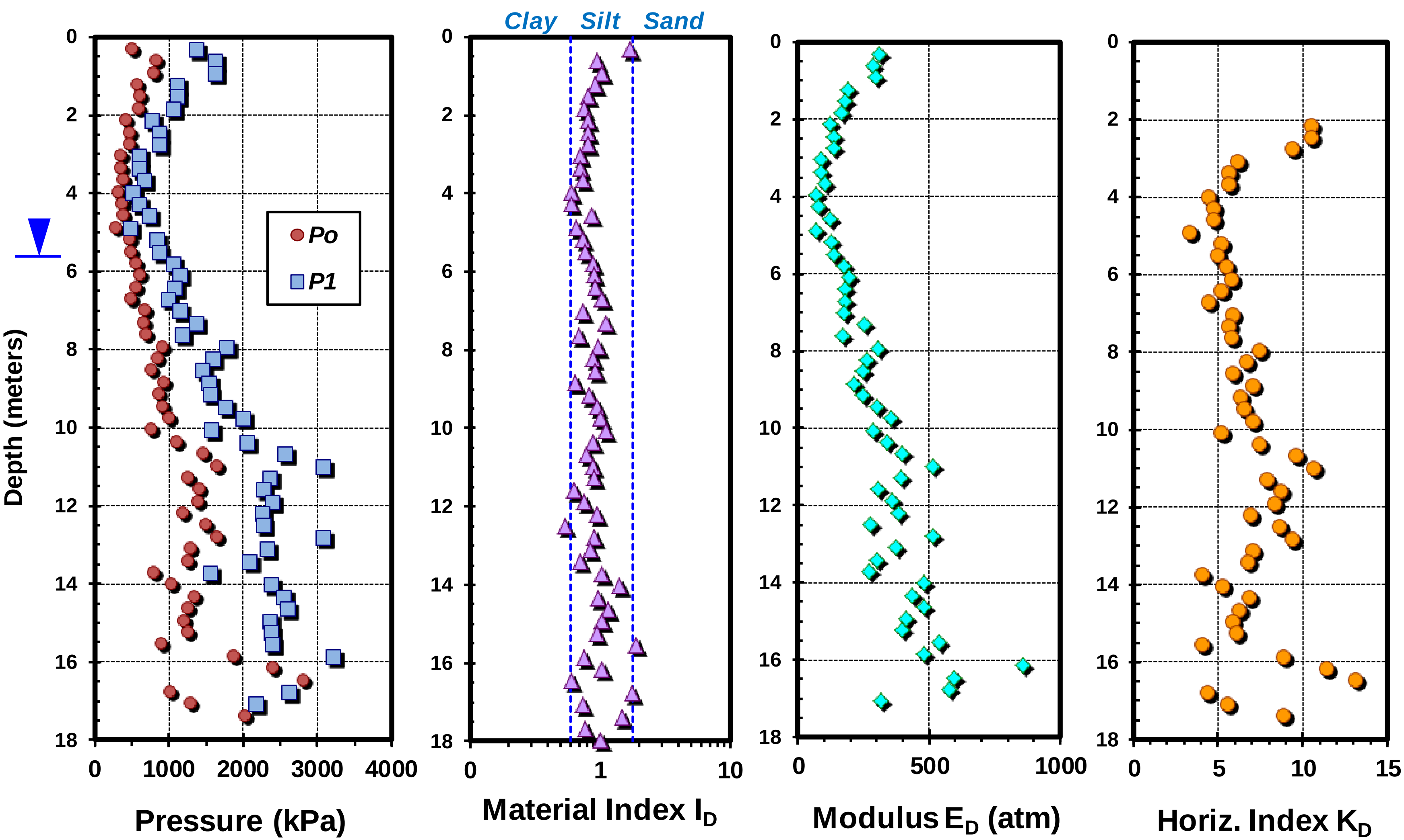
GT Load Test Site, West Campus



In-Situ Testing in the Piedmont

- SPT = standard penetration testing
- PMT = pressuremeter testing
- DP = dynamic penetrometers
- percussive soundings (air-track)
- VST = vane shear testing ← **Miller & Sowers (1967). Shear characteristics of Piedmont soils using rotating vanes**
- DMT = flat plate dilatometer
- CPT = cone penetration testing
- CPTu = piezocone testing
- V_s = shear wave velocity
- SCPTu = seismic piezocone
- SDMT = seismic dilatometer

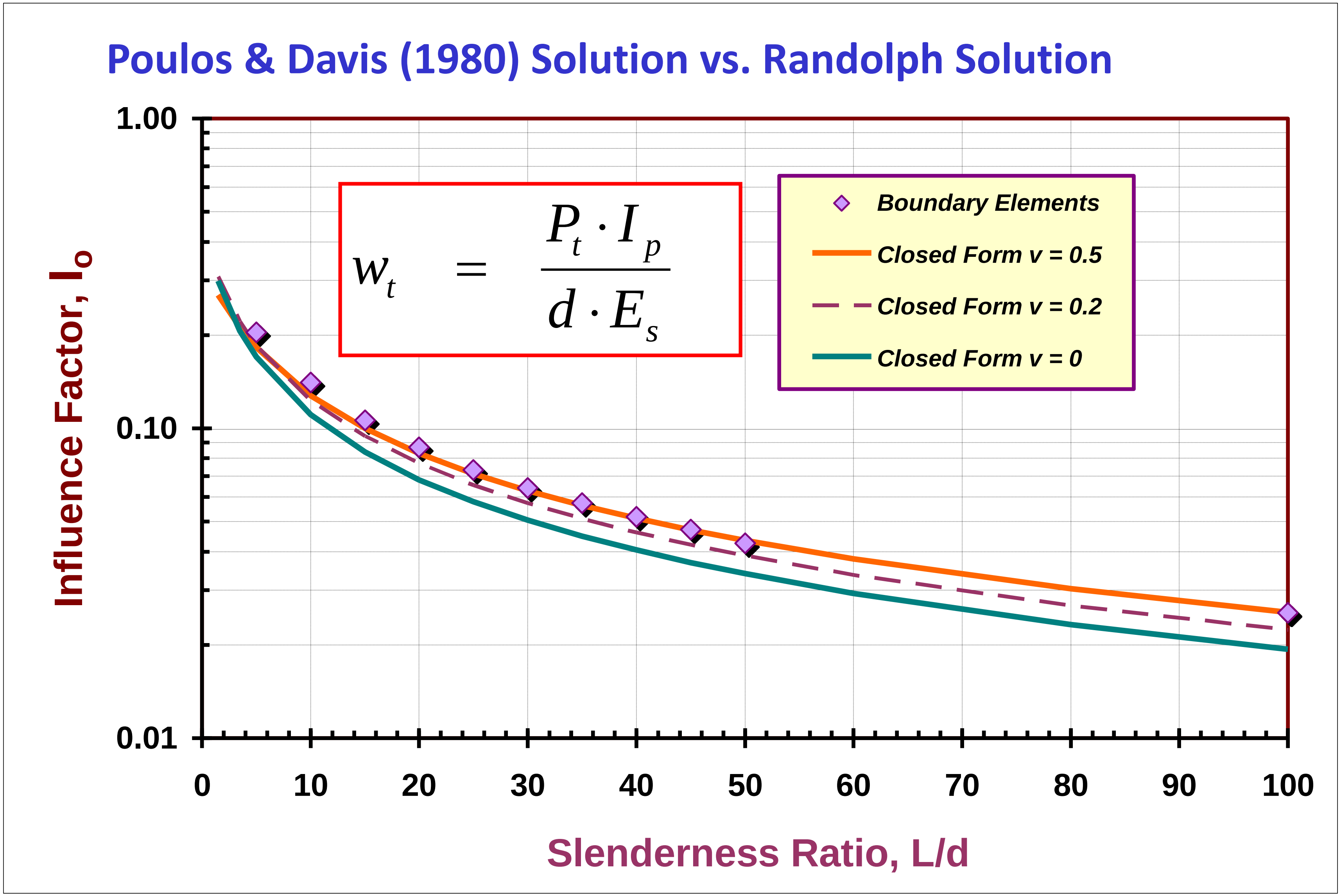
SCPTU in Piedmont residual silts Winston-Salem, NC



Fairfax Hospital, Northern Virginia (1984)

Case Study: Drilled shaft (L = 65' and d = 3') in Piedmont residuum

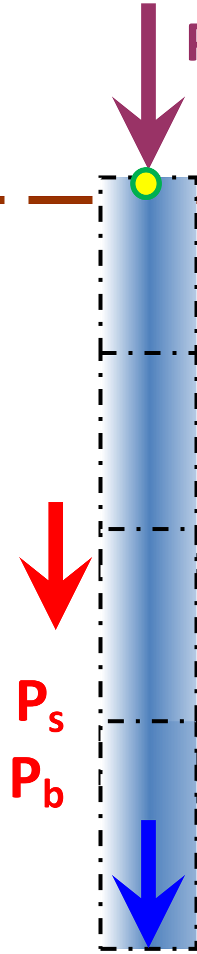
Axial Pile Influence Factors (Rigid Pile)



RIGID PILE RESPONSE
Length L and diameter d

P_t = load at top = $P_s + P_b$

Ground Surface *Top Displacement, w_t*



Randolph Solution

Homogeneous Soil:

E_s = Elastic modulus

ν' = Poisson's ratio

$$w_t = \frac{P_t \cdot I_\rho}{d \cdot E_s}$$

$$I_\rho = \frac{1}{\frac{1}{1-\upsilon^2} + \frac{\pi}{(1+\upsilon)} \cdot \frac{(L/d)}{\ln[5(L/d)(1-\nu)]}}$$

Side Load, P_s = $P_t - P_b$

Load Transfered to Base:

$$\frac{P_b}{P_t} = \frac{I_\rho}{1-\upsilon^2}$$

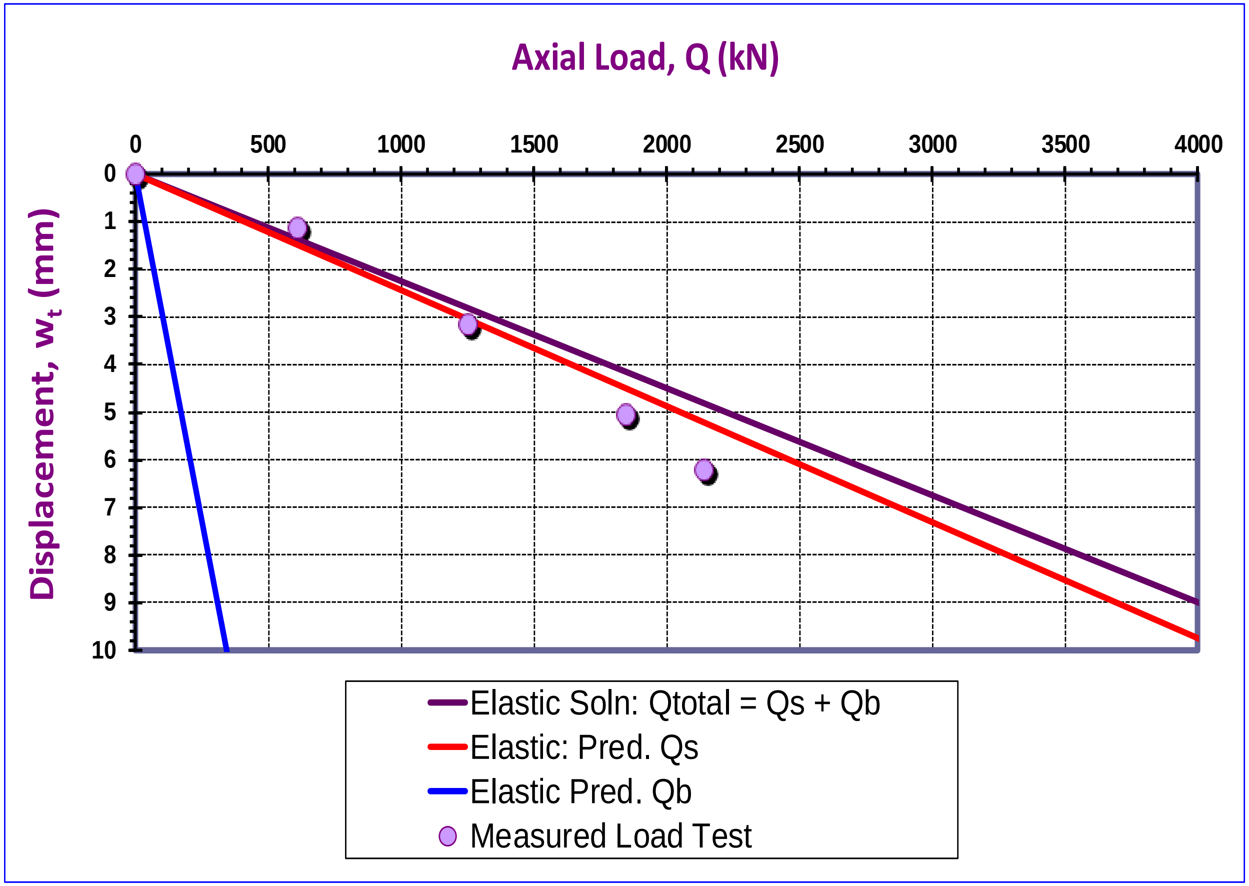
P_b = Base load

Fairfax Hospital, Northern Virginia

E' ≈ E_D (ave. 64 DMTs) = 35 MPa = 364 tsf

L = 65 feet and d = 3 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

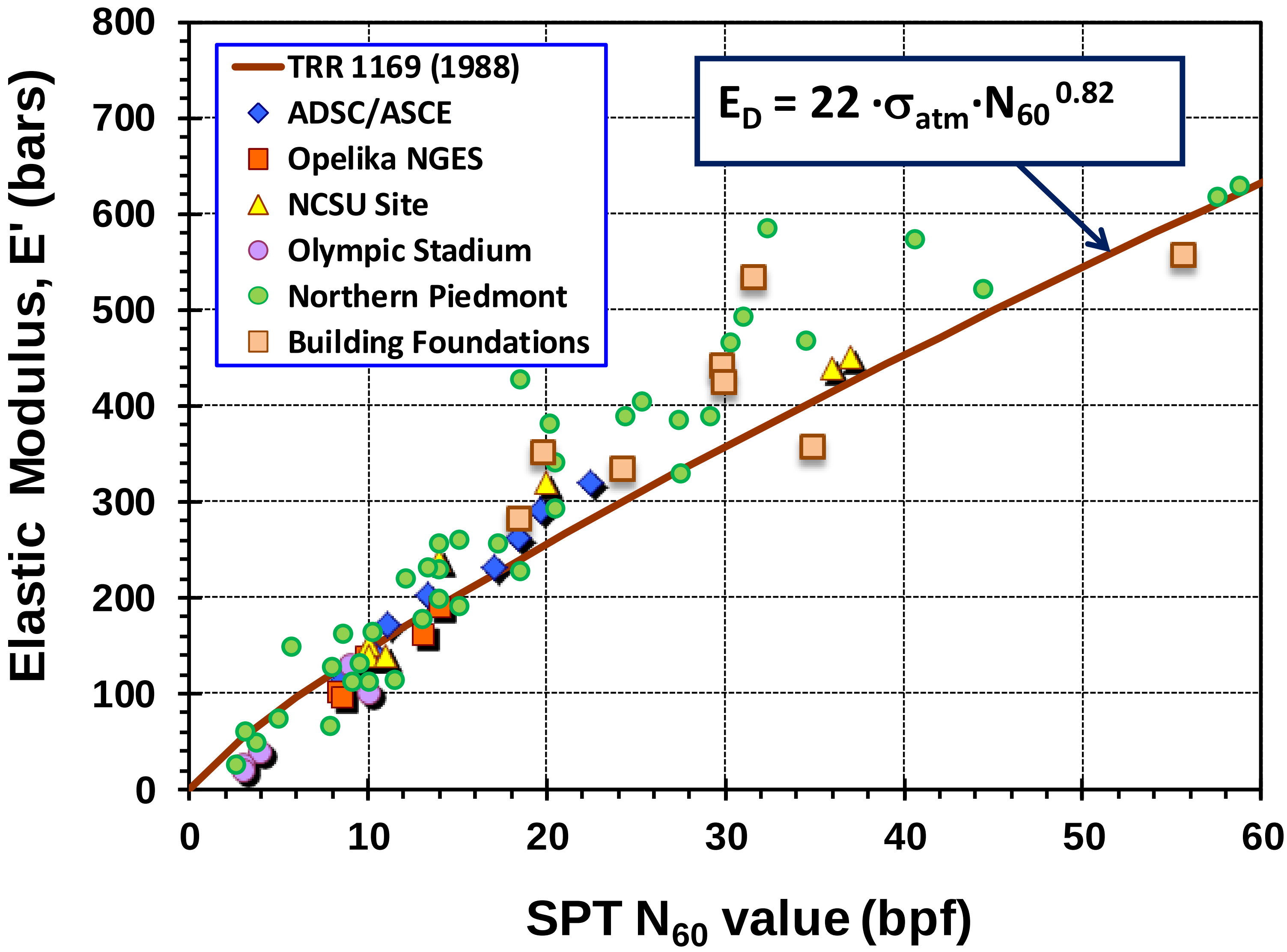







DMT-SPT Correlation in Piedmont Residuum

(Mayne & Frost, TRR 1988) Also EPRI Manual (1990)



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^k

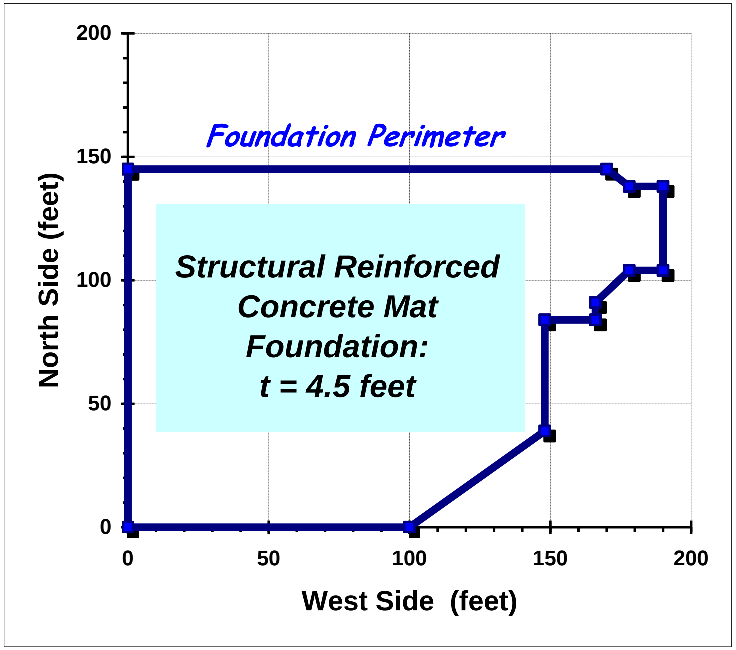
Bearing Elev = +495 feet msl

Mat Thickness, t = 4.5 ft

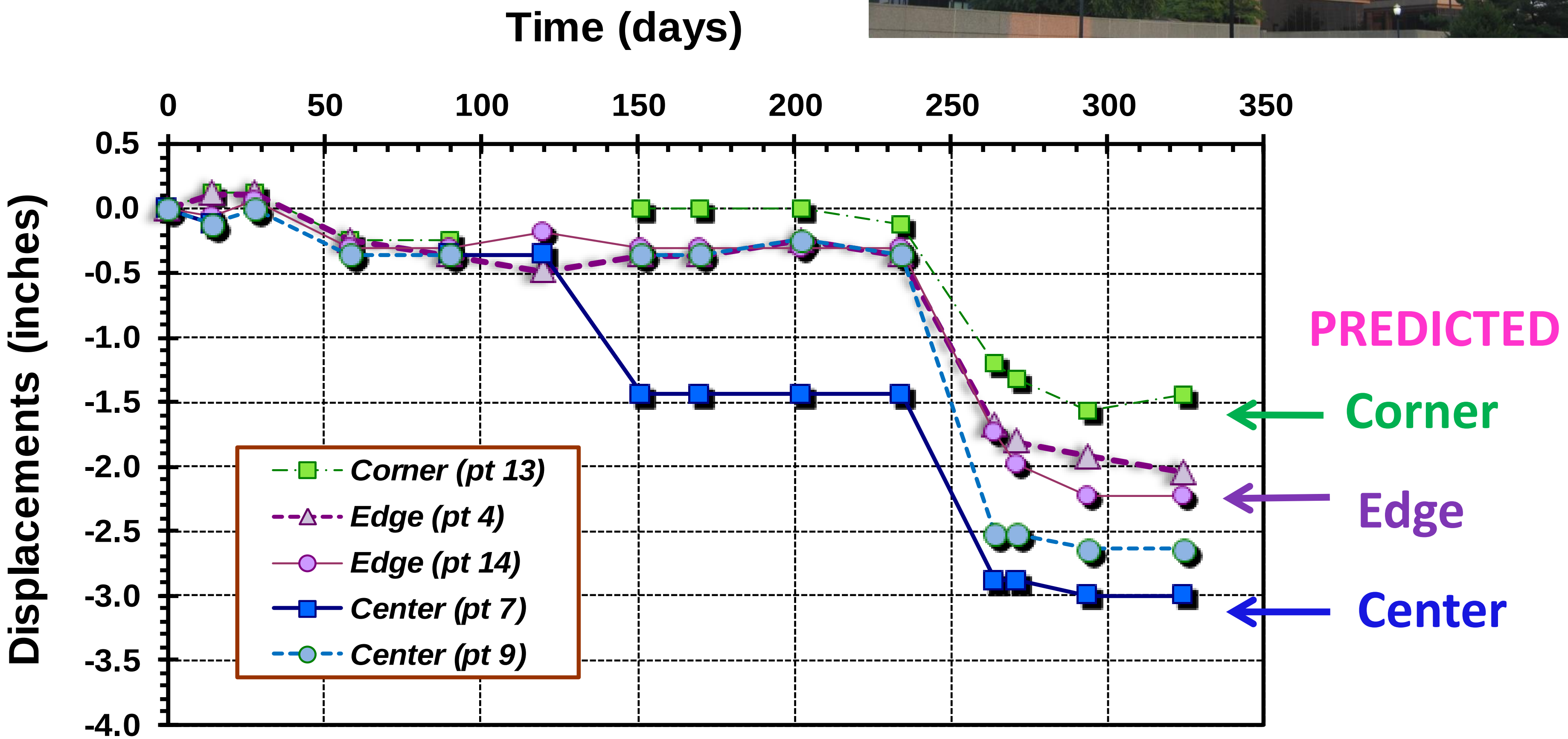
Applied Stress: q = 3.47 ksf

22-story Bank Building - Mat Foundation

Tysons Corner, Virginia



Wachovia/Wells Fargo Tysons Corner, VA

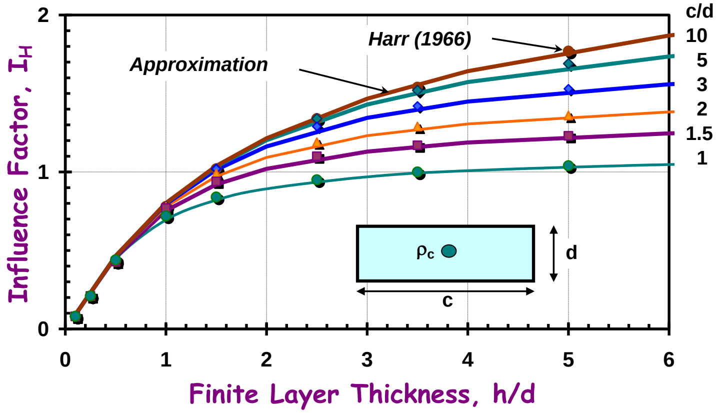


Settlements: GSU Dormitory, Atlanta

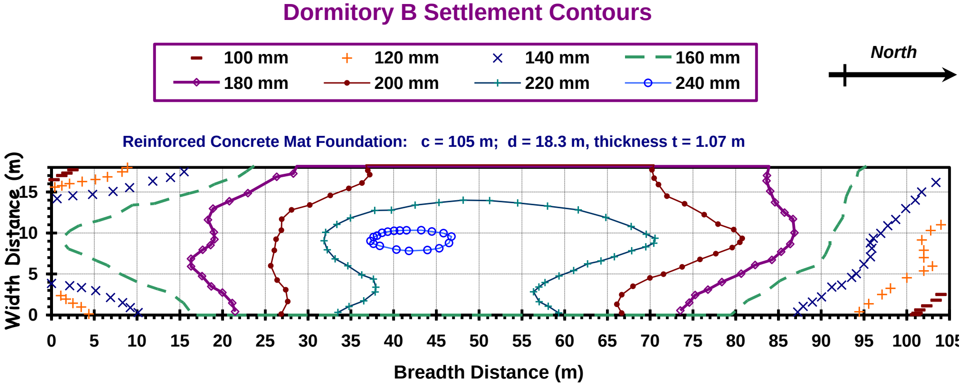
www.geoengineer.org

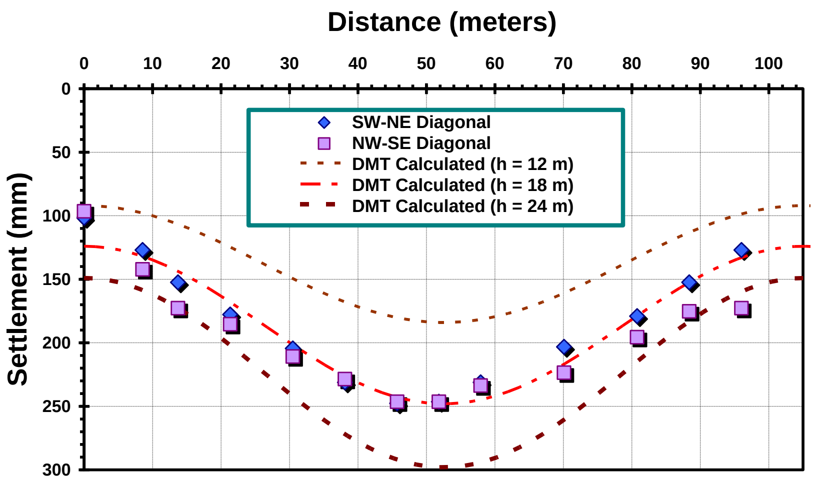
10" mat settlements

DMT E_D = 85 tsf



$$\text{Center Deflection} : \rho_c = \frac{q \cdot d \cdot I_H (1 - \nu^2)}{E_s}$$





ADSC-ASCE-FHWA Load Test Program

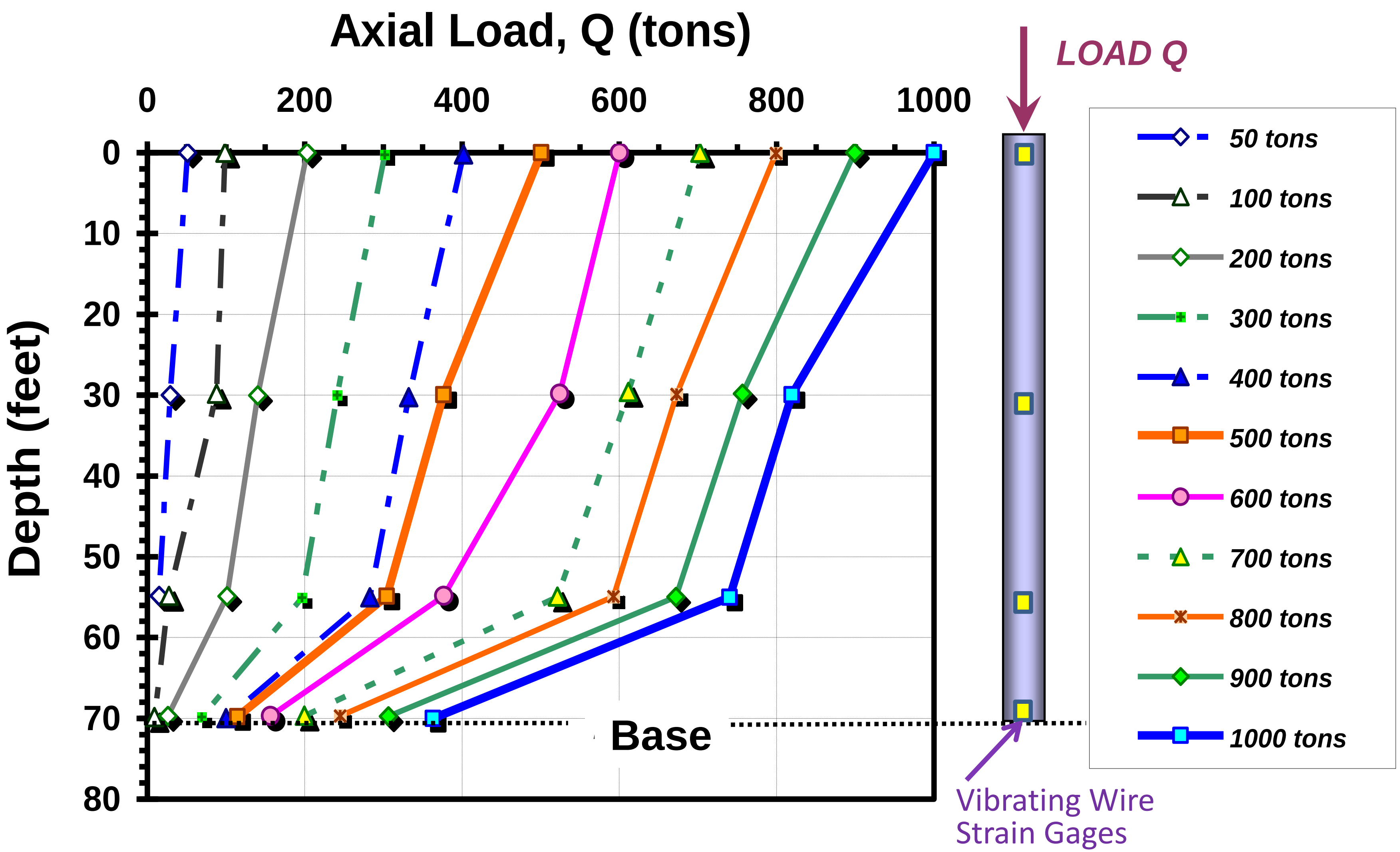
Georgia Tech, Atlanta

Load Tests

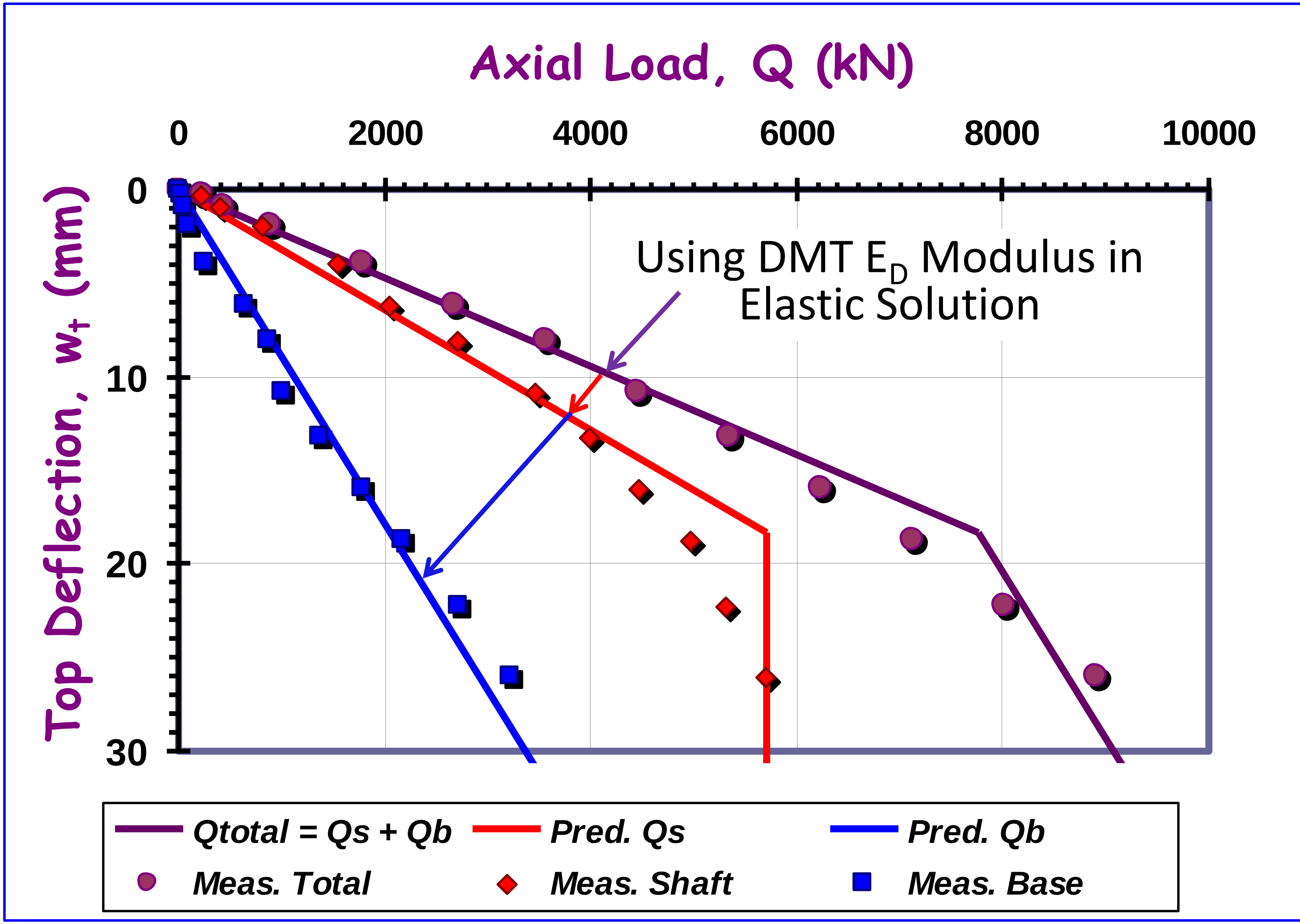
- End-bearing drilled shaft: d = 0.76 m L = 19.2 m
- Friction-type drilled shaft: d = 0.76 m L = 16.9 m
- Deep plate load test: d = 0.61 m z = 16.9 m

GT End-Bearing Shaft C1: d = 2.5' by L = 70'

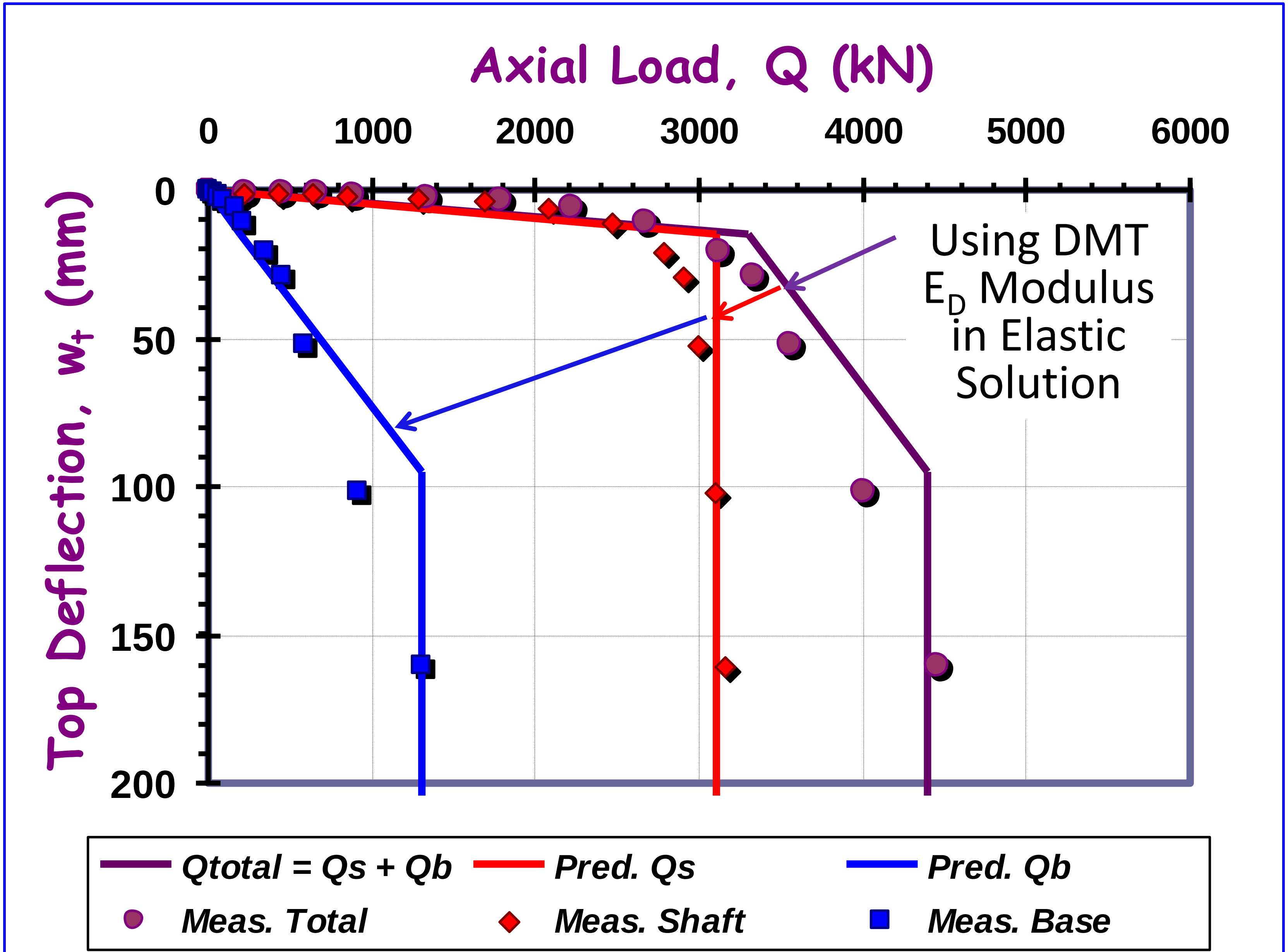
Axial Load Transfer Distribution



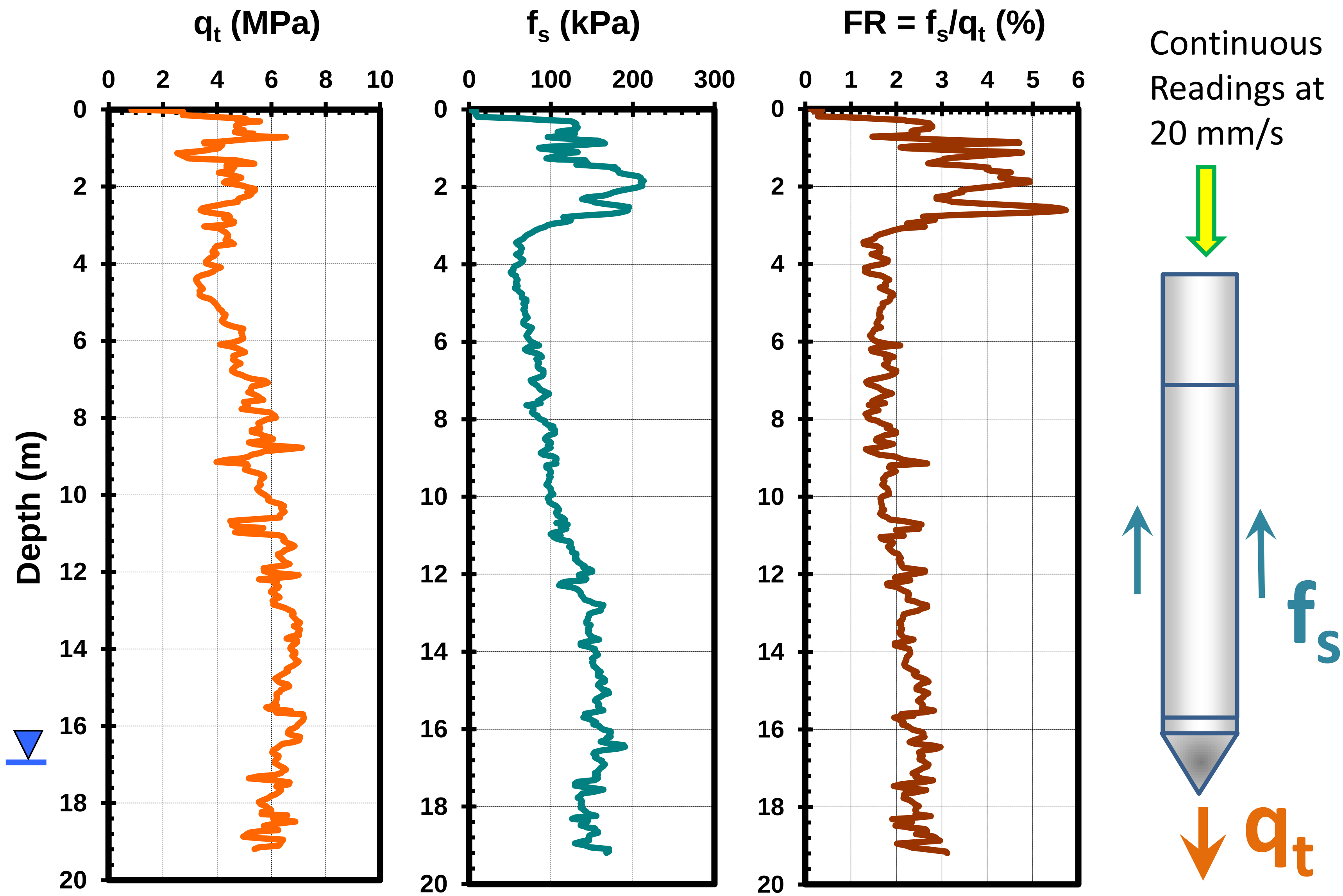
Elastic Continuum Response - GT Shaft C1



Elastic Continuum Response - Shaft C2



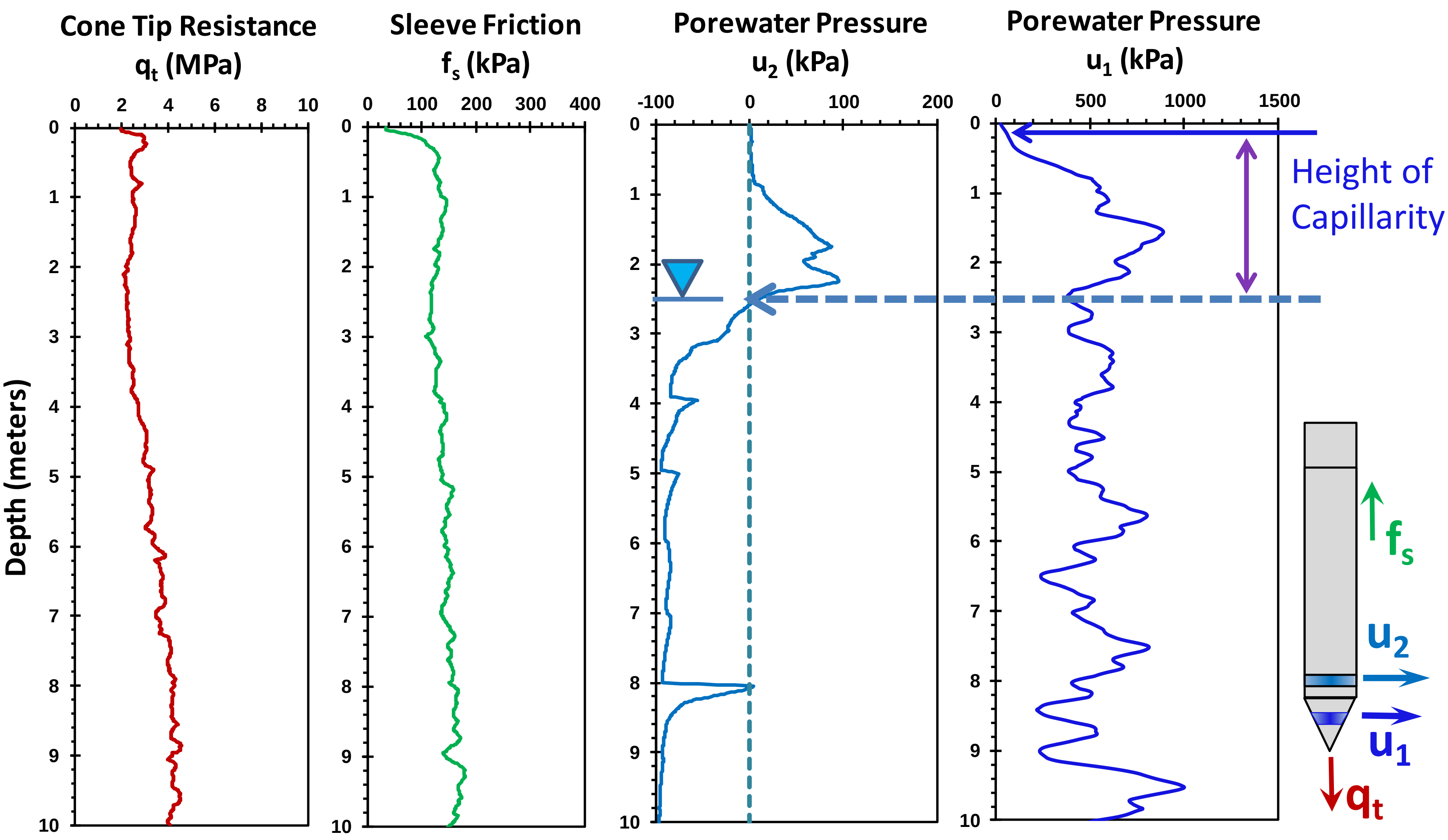
Cone Penetration Tests (CPT) at GT West Campus



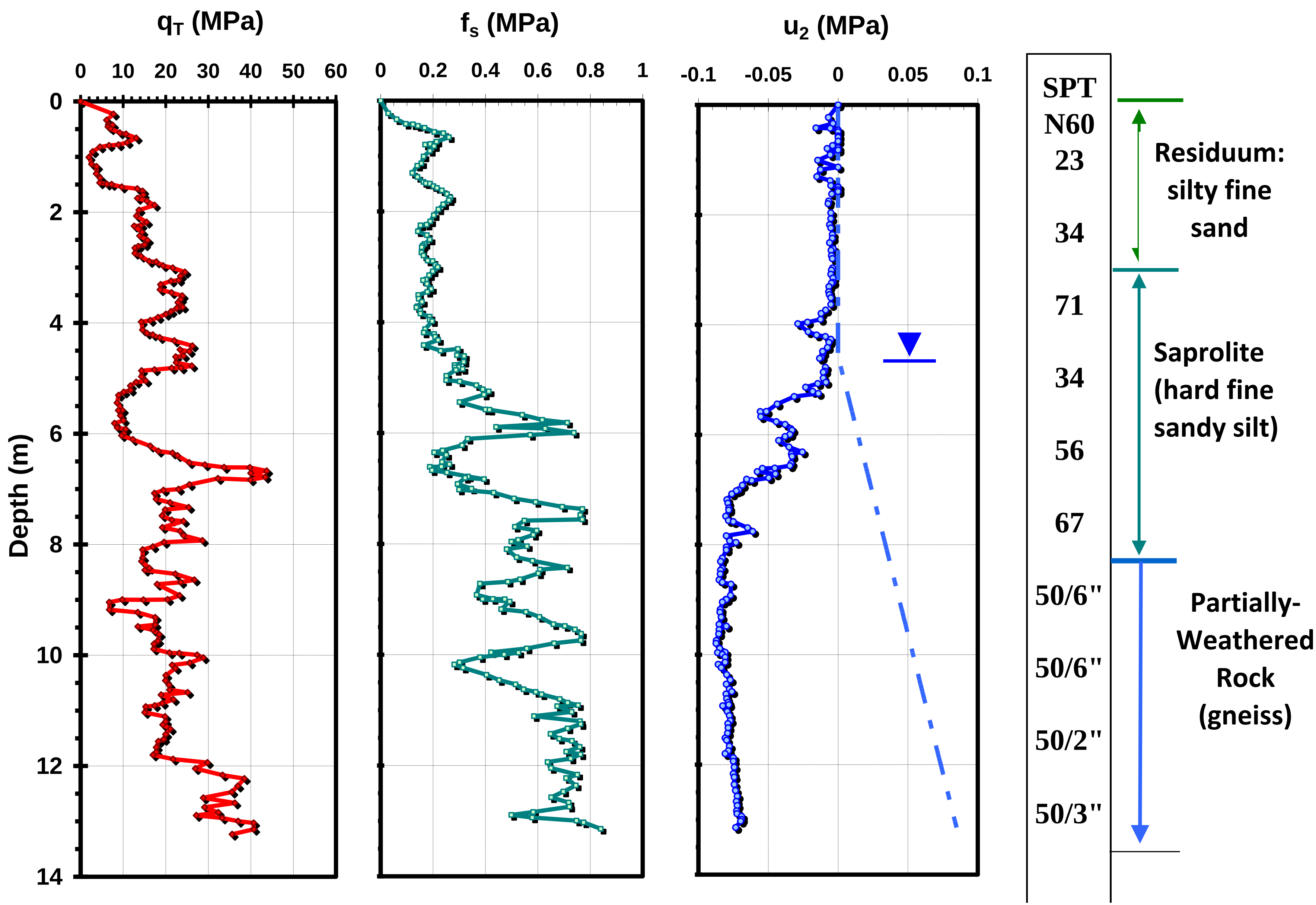
CPT

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

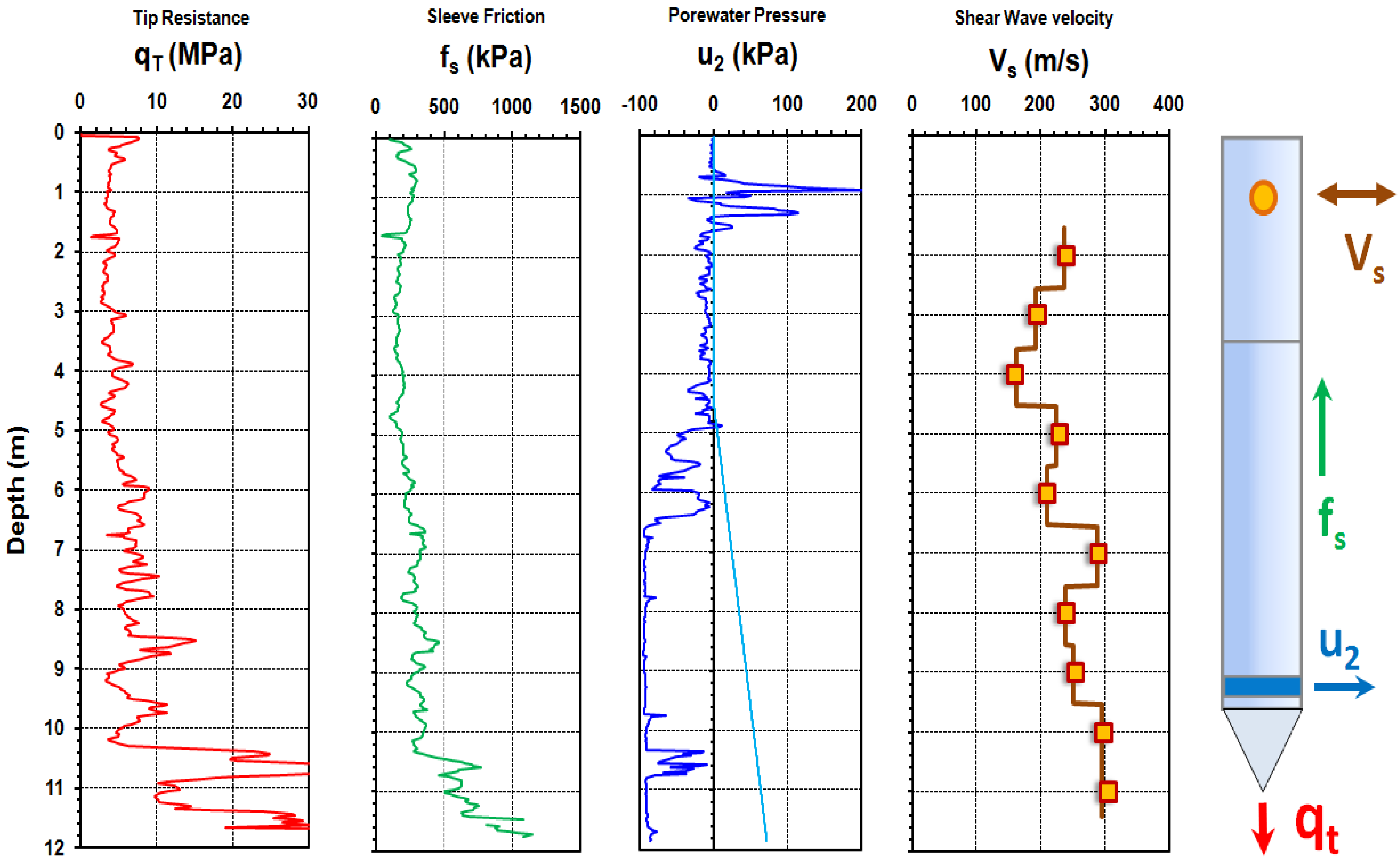
Piezocone Response in the Piedmont



CPTu in Piedmont PWR- Atlanta, GA



SCPTU in Piedmont residual silts Winston-Salem, NC



Geotechnics 2013 in the Piedmont

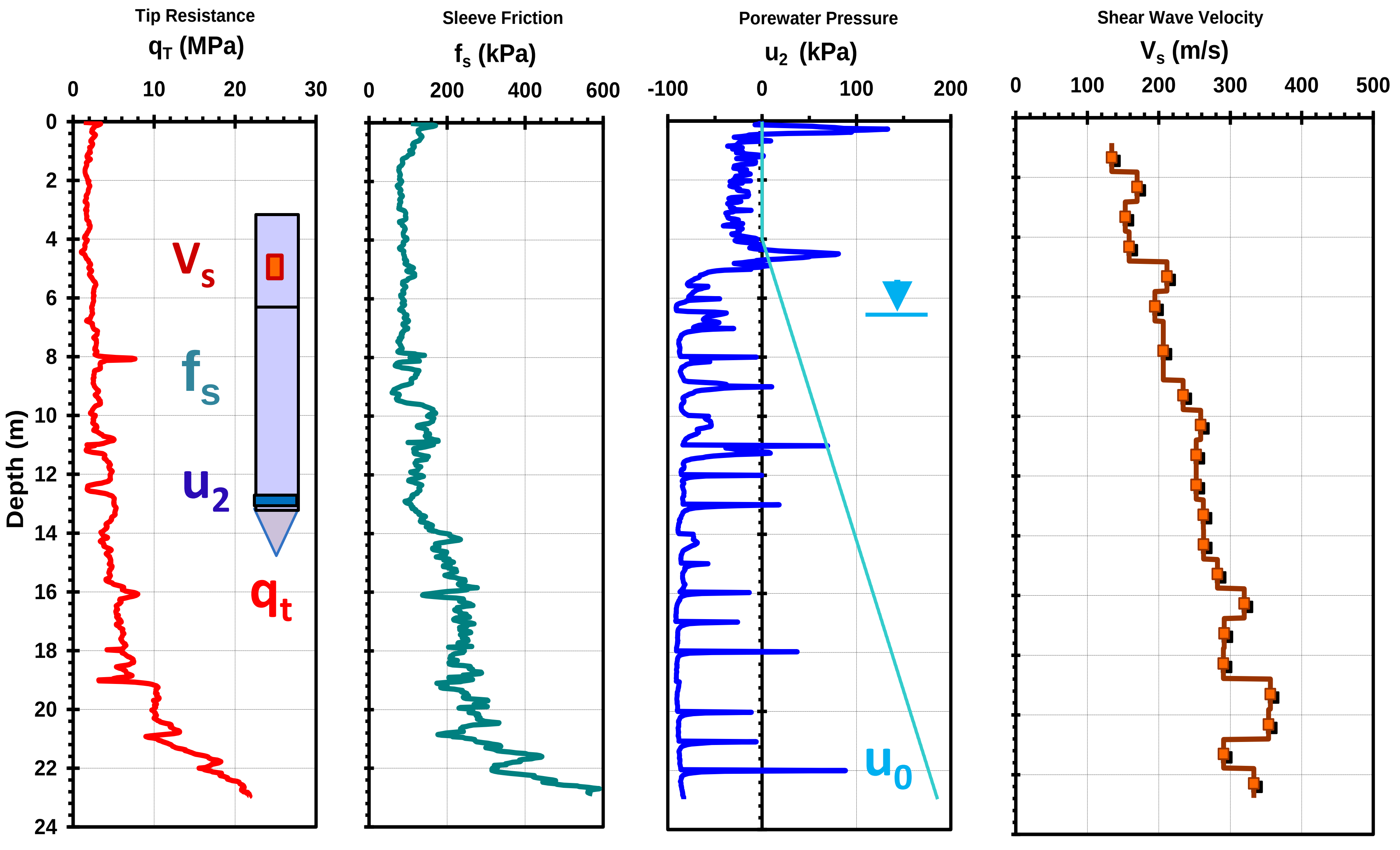
More Measurements

is

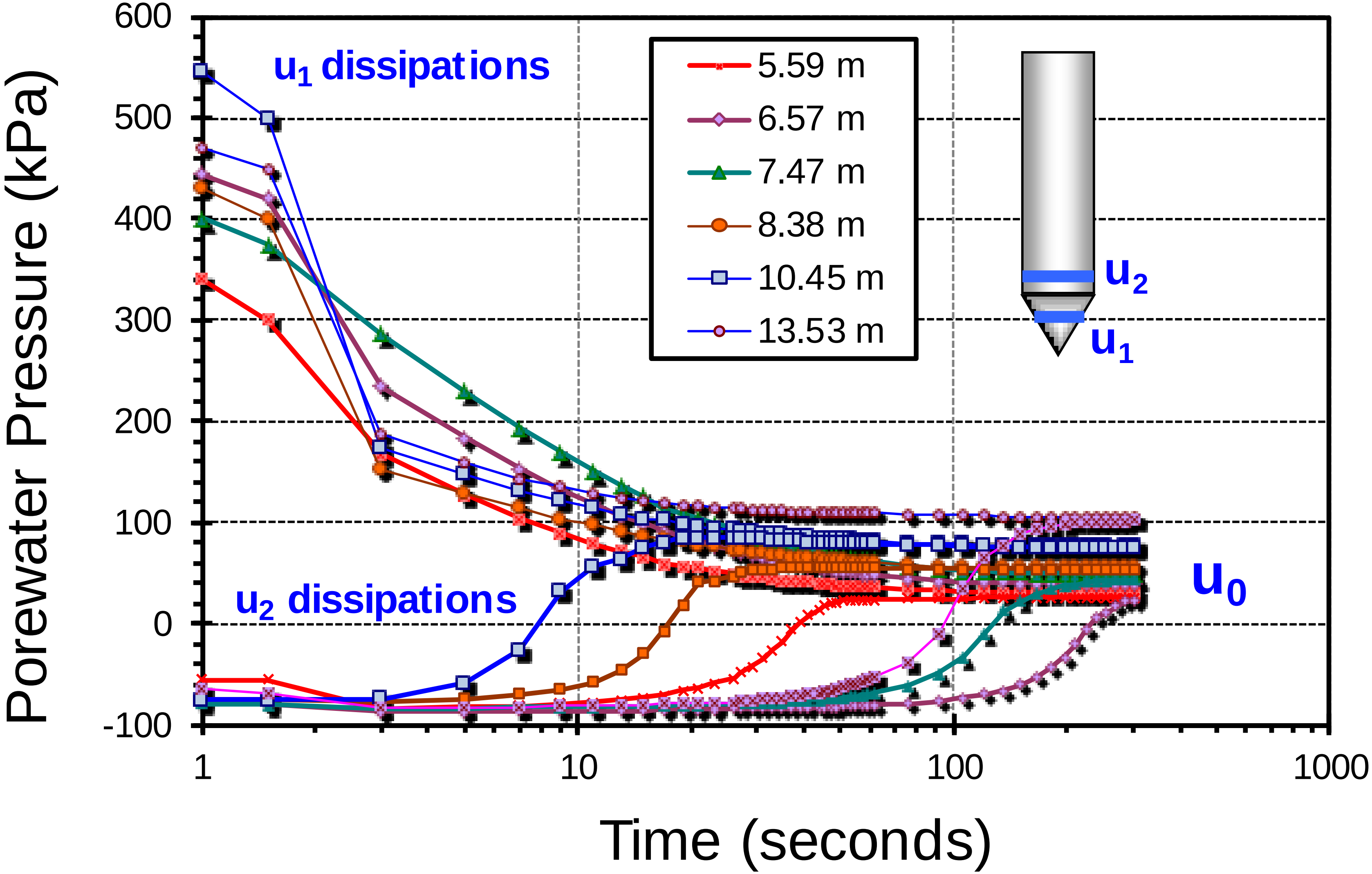
More Better

Mas Mejor

Seismic Piezocone (SCPTu)
Piedmont silts in Marietta, GA

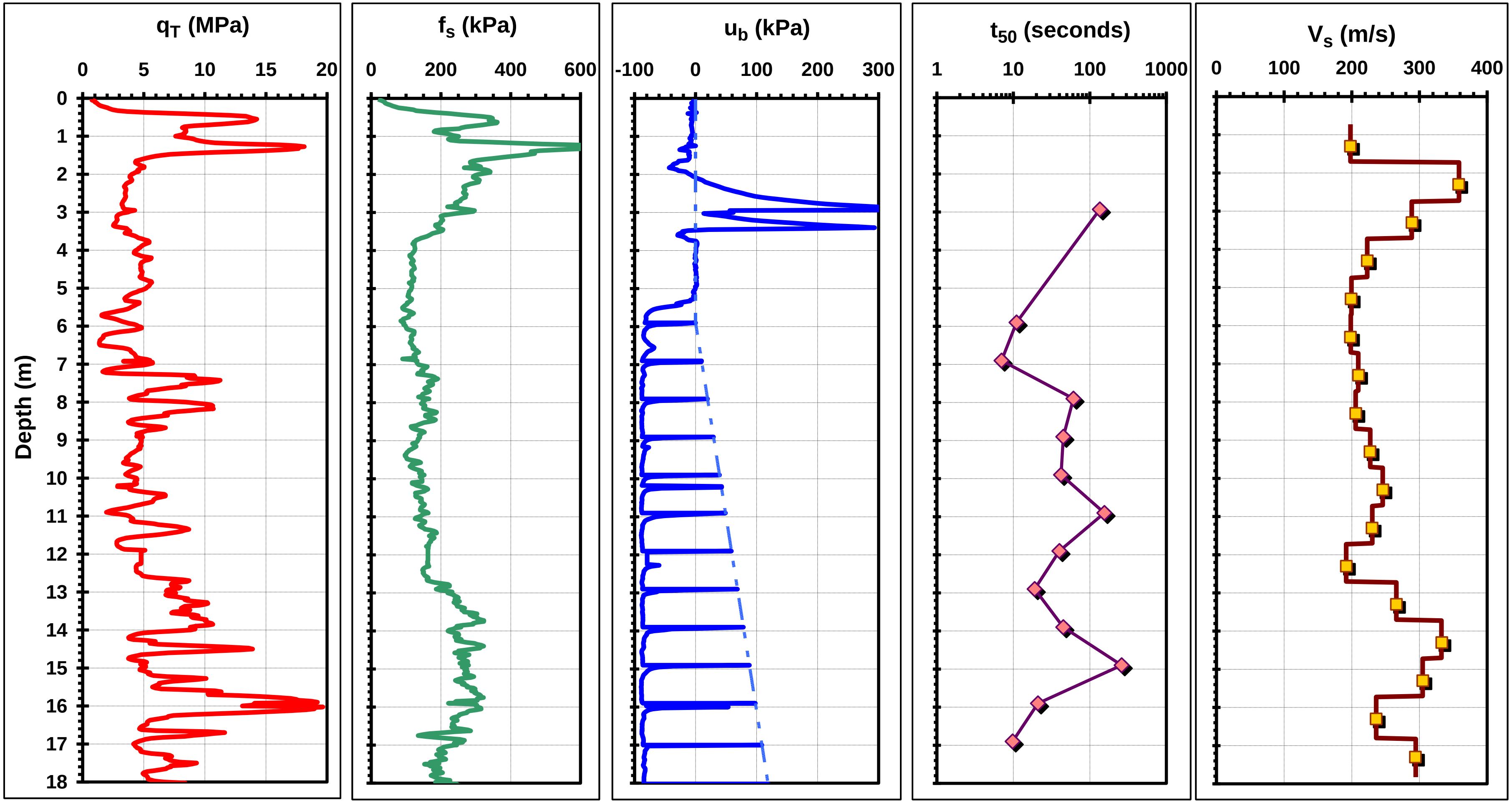


Piezo-Dissipation in Piedmont Residuum



SCPTù at Atlanta Airport Runway 5

Five Independent Readings of Soil Behavior: q_t, f_s, u_b, t_{50}, V_s

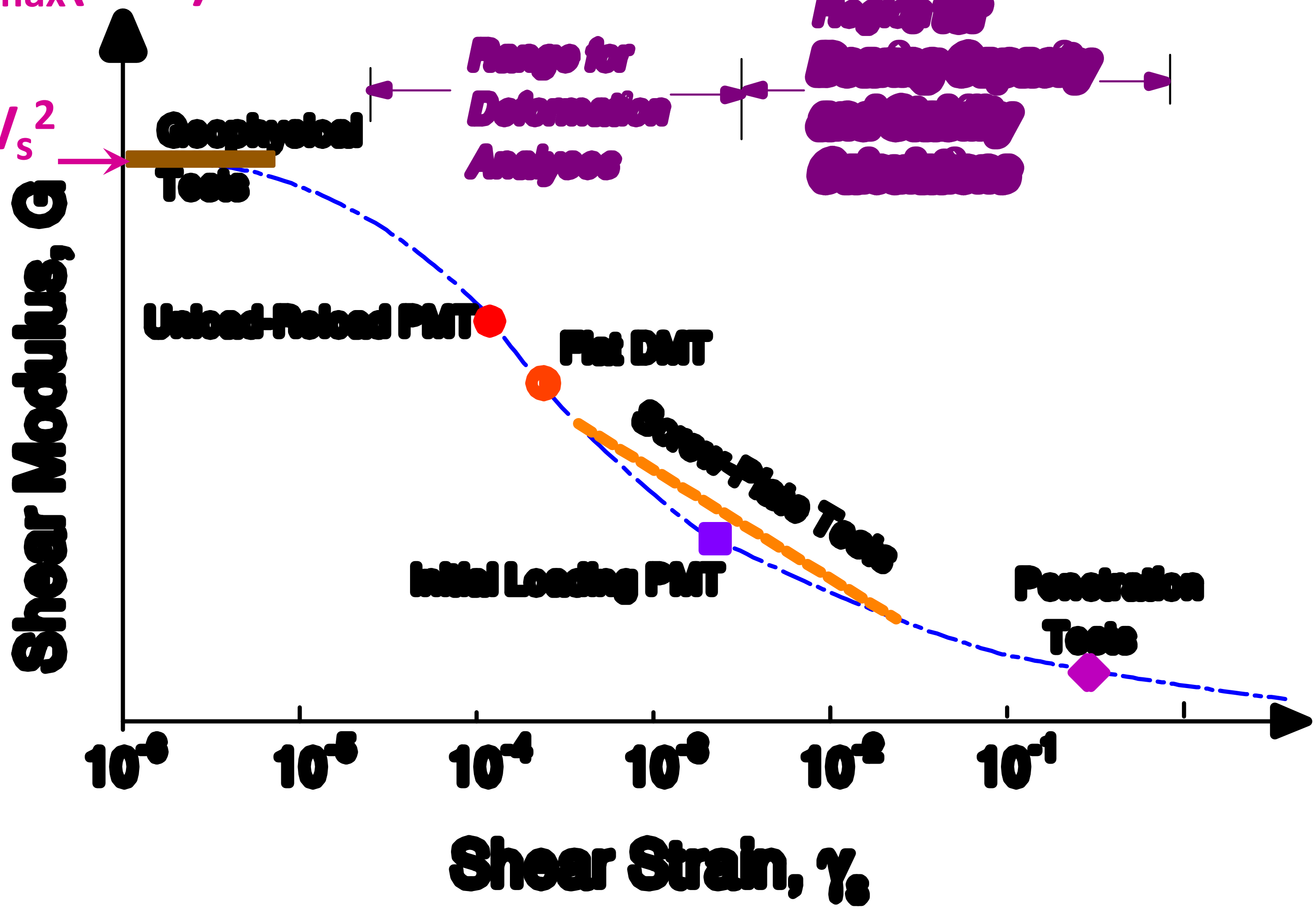


Equivalent Elastic Modulus for Static Loading

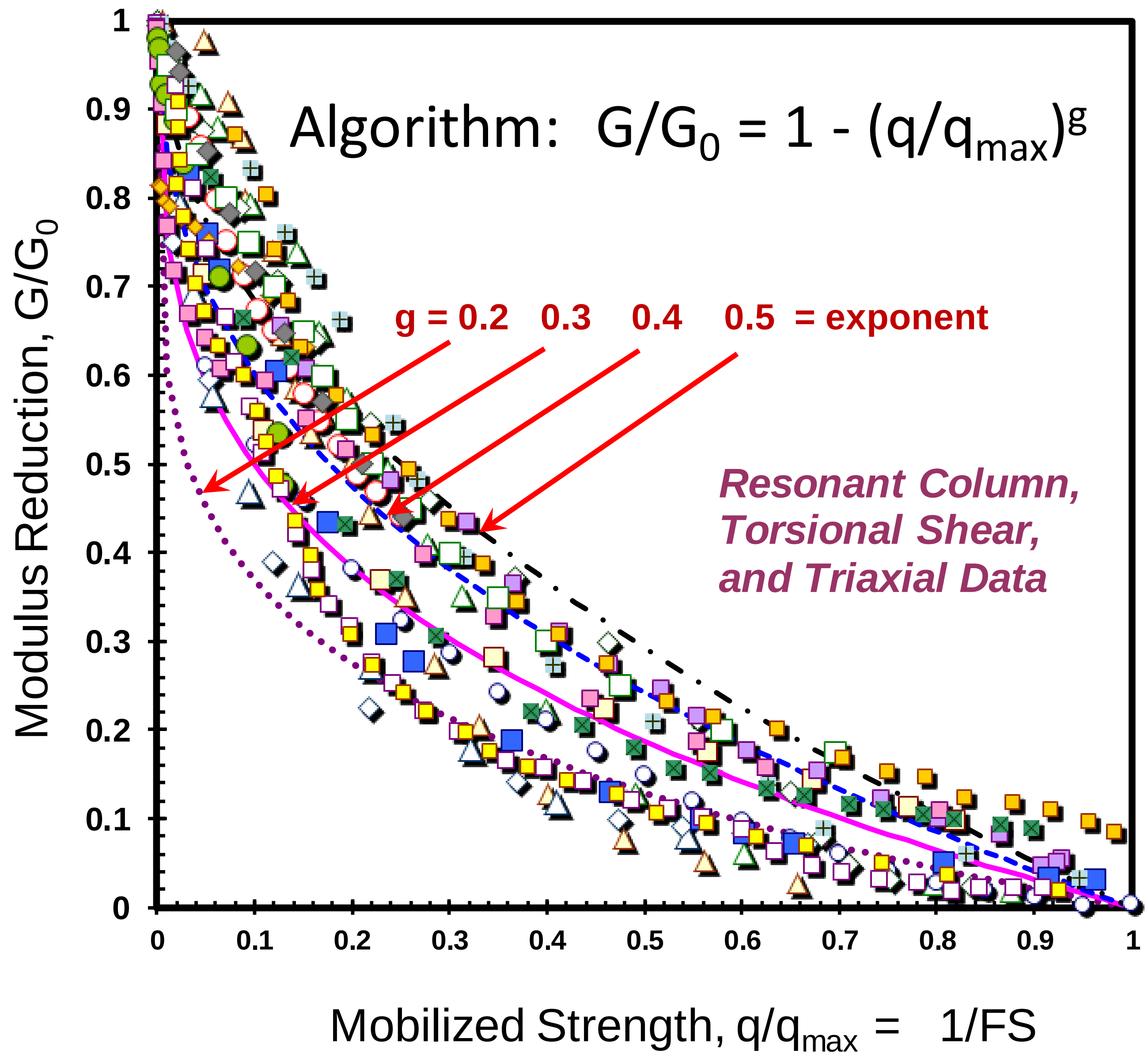
$$E_{max} = 2G_{max}(1+\nu)$$

$$G_{max} = \rho_t V_s^2$$

$$\rho_t = \gamma_t/g$$



Modulus Reduction Scheme (Fahey & Carter 1993)



Randolph Compressible Pile

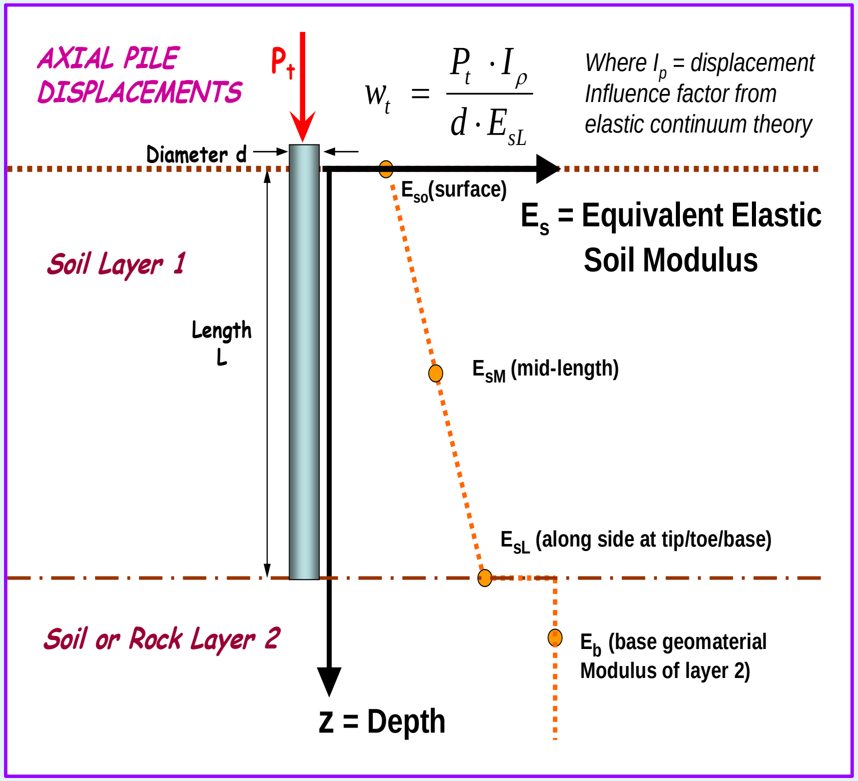
$$[1]: \quad w_t = \frac{P_t \cdot I_p}{d \cdot E_{sL}}$$

[2] $I_p = x_1/x_3$

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

$$x_2 = \frac{4}{(1-\nu)}\cdot\frac{\eta}{\xi}\cdot\frac{1}{\cosh(\mu L)}$$

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



The proportion of load transferred from the top to base:

[3] $P_b/P_t = x_2/x_3$

The proportion of load carried in side shear is:

[4] $P_s/P_t = 1 - P_b/P_t$

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

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

[6] $\eta = d_b/d$ = eta factor (Note: d_b = base diameter, so that $\eta = 1$ for straight shaft piles)
[7] $\xi = E_{sL}/E_b$ = xi factor (Note: $\xi = 1$ for floating pile; $\xi < 1$ for end-bearing pile)
[8] $\rho_E = E_{sm}/E_{sL}$ = rho term. The parameter can be evaluated from: $\rho_E = ½(1+E_{s0}/E_{sL})$.
[9] $\lambda = 2\cdot(1+\nu)\cdot E_p/E_{sL}$ = lambda factor
[10] $\zeta = \ln\{[0.25 + (2.5\cdot \rho_E\cdot(1-\nu) - 0.25)\cdot\xi]\,(2\cdot L/d)\}$ = zeta factor
[11] $\mu L = 2\cdot(2/\zeta\cdot\lambda)^{0.5}\cdot(L/d)$ = mu factor

National Geotechnical Experimentation Site
Opelika, Alabama

Opelika NGES, Alabama - Piedmont Residuum

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

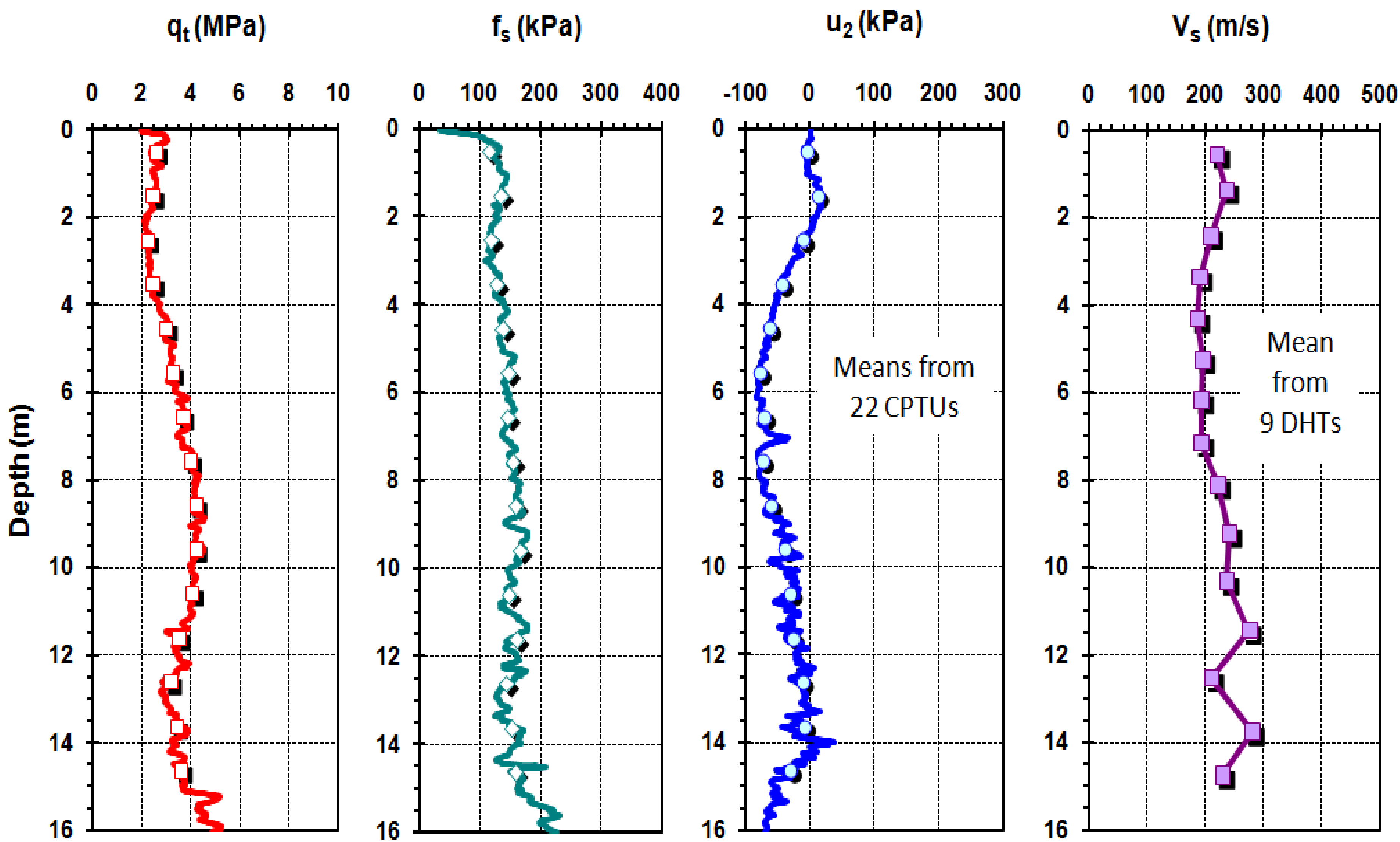
FULL-SCALE LOAD TESTS

- 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

IN-SITU TESTING and GEOPHYSICS

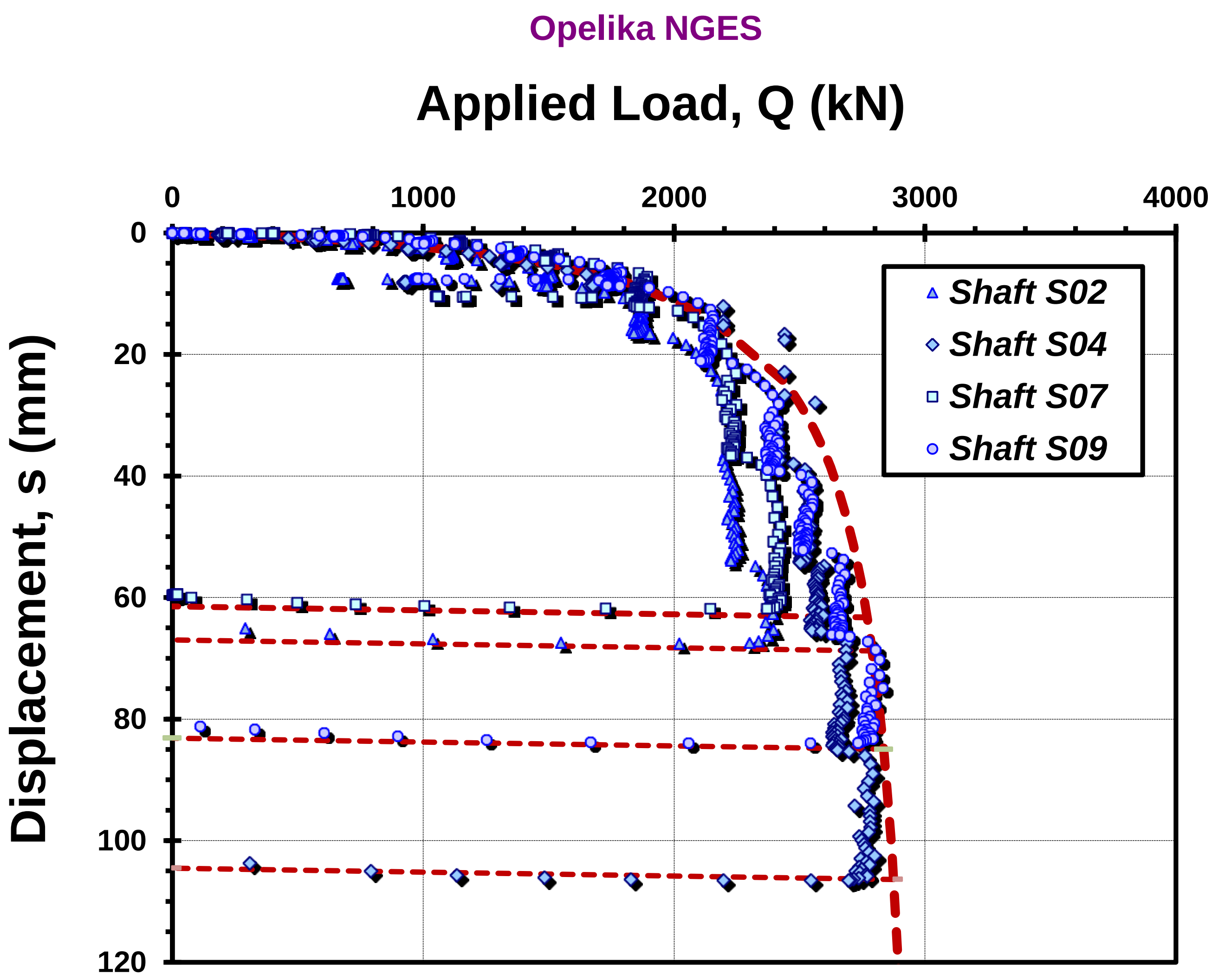
- Standard penetration tests (SPT)
- Full-displacement pressuremeter (FDPMT)
- Menard pre-bored pressuremeter (PMT)
- Flat plate dilatometer tests (DMT)
- Cone penetration tests (CPT)
- Piezocone tests with dissipations (CPTù)
- Seismic dilatometer tests (SDMT)
- Dual element piezocones (CPTu1u2)
- Resistivity 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 V_s profiling
- Surface resistivity surveys

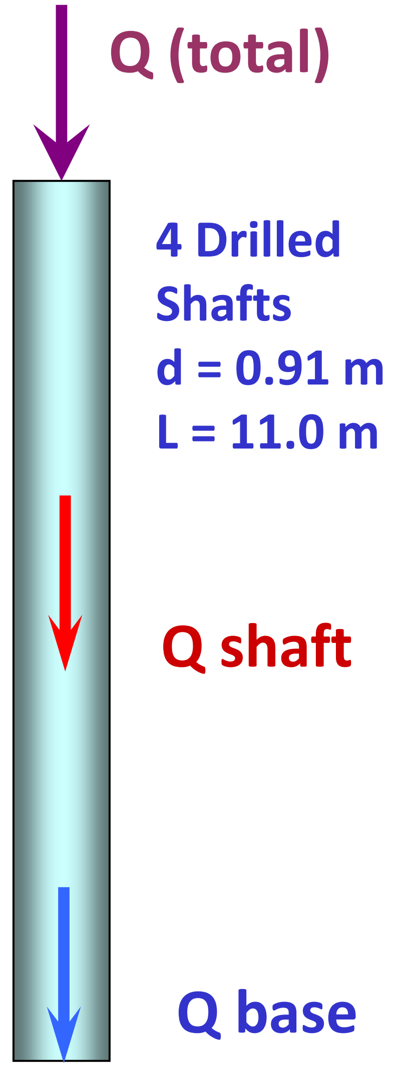
Mean SCPTu Profiles
Opelika NGES, Alabama



Opelika NGES in the Piedmont

Drilled Shaft Load Tests: Opelika, Alabama (Brown 2002)





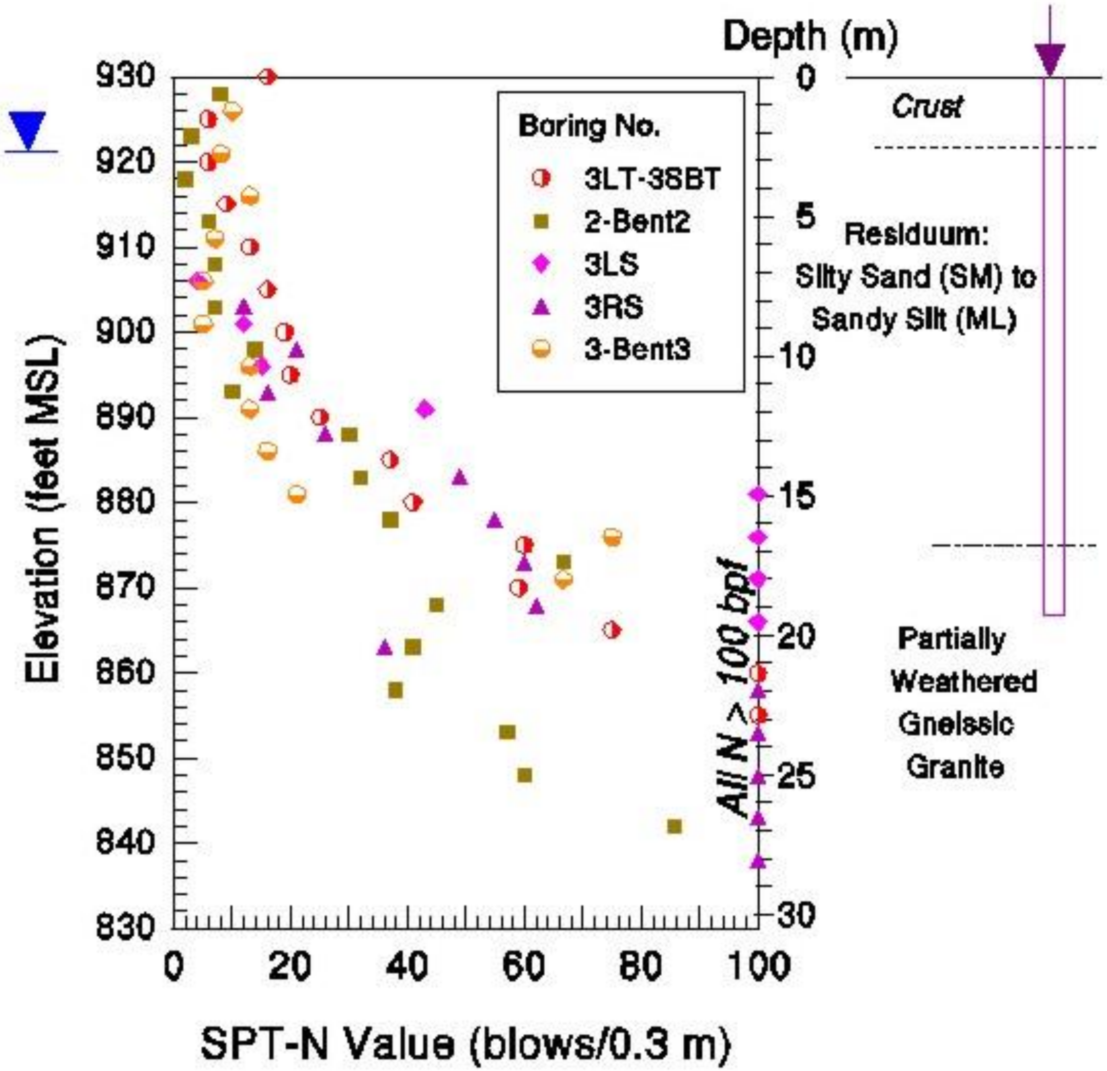
Load Test at I-85 Bridge, Coweta County, GA

GDOT Drilled Shaft Load Test:

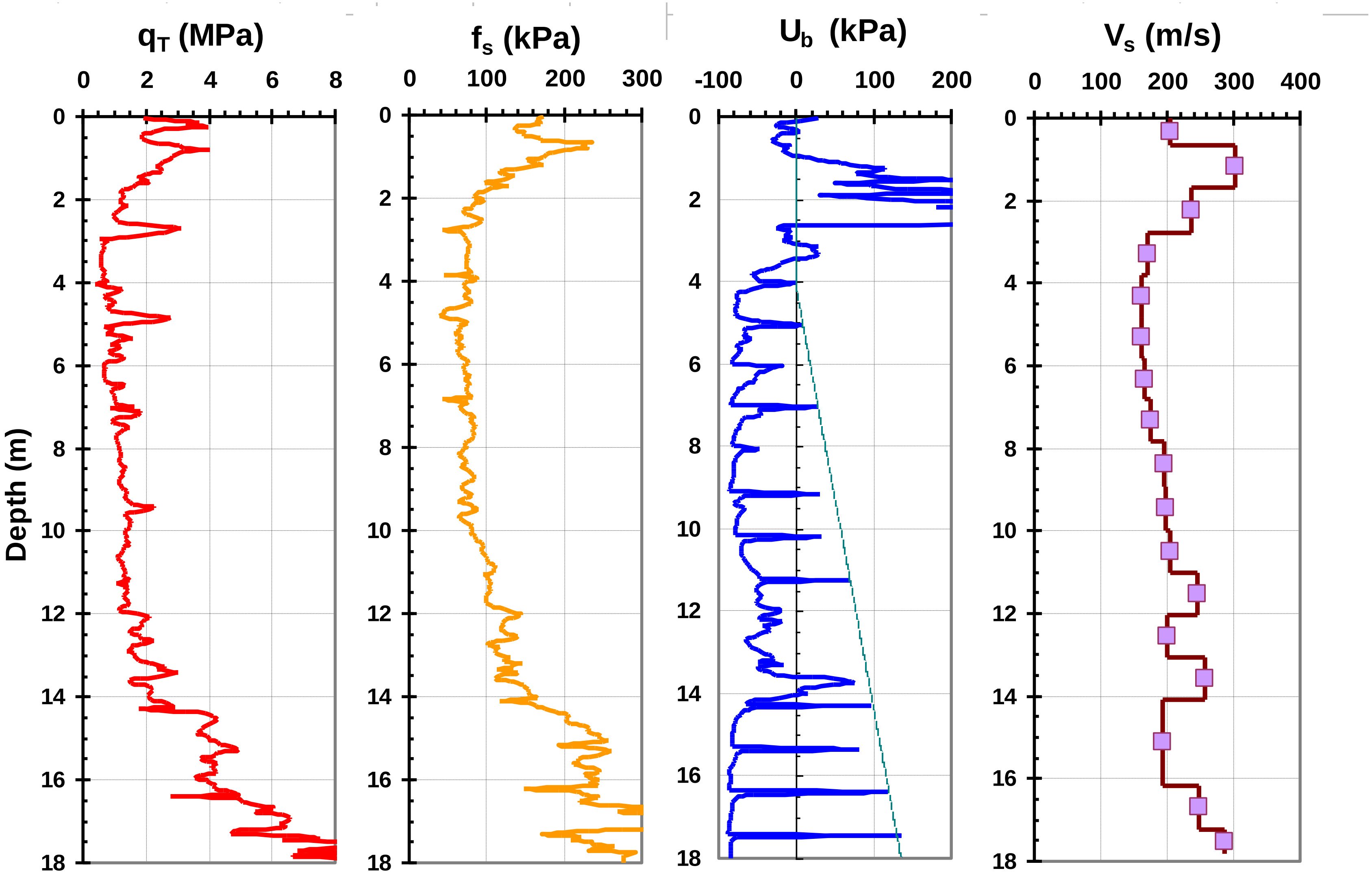
D = 0.91 m

L = 20.1 m

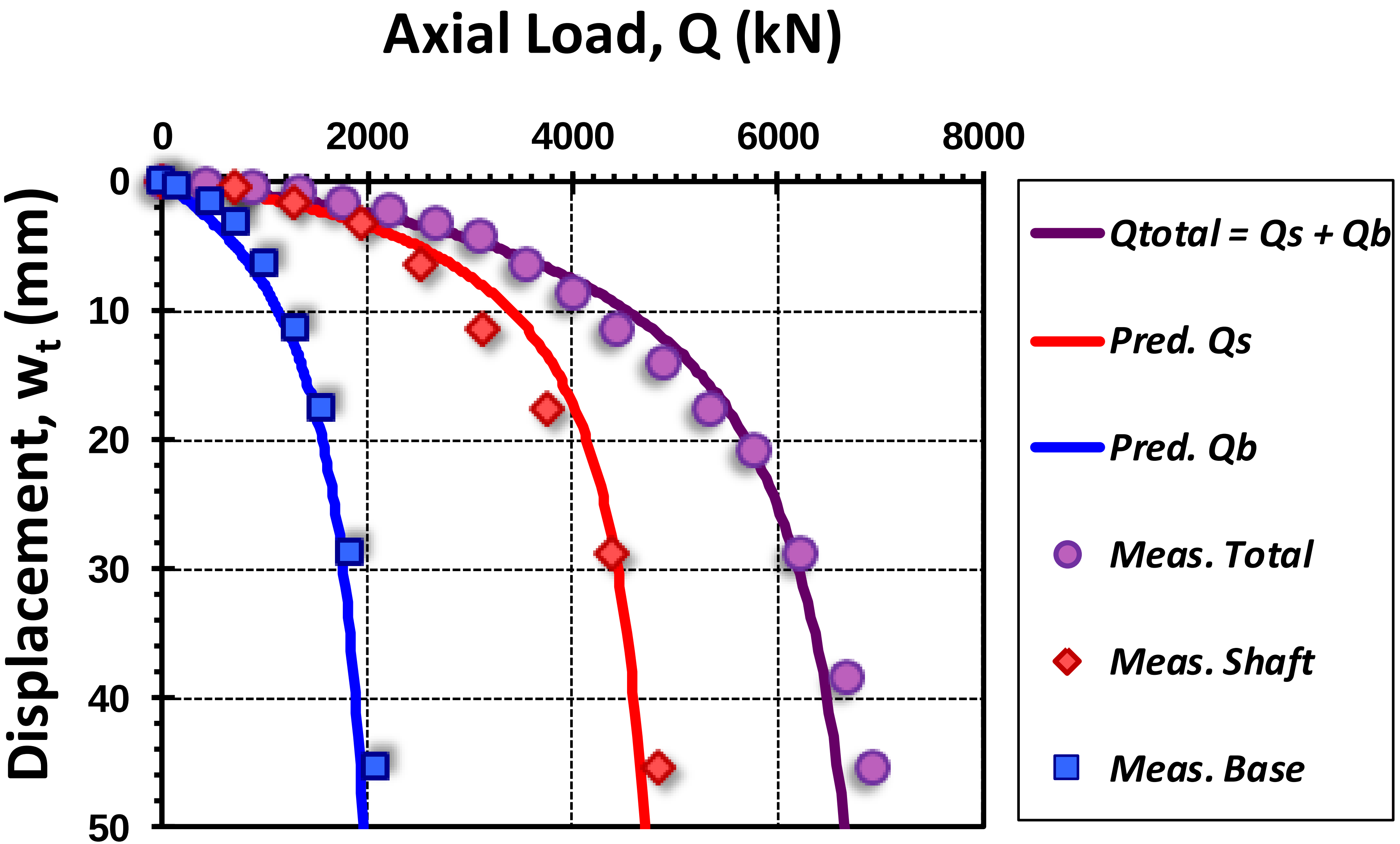
Load Test Directed by Mike O'Neill



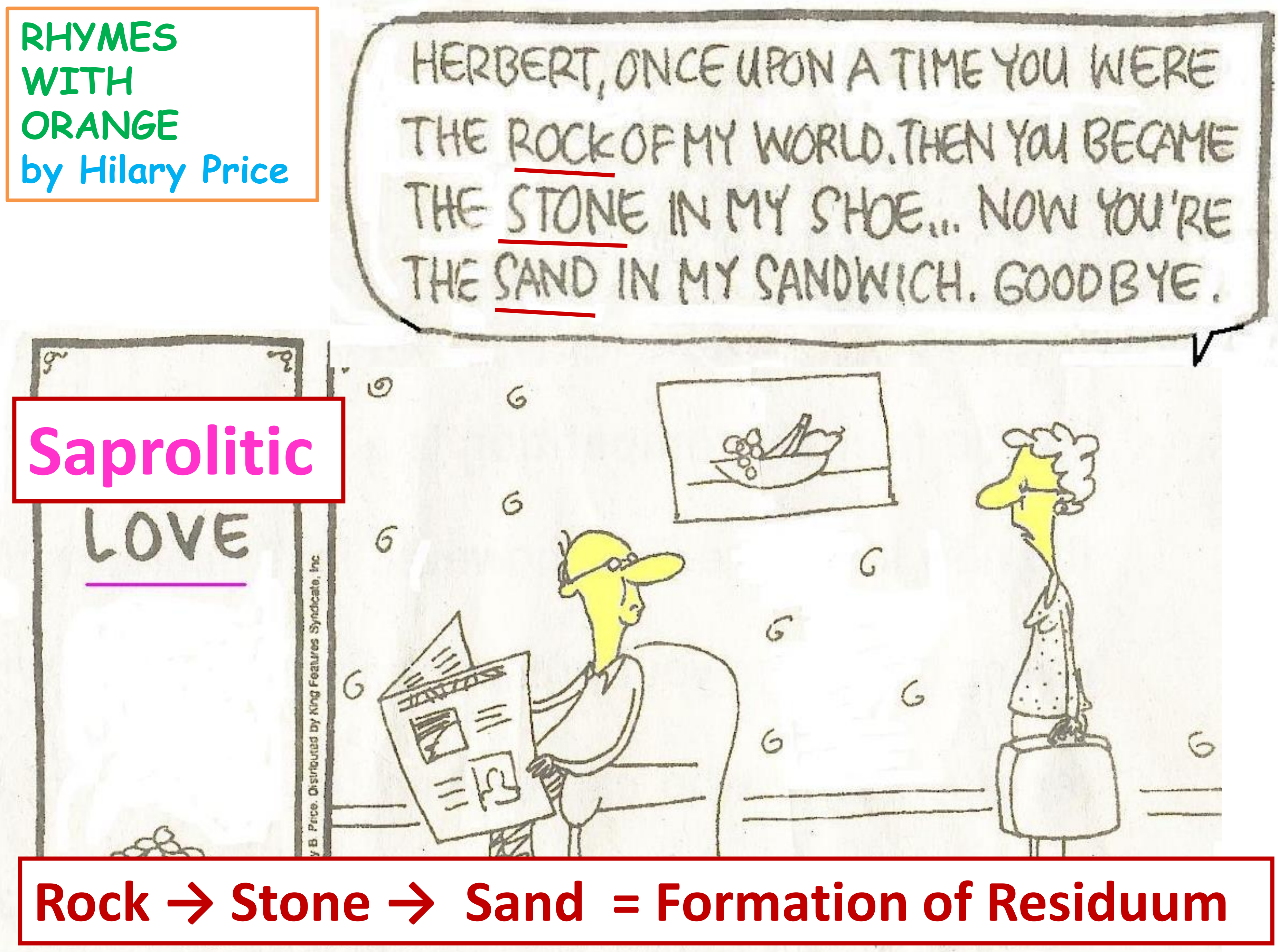
SCPTu at I-85 Bridge, Newnan, GA



Drilled Shaft Response, Coweta County, GA



RHYMES WITH ORANGE
by Hilary Price



Saprolitic

Rock → Stone → Sand = Formation of Residuum

Class “A” Prediction of Axial Pile Response

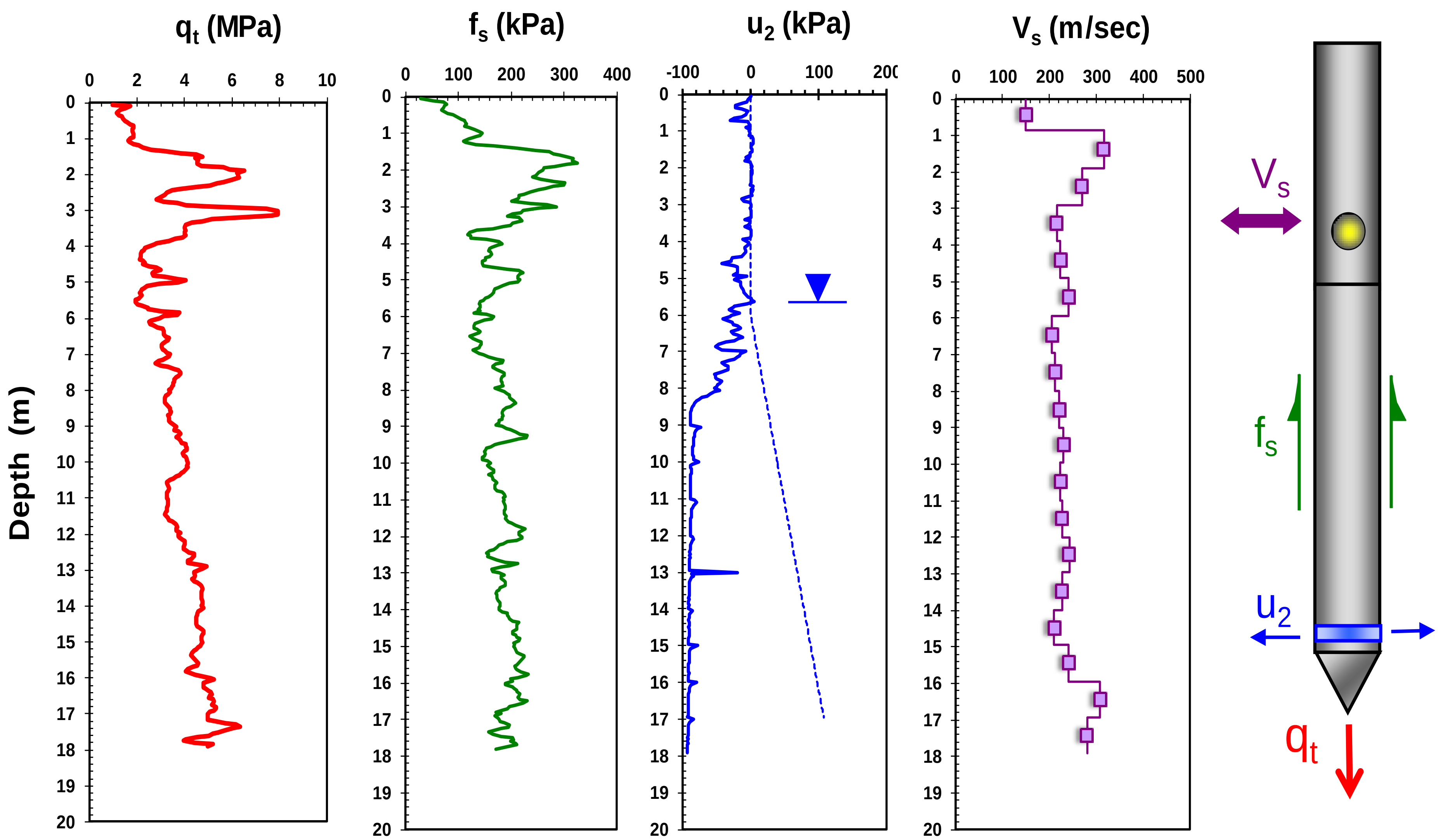
Jackson County, Georgia

Turbine Foundations,
Plant Dahlberg Power Station
Southern Companies

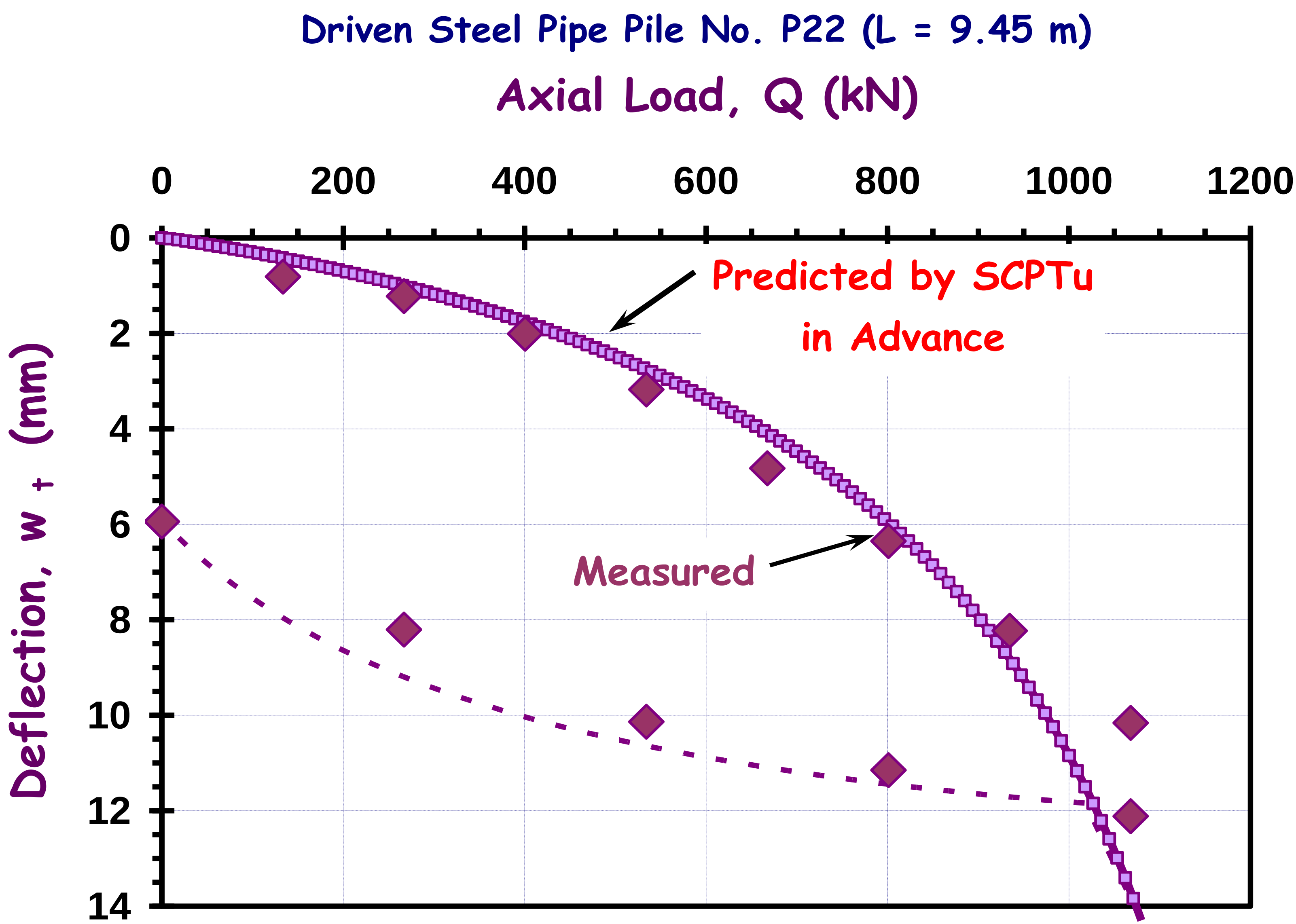
Courtesy Marty Meeks

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

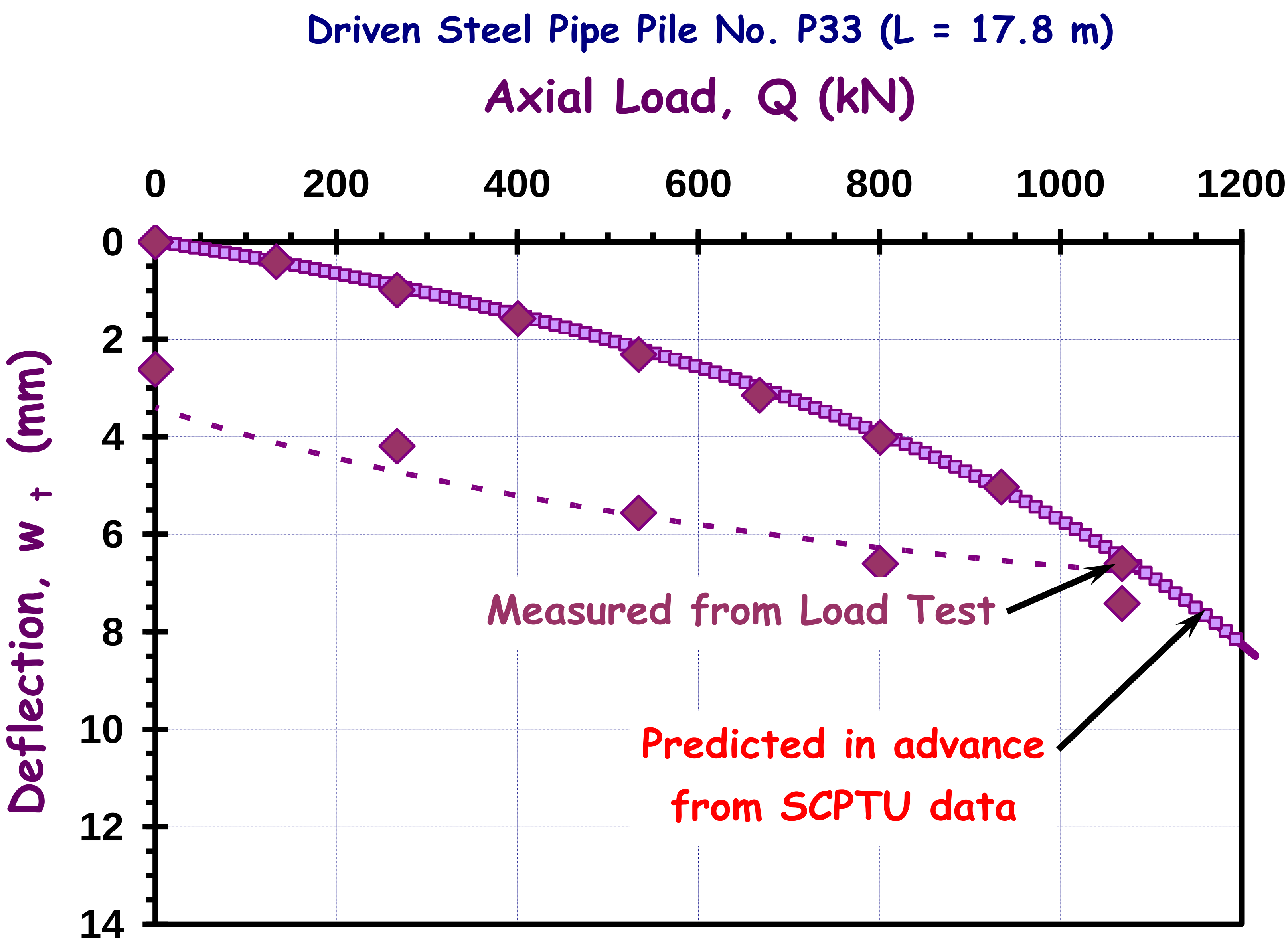
Seismic Piezocone Sounding, Jackson County, GA



Axial Pile Response from SCPTu, Jackson County, GA



Axial Pile Response from SCPTu, Jackson County, GA



Pile Load Tests

Dead Weight
www.hindu.com

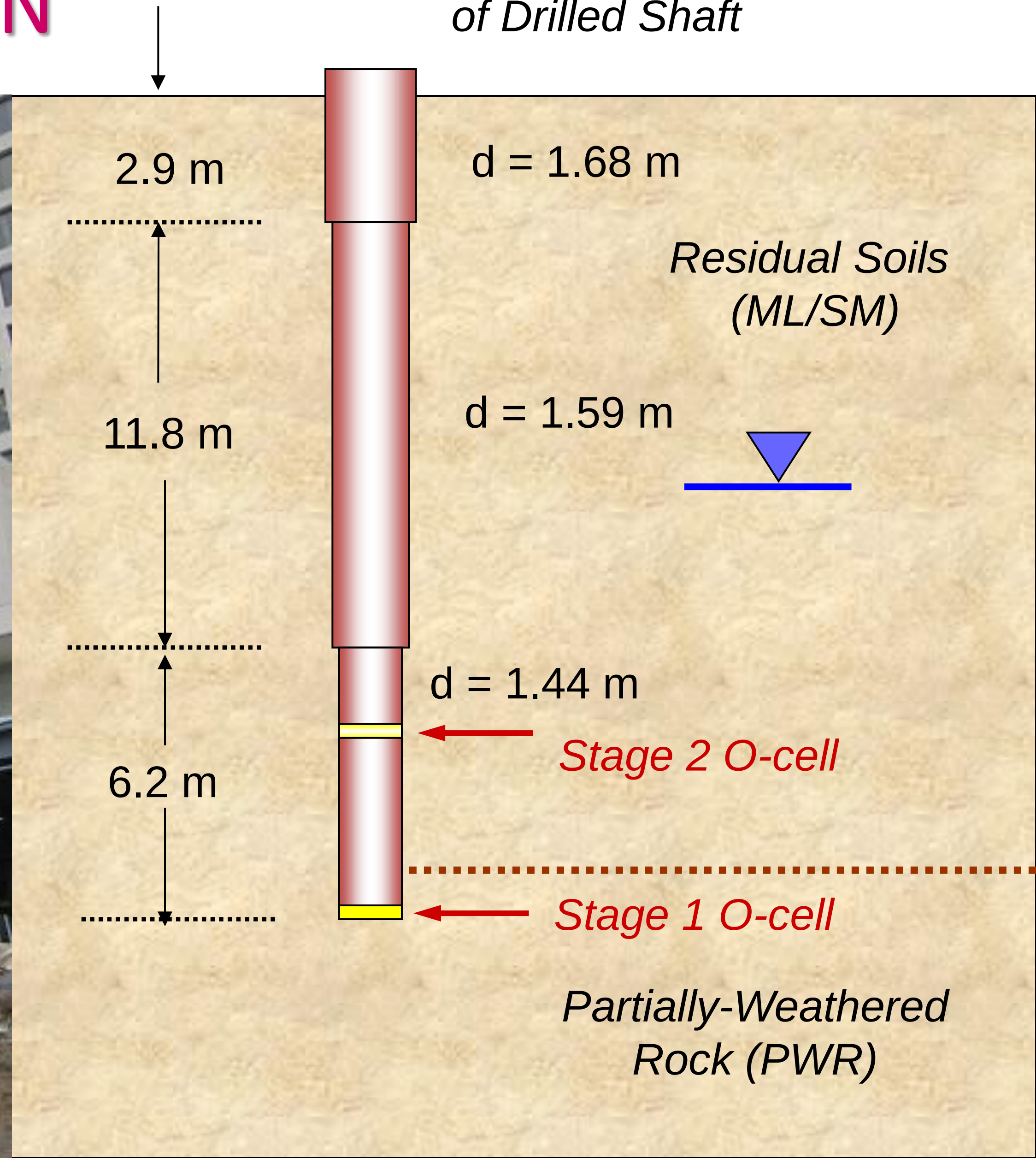
Reaction Frame
www2.dot.ca.gov

Statnamic Load Test
www.statnamiceurope.com

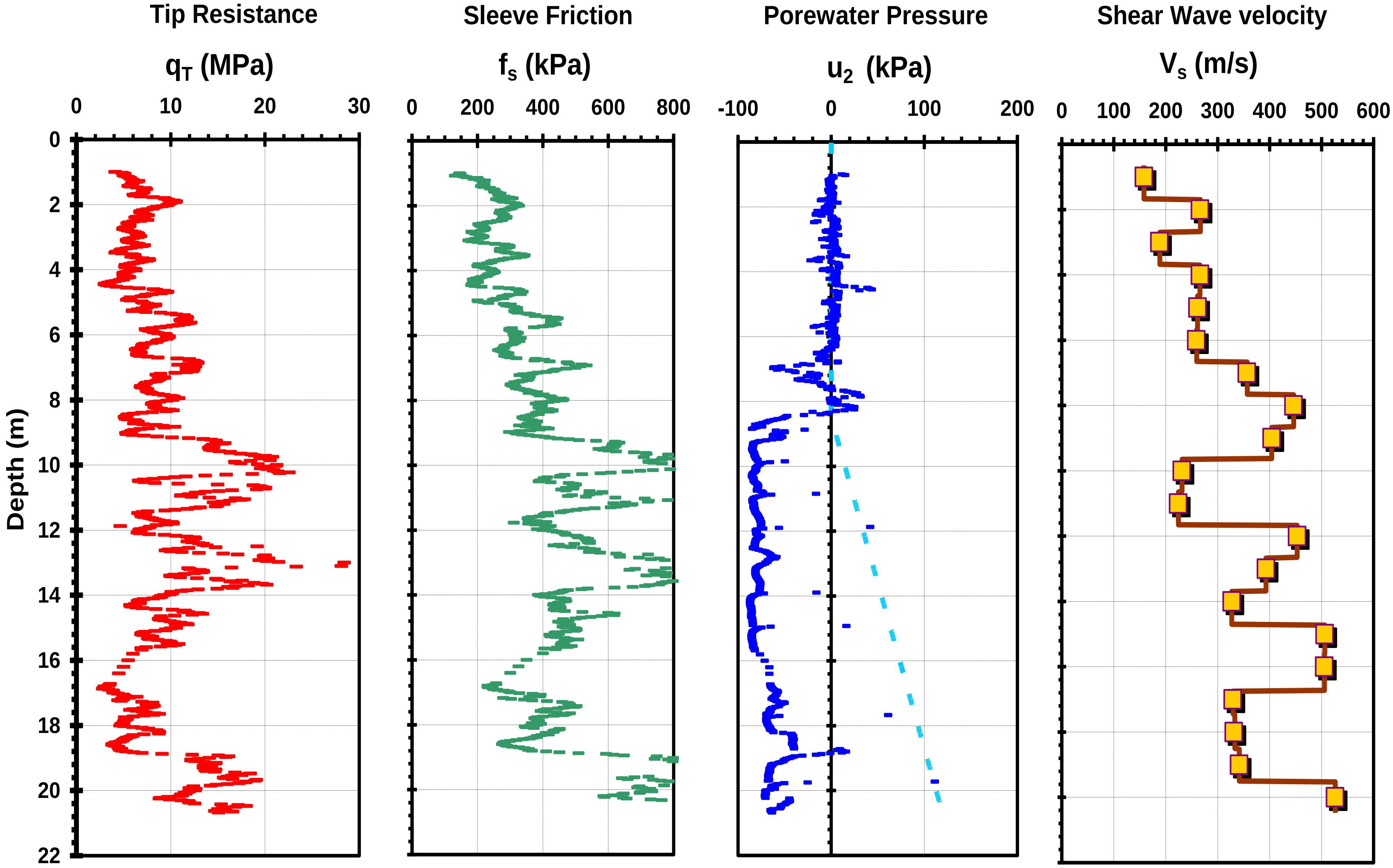
Osterberg Cell
www.fhwa.dot.gov

GDOT O-Cell Load Test for Viaduct at CNN

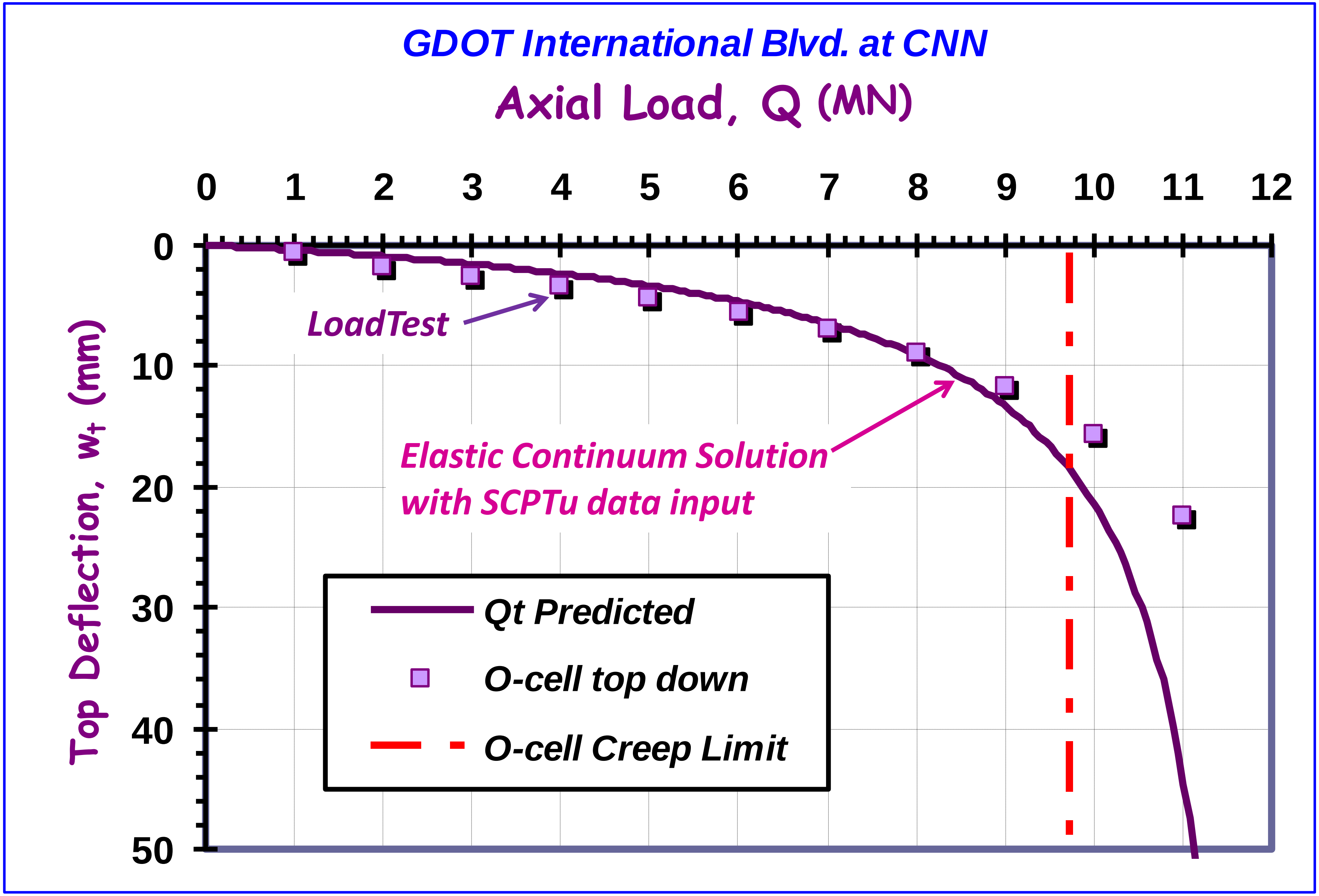
Constructed Dimensions of Drilled Shaft



GT Seismic Piezocone Sounding (SCPTu)
GDOT - International Blvd.



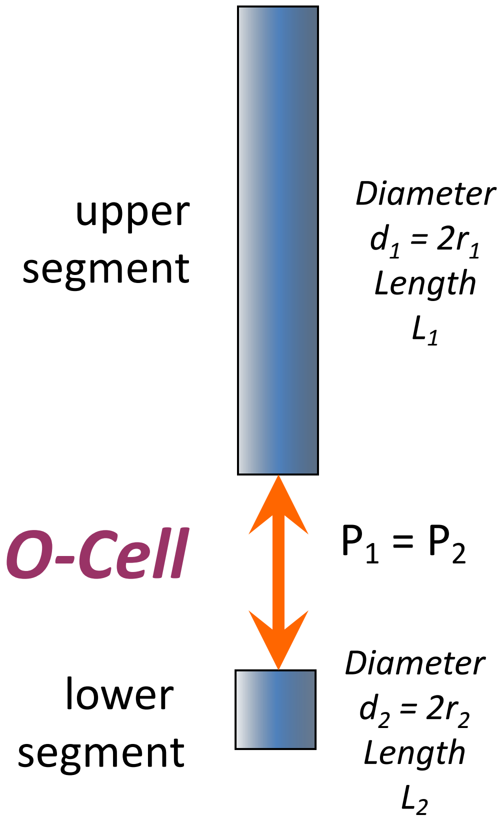
Class A Prediction - GDOT Bridge at CNN



O-cell load tests in Piedmont rocks

Drilled shafts - Lawrenceville, GA (2011)

O-Cell Elastic Solution



Rigid pile shaft under upward loading

$$\frac{P_1}{G_{s1} r_{o1} w_1} = \frac{2\pi}{\zeta_1} \cdot \frac{L_1}{r_{01}}$$

Rigid pile or plate under compression loading

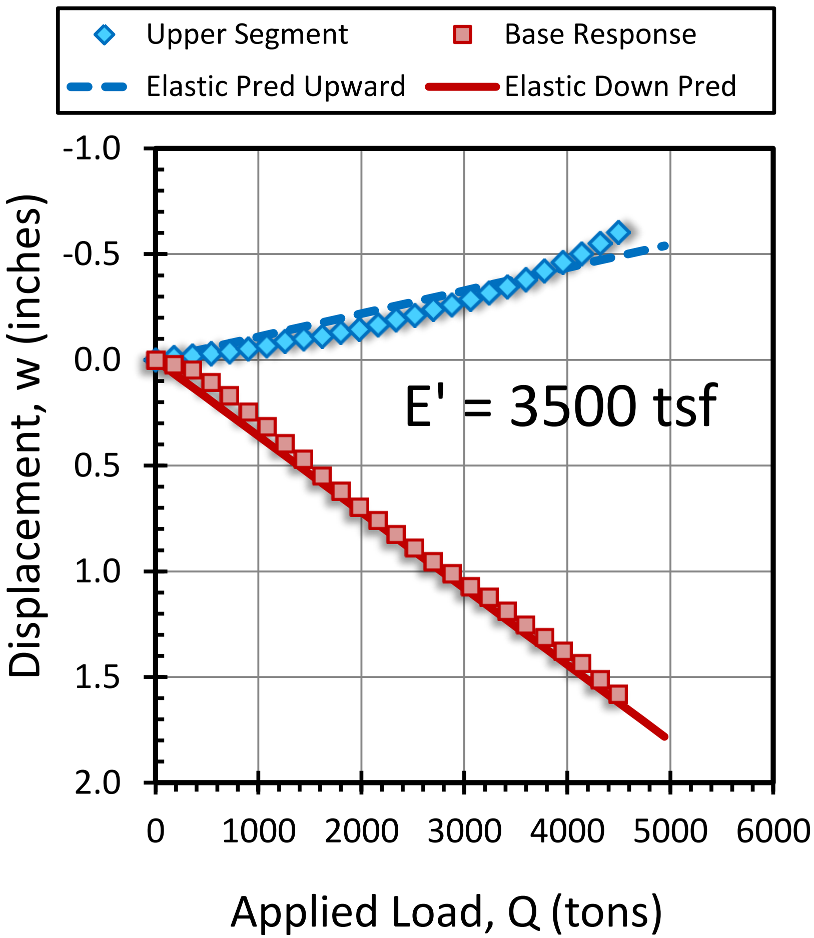
$$\frac{P_2}{G_{s2} r_{o2} w_2} = \frac{4}{(1-\upsilon)\xi} + \frac{2\pi}{\zeta_2} \cdot \frac{L_2}{r_{o2}}$$

P = applied force	w = pile displacement
L = pile length	I = E_p/G_{sL} = soil-pile stiffness ratio
r_o = pile radius	$\xi = G_{s2}/G_{sb}$ (Note: floating pile: ξ = 1)
E_p = pile modulus	G_{sb} = soil modulus below pile base/toe
G_s = soil side shear modulus	$\zeta = \ln(r_m/r_o)$ = soil zone of influence
ν = Poisson's ratio of soil	$r_m = L\{0.25 + \xi\,[2.5\,(1-\nu) - 0.25]\}$ = magic radius

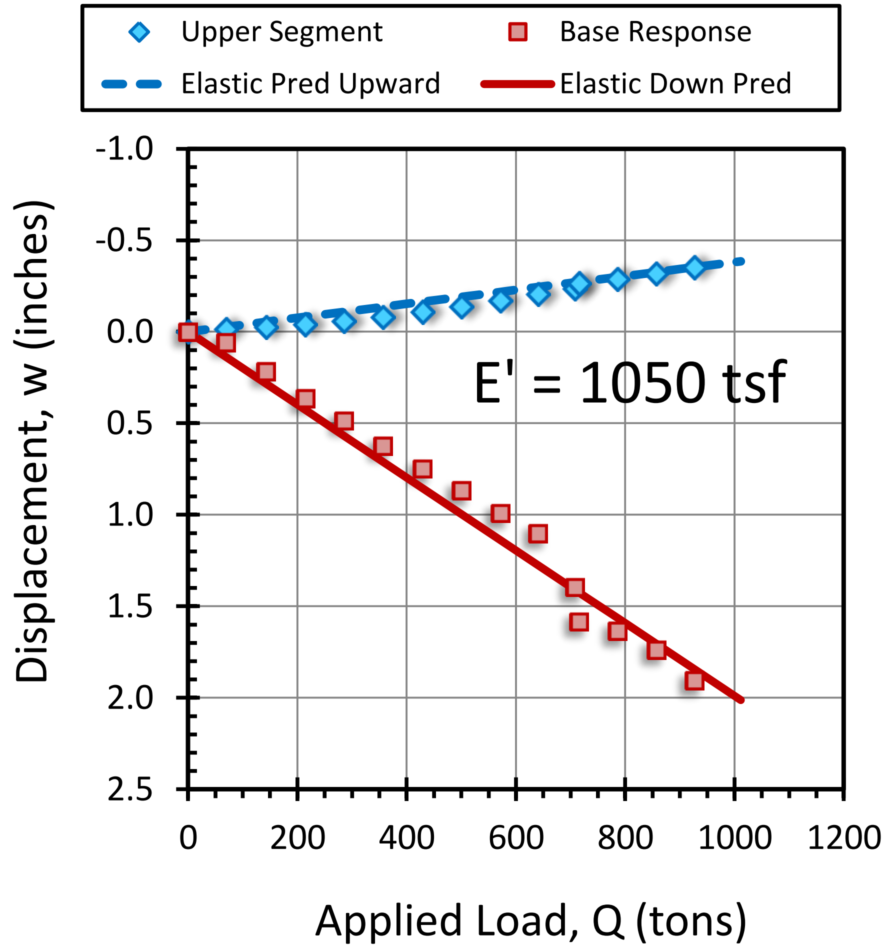
O-cell tests - ADSC/ASCE Lawrenceville, GA

Application of Randolph Elastic Solution

Test Shaft 1 in Rock

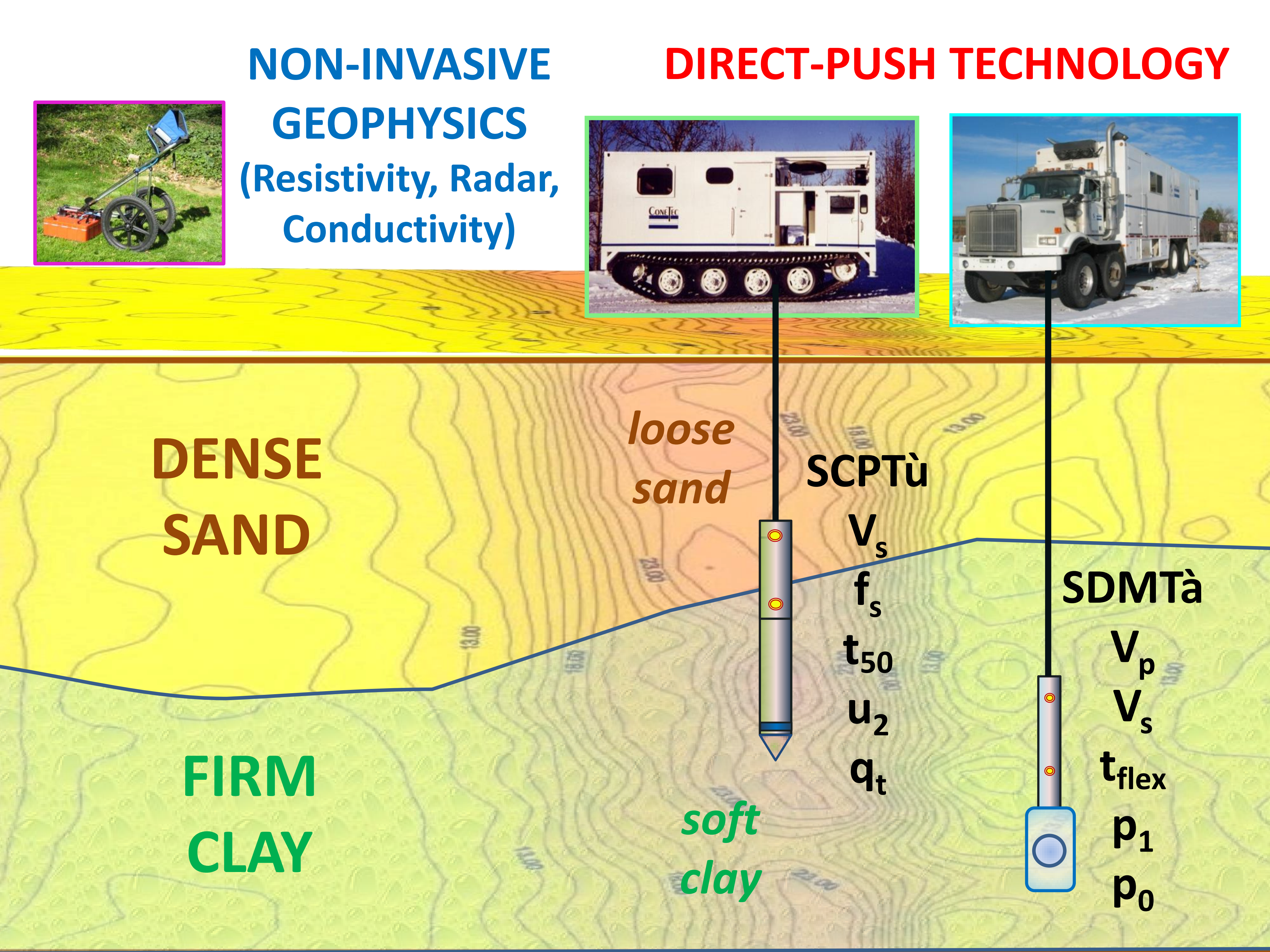


Test Shaft 2 in PWR



Recommendations to Geotechnical Practice

Site Characterization in the Piedmont


NON-INVASIVE GEOPHYSICS
(Resistivity, Radar, Conductivity)
DIRECT-PUSH TECHNOLOGY
DENSE SAND
loose sand
SCPTù
V_s
f_s
t_{50}
u_2
q_t
SDMTà
V_p
V_s
t_{flex}
p_1
p_0
FIRM CLAY
soft clay

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

Manufacturer Type	ID No.	Mean Energy Ratio (%)	Reference
Diedrich D-120	ID 26	46	UDOT
Diedrich D-50	321870551	56	GRL
CME 850	ID 21	62.7	UDOT
BK-81 w/ AW-J rods	B2	68.6	ASCE
Mobile B-80	ID 18	70.4	UDOT
SK w/ CME hammer	B6	72.9	ASCE
Diedrich D50	UF5	76	UF
CME 55	UF2	78.4	FDOT
CME 850	296002	79	GRL
CME 45	UF1	80.7	UF
CME 85	UF4	81.2	UF
CME 75 w/ AW-J rods	A3	81.4	ASCE
CME 75	UF3	83.1	UF
CME 750	ID 4	86.6	UDOT
Mobile B-57	DR-35	93	GRL
CME 75 rig	ID 10	94.6	UDOT

Factor of 2.1

O-cell load tests in Piedmont rocks

Drilled shafts - Lawrenceville, GA (2011)

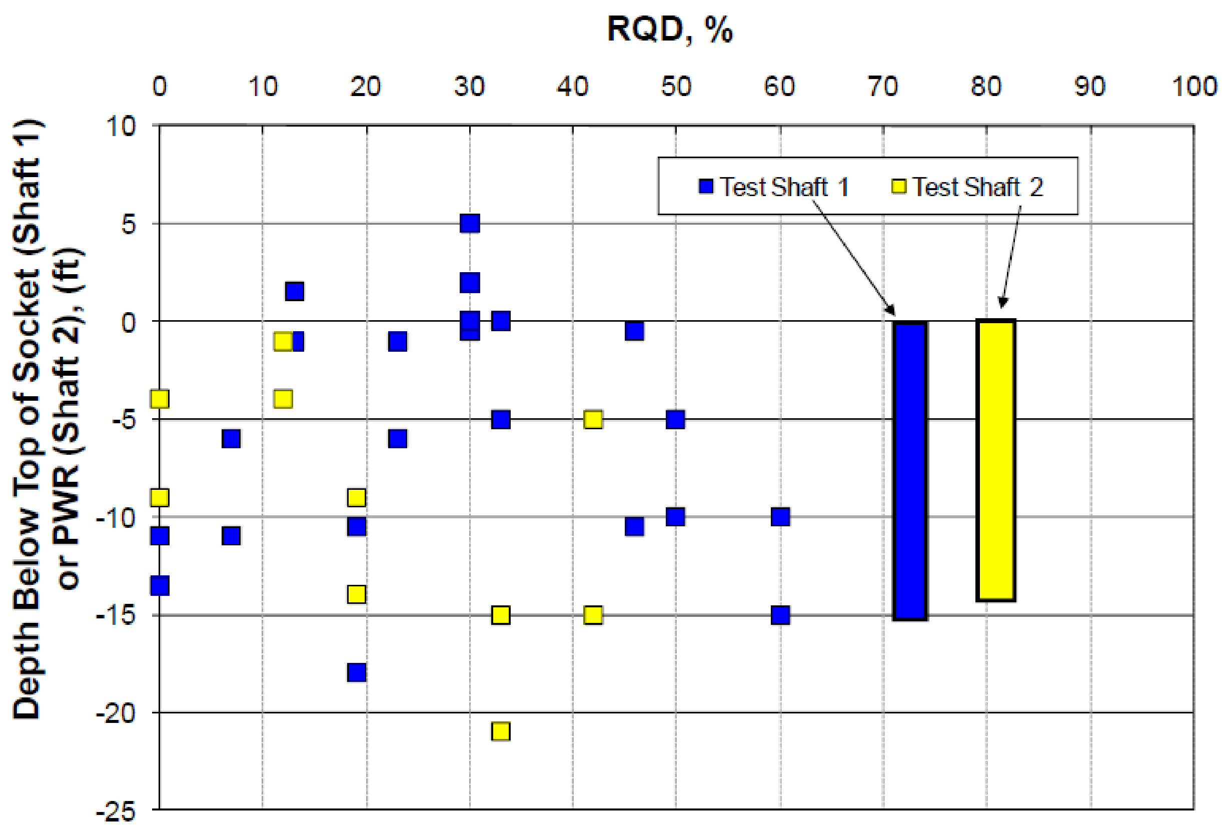


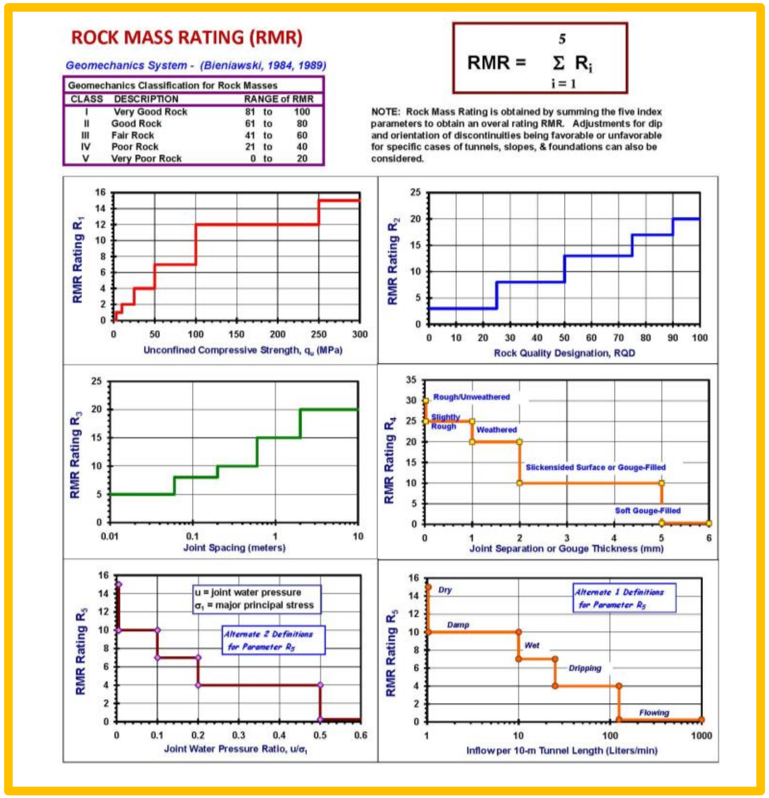
Figure 7 % RQD from Rock Cores

Methods for Rating Rock Masses

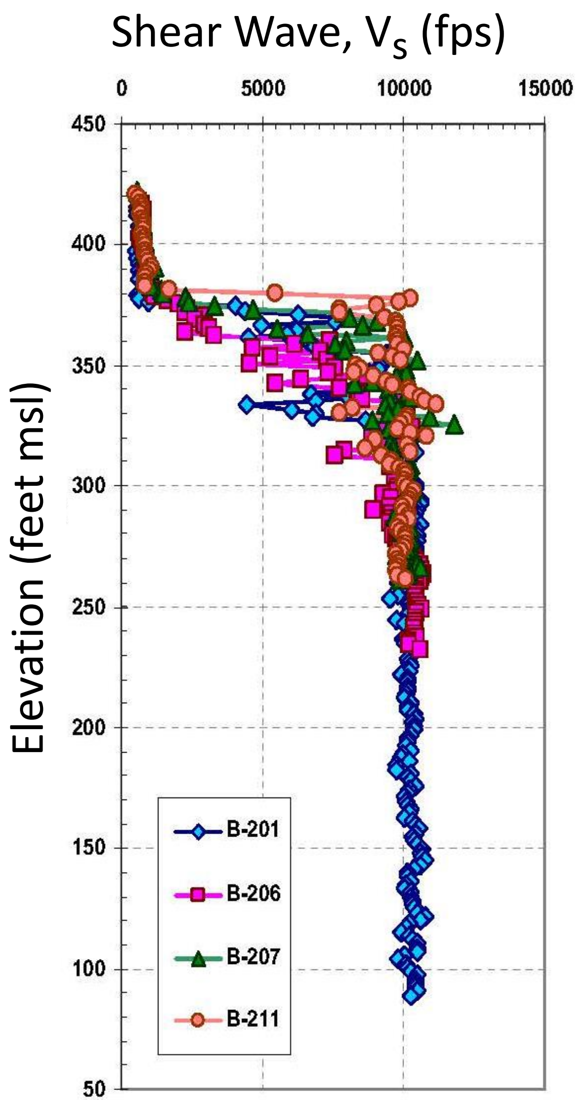
- Core Recovery (CR)
- Rock Quality Designation (RQD); Deere et al. (1966)
- Rock Mass Rating (RMR); Bieniawski (1976, 1989)
- Q-System by NGI; Barton et al. (1976, 1991)
- Geological Strength Index (GSI); Hoek (1995, 2009)

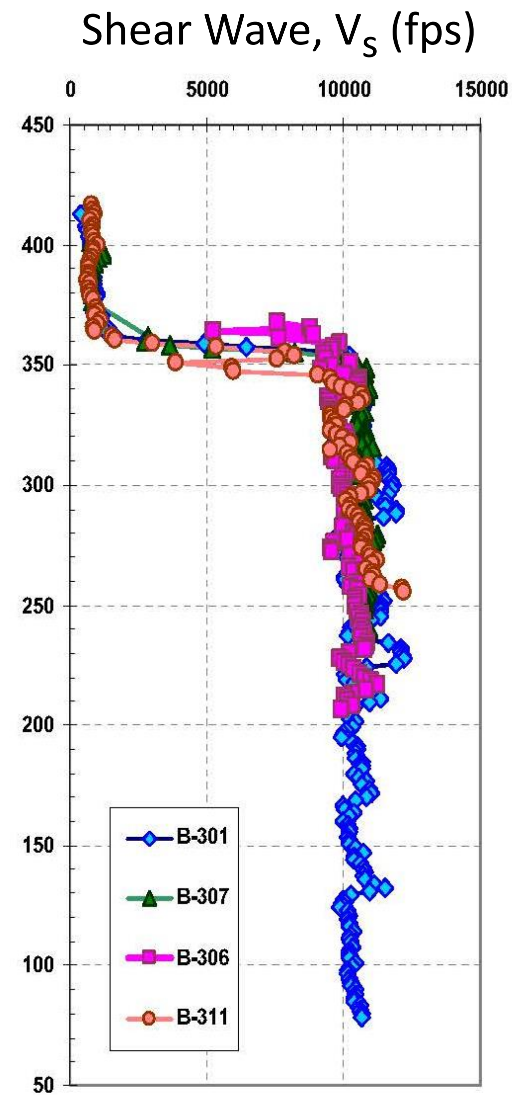
Rock Mass Rating (RMR)

- 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





V_s from suspension logging in boreholes

Intact Rock

CR = 98 - 100%

RQD = 97 - 100%

V_s = 10,100 fps = 3078 m/s

q_u = 25 ksi = 170 MPa

γ_t = 180 pcf = 28 kN/m^3

Geotechnics 2013 in the Piedmont

- 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: $G_{max} = \rho V_s^2$
- Presented case studies in Piedmont
- Use of Rock Mass Rating (RMR)
- Recommended more use of geophysics for site characterization, particularly V_s profiling

G-I ASCE

GEOVIRGINIA 2013

CONETEC

In-Situ Soil Testing, L.C.

thanks

U.S. DEPARTMENT OF ENERGY