Bottom Side Grouting of Drilled Shafts Prior to Tip Grouting

Civil & Coastal Engineering

FDOT Contract No.: BDK-75-977-46

Project Managers:
Peter Lai, PE
Rodrigo Herrera, PE

Principal Investigator:
Mike McVay, PhD
David Bloomquist, PhD, PE

Primary Researchers:
John Schwartz III, MS
Sudheesh Thiyyakkandi, PhD

GATOR Engineering

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Presentation Overview

Civil & Coastal Engineering

- Previous Research
- FDOT Test Chamber
  - Shot Shaft (3' x 6')
  - Long Shaft (3' x 25')
  - Top-Down Test on Long Shaft (3' x 25')
- FDOT Test Site
  - Field Shaft (3-½' x 25')
  - Top-Down Test on Field Shaft (3-½' x 25')
  - Statnamic Test on Field Shaft (3-½' x 25')
- Predicted and Measured Capacities
  - Before Grouting
  - After Grouting

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Previous Research

Civil & Coastal Engineering

- Post Grouted Drilled Shaft Tips (Mullins, 2001 & 2004)
  - No Side Grouting Prior to Tip Grouting
  - Grout Flows along Path of Least Resistance during Tip Grouting
  - No Cavity Expansion during Tip Grouting
  - Did Not Significantly Improve Soil Conditions around Shaft
  - No Significant Increase in Tip Capacity of Drilled Shaft

- End Bearing Prediction of Post-Grouted Drilled Shaft (No Side Grouting)
  - Mullins, 2006 Method for Tip Grouted Shaft (GP_{max}, GPI, & TCM)
  - Thiyyakkandi (2013) Estimates Tip Area and Tip Pressure – mobilized tip resistance vs. displacement

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Previous Research

Civil & Coastal Engineering

- Prestressed Concrete Pile Installation – Utilizing Jetting and Pressure Grouting (McVay, 2009)
  - No Side Membrane Initially (Side Grout Ports Only)
  - Grout Followed Path of Least Resistance during Tip Grouting
  - Tested Flexible and Semi-Rigid Membranes
  - Improved Contact Area between Grout and Foundation Element

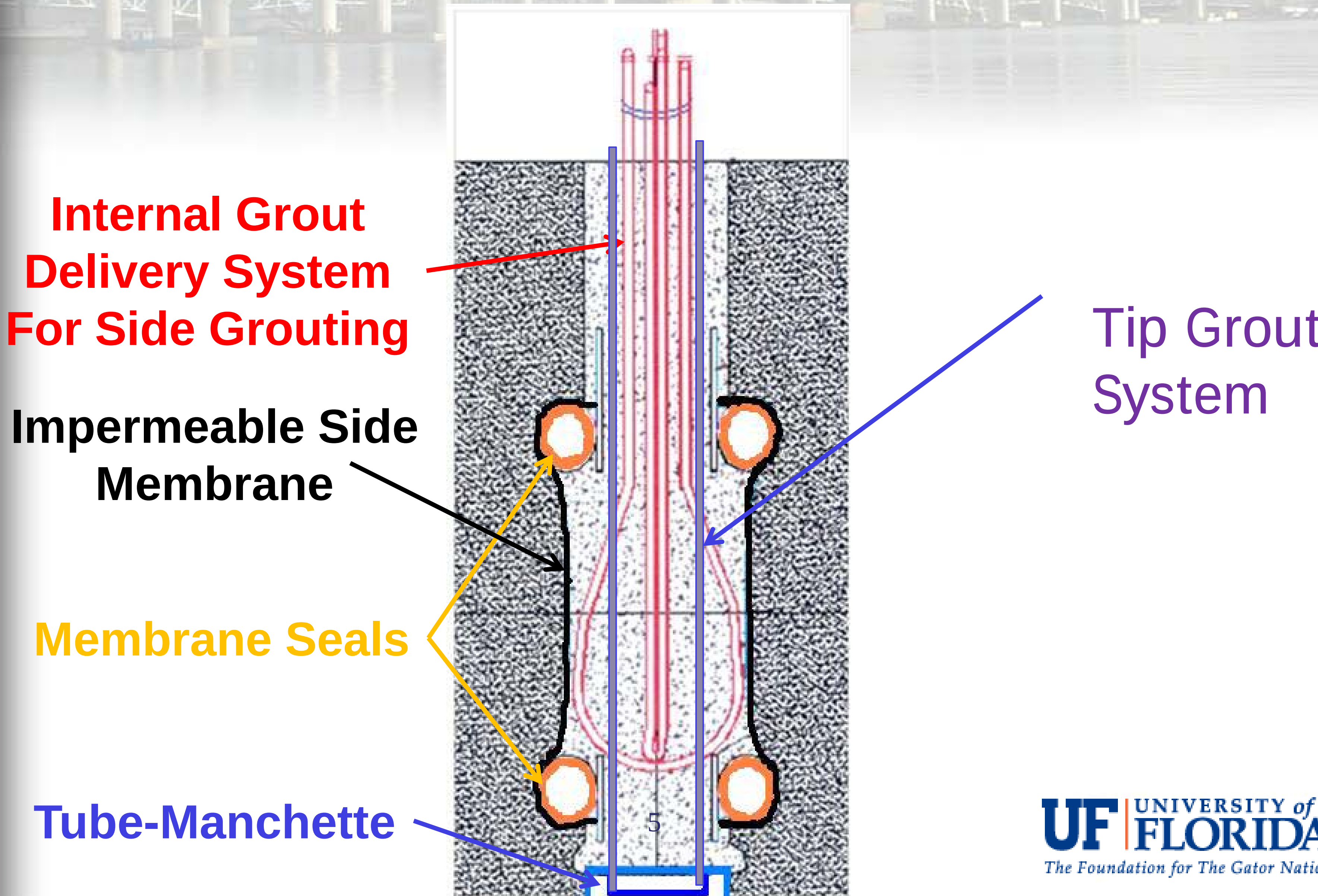
- Piles Group Efficiencies of Grout-Tipped Drilled Shafts and Jet-Grouted Piles (McVay, 2010)
  - Multiple Grouting Phases using Different Color Grout (Died Grout)
  - Identified Grout Flow during Subsequent Tip Grouting Phases
  - Developed FEM Model and Design Approach for Side Grouted Foundations (K_g Method)

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Civil & Coastal Engineering

FDOT Test Chamber

Design of Side Grouting System



UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Chamber

Short Shaft (3’ x 6’) – Fabrication

Civil & Coastal Engineering

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Chamber
Short Shaft (3’ x 6’) – Construction

Civil & Coastal Engineering

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Civil & Coastal Engineering

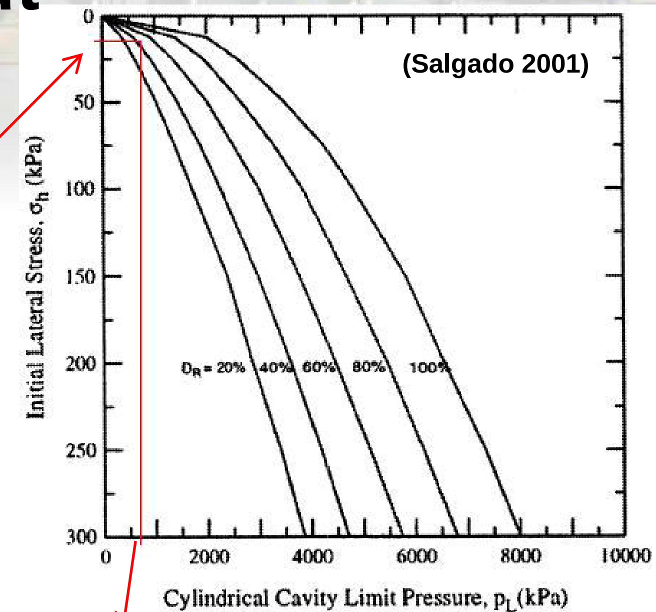
FDOT Test Chamber

Short Shaft (3’ x 6’) – Side Grout

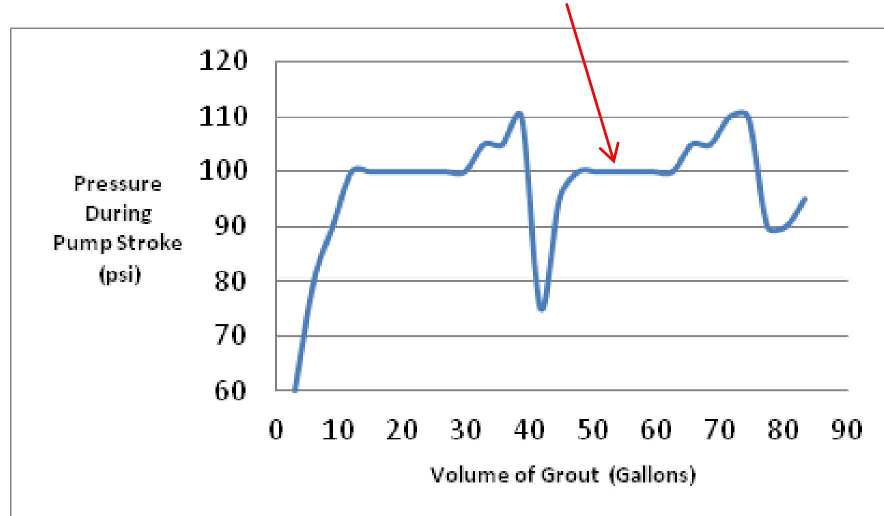
Average Depth of Side Grout Zone = 5’

Initial Lateral Stress, $\sigma_h = \sigma_v{*}K_0 \approx 1.9$ psi

or 13 kPa



700 kPa ≈ 102 psi



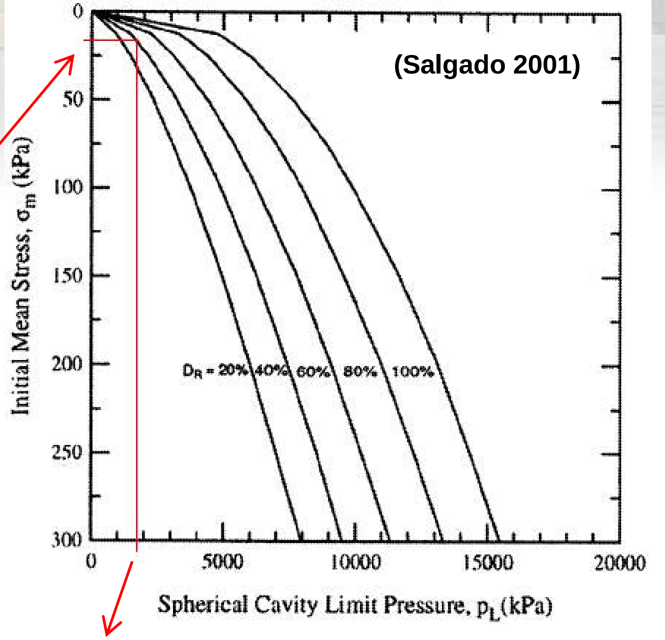
No Upward Grout Flow

FDOT Test Chamber

Short Shaft (3' x 6') – Tip Grout

Depth of Tip Grout Zone = 6'

Initial Mean Stress, $\sigma_m = \frac{(2*\sigma_h)+\sigma_v}{3}$ ≈ 3psi or 20 kPa



1800 kPa ≈ 261 psi (Max)

Shaft moved up

Cavity Expansion!

FDOT Test Chamber

Long Shaft (3' x 25') – Shaft Casing

FDOT Test Chamber
Long Shaft (3’ x 25’) – Shaft Casing

Civil & Coastal Engineering

FDOT Test Chamber

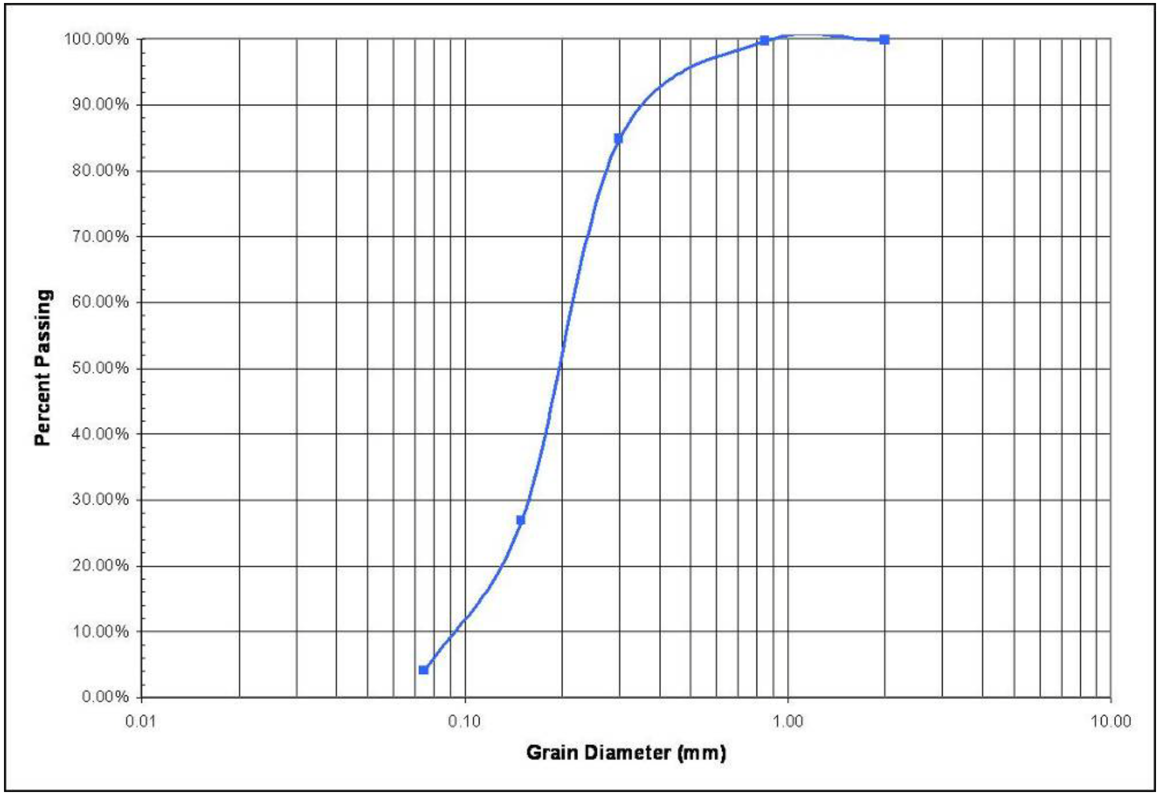
Long Shaft (3' x 25') – Soil Placement

Civil & Coastal Engineering

Test Soil: A-2-4 (Silty Sand – from FDOT Borrow Pit in Lake City, FL)

18 Inch Soil Lifts
8% Moisture Content
50% Relative Density
$\gamma \approx 110$ lb/ft^3 & $\Phi' \approx 33°$

SPT Blow Counts:
3 – 5 at 8 ft Depth
15 – 20 at 25 ft Depth



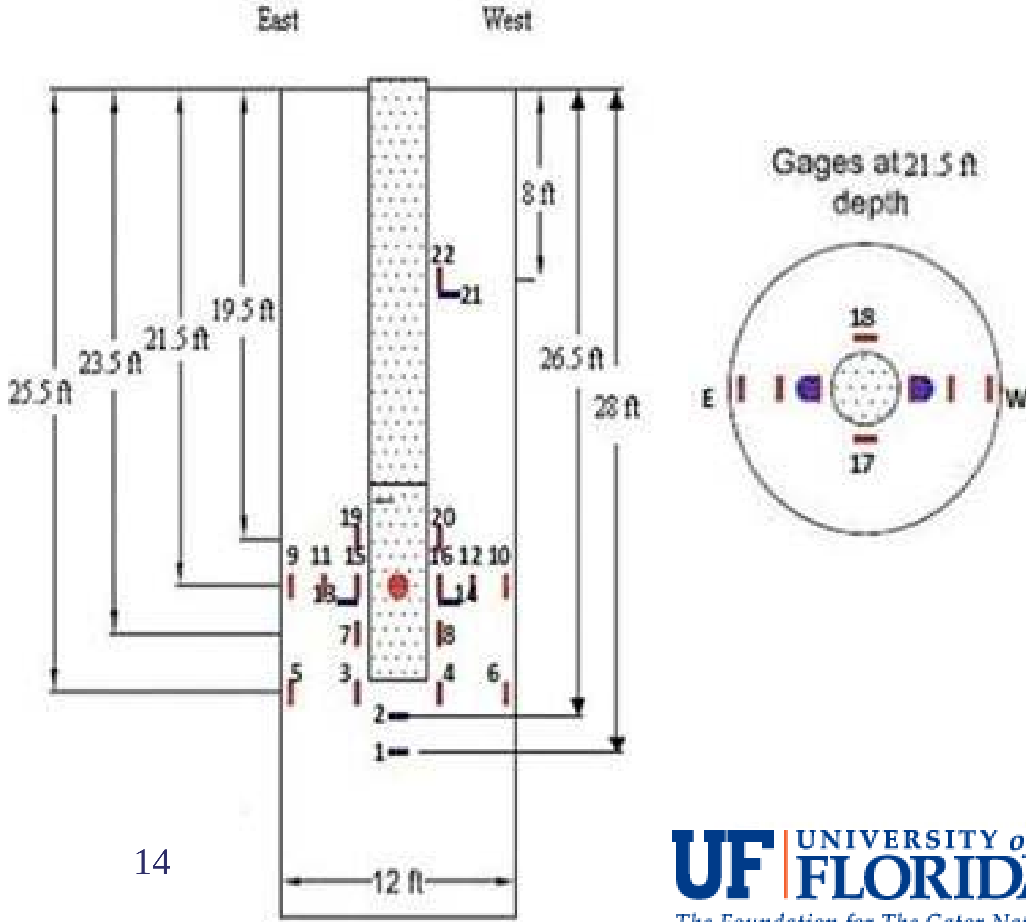
UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Chamber

Long Shaft (3' x 25') – Soil Placement

FDOT Test Chamber

Long Shaft (3’ x 25’) – Pressure Cell Placement



FDOT Test Chamber

Long Shaft (3’ x 25’) – Fabrication

FDOT Test Chamber

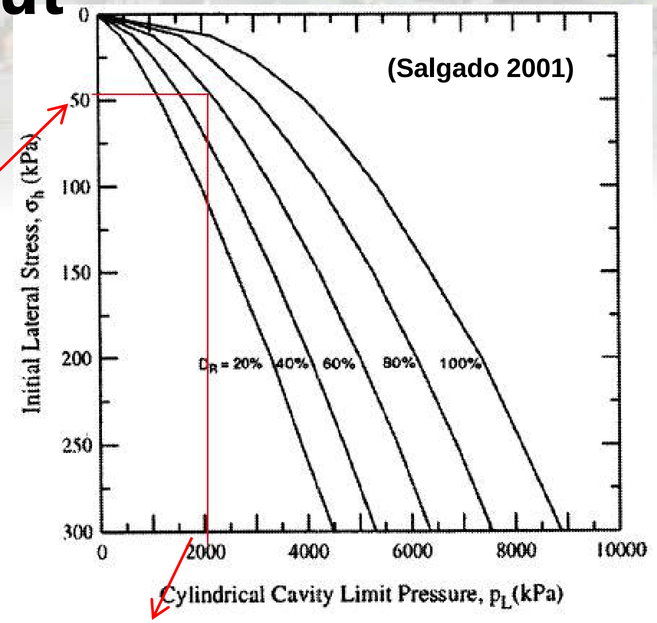
Long Shaft (3’ x 25’) – Construction

Civil & Coastal Engineering

Civil & Coastal Engineering

FDOT Test Chamber

Long Shaft (3' x 25') – Side Grout

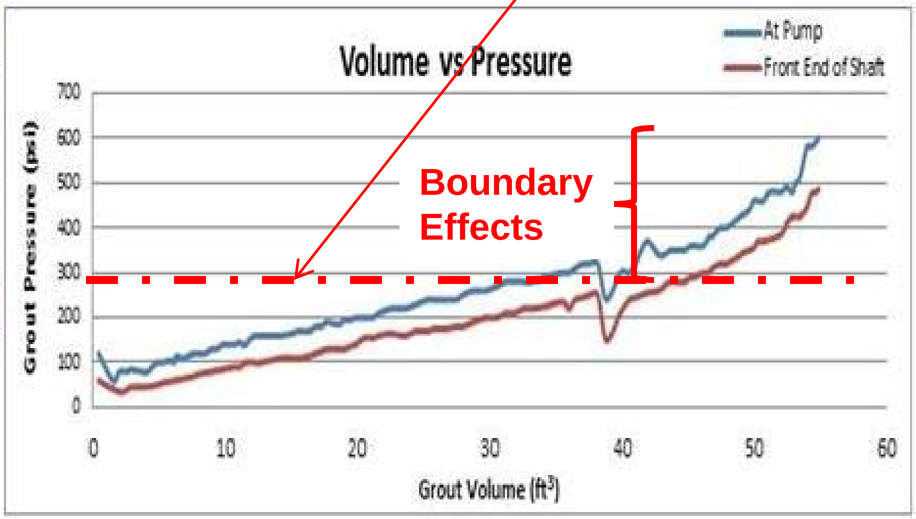


Average Depth of Side Grout Zone = 20'

Initial Lateral Stress, $\sigma_h \approx 7$ psi

or 48 kPa

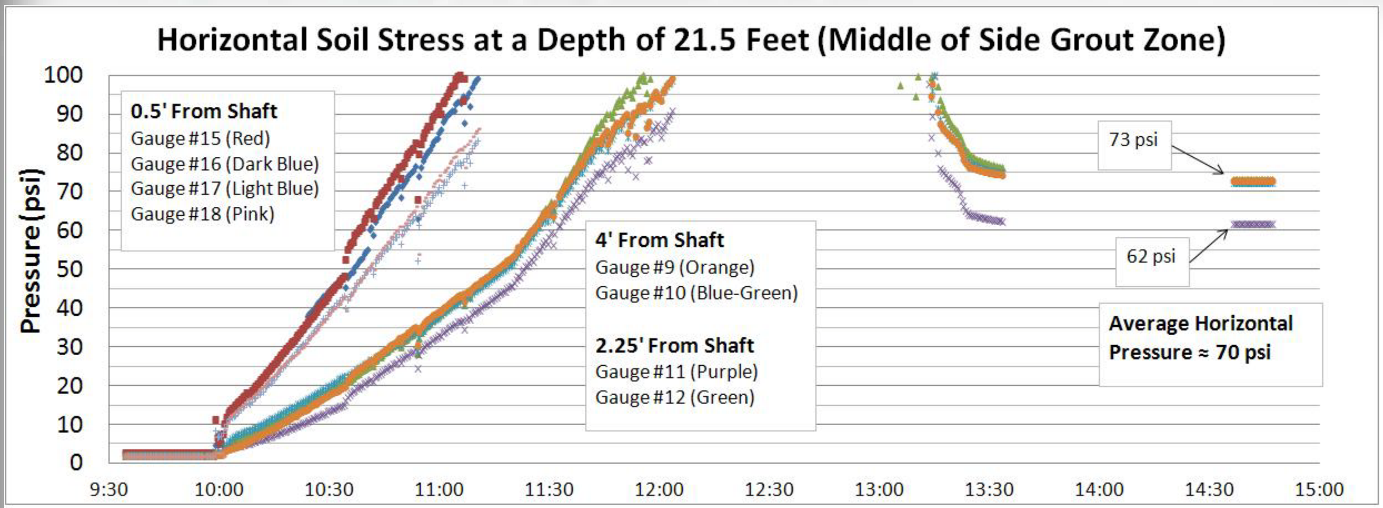
2050 kPa ≈ 297 psi

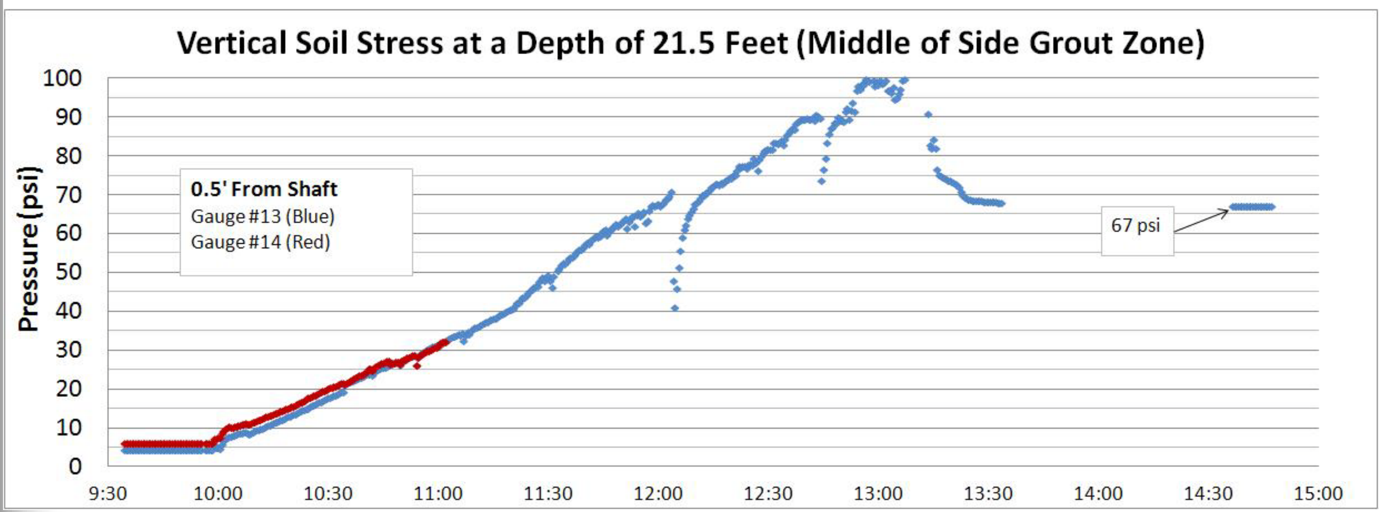


No Upward Grout Flow

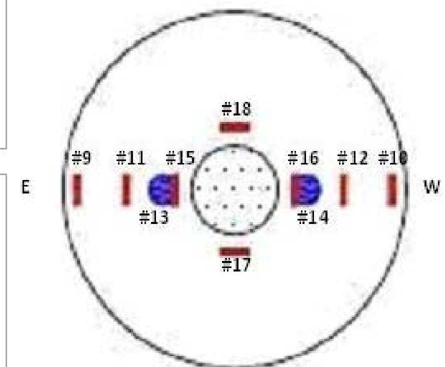
FDOT Test Chamber
Long Shaft (3’ x 25’) – Side Grout

Civil & Coastal Engineering





Pressure Cells at Depth of 21.5’ (Middle of Side Grouted Zone)



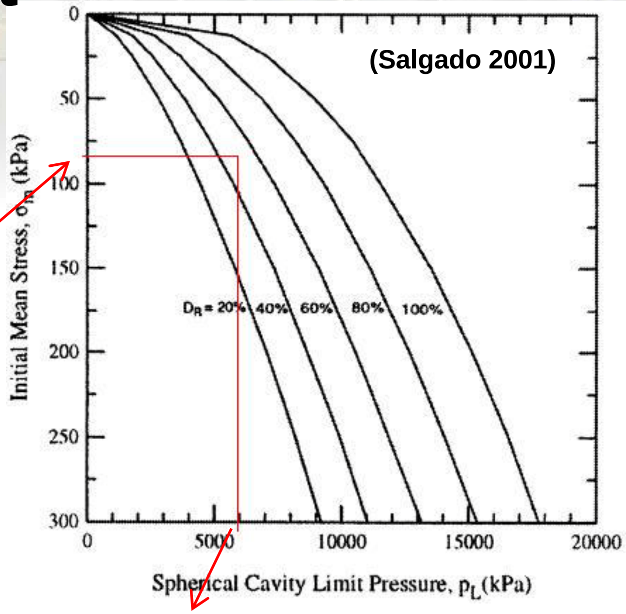
UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Chamber

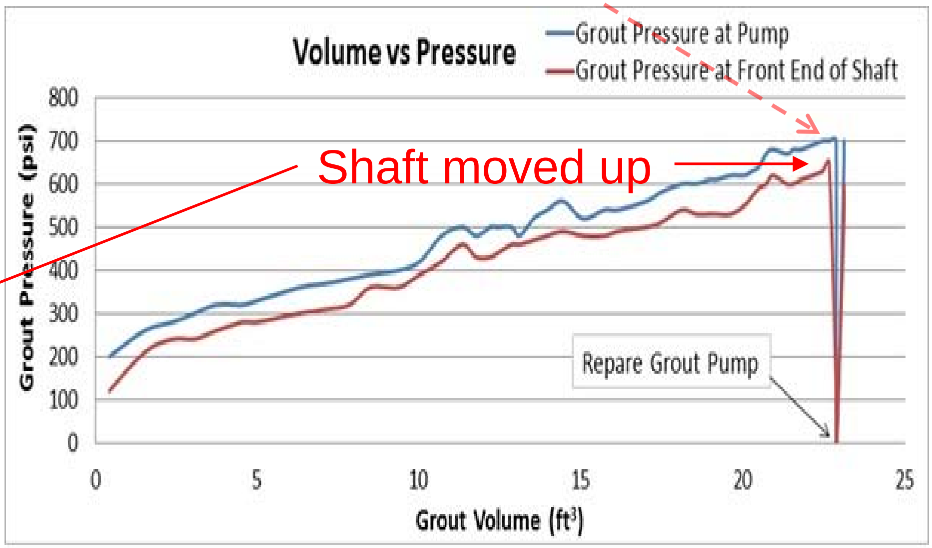
Long Shaft (3’ x 25’) – Tip Grout

Depth of Tip Grout Zone = 25’

Initial Mean Stress, $\sigma_m = \frac{(2*\sigma_h)+\sigma_v}{3}$ ≈ 12 psi or 83 kPa

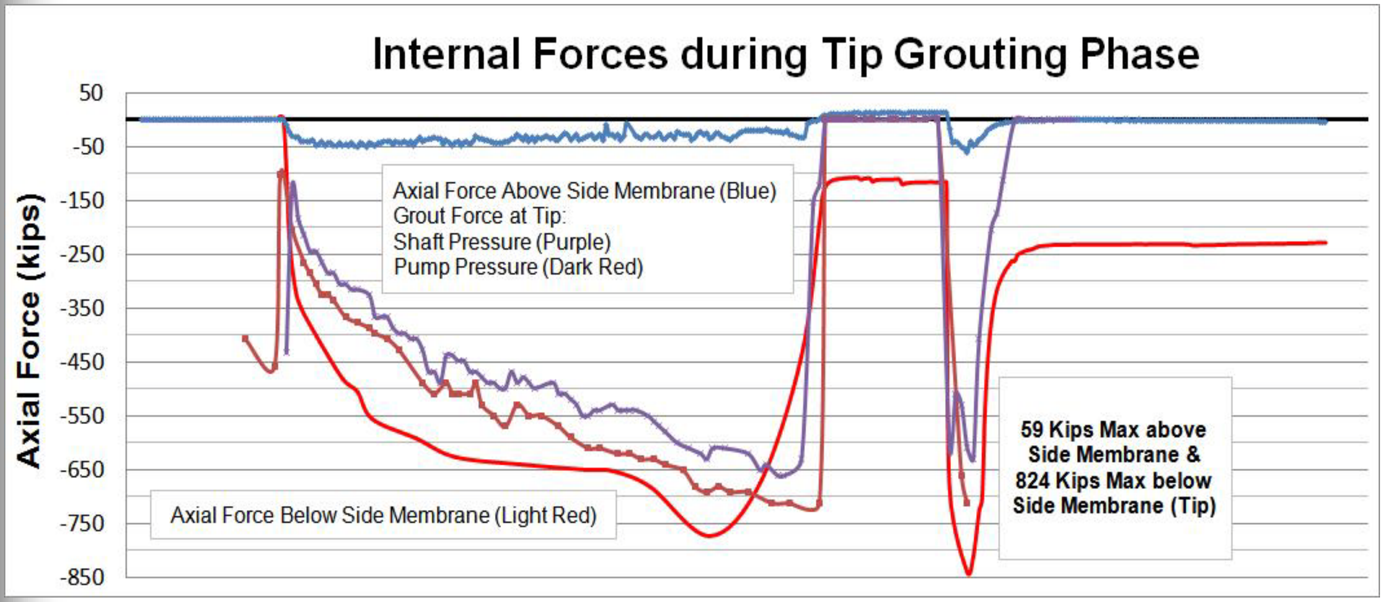


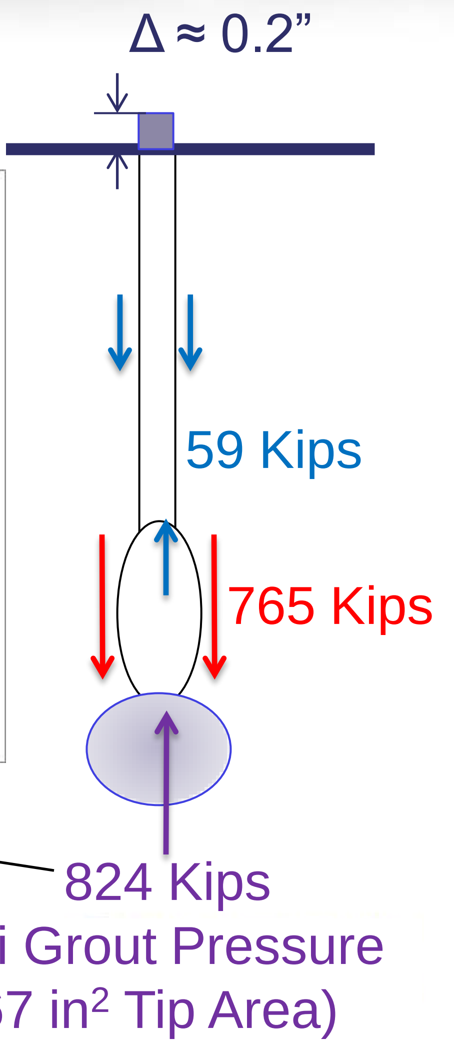
5900 kPa ≈ 856 psi (Max)



0.4” Upward Shaft Movement
(0.2” Differential Movement with Soil)

FDOT Test Chamber
Long Shaft (3' x 25') – Tip Grout





Shaft Capacity ≥ 2 x Skin = 1648 Kips

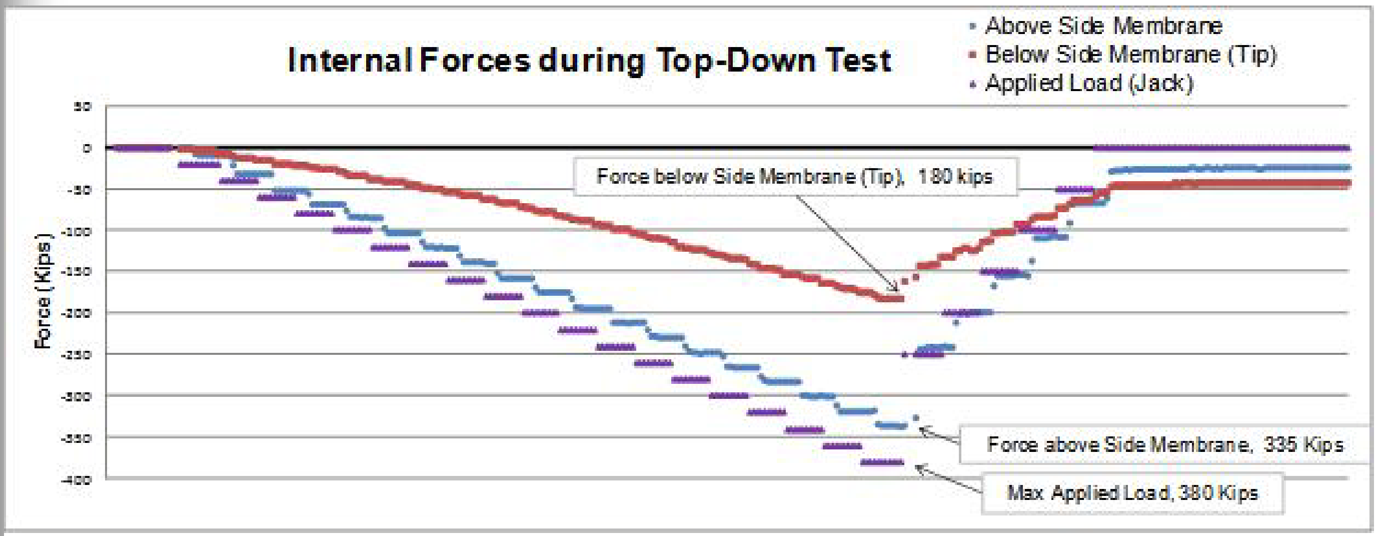
FDOT Test Chamber
Long Shaft (3’ x 25’) – Top-Down Test

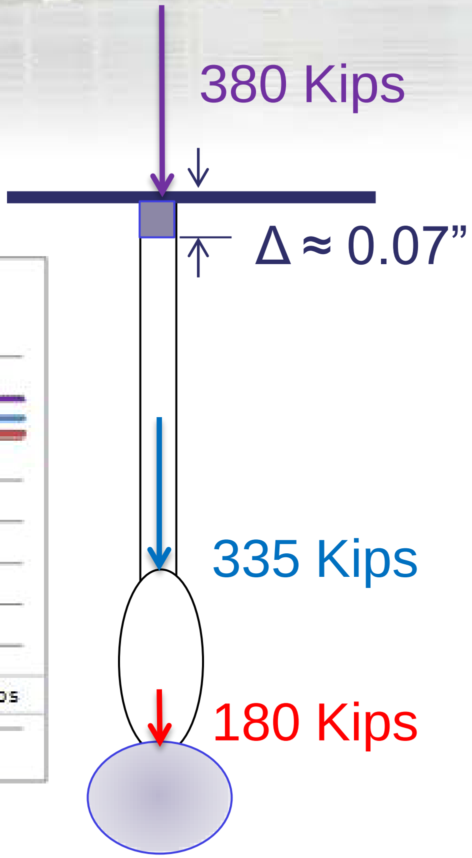
Civil & Coastal Engineering

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Chamber
Long Shaft (3’ x 25’) – Top-Down Test

Civil & Coastal Engineering

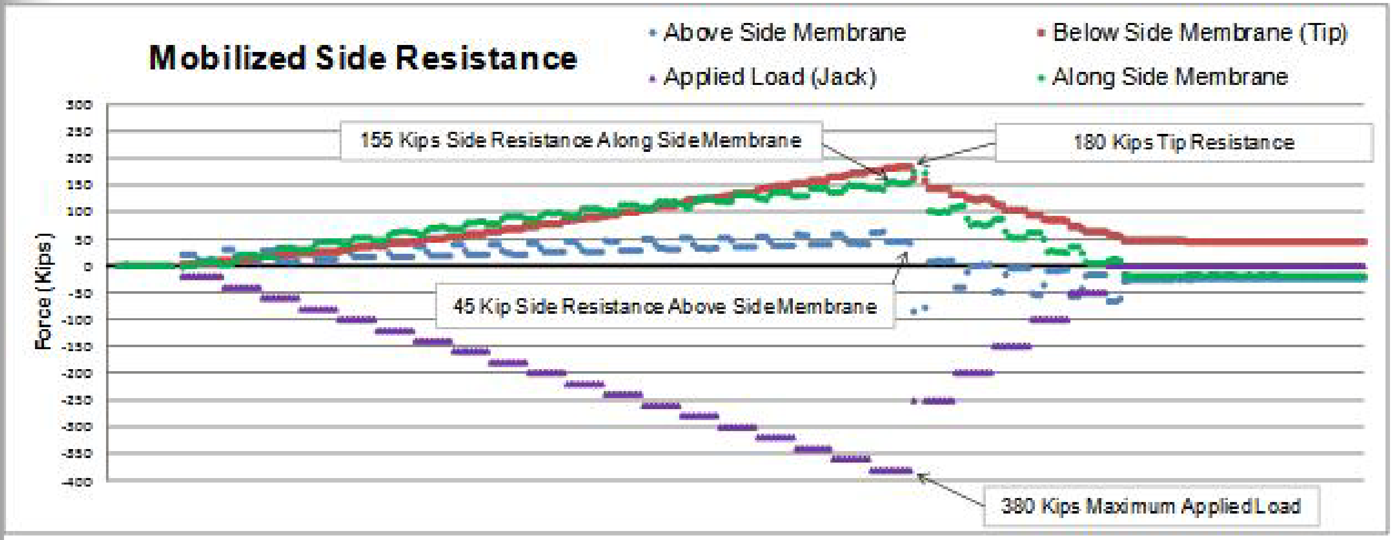


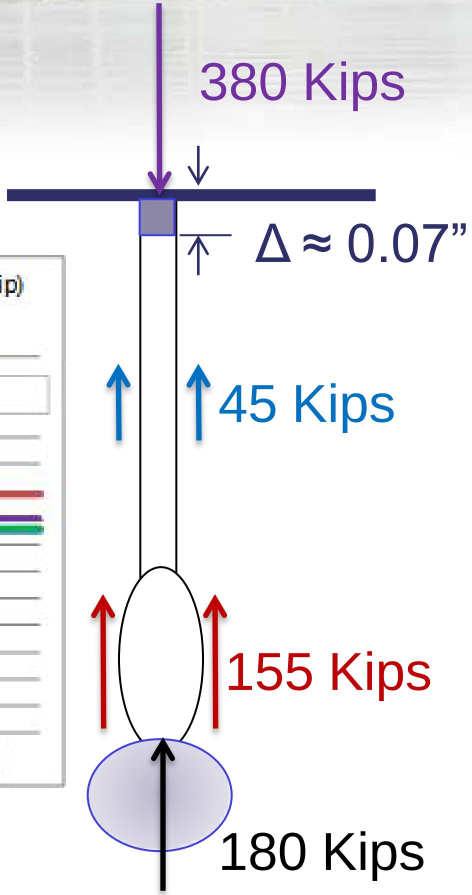


UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Chamber

Long Shaft (3’ x 25’) – Top-Down Test

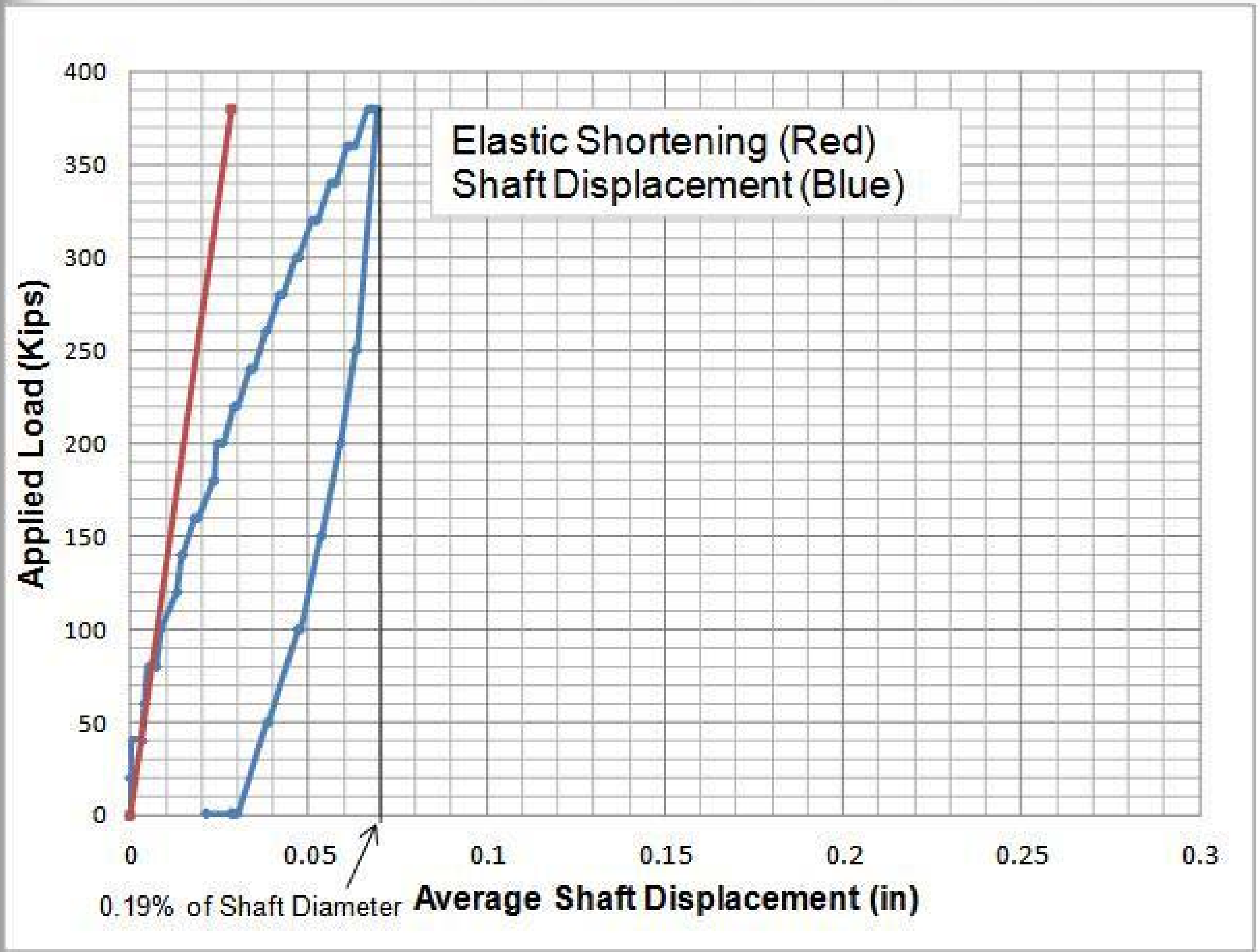




40% of Applied Load Carried by Side Grouted Zone!!!

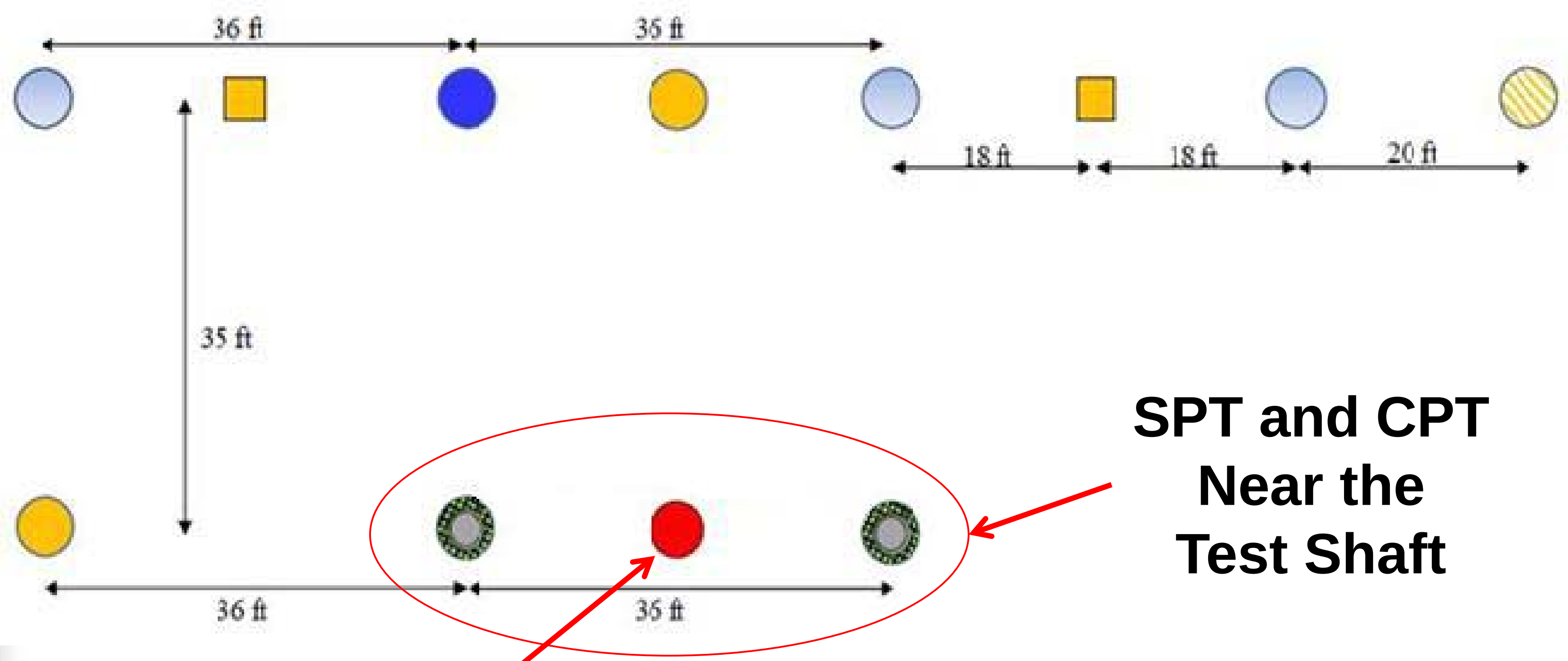
FDOT Test Chamber
Long Shaft (3' x 25') – Top-Down Test

Civil & Coastal Engineering



FDOT Test Site

Field Shaft (3-½’ x 25’) – Site Layout

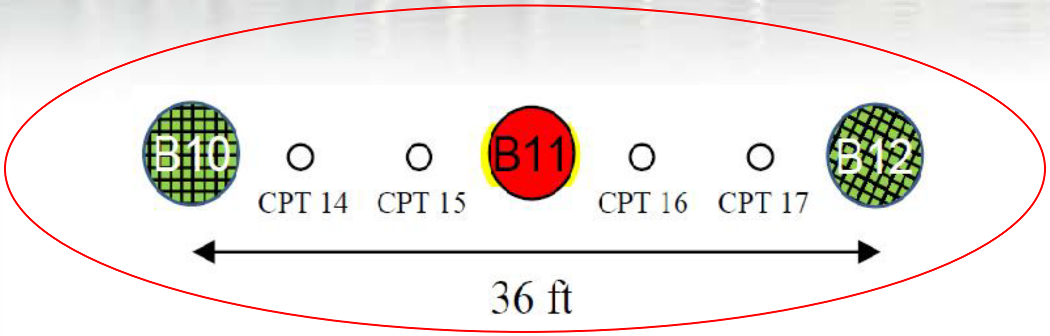


SPT and CPT Near the Test Shaft

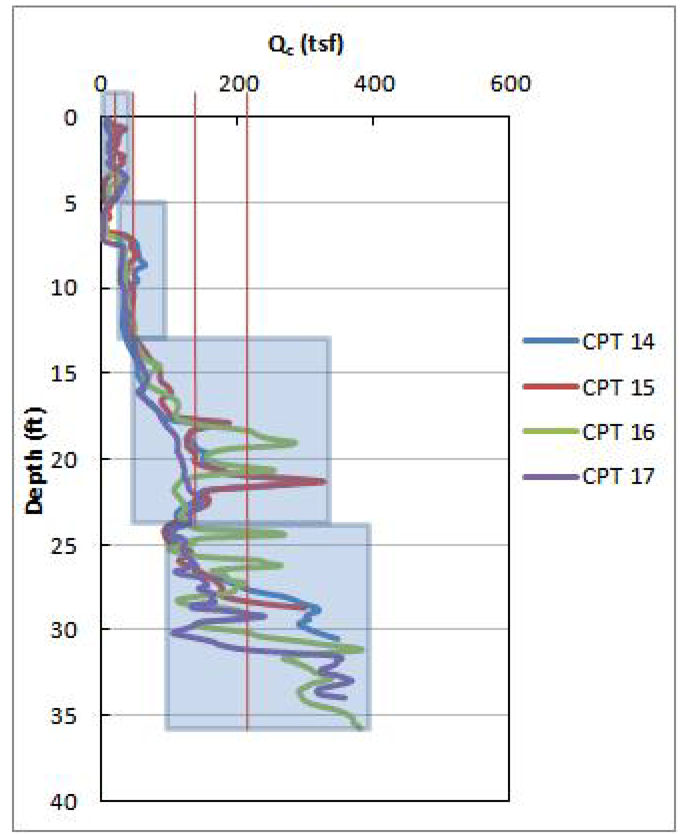
Side and Tip Grouted Drilled Shaft

FDOT Test Site

Field Shaft (3-½’ x 25’) – Soil Layers



SAMPLE NUMBER	SAMPLE DEPTH (ft)	AASHTO CLASS	UNIFIED CLASS	SPT N-Value	Avg SPT N-Value	Soil Layers
B11						
1	1.0 - 2.5	A-2-6	SC	5	6.0	1
2	2.5 - 4.0	A-7-6	CH	7		
3	4.0 - 5.5	A-7-6	CH	5		
4	5.5 - 7.0	A-6	SC	6		
5	7.0 - 8.5			7		
6	8.5 - 10.0	A-3	SP-SM	6	5.5	2
7	13.5 - 15.0	A-3	SP	5		
8	18.5 - 20.0	A-3	SP-SM	19	16.0	3
9	23.5 - 25.0	A-3	SP	13		
10	28.5 - 30.0	A-3	SP	27	55.0	4
11	33.5 - 35.0	A-3	SP-SM	54		
12	38.5 - 40.0	A-3	SP	84		



UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Civil & Coastal Engineering

FDOT Test Site

Field Shaft (3-½' x 25') – Soil Properties

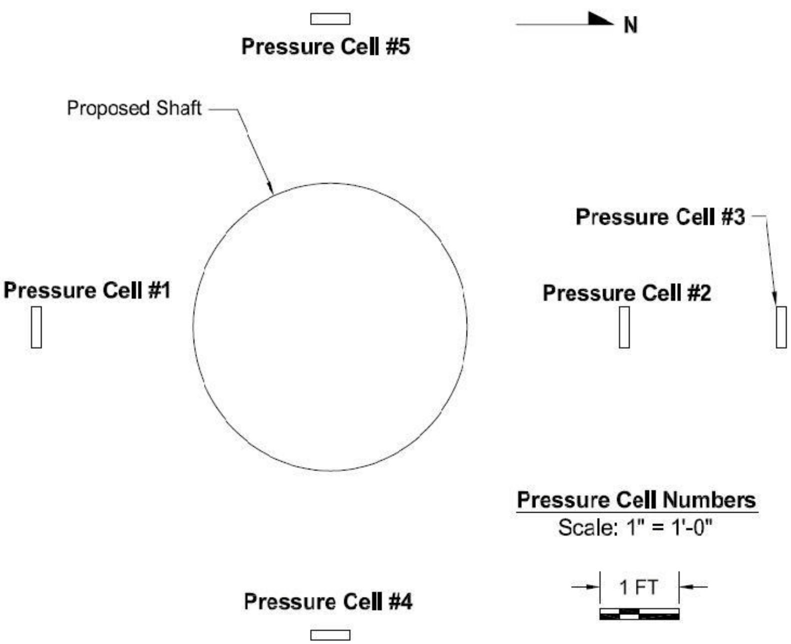
Soil Layer (#)	Depth (ft)	Depth to Mid-Point of Soil Layer (ft)	Peak Friction Angle, ϕ_p	Ultimate Friction Angle, ϕ_u	Moist Unit Weight (lb/ft^3)
1	0 - 8	4	35	---	115
2	8 - 15	11.5	35	---	120
3	15 - 25	20	41.2	36.2	125
4	25 - 40	32.5	41.2	---	130

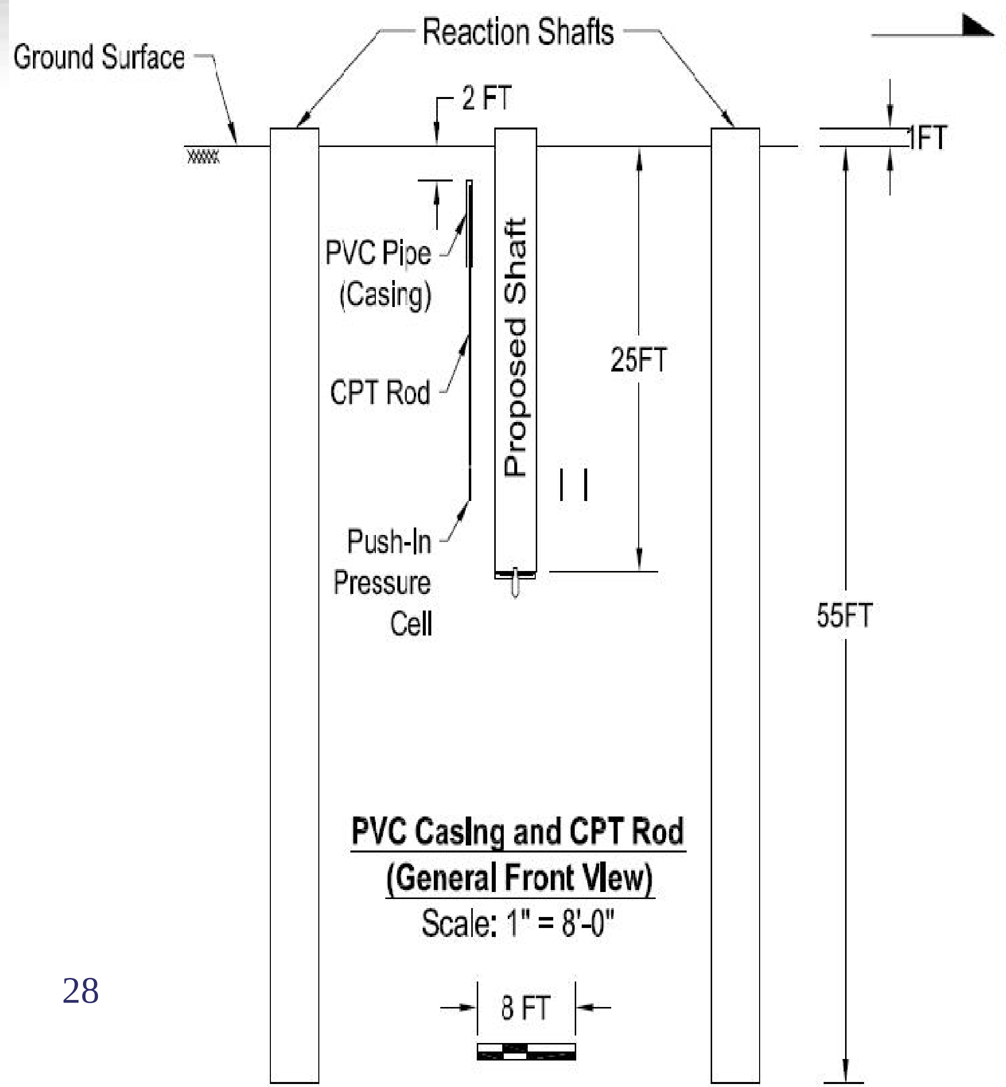
Soil Layer (#)	Depth (ft)	Vert. Effective Stress, σ_v' (lb/ft^2)	Vert. Effective Stress, σ_v' (lb/in^2)	(1) Lateral Earth Pressure Coef., K_0	Horiz. Effective Stress, σ_h' (lb/ft^2)	Horiz. Effective Stress, σ_h' (lb/in^2)
1	0 - 8	460	3.2	0.43	196.2	1.4
2	8 - 15	1122	7.8	0.43	478.3	3.3
3	15 - 25	1636	11.4	0.34	558.5	3.9
4	25 - 40	2456	17.1	0.34	838.3	5.8

(1) Lateral Earth Pressure Coefficient (Jaky 1960), $K_0 = 1 - \sin(\phi_p)$

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Site
Field Shaft (3-½' x 25') – Push-In Pressure Cells





FDOT Test Site

Field Shaft (3-½' x 25') – Fabrication

Civil & Coastal Engineering

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Site

Field Shaft (3-½’ x 25’) – Construction

Civil & Coastal Engineering

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

FDOT Test Site

Field Shaft (3-½’ x 25’) – Grouting

Civil & Coastal Engineering

Completed Shaft Construction and All Grouting in 2 Weeks!

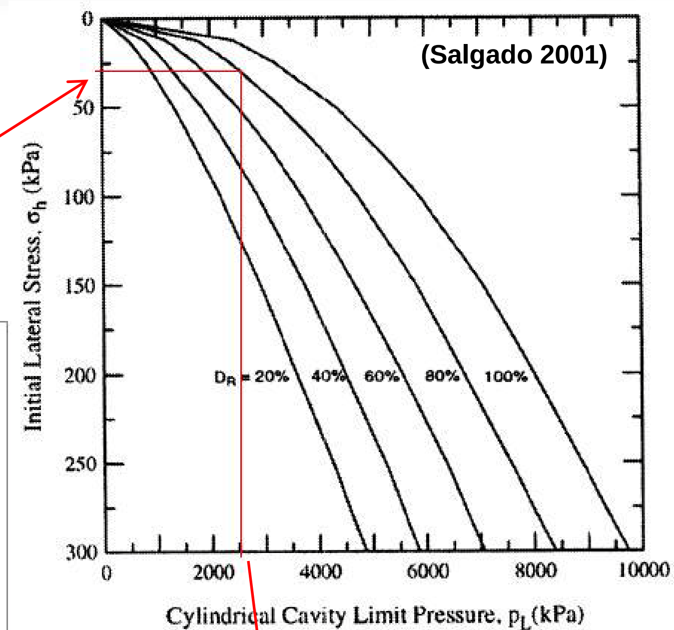
- Grout Membrane Seals (24 hr.)
- Grout Side Membrane (4 & 6 Days)
- Grout Tip (13 Days after Shaft Const.)

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

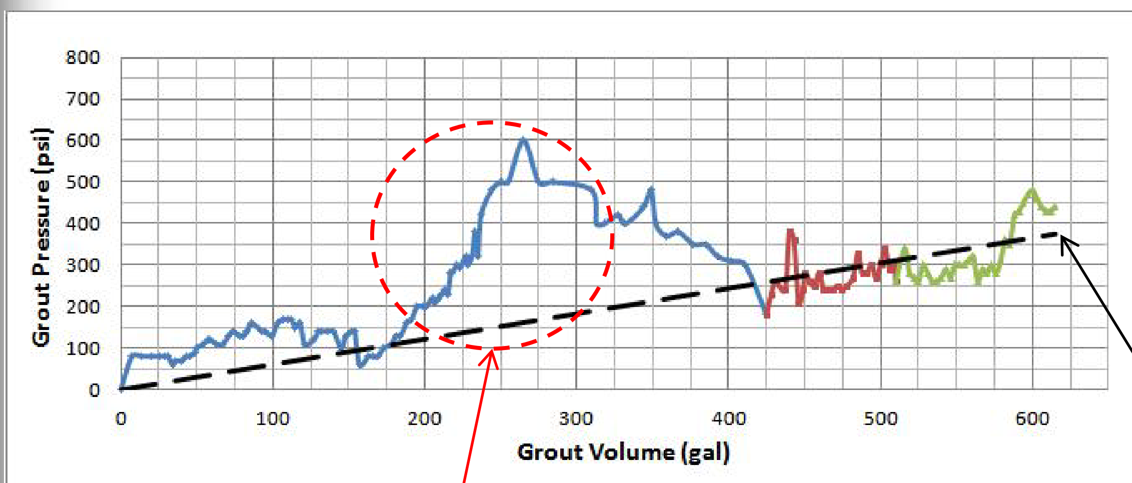
FDOT Test Site

Field Shaft (3-½' x 25') – Side Grouting

Average Depth of Side Grout Zone = 20'
Initial Lateral Stress, $\sigma_h \approx 3.9$ psi
or 26.7 kPa



2500 kPa ≈ 363 psi



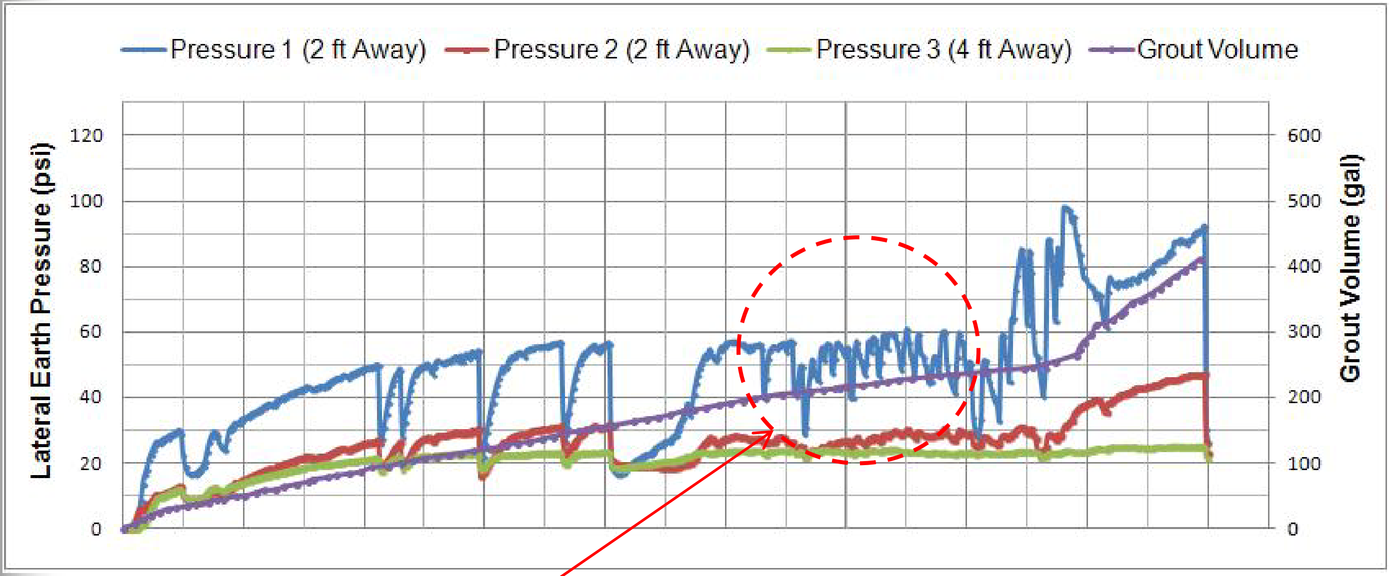
375 psi

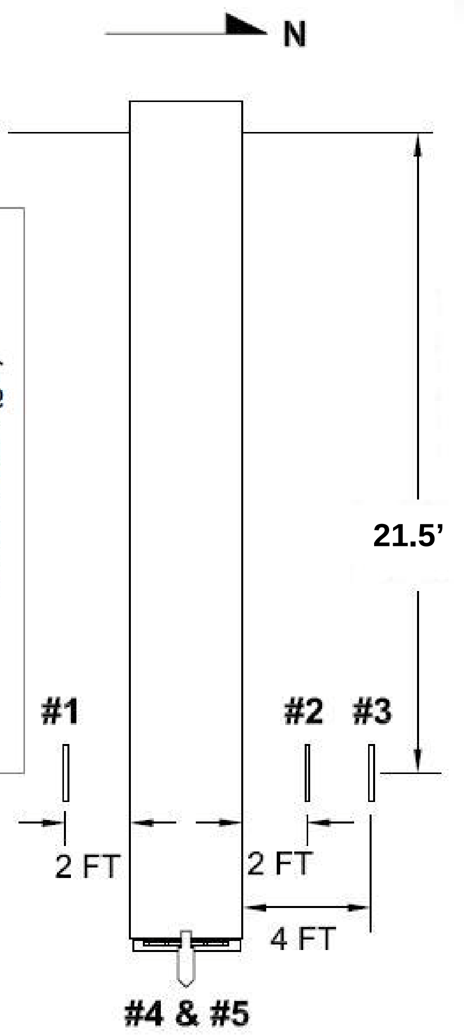
Grout Pump Recirculating back into Reservoir at the End of Stroke

FDOT Test Site

Field Shaft (3-½’ x 25’) – Side Grouting

Push-In Pressure Cells at Depth of 21.5’
(Middle of Side Grouted Zone)





Grout Pump Recirculating back into Reservoir at the End of Stroke

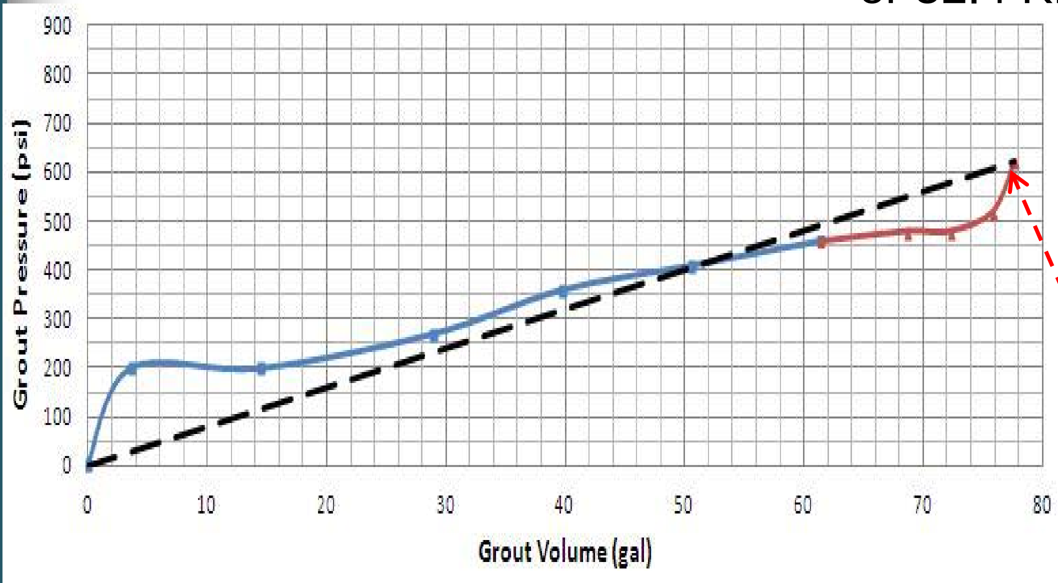
FDOT Test Site

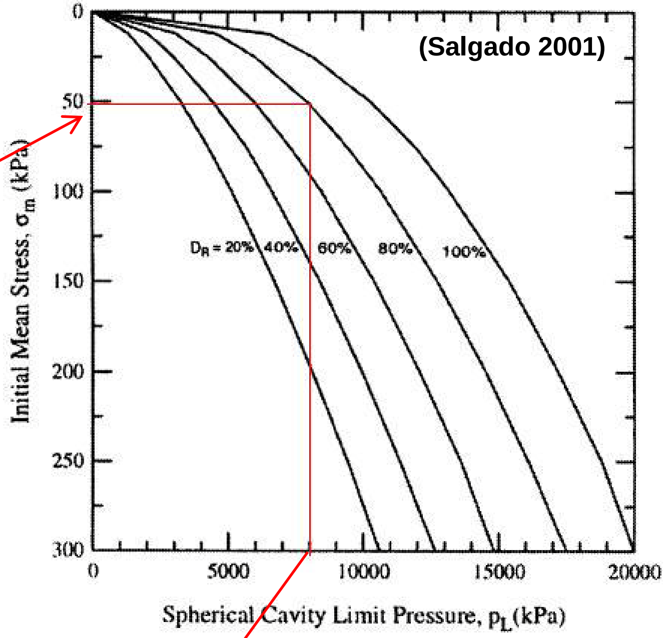
Field Shaft (3-½' x 25') – Tip Grouting

Civil & Coastal Engineering

Depth of Tip Grout Zone = 25'

Initial Mean Stress, $\sigma_m = \frac{(2*\sigma_h)+\sigma_v}{3}$ ≈ 7.6 psi or 52.4 KPa





8000 kPa ≈ 1160 psi (Max)

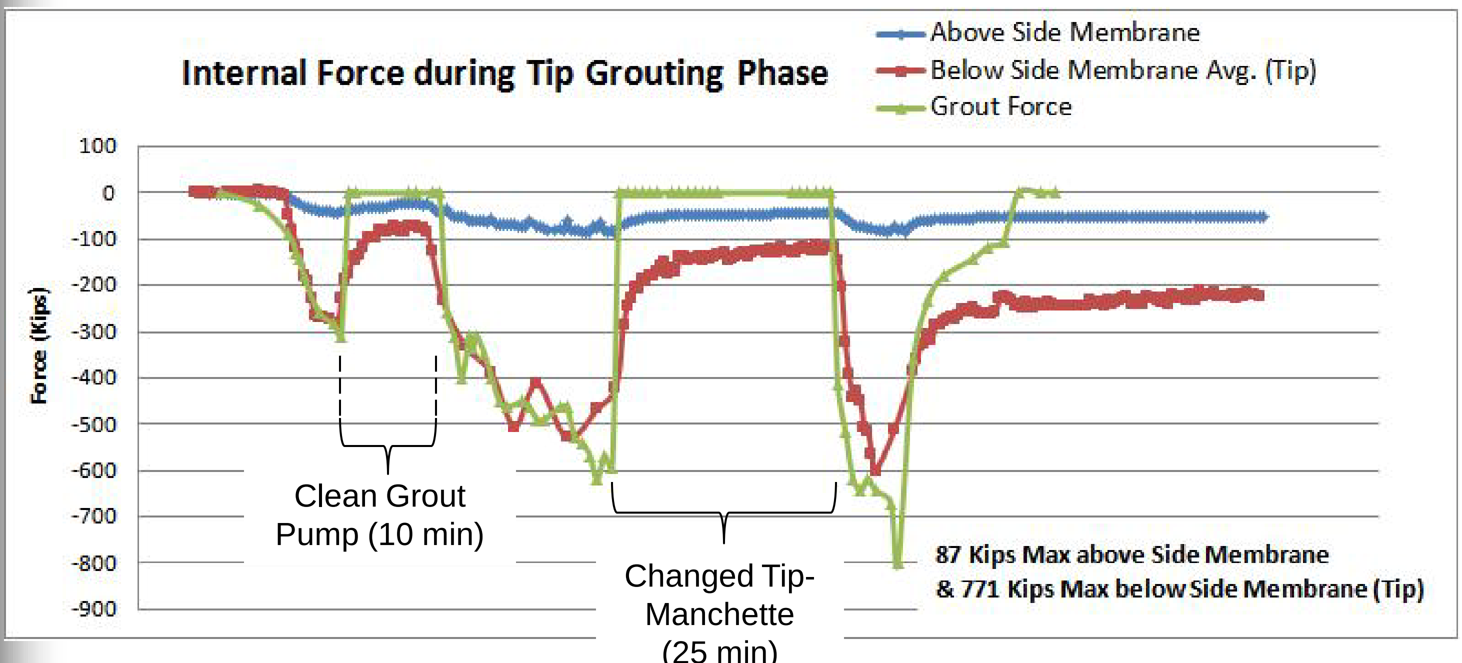
Observed: 620 psi (Max)

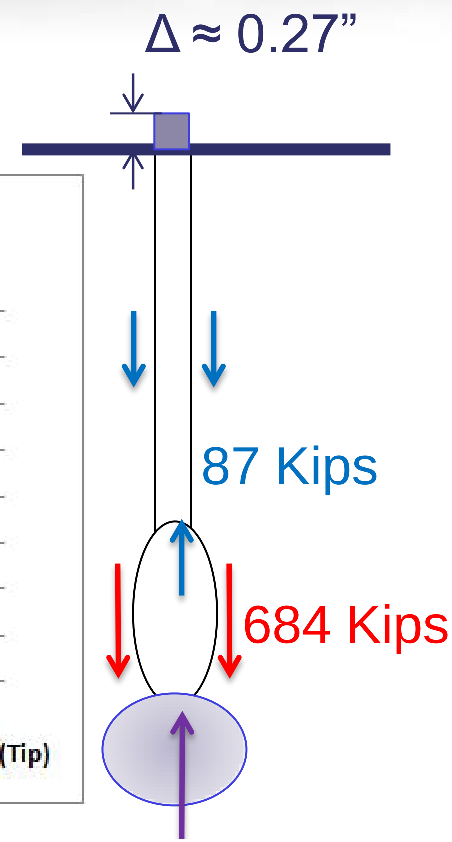
0.34" Upward Shaft Movement
(0.27" Differential Movement with Soil)

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Civil & Coastal Engineering

FDOT Test Site
Field Shaft (3-½’ x 25’) – Tip Grouting





Shaft Capacity ≥ 2 x Skin = 1542 Kips

771 Kips
(620 psi Grout Pressure
& 1243 in^2 Tip Area)

FDOT Test Site

Field Shaft (3-½' x 25') – Top-Down Test

Civil & Coastal Engineering

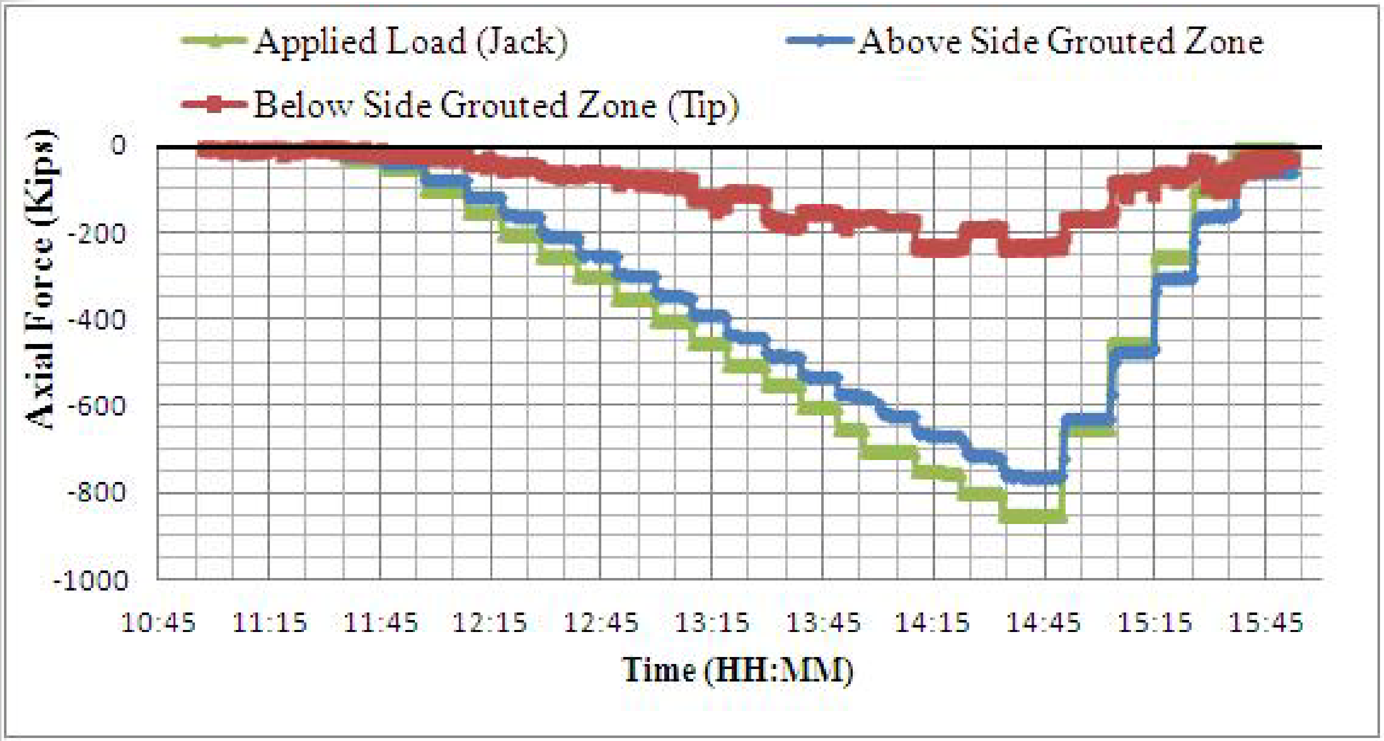
UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

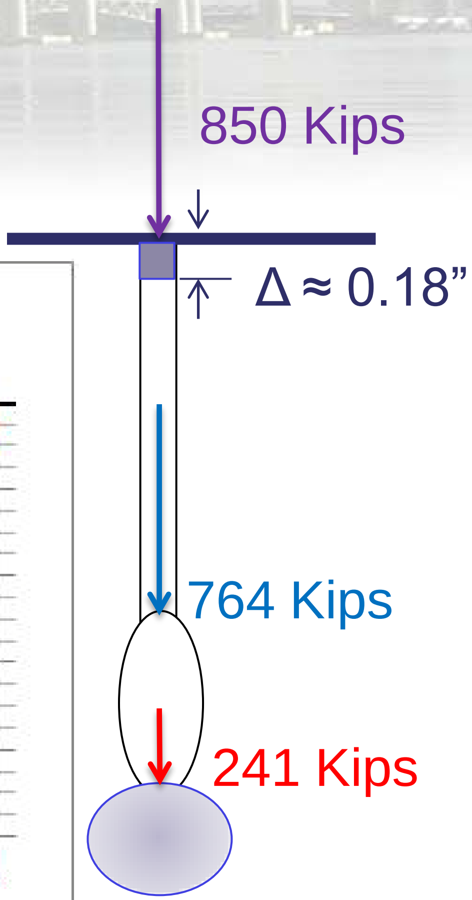
FDOT Test Site

Field Shaft (3-½' x 25') – Top-Down Test

Civil & Coastal Engineering

Internal Forces during Top-Down Test





Failed Reaction Shafts (4' x 55')

Maximum Upward Displacements
- South Shaft – 0.58"
- North Shaft – 0.37"

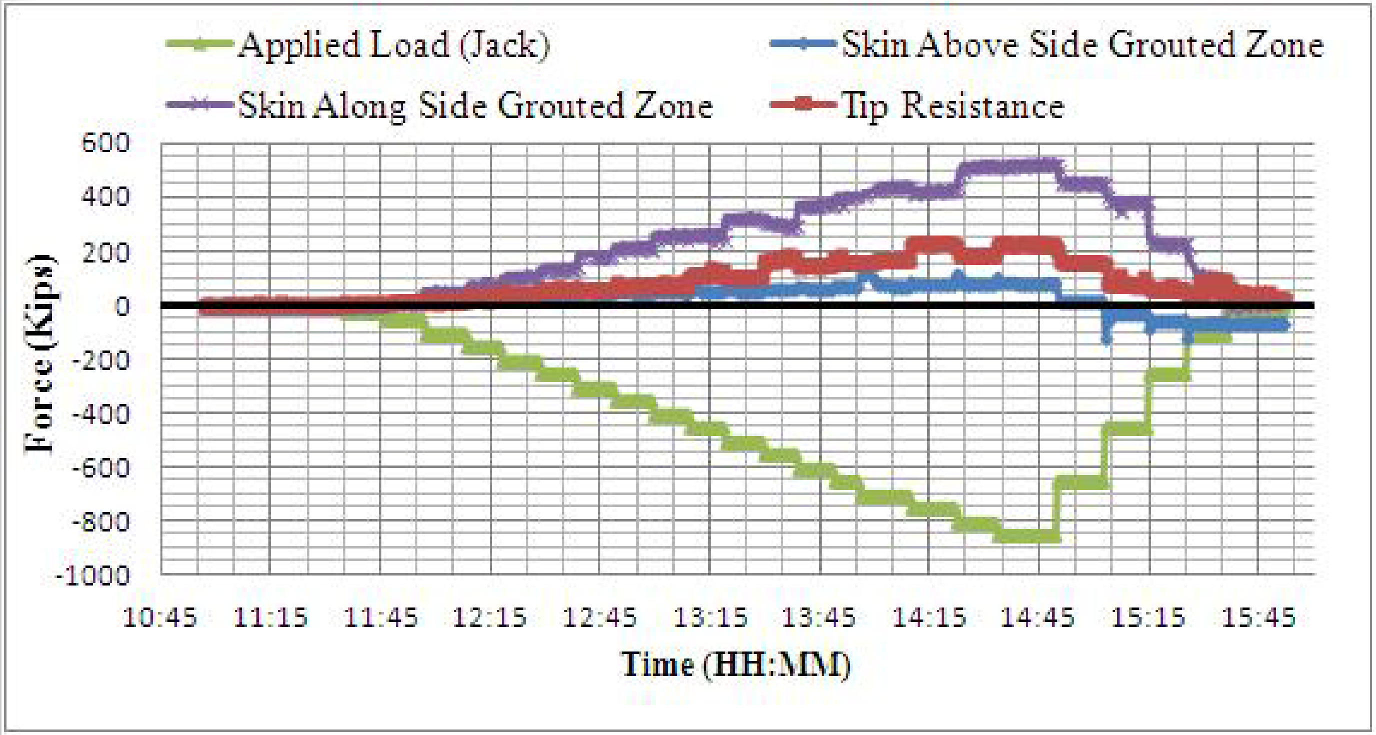
UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

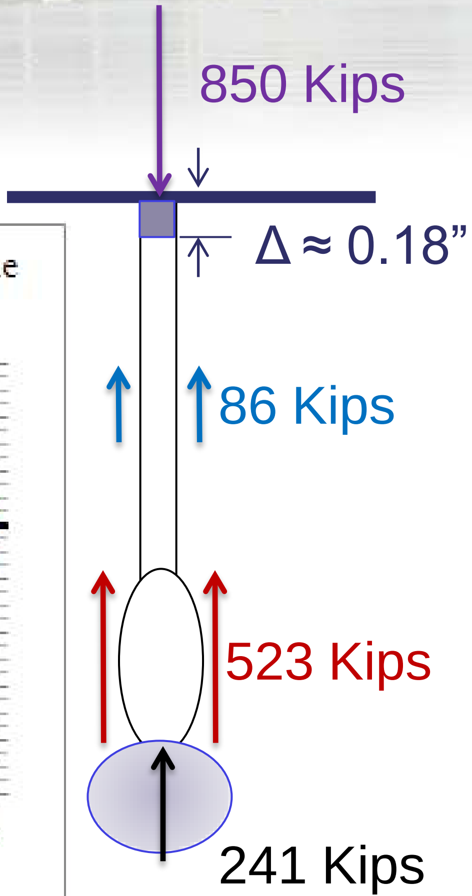
FDOT Test Site

Field Shaft (3-½’ x 25’) – Top-Down Test

Civil & Coastal Engineering

Mobilized Resistance during Top-Down Test





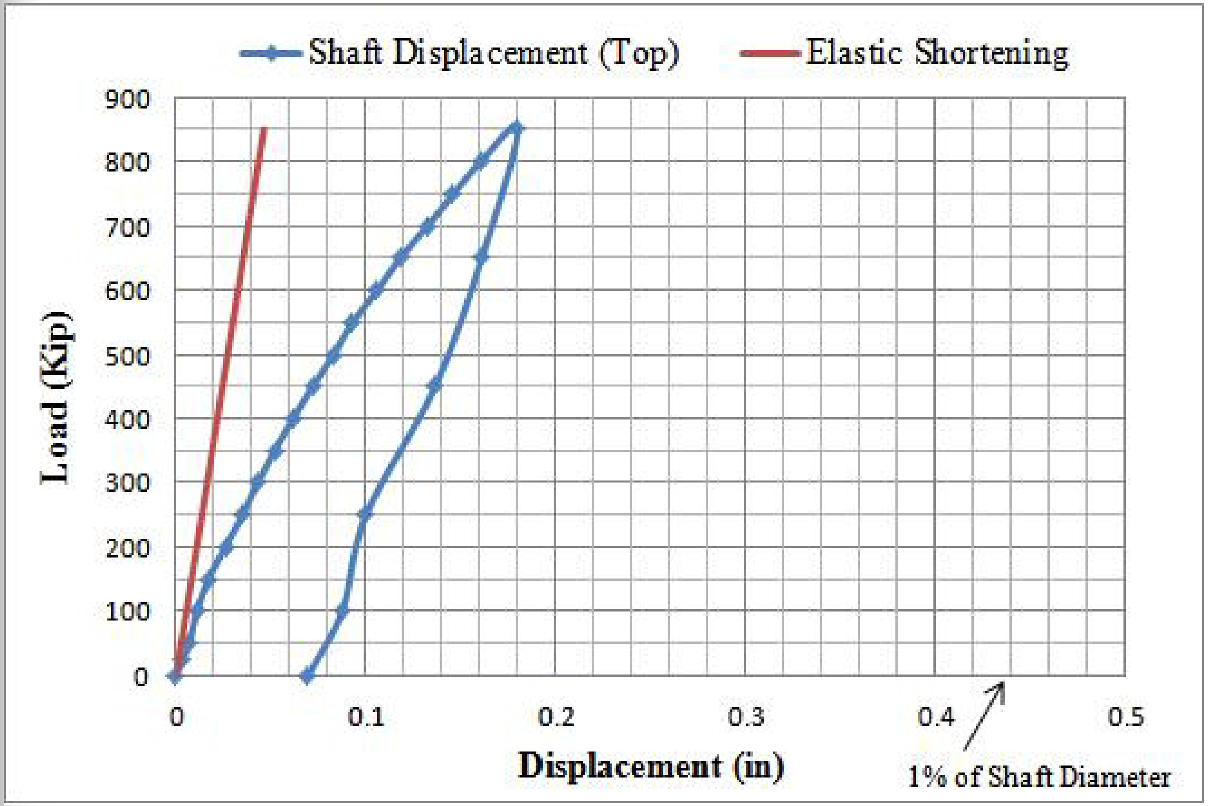
61% of Applied Load Carried by Side Grouted Zone!!!

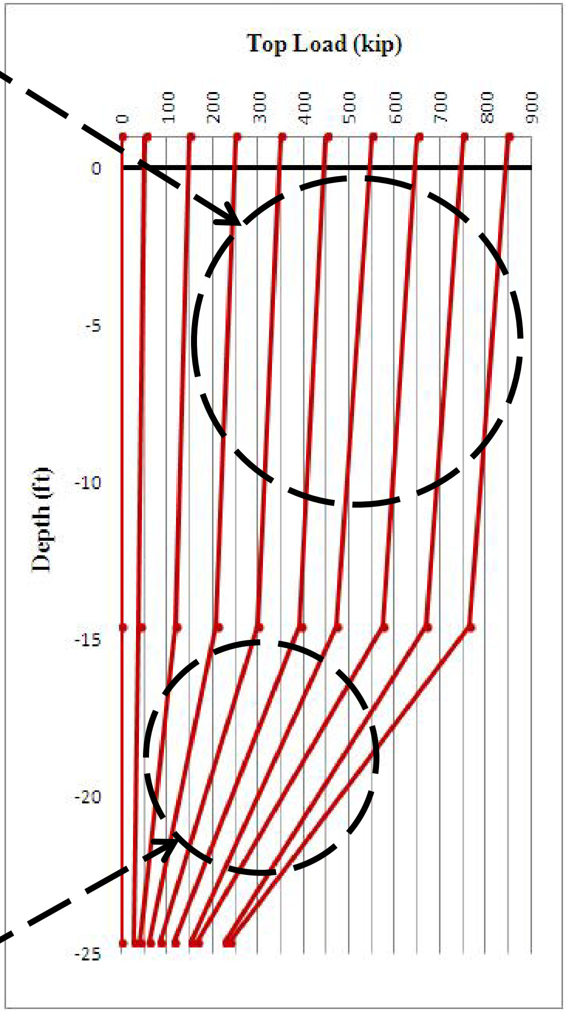
FDOT Test Site

Field Shaft (3-½' x 25') – Top-Down Test

Civil & Coastal Engineering

Fully Mobilized above Side Grouted Zone





Not Fully Mobilized along Side Grouted Zone

Ungrouted Drilled Shafts

Predicted Capacity – Skin (Alpha & Beta) (FHWA / AASHTO, 2007)

Civil & Coastal Engineering

Layer (#)	Soil Type	Depth (ft)	Depth to Mid-Point of Zone, z (ft)	Avg. Cone Tip Resist., Q_c (ton/ft^2)	Vertical Stress, σ_v (lb/ft^2)	Undrained Shear Strength, C_u (kip/ft^2)	(1) Alpha Value, α	(2) Unit Side Resistance, f_{su1} (kip/ft^2)	Surface Area (Top 8 ft), A_{side1} (ft^2)	Side Resistance (Top 8 ft), (kip)	
1	Clay	0 - 8	4	18.06	460	1	0.55	0.55	87.96	48	$= q_{s1}$

(1) $\alpha = 0$ (if z < 5 ft); $\alpha = 0.55$ (if z > 5 ft); $\alpha = 0$ (bottom of shaft for 1 diameter length & length of casing)

(2) Ultimated Unit Load Transfer in Side Resistance, $f_{su} = \alpha * C_u$

Layer (#)	Soil Type	Depth (ft)	Depth to Mid-Point of Zone, z (ft)	Avg. Uncorrected Blow Count (N-Value)	Vertical Effective Stress, σ_v' (lb/ft^2)	(1) Beta Value (β_0)	(2) Corrected Beta Value (β)	(3) Unit Side Resistance, f_s (kip/ft^2)	Surface Area, A_{side} (ft^2)	Side Resist., q_s (kip)	
2	Sand	8 - 15	11.5	5.5	1122	1.0422	0.3821	0.43	77	33	$= q_{s2}$
3	Sand	15 - 25	20	16	1636	0.8963	0.8963	1.47	110	161	$= q_{s3}$
4	Sand	25 - 40	32.5	55	2456	0.7304	0.7304	1.79	N/A	N/A	

(1) $\beta_0 = 1.2$ (if z < 5 ft); $\beta_0 = 1.5 - 0.135\sqrt{z}$ (if 5 ft < z < 86 ft); $\beta_0 = 0.25$ (if z > 86 ft)

(2) Corrected Beta, $\beta = (N/15)*\beta_0$ (if N < 15)

(3) Unit Side Resistance, $f_s = \beta * \sigma_v'$

Ungrouted Drilled Shafts
Predicted Capacity – Skin & Tip (FHWA/AASHTO, 2007)

Civil & Coastal Engineering

Side Resistance above Side Grouted Zone, $Q_{s\text{-above}}$ (kip)	81	$= q_{s1} + q_{s2}$ **vs. 86 & 87 Meas.**
Side Resistance along Side Grouted Zone, $Q_{s\text{-along}}$ (kip)	161	$= q_{s3}$
Total Side Resistance, $Q_{s\text{-Total}}$ (kip)	**243**	$= q_{s1} + q_{s2} + q_{s3}$

Tip Area, A_T (in^2)	1385.44
Tip Area, A_T (ft^2)	9.62
(1) Avgerage Tip N-Value	28
(2) Unit Tip Resistance, q_T (ton/ft^2)	16.8
(3) Tip Resistance, Q_T (kip)	323

(1) Average N-Value of Soil 1.5*D above Tip down to 3*D below Tip

(2) Unit Tip Resistance (AASHTO 2007), q_T (ton/ft^2) = 0.6*N

(3) Tip Resistance, Q_T (kip) = $A_T(ft^2)*q_T(ton/ft^2)*2(kip/ton)$

566 Kips Total Axial Resistance before Grouting (Conventional Drilled Shaft)

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Side and Tip Grouted Shafts

Predicted Capacity – K_g Method (Thiyyakkandi & McVay, 2013)

Civil & Coastal Engineering

Soil Layer (#)	Depth (ft)	Depth to Mid-Point of Soil Layer (ft)	Peak Friction Angle, ϕ_p	Post Grout Surface Area, A_{sg} (ft^2)	Vertical Effective Stress, σ_v' (lb/ft^2)	(1) K_g	(2) Post Grout Vertical Stress, σ_{vg}' (lb/ft^2)	(3) Post Grout Unit Side Resist., $f_{s3\text{-}Kg}$ (kip/ft^2)	(4) Post Grout Side Resist., $q_{s3\text{-}Kg}$ (kip)
3	15 - 25	20	41.2	156.69	1636	1.85	3027	4.40	689

$= q_{s3\text{-}Kg}$

(1) Use $\phi_c = \phi_u = 36.2°$ (See Plot Below)

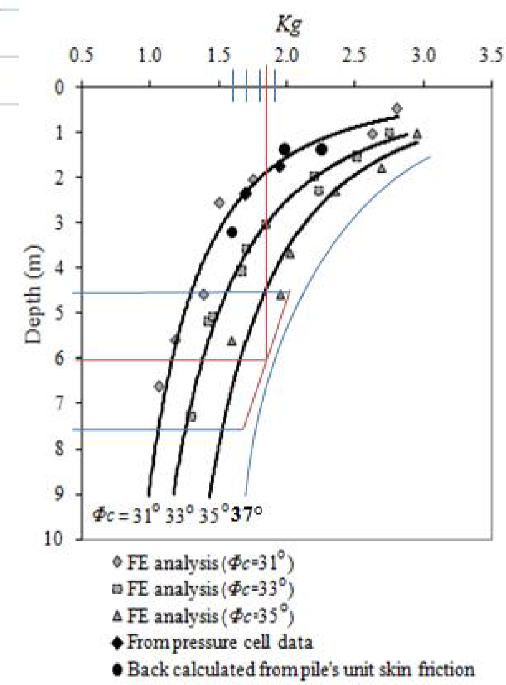
(5) Total Side Resistance (Post Side Grout), $Q_{sg\text{-}Total\text{-}Kg}$ = 770 = 689 + 81 kips

(2) Post Side Grout Vertical Effective Stress, $\sigma_{vg}' = K_g * \sigma_v'$

(3) Post Grout Unit Side Resistance along Side Grouted Zone, $f_{s3\text{-}Kg} = \sigma_{vg}' * [\sin\phi_p/(1-\sin\phi_p)] * \sin(90-\phi_p)$

(4) Post Grout Side Resistance along Side Grouted Zone, $q_{s3\text{-}Kg} = f_{s3\text{-}Kg} * A_{sg}$

(5) Total Side Resistance after Side Grouting, $Q_{sg\text{-}Total\text{-}Kg} = Q_{s\text{-}above} + q_{s3\text{-}Kg}$



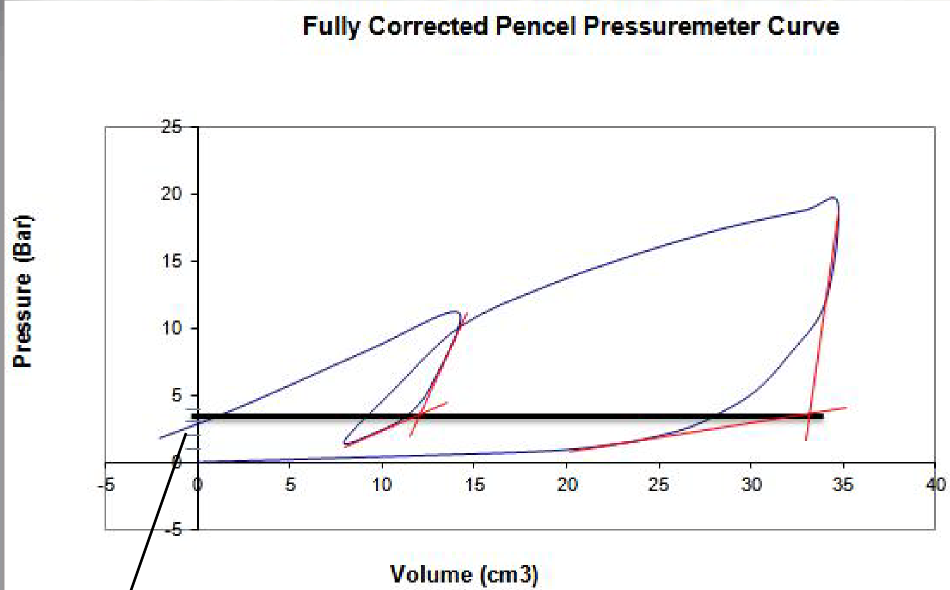
Estimated Total Capacity = Skin + Tip

Since,
Total Skin < Tip Spherical Expansion Pressure x Tip Area

Total Capacity > 2 x Skin = 2 x 770 = **1540 Kips**

Side and Tip Grouted Shafts
Predicted Capacity – PMT Method
(FDOT BDK-545 #31, 2009)

Civil & Coastal Engineering



Estimated Total Capacity = Skin + Tip

Since,
Total Skin < Tip Spherical Expansion Pressure x Tip Area

Total Capacity > 2 x Skin = 2 x 824 = **1648 Kips**

Residual Stress (Bar)	Residual Stress (lb/in^2)	Peak Friction Angle, ϕ_p	Post Grout Surface Area, A_{sg} (ft^2)	(1) Unit Side Resist. along Side Grouted Zone, $f_{s3\text{-}PMT}$ (ksf)	(2) Friction along Side Grouted Zone, $q_{s3\text{-}PMT}$ (kip)	(3) Total Side Resist., $Q_{sg\text{-}Total\text{-}PMT}$ (kip)
3.5	50.76	41.2	156.69	4.74	743	824

= 743 + 81 kips

(1) Post Grout Unit Side Resistance along Side Grouted Zone, $f_{sg\text{-}PMT}$ = ("Residual Stress")*tan(δ_i')
where: Interface Friction Angle, $\delta_i' = \Delta_i * \phi_p = 33°$

(2) Post Grout Side Resistance along Side Grouted Zone, $q_{s3\text{-}PMT} = f_{s3\text{-}PMT} * A_{sg}$

(3) Total Side Resistance after Side Grouting, $Q_{sg\text{-}Total\text{-}PMT} = Q_{s\text{-}above} + q_{s3\text{-}PMT}$

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Side and Tip Grouted Shafts

Predicted & Measured Capacities

Civil & Coastal Engineering

	Above Side Grouted Zone (Top 15 ft of Shaft)		Along Side Grouted Zone (Bottom 10 ft of Shaft)				
	Unit Side Resistance (ksf)	Side Resistance (Kip)	Unit Side Resistance (ksf)	Side Resistance (Kip)	Total Side Resistance (Kip)	Tip Resistance (Kip)	Ultimate Load (Kip)
Ungrouted Drilled Shaft (Neglect Tip Resist.)	0.49	81	1.47	161	243	---	243
Ungrouted Drilled Shaft (Include Tip Resist.)	0.49	81	1.47	161	243	323	566
Side & Tip Grouted Drilled Shaft, Kg Method	---	---	4.40	689	770	---	1540
Side & Tip Grouted Drilled Shaft, PMT Method	---	---	4.74	743	824	---	1648
*Mobilized during Tip Grouting (Max)	0.53	87	4.37	684	771	771	1542
**Mobilized during Top-Down Test (Max)	0.52	86	3.34	523	609	241	850***
*Upward Displacement (Top of Shaft) = 0.34 Inch (0.81% of Shaft Diameter)							
**Downward Displacement (Top of Shaft) = 0.18 Inch (0.43% of Shaft Diameter)							
***Maximum Applied Load during Top-Down Test so Not an Ultimate Load							

Quantify the Ultimate Capacity by Performing Statnamic Axial Test (up to 2000 Kips Maximum Load)

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Civil & Coastal Engineering

References:

1. Mullins, G., Dapp, S., Frederick, I, and Wagner. R. “Post Grouting Drilled Shaft Tips – Phase I, ***FDOT Final Report***, Dec. 2001, 308 pages.

2. Mullins, G., Winters, D., “Post Grouting Drilled Shaft Tips – Phase II”, ***FDOT Final Report***, June 2004, 165 pages.

3. O’Neil, M. W., and Reese, L. C. (1999). “Drilled shafts: Construction procedures and design methods,” **FHWA, Publication** No. FHWA-IF-95-025.

4. Salgado, R., and Randolph, M. F. (2001). “Analysis of Cavity Expansion in Sand,” ***International Journal of Geomechanics****,* ASCE, 1(2), 175-192.

5. Thiyyakkandi, S., McVay, M., Bloomquist , D., and Lai P. (2013), “Measured and Predicted Response of a New Jetted and Grouted Precast Pile with Membranes in Cohesionless Soils,” ***Journal of Geotechnical and Geoenvironmental Engineering***, 139 (8), 1334-1345.

6. Thiyyakkandi, S., McVay, M., Bloomquist , D., and Lai P. (2013),”Experimental Study, Numerical Modeling of and Axial Prediction Approach to Base Grouted Drilled Shafts in Cohesionless Soils,” ***Acta Geotechnica***, DOI 10.1007/s11440-013-0246-3

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

Civil & Coastal Engineering

Thank You

Questions?

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation