Civil & Coastal Engineering

Bottom Side Grouting of Drilled Shafts Prior to Tip Grouting

FDOT Contract No.: BDK75-977-46

Project Managers:

Peter Lai, P.E.
Rodrigo Herrera, P.E.

Principal Investigator:

Mike McVay, Ph.D.
David Bloomquist, Ph.D., P.E.

Primary Researchers:

John Schwartz III, P.h.D. student
Sudheesh Thiyyakkandi, P.h.D.

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Scope

Increase Axial Capacity of Drilled Shafts in Florida's Sands and Silts (i.e., Cohesionless Soils) through Side and Tip Grouting

Tasks:

- Design Side Grouting System
- Small Scale Shaft Test to Evaluate Side Grout System
- Larger Scale Test Shaft (3'x25') in FDOT Test Chamber (Controlled Test)
  - Monitor Soil and Shaft Stresses and Load Transfer
  - Excavate and Evaluate Side and Tip Grouting Process
- Full Scale Test Shaft at Keystone Heights Florida (3.5'x25') (Field Conditions)
- Develop Design Approach for Side and Tip Grouted Drilled Shafts in Cohesionless Soils

Why Grout a Drilled Shaft in Cohesionless Soils?

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Out of the Various Deep Foundation Types, Drilled Shafts have one of the Lowest Unit Side Resistance and Unit End Bearing in Cohesionless Soils.

For Example

Driven Concrete Pile	VS.	Drilled Shaft
Perimeter = 40′		Perimeter = 40′
N=30		N = 30
f_s = 1,150 (psf)		f_s = 850 (psf)
q_t = 96 (tsf)		q_t = 18 (tsf)

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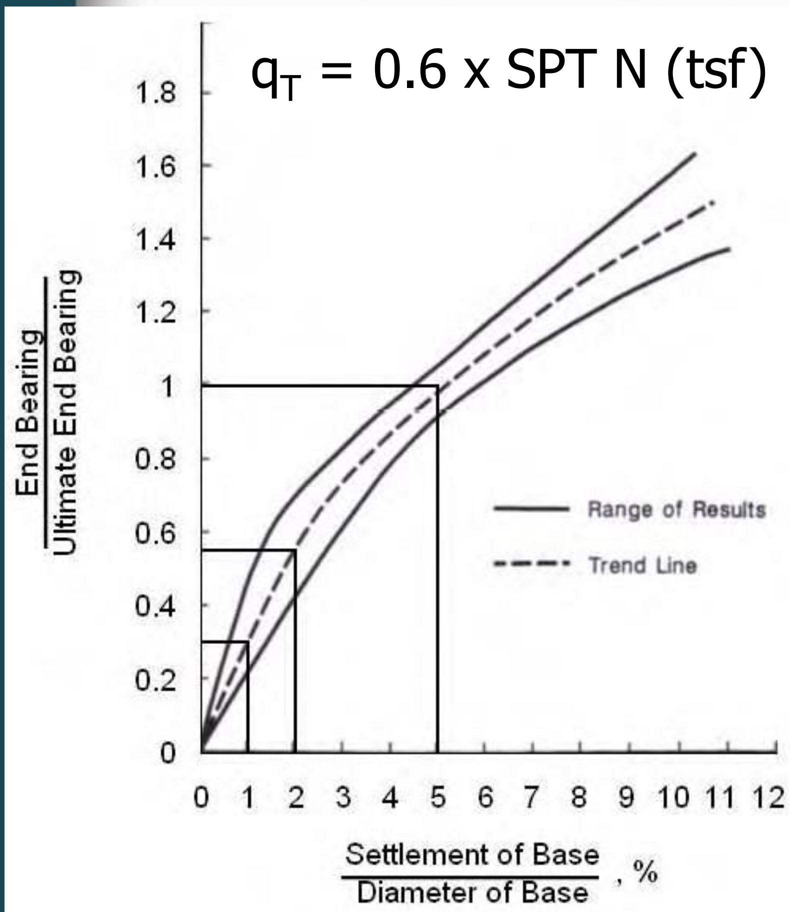
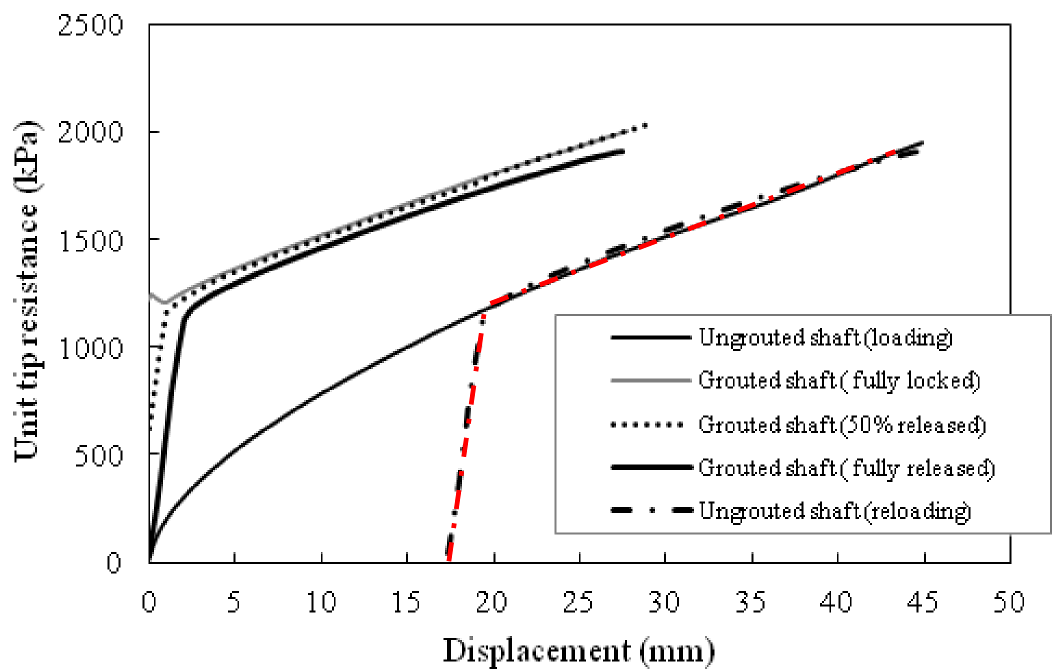
Introduction of Tip Grouting
Drilled Shaft Tip Resistance – FHWA

Un-Grouted Shaft

Conventional Base Grouted Shaft

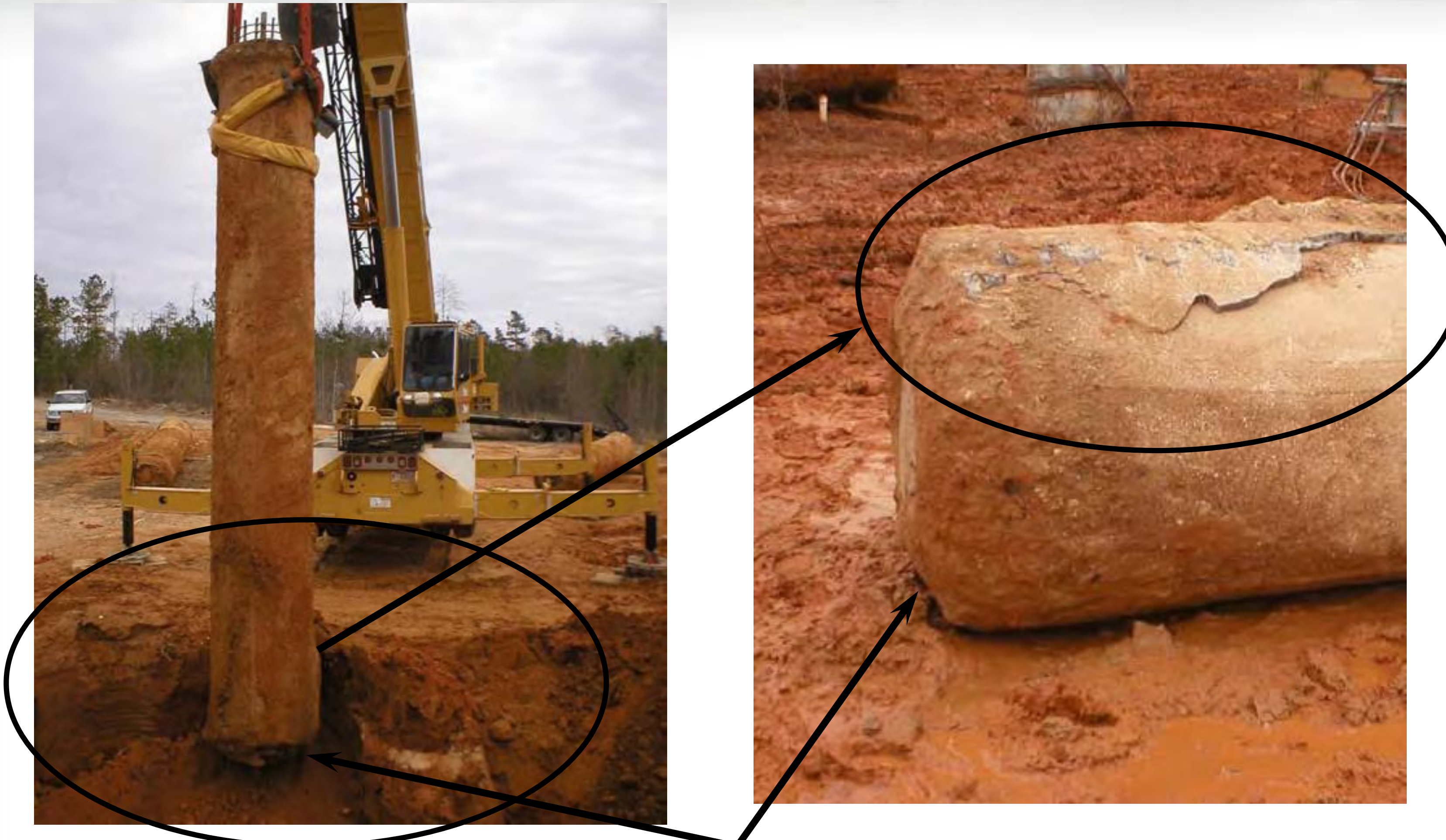




Reese and O'Neill, 1988 (Left); Thiyyakkandi et. al., 2013b (Right)

Tip Grout Flow

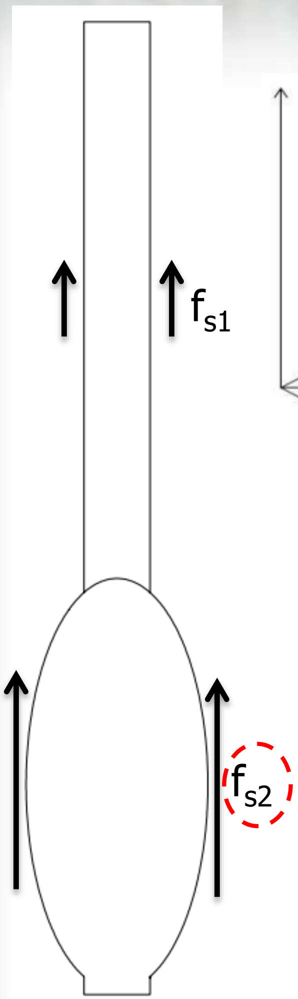
Conventional Tip Grouting

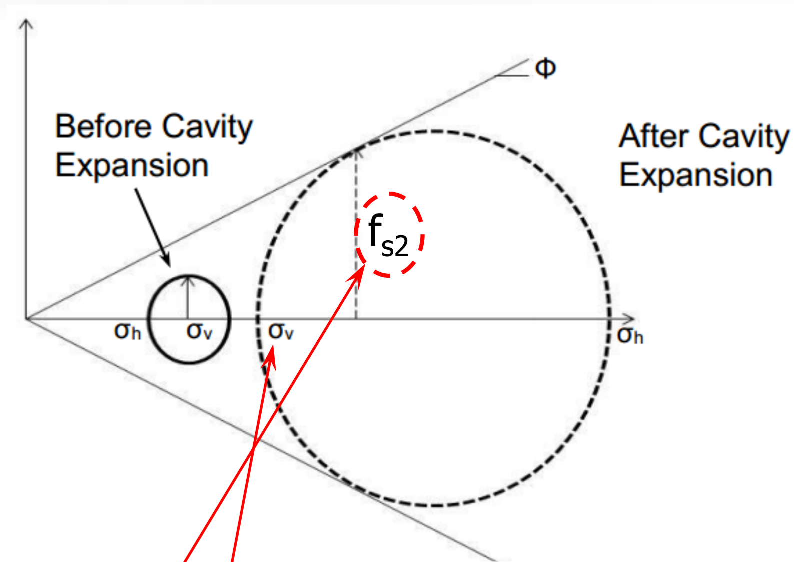


No Tip Grout Bulb

Mullins and Winters, 2004

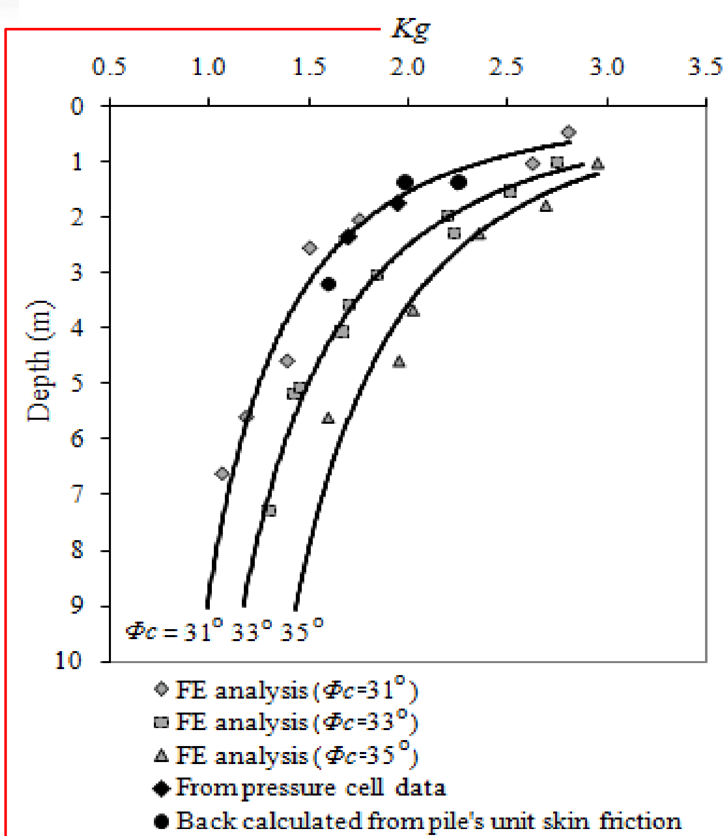
Skin Resistance
After Side Grouting





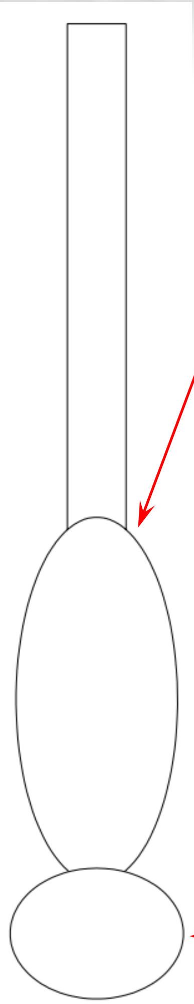
$$f_s = \sigma'_{vg}\left[\frac{\sin\phi_c}{1-\sin\phi_c}\right]\sin(90-\phi_c)$$

$$\sigma_{vg} = K_g \times \sigma_v$$

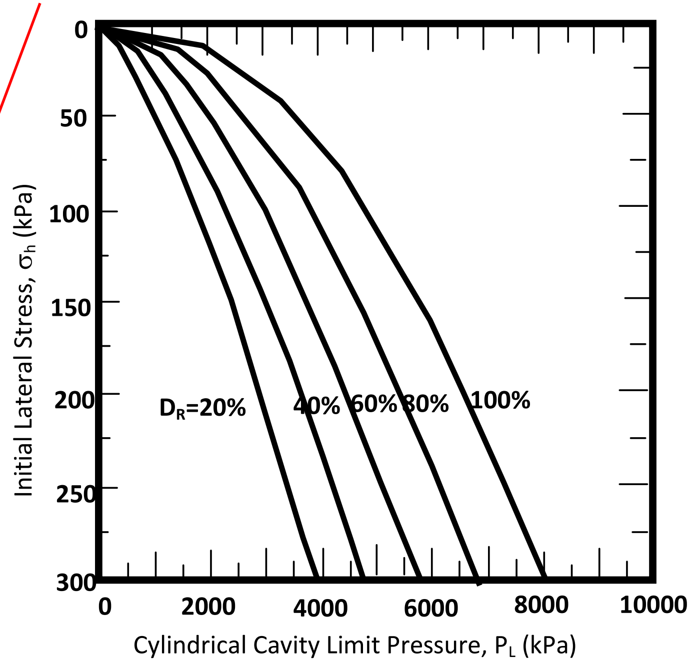


Thiyyakkandi et. al., 2013b (Right)

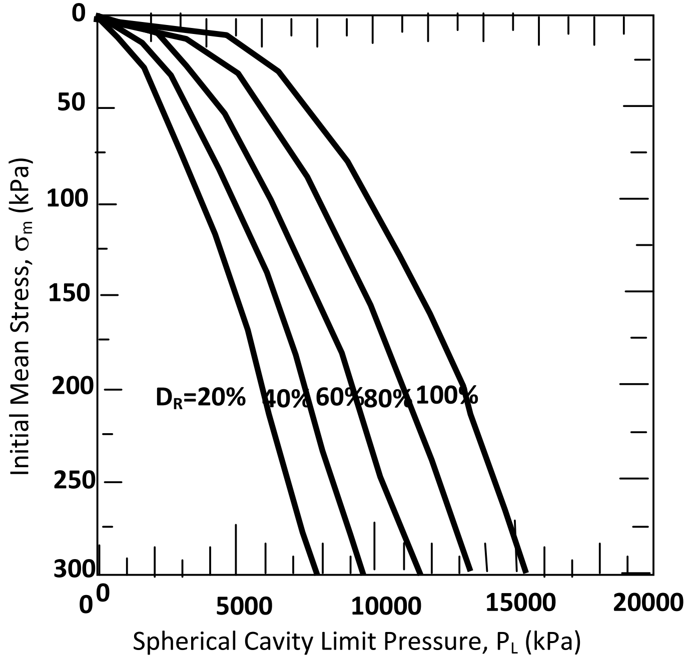
Soil Stresses
Side & Tip Grouting



Cylindrical Cavity Expansion



Spherical Cavity Expansion



Salgado and Randolph, 2001 (Cavity Limit Pressure Charts)

Design of Side & Tip Grouting System

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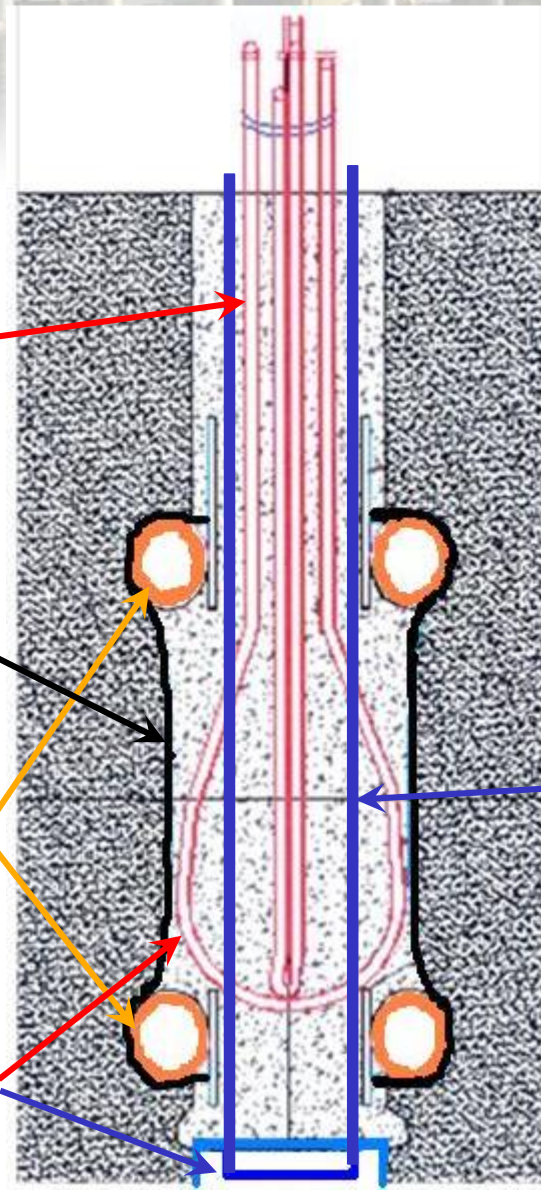
Internal Grout Delivery System for Side Grouting

Impermeable Side Membrane

Membrane Seals

Tube-a-Manchette



Internal Grout Delivery System for Tip Grouting

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Membrane Seal Design

Testing Design of Seals using Water
Over 100 psi in Ground with No Leaks

Short Shaft (3′ x 6′)
Construction of Side & Tip Grout Systems

Side Grout Tubes

RHDPP Membrane

Membrane Seal

Short Shaft (3′ x 6′)

Shaft Construction – FDOT Test Chamber

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Membrane Seal

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Short Shaft (3′ x 6′)
Side Grouting

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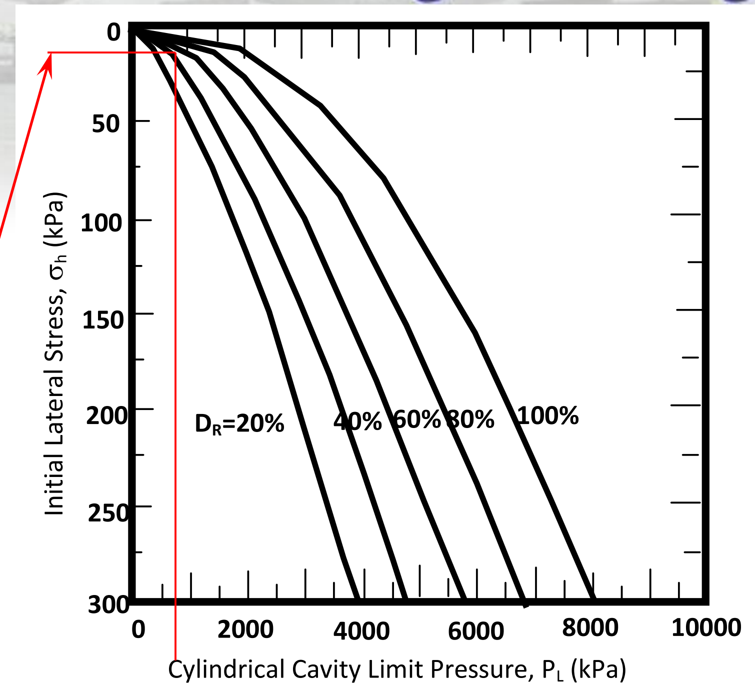
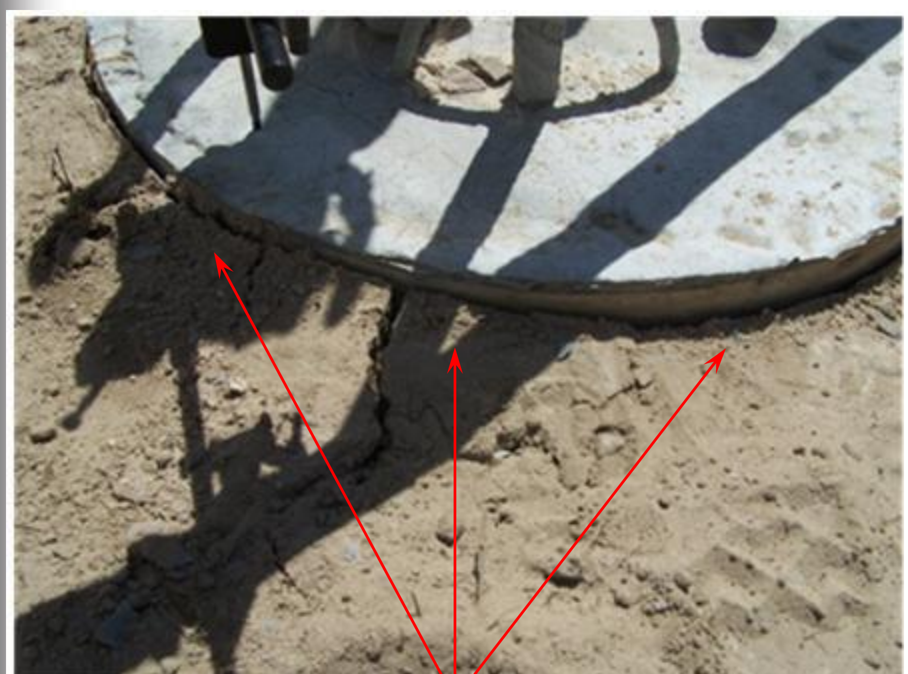
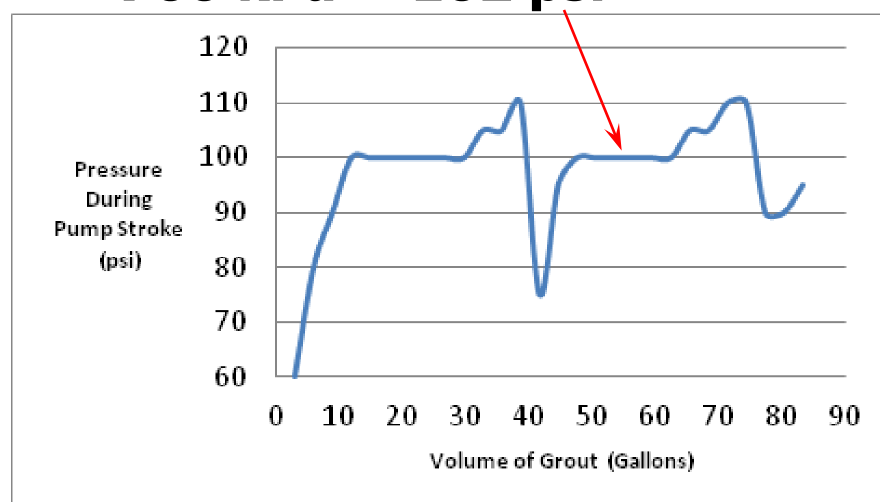
3′ x 6′ Shaft
Average Depth of Side Grout Zone = 5′
Initial Lateral Stress, $\sigma_h = \sigma_v * K_0 \approx 1.9$ psi
or 13 KPa





700 kPa = 102 psi



No Upward Grout Flow

Short Shaft (3′ x 6′)
Tip Grouting

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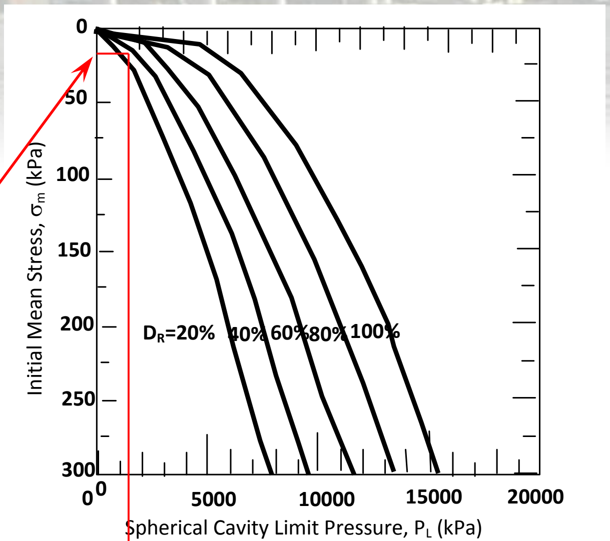
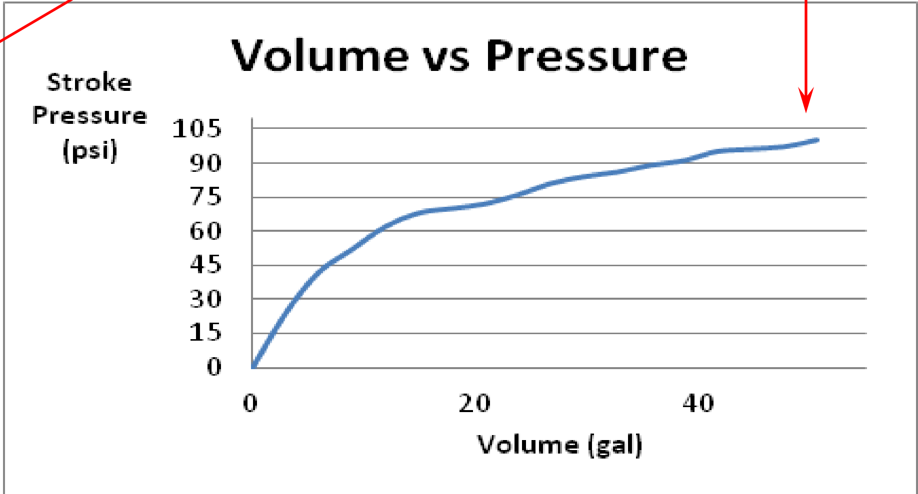
3′ x 6′ Shaft
Depth of Tip Grout Zone = 6′
Initial Mean Stress, $\sigma_m = \frac{(2*\sigma_h)+\sigma_v}{3} \approx 3$psi
or 20 KPa



1,100 kPa=155 psi (Max)

Cavity Expansion Below Tip



Short Shaft (3′ x 6′)

Summary & Conclusion

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Membrane Seal Prevented Concrete Flow to the Outside of Side Membrane

Side Grouting Prior to Tip Grouting Increases stresses in Vicinity of Shaft Tip

Grouted Membrane Seal & Side Membrane Prevented Grout Flow in the Upwards Direction during Side Grouting

Increased Stresses due Side Grouting Leads to Cavity Expansion during Tip Grouting

Long Shaft (3′ x 25′)

FDOT Test Chamber – Soil Placement

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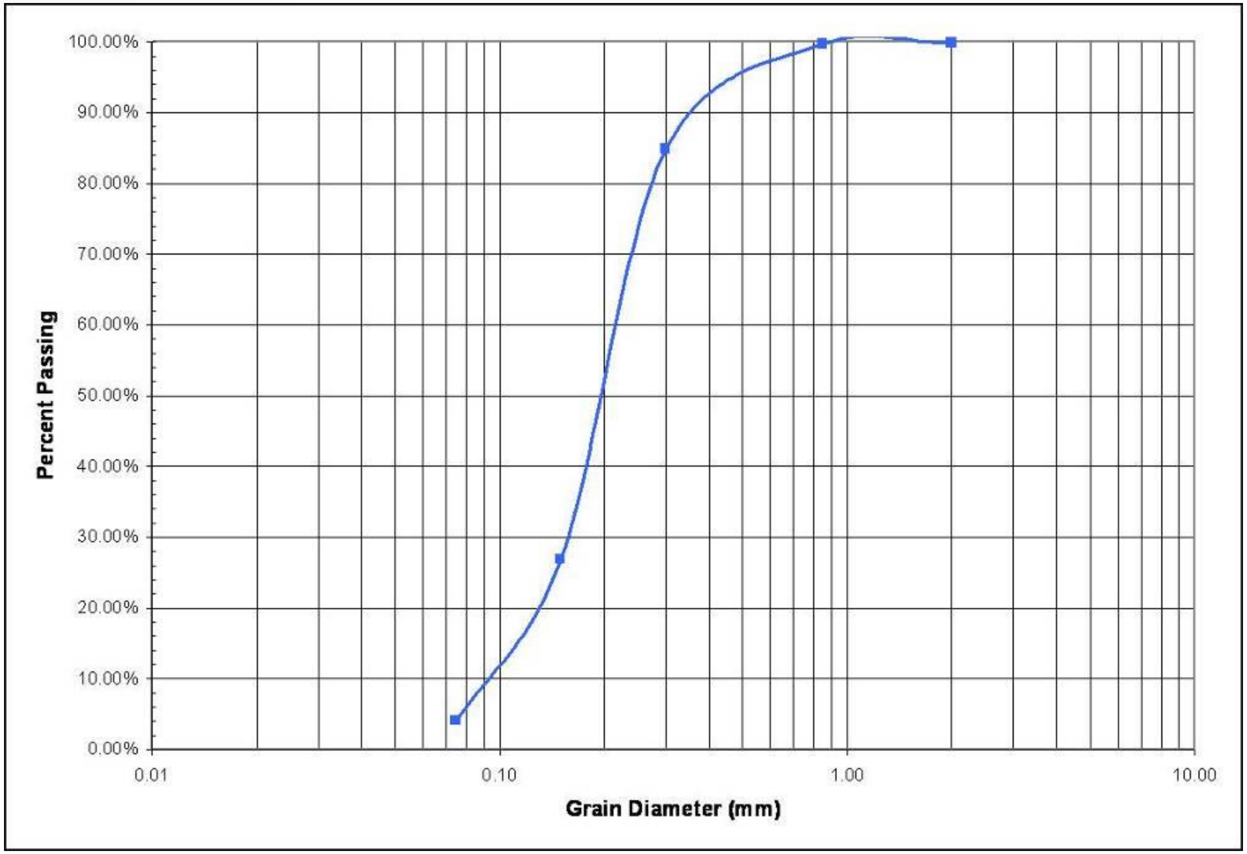
Test Soil: A-2-4
(Silty Sand – from
FDOT Borrow Pit
in Lake City, FL)

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



Estimated SPT Blow Counts:
3 – 5 at 8 ft Depth (Middle of Side Grout Zone)
15 – 20 at 25 ft Depth (Tip Grout Zone)

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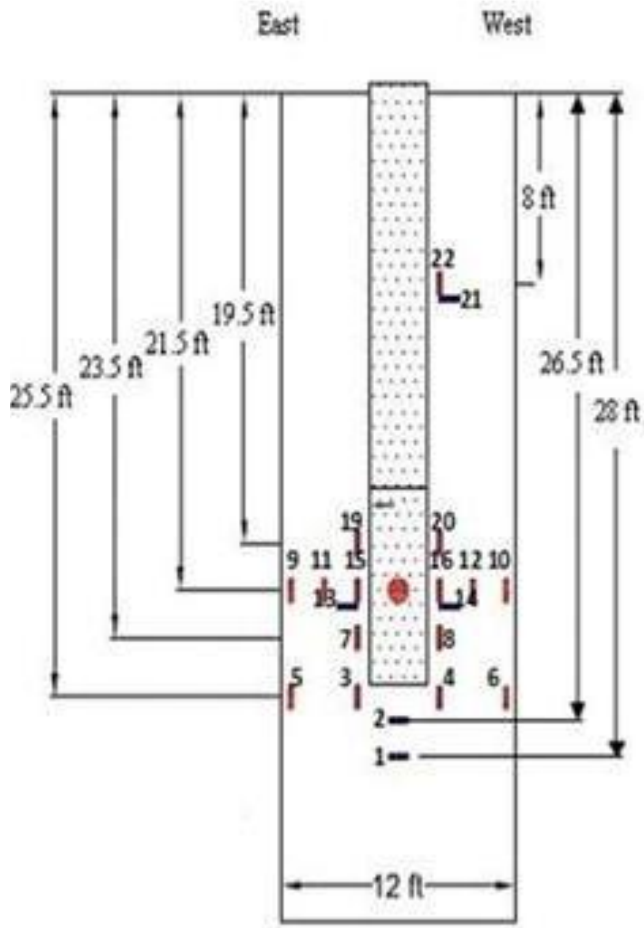
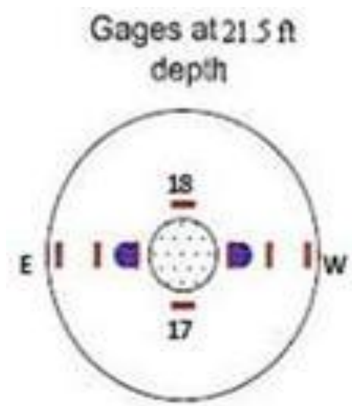
Long Shaft (3’ x 25’)
FDOT Test Chamber – Pressure Cells





Long Shaft (3' x 25')
FDOT Test Chamber – Casing & Soil Lifts

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Placement of Casing, Soil Lifts, & Pressure Cells in Test Chamber

Monitoring Density & Moisture Content (Performed by SMO)

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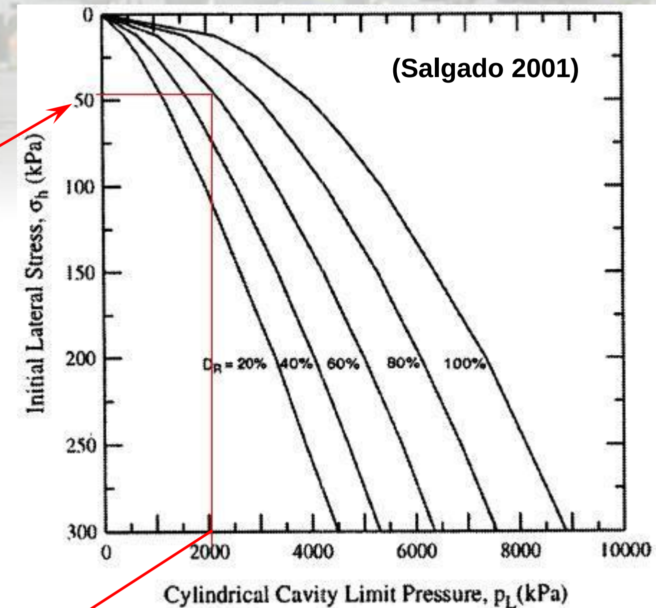
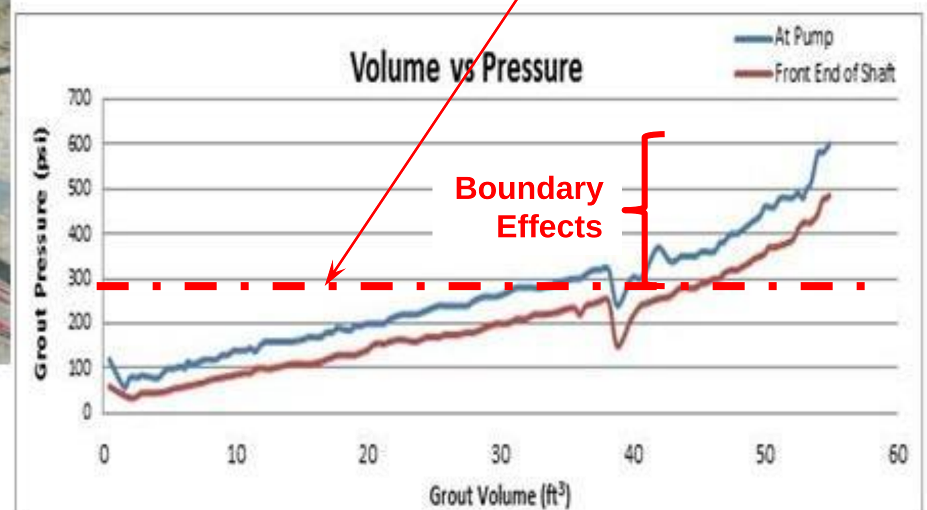
Long Shaft (3' x 25')
Side Grouting

Average Depth of Side Grout Zone = 20'
Initial Lateral Stress, $\sigma_h \approx 7$ psi
or 48 kPa



2,050 kPa ≈ 297 psi



No Upward Grout Flow

Long Shaft (3’ x 25’)
Pressure Cell Data during Side Grouting

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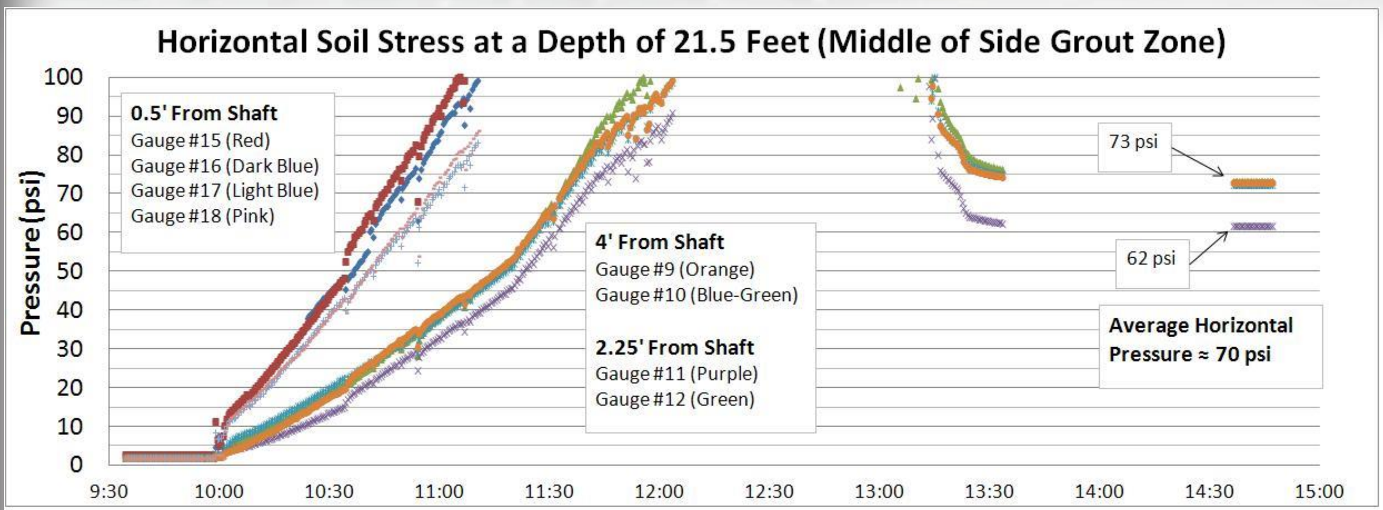
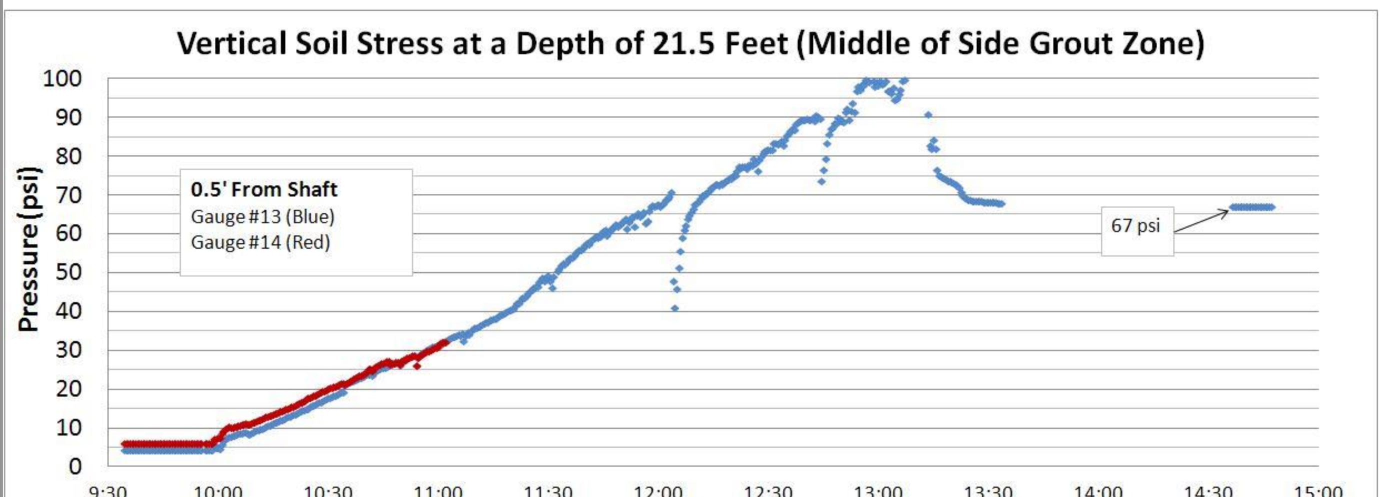
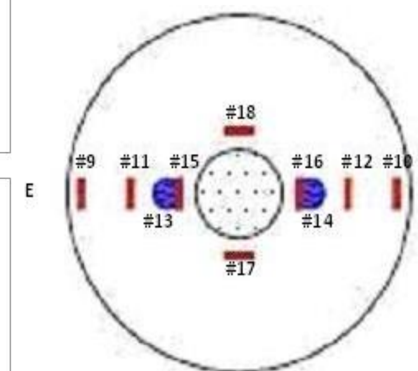




Pressure Cells at Depth of 21.5’ (Middle of Side Grouted Zone)



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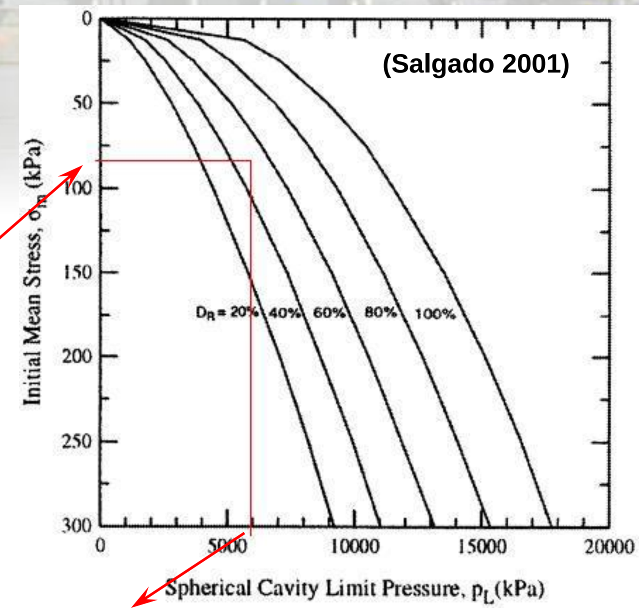
Long Shaft (3’ x 25’)
Tip Grouting

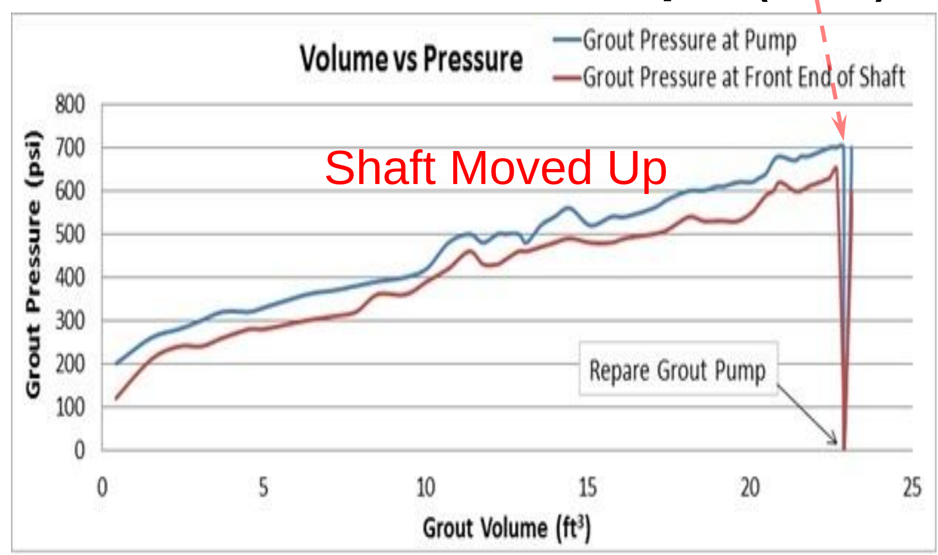
Depth of Tip Grout Zone = 25’

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



5,900 kPa ≈ 856 psi (Max)

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



Long Shaft (3′ x 25′)
Strain Data during Tip Grouting

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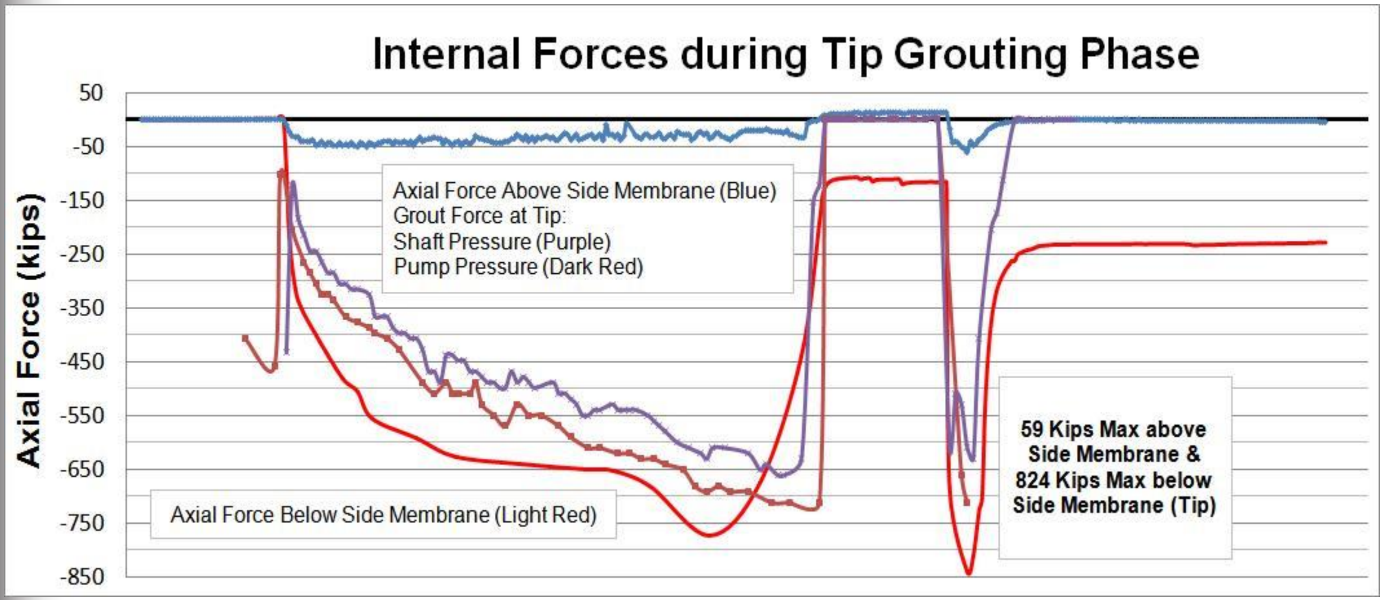

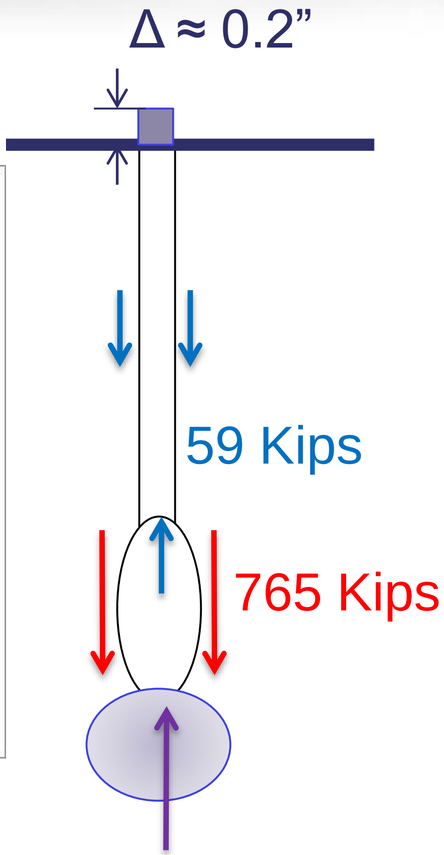

Shaft Capacity ≥ 2 x Skin = 1,648 Kips

824 Kips
(650 psi Grout Pressure
& 1267 in^2 Tip Area)

Long Shaft (3’ x 25’)
Top-Down Test

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Long Shaft (3′ x 25′)

Strain Data during Top-Down Test

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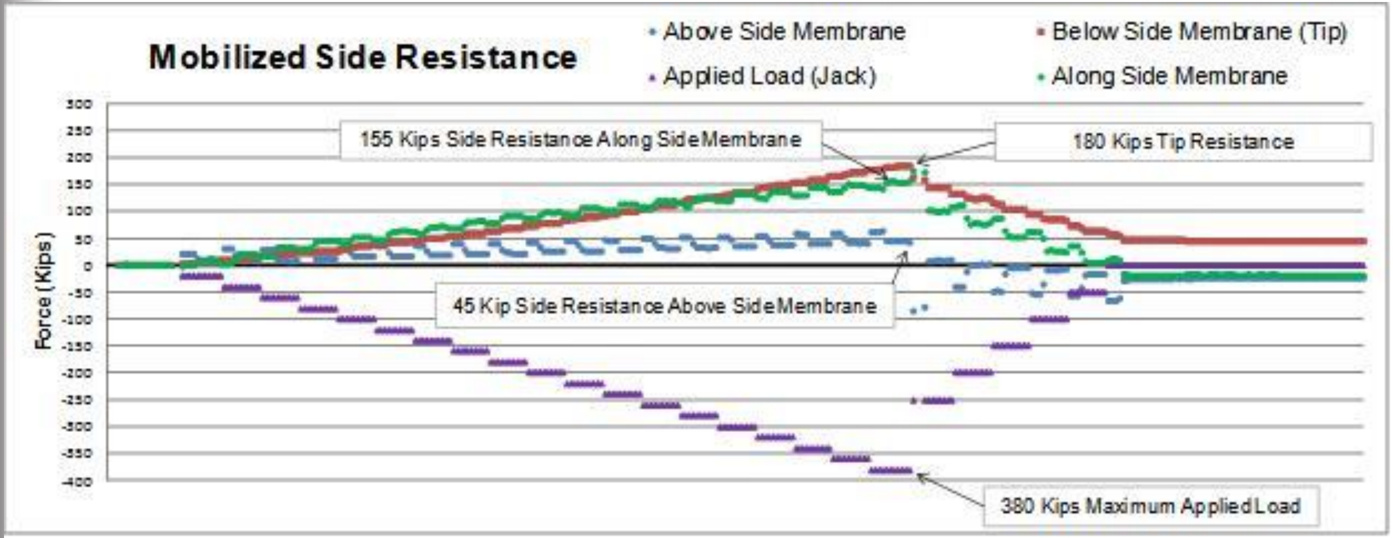

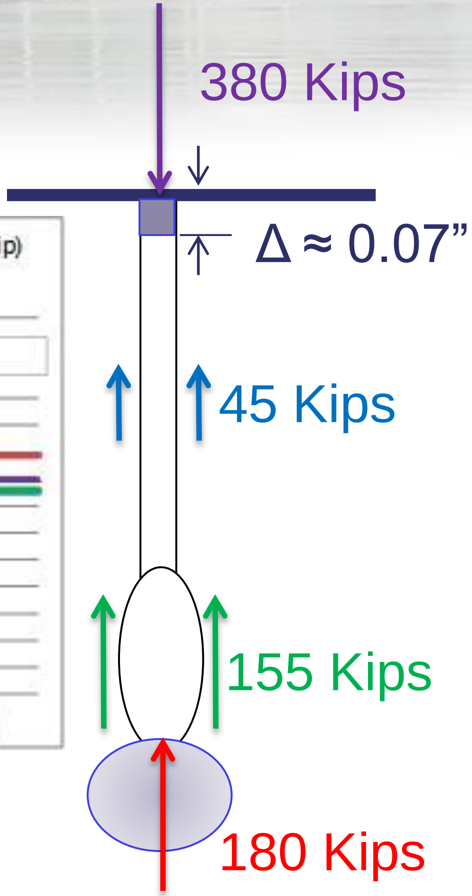

40% of Applied Load Carried by Side Grouted Zone

Long Shaft (3′ x 25′)

Load vs. Displacement (Top-Down Test) & Exhumed Side & Tip Grouted Shaft

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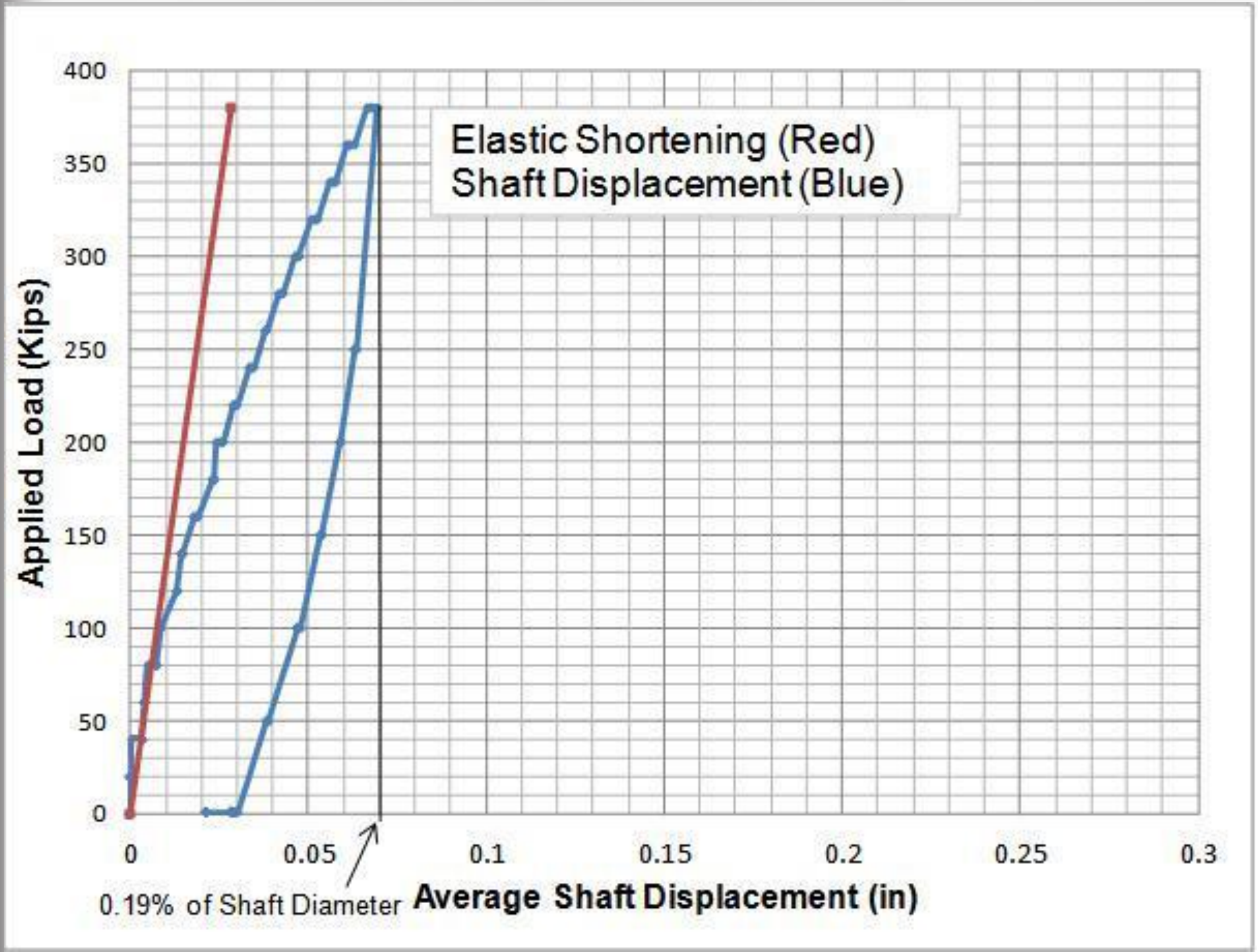
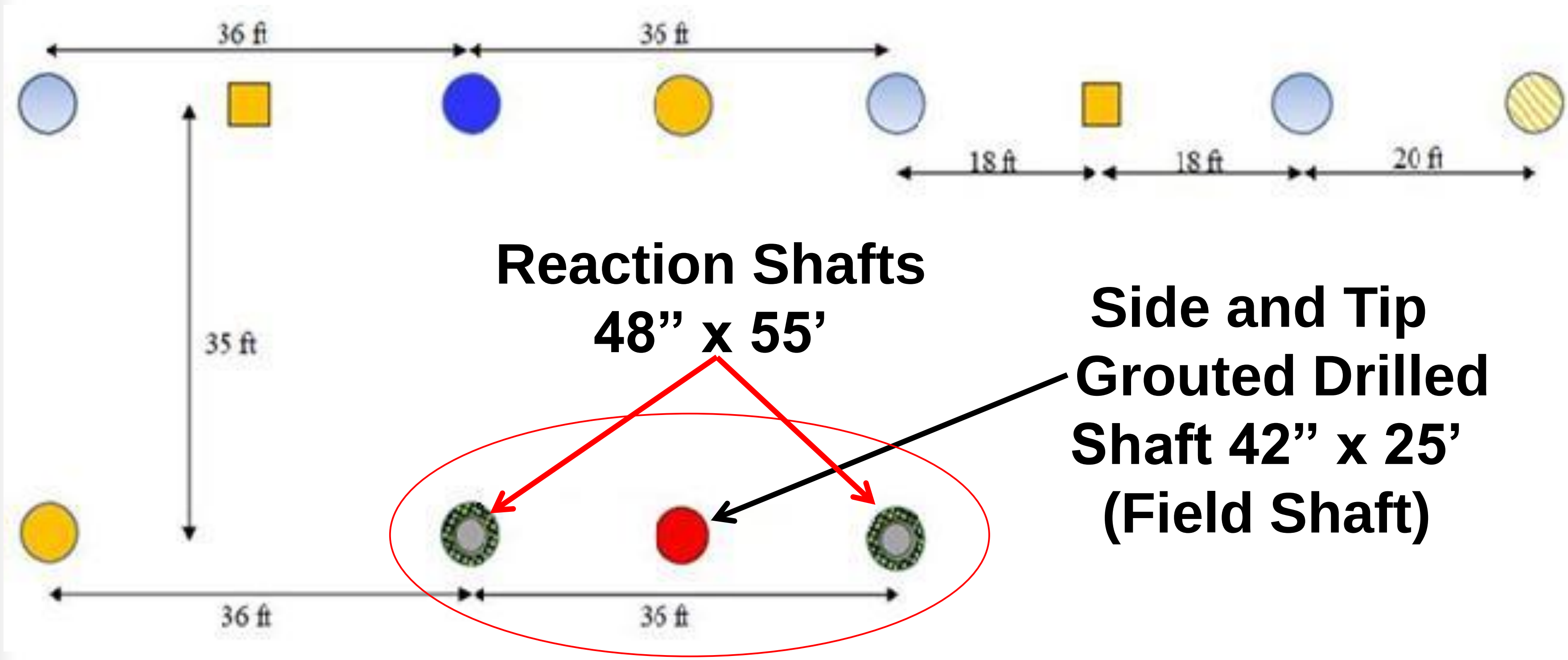


Field Shaft (3-½′ x 25′)

FDOT Test Site – Layout (Piles, Shafts, In Situ tests)



Field Shaft (3-½′ x 25′)

FDOT Test Site – Stratigraphy

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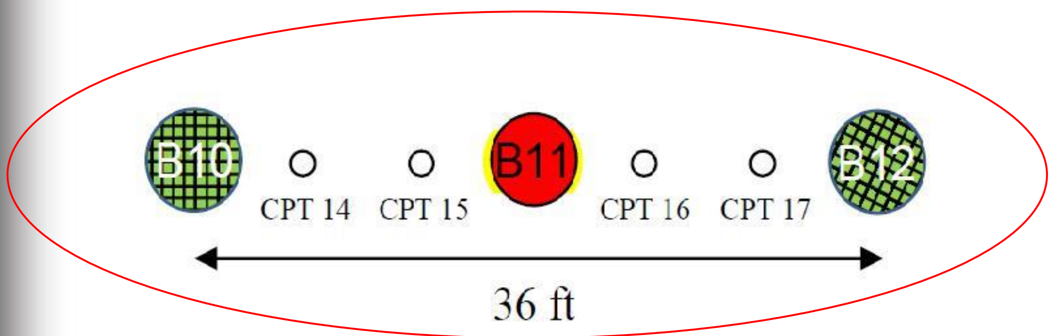

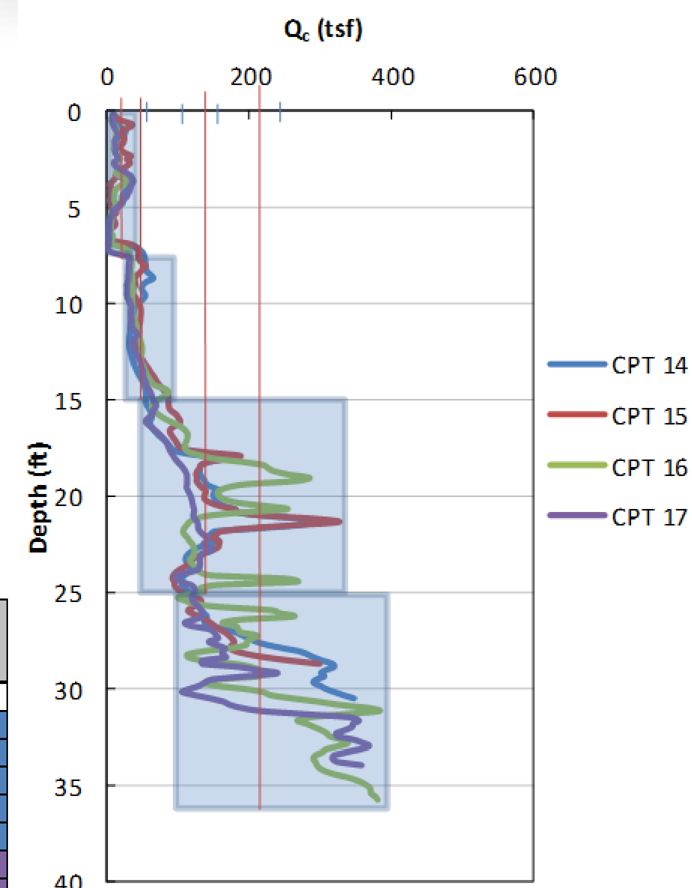

SAMPLE NUMBER	SAMPLE DEPTH (ft)	PERCENT MOISTURE	Percent Passing #10	Percent Passing #40	Percent Passing #60	Percent Passing #100	Percent Passing #200	LL / PI	ORGAN %	AASHTO CLASS	UNIFIED CLASS	SPT N-Value
B11												
1	1.0 - 2.5	15.9	100	98.3	92.9	48.3	33.1	26 / 11		A-2-6	SC	5
2	2.5 - 4.0	17.9	100	97.8	94.4	72.6	60.3	50 / 34		A-7-6	CH	7
3	4.0 - 5.5	33.5	100	99.1	98.3	90.4	86.2	72 / 51		A-7-6	CH	5
4	5.5 - 7.0	108.2	100	99.0	93.9	51.3	38.6	25 / 12	1.4	A-6	SC	6
5	7.0 - 8.5	14.9										7
6	8.5 - 10.0	19.7	100	99.5	94.8	26.7	7.8	N.P.		A-3	SP-SM	6
7	13.5 - 15.0	28.8	100	99.9	96.7	22.5	3.6	N.P.		A-3	SP	5
8	18.5 - 20.0	27.6	100	100	99.0	32.3	5.1	N.P.		A-3	SP-SM	19
9	23.5 - 25.0	28.8	100	100	97.6	21.2	4.0	N.P.	2.7	A-3	SP	13
10	28.5 - 30.0	27.1	100	99.3	95.8	29.5	3.8	N.P.	2.8	A-3	SP	27
11	33.5 - 35.0	26.2	100	99.0	90.6	23.2	5.2	N.P.	2.5	A-3	SP-SM	54
12	38.5 - 40.0	28.3	100	99.3	94.4	24.5	4.6	N.P.		A-3	SP	84

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Field Shaft (3-½′ x 25′)
FDOT Test Site – Soil Properties

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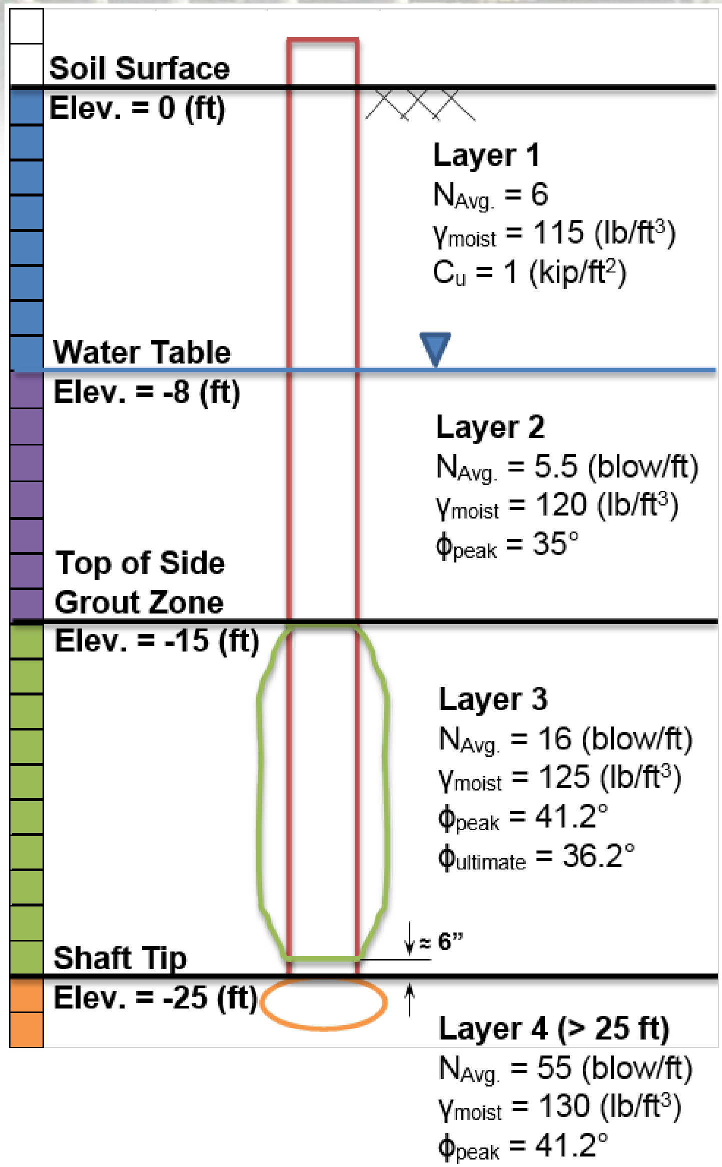

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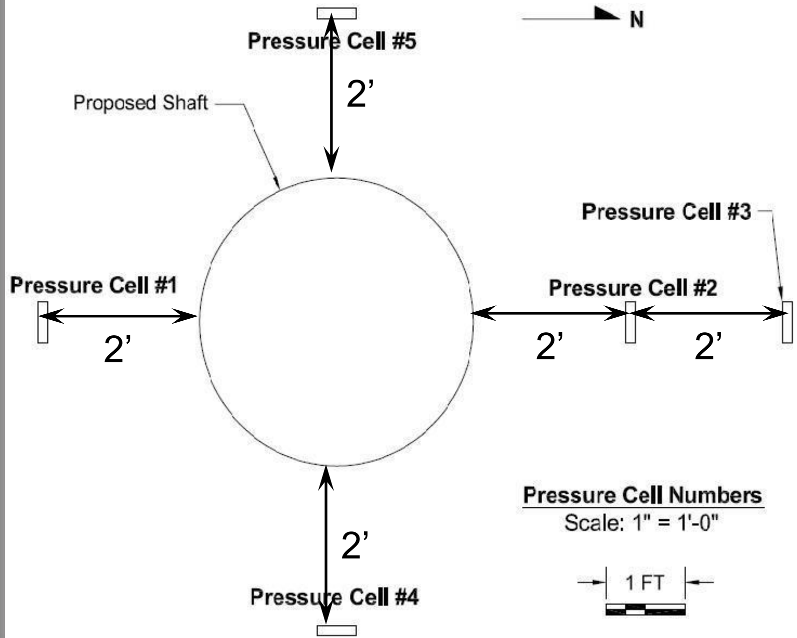
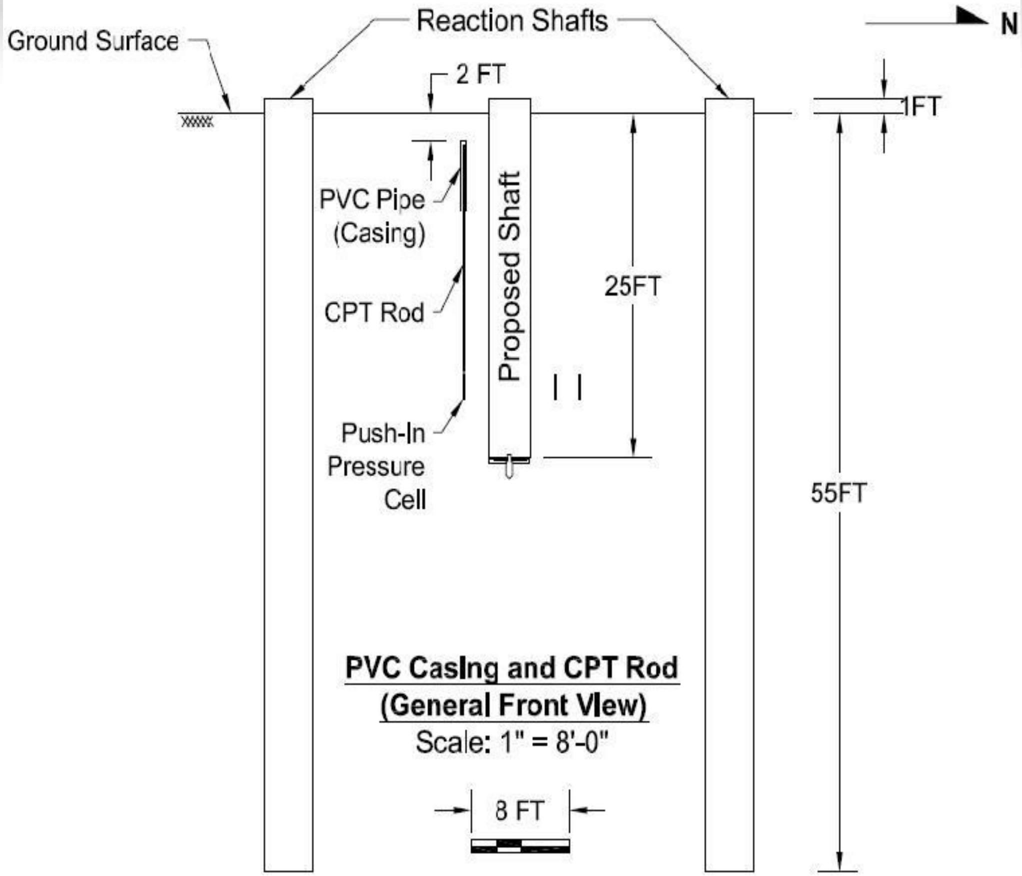
Field Shaft (3-½' x 25')
FDOT Test Site – Push-In Pressure Cells





Field Shaft (3-½′ x 25′)
Construction of Side & Tip Grout Systems

Field Shaft (3-½′ x 25′)

Shaft Construction – FDOT Test Site

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Pressurized Membrane Seal

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Field Shaft (3-½' x 25')
Construction Timeline

Completed Shaft Construction & All Grouting in 2 Weeks

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


Field Shaft (3-½′ x 25′)
Side Grouting

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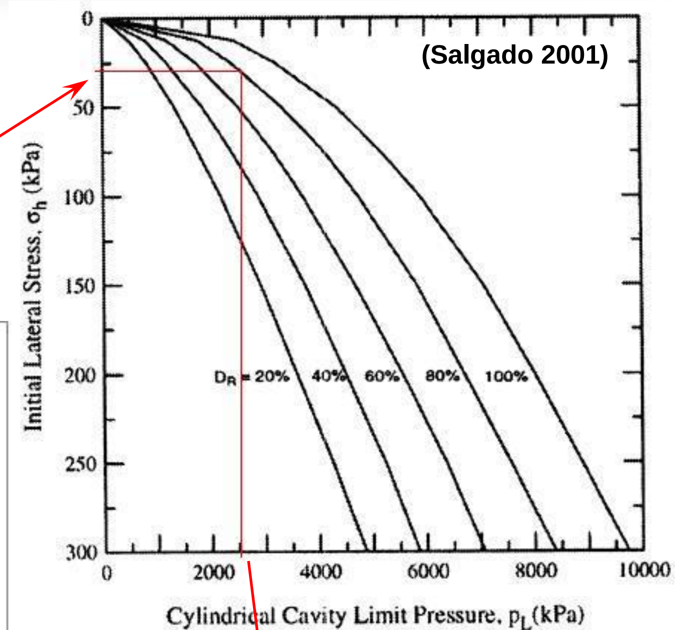
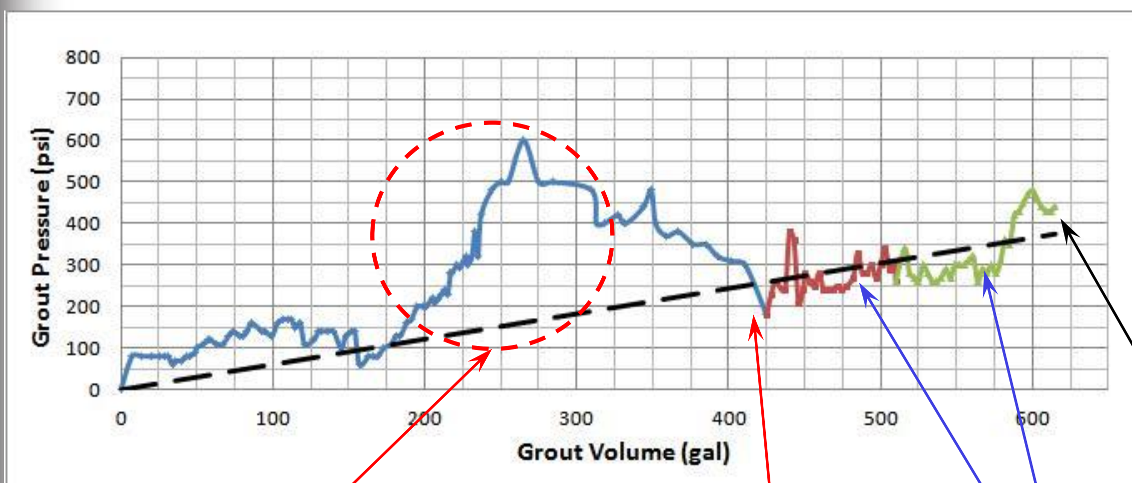
Average Depth of Side Grout Zone = 20'
Initial Lateral Stress, $\sigma_h \approx 3.9$ psi
or 26.7 kPa





2,500 kPa ≈ 363 psi

400 psi

Diameter 42 → 57.5"

Grout Pump Leaking Past Ball Valve – Reduced Flow & Increase Greater Pressures

Repaired Pump

Switched Delivery Pipes

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Field Shaft (3-½' x 25')

Pressure Cell Data during Side Grouting

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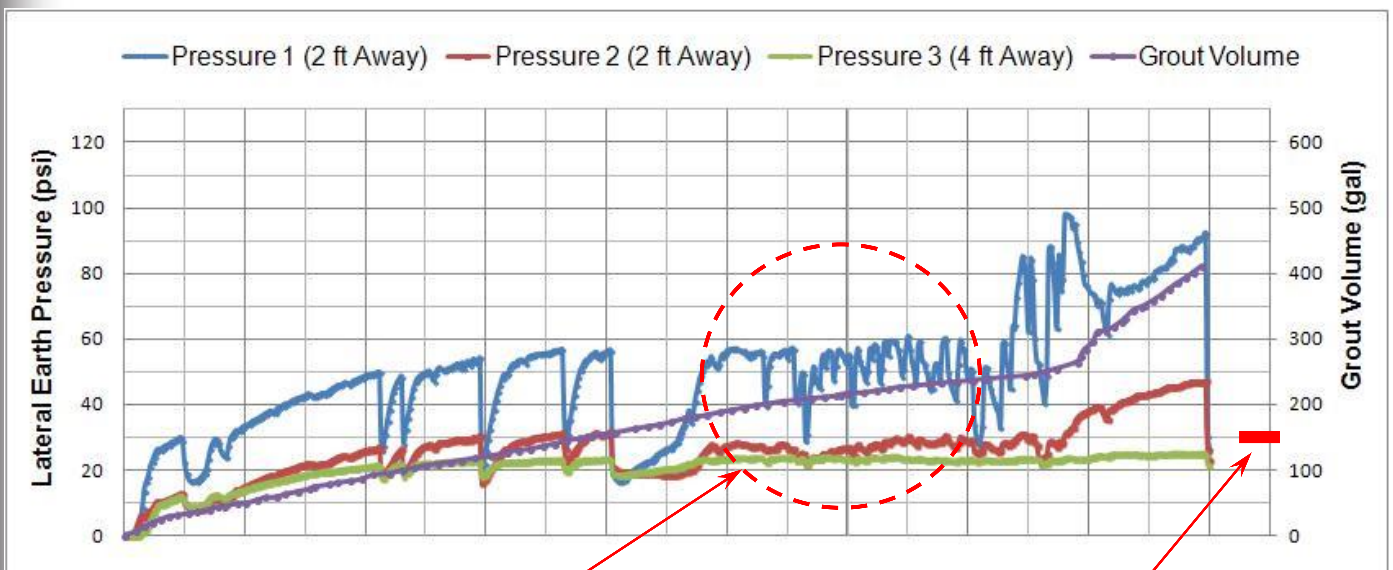
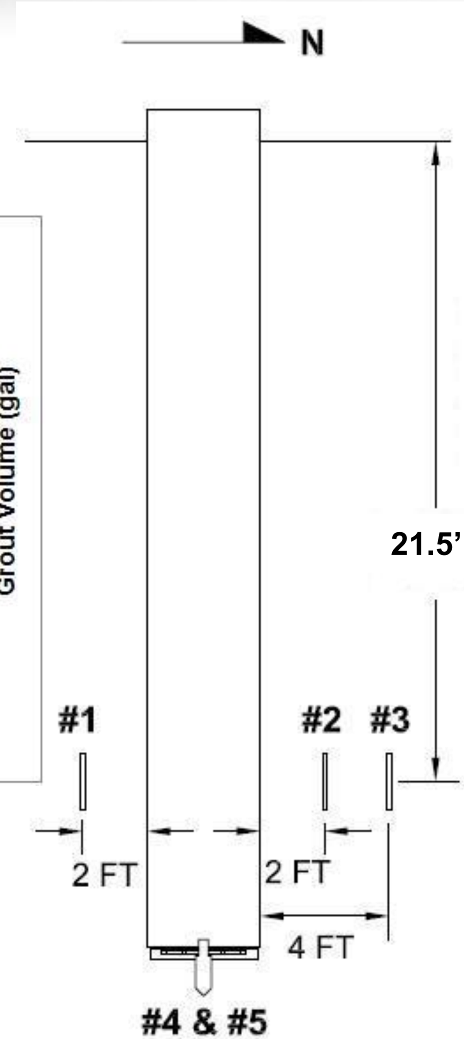
Push-In Pressure Cells at Depth of 21.5'
(Middle of Side Grouted Zone)





Residual Horizontal Stress, 30 psi

Grout Pump Recirculating back into Reservoir

Field Shaft (3-½′ x 25′)
Tip Grouting

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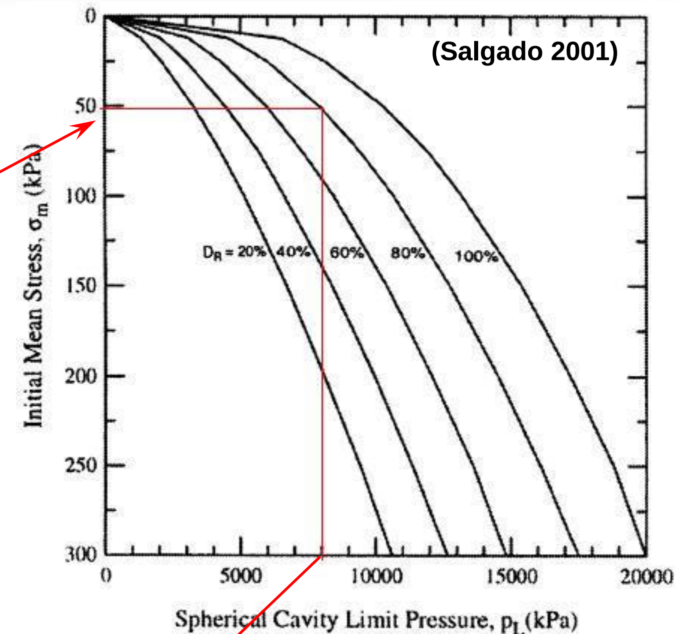
Depth of Tip Grout Zone = 25’

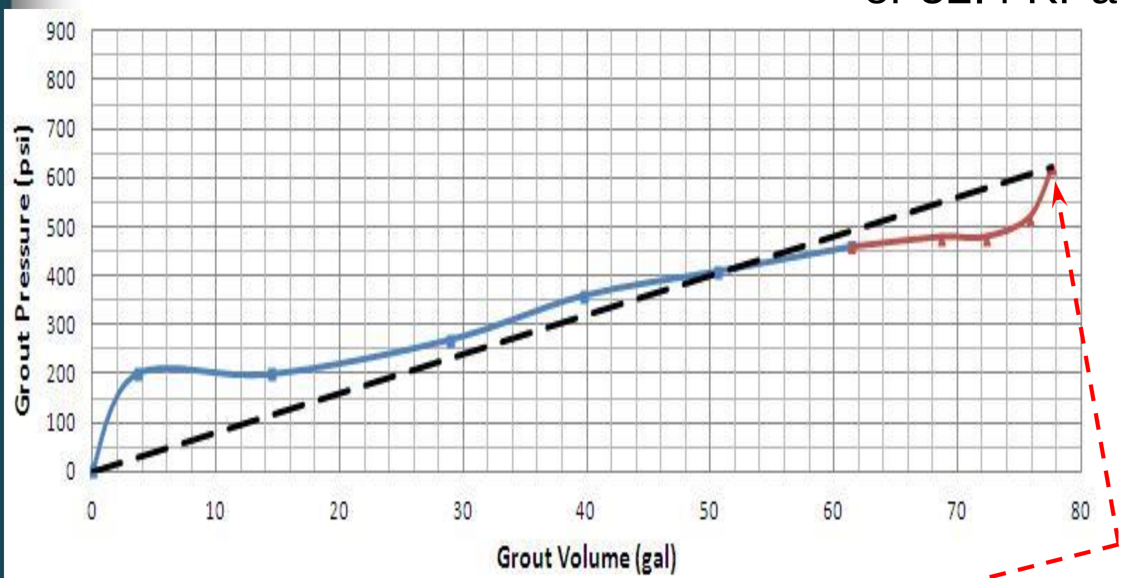
Initial Mean Stress, $\sigma_m = \frac{(2*\sigma_h)+\sigma_v}{3}$ ≈ 7.6 psi or 52.4 KPa



8,000 kPa ≈ 1,160 psi (Max)

Observed: 600 psi (Max)

80 gals → Estimate 41” x 14” tip



0.34” Upward Shaft Movement

(0.27” Differential Movement with Soil)

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Field Shaft (3-½′ x 25′)
Strain Data during Tip Grouting

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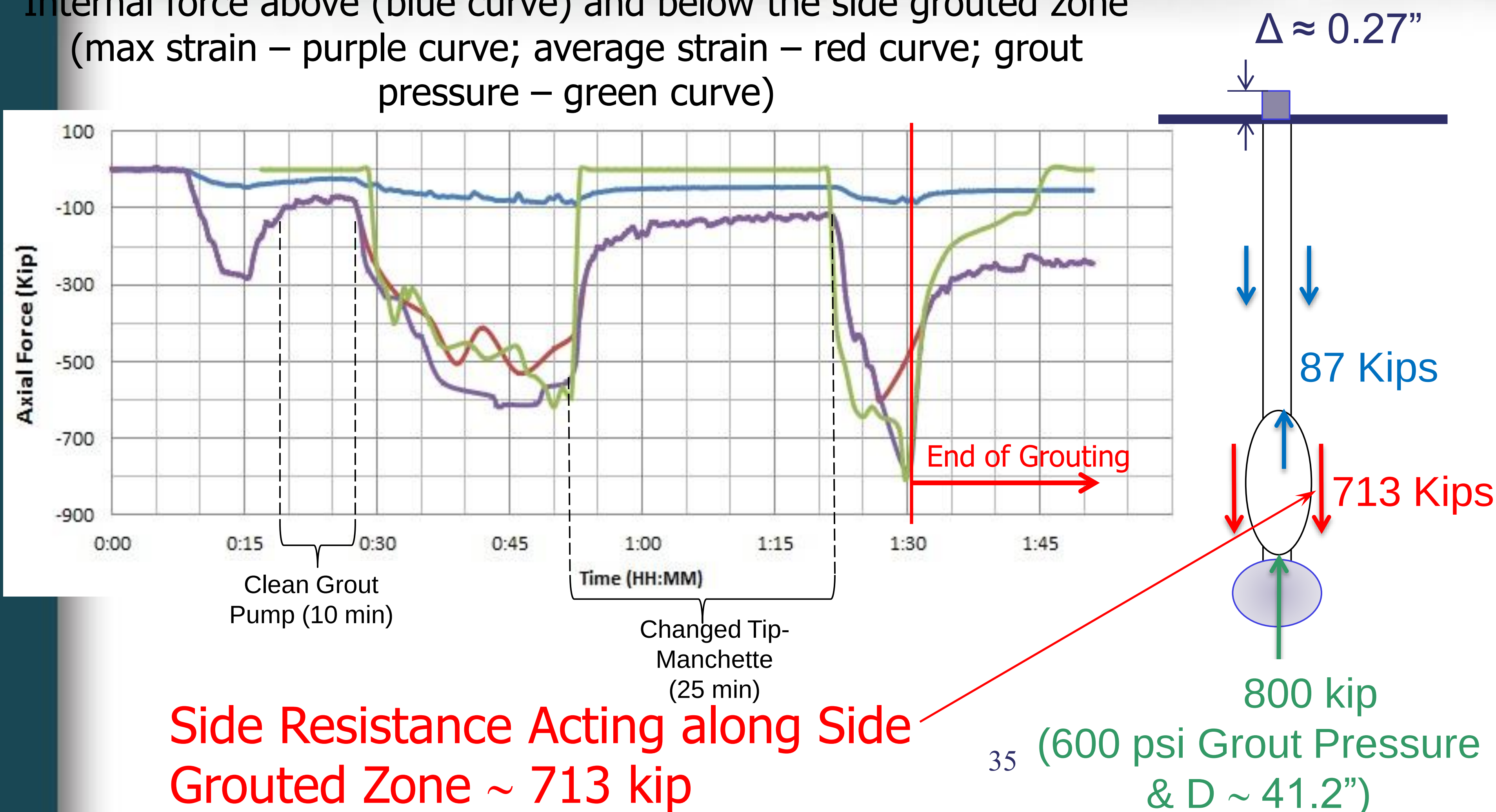
Internal force above (blue curve) and below the side grouted zone (max strain – purple curve; average strain – red curve; grout pressure – green curve)



Side Resistance Acting along Side Grouted Zone ~ 713 kip

Field Shaft (3-½′ x 25′)

Top-Down Test

Reaction Shafts 48″ x 55′

Field Shaft (3-½′ x 25′)

Strain Data during Top-Down Test

Measured Internal Force

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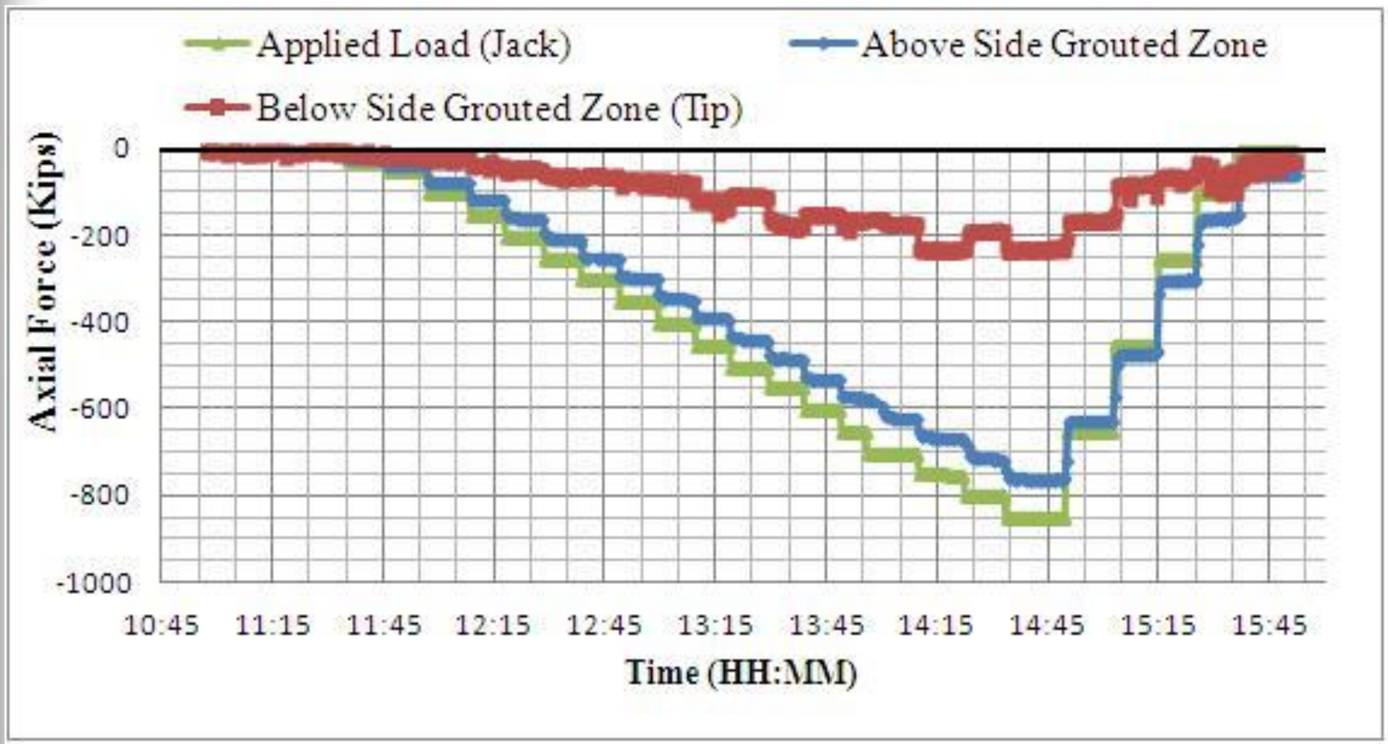
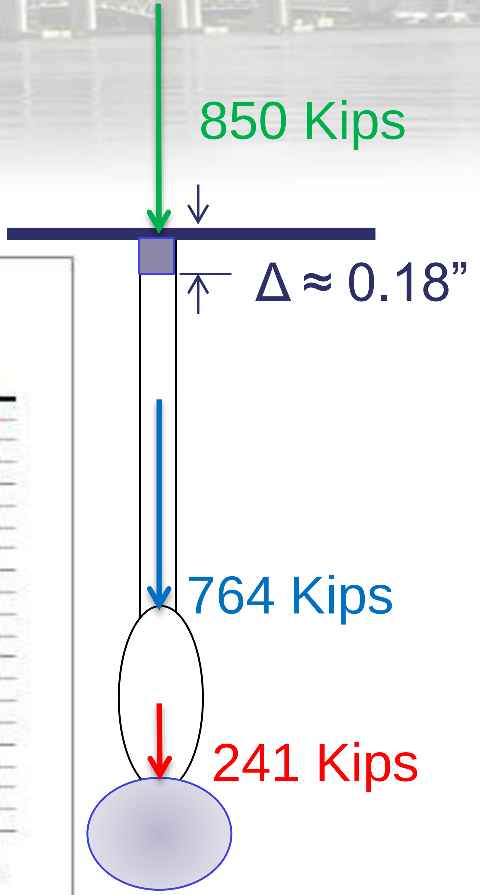
Internal Forces during Top-Down Test





Failed Reaction Shafts (4’ x 55’)

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

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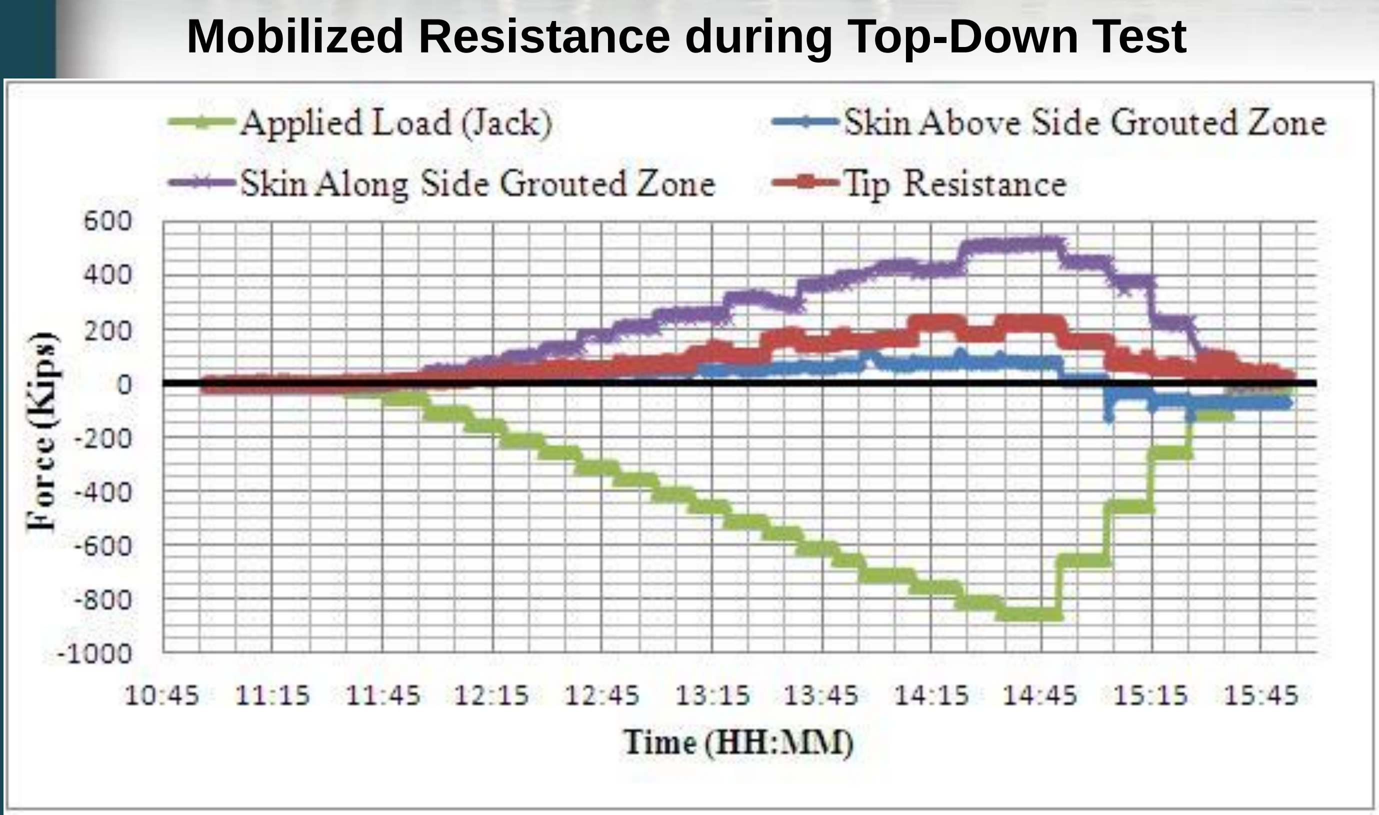
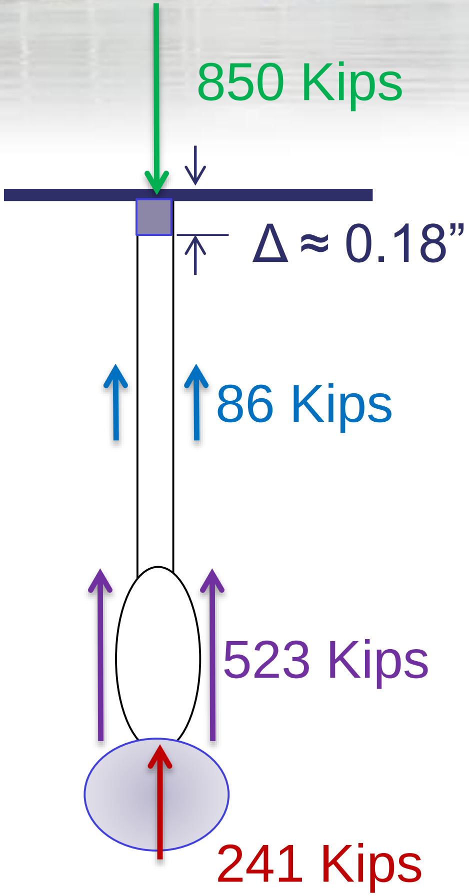
Field Shaft (3-½′ x 25′)

Strain Data during Top-Down Test
Measured Mobilized Force

Civil & Coastal Engineering





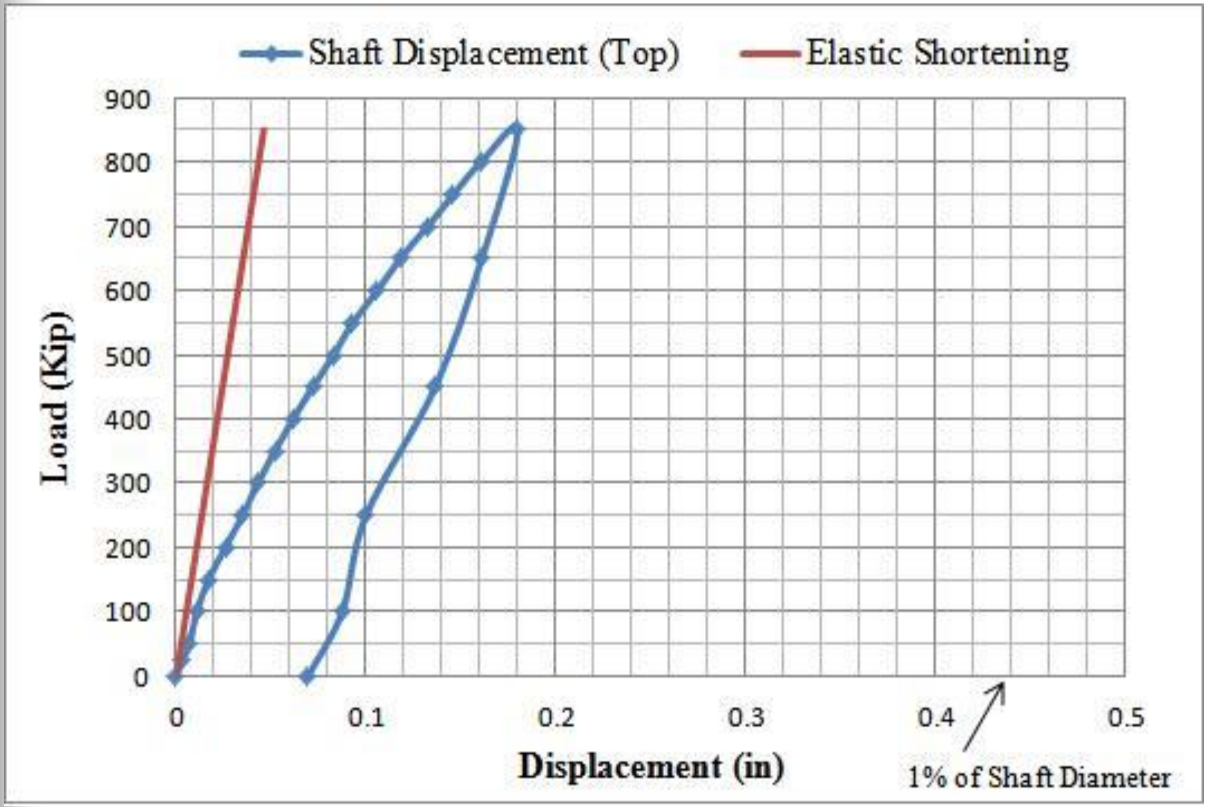
Recall during Tip Grouting
~ 713 kip Acting along Side Grouted Zone
~ 800 kip Mobilized End Bearing

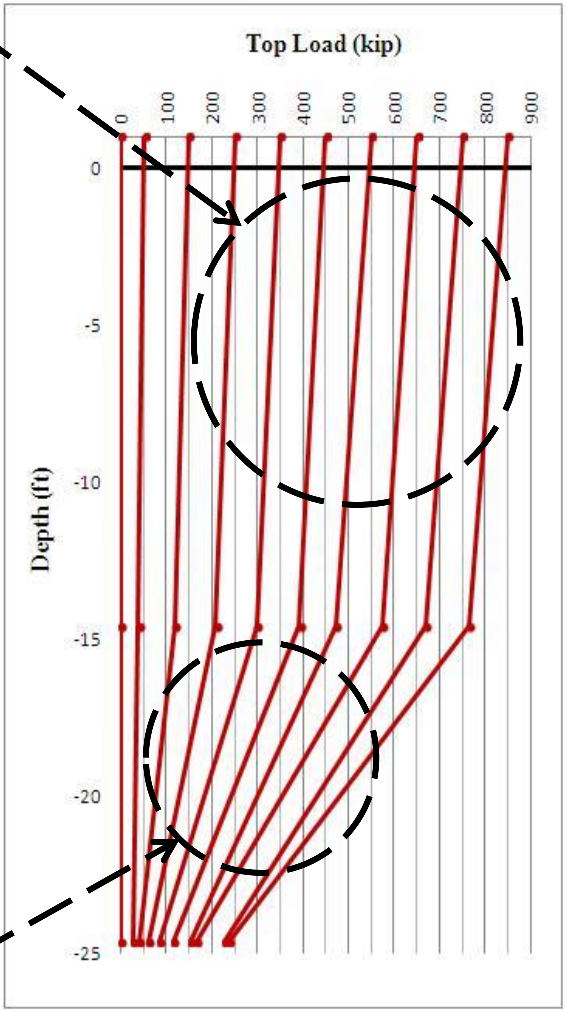
61% of Applied Load Carried by Side Grouted Zone

Field Shaft (3-½′ x 25′)
Load vs. Displacement & Load Distribution during Top-Down Test

Civil & Coastal Engineering

Fully Mobilized above Side Grouted Zone





Not Fully Mobilized along Side Grouted Zone

Field Shaft (3-½′ x 25′)
Statnamic Load Test – Additional Instrumentation

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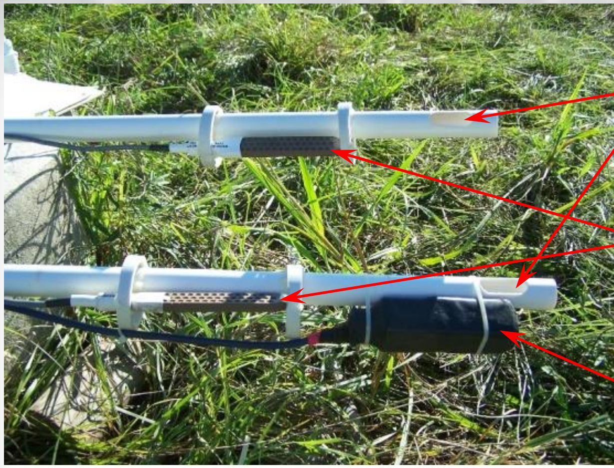

Grout Delivery

Strain gages

Accelerometer

Grout Instrumentation (i.e., Embedded)

Grout Pump

Grout Cap

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Field Shaft (3-½′ x 25′)
Statnamic Load Test

Civil & Coastal Engineering

Set Up Catch Frame & Place Reaction Weights (Dead Load)



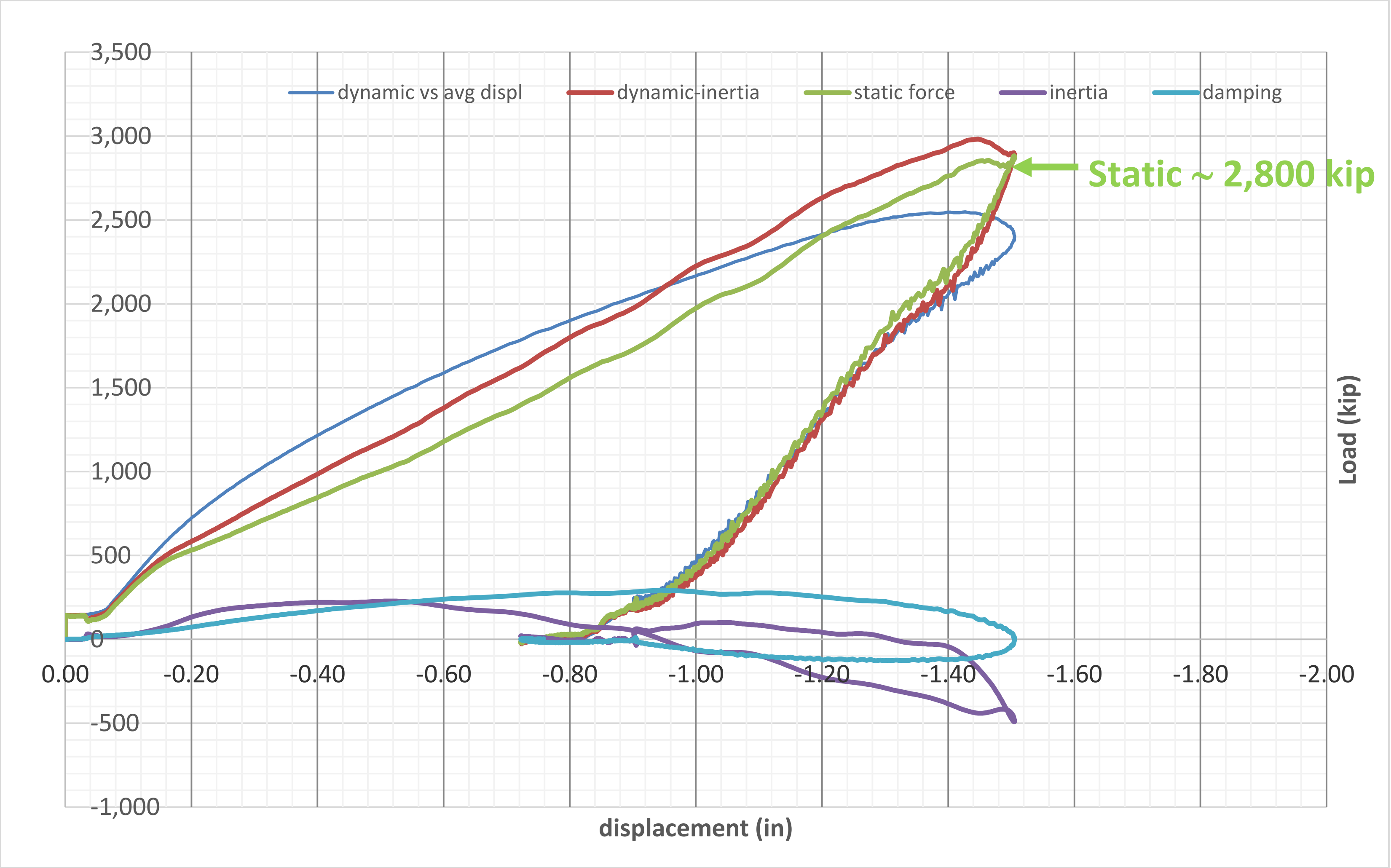
Perform Statnamic Load Test (2,550 kip Total Statnamic Load)



Field Shaft (3-½′ x 25′)
Unloading Point Method (Middendorp, 1992)

Civil & Coastal Engineering

1.45″ Displacement (~ 3.5% Diameter)



Field Shaft (3-½′ x 25′)

Load Distribution during Statnamic Load Test

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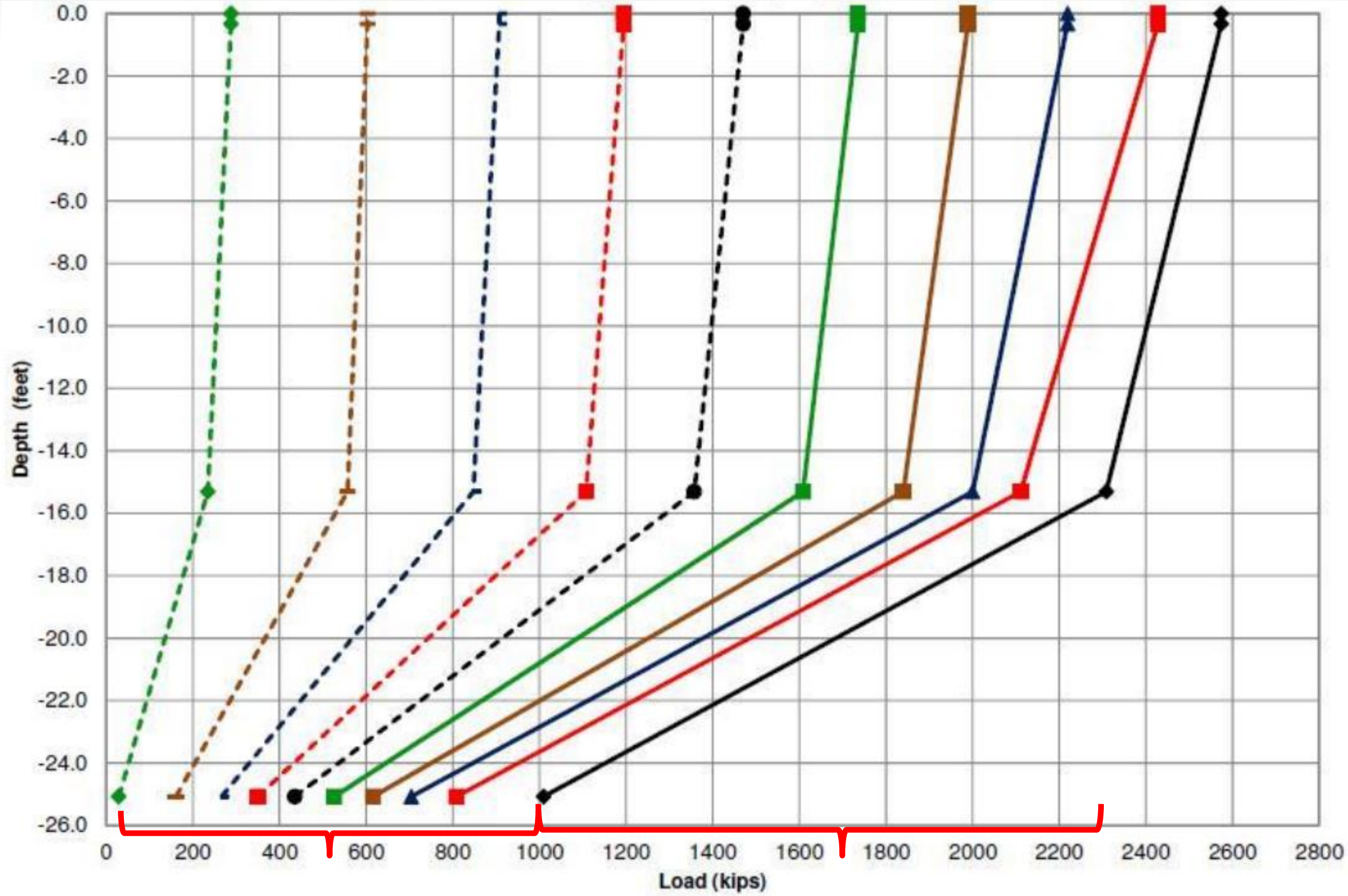
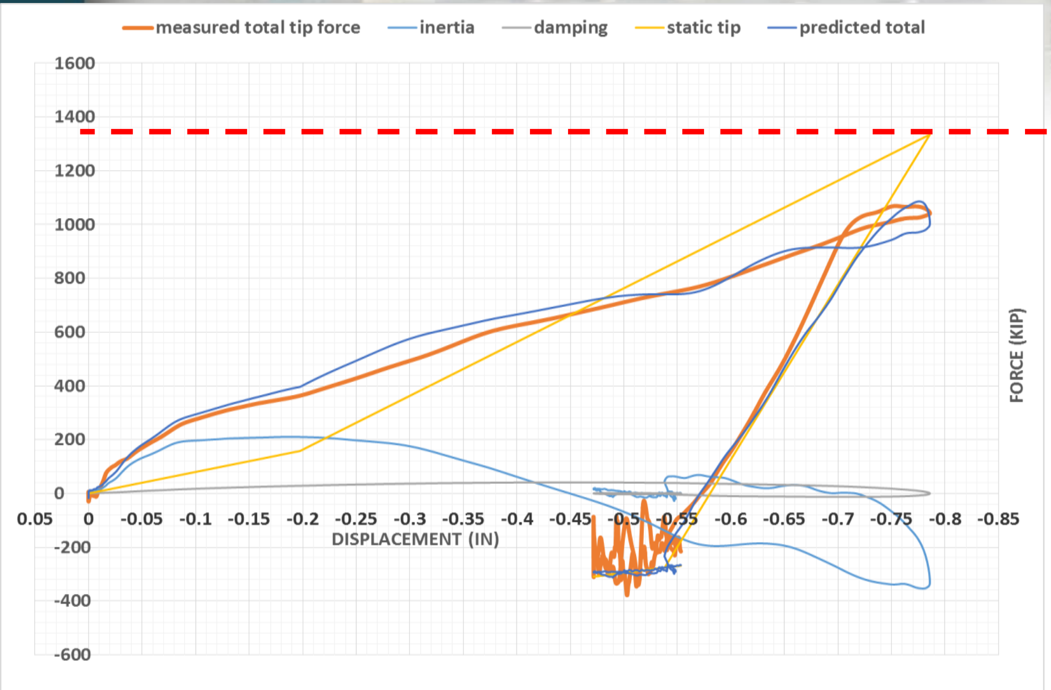
Static Resistance ~ 2,600 kip



Tip ~ 1,000 kip **Side Grout Zone ~ 1,350 kip**

Field Shaft (3-½′ x 25′)
Force & Energy Method
(Tran & McVay, 2012)

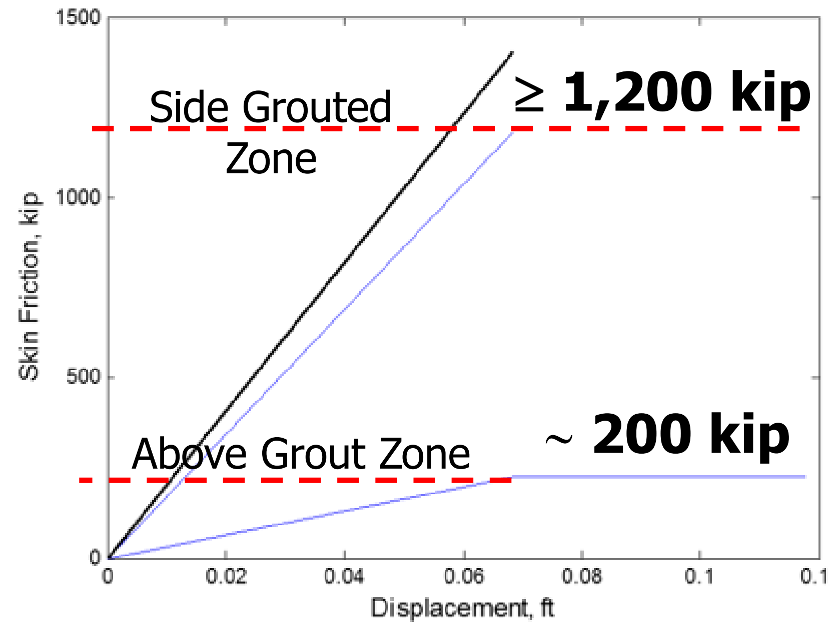
Civil & Coastal Engineering



Static End Bearing (Tip)
~ 1,300 kip
Balance Force & Energy

Static Side Resistance
Match Force & Velocity

- Above Side Grouted Zone
- Side Grouted Zone



Total Static Resistance:
1,300 kip + 1,400 kip ≈ 2,700 kip
(Tip) (Total Side)

Field Shaft (3-½′ x 25′)

Mobilized Side Resistance along Side Grouted Zone – Statnamic Load Test

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Why a Greater Mobilized Side Resistance along Side Grouted Zone during Statnamic Load Test?

1,200 to 1,350 kip during Statnamic Load Test

vs.

713 kip during Tip Grouting

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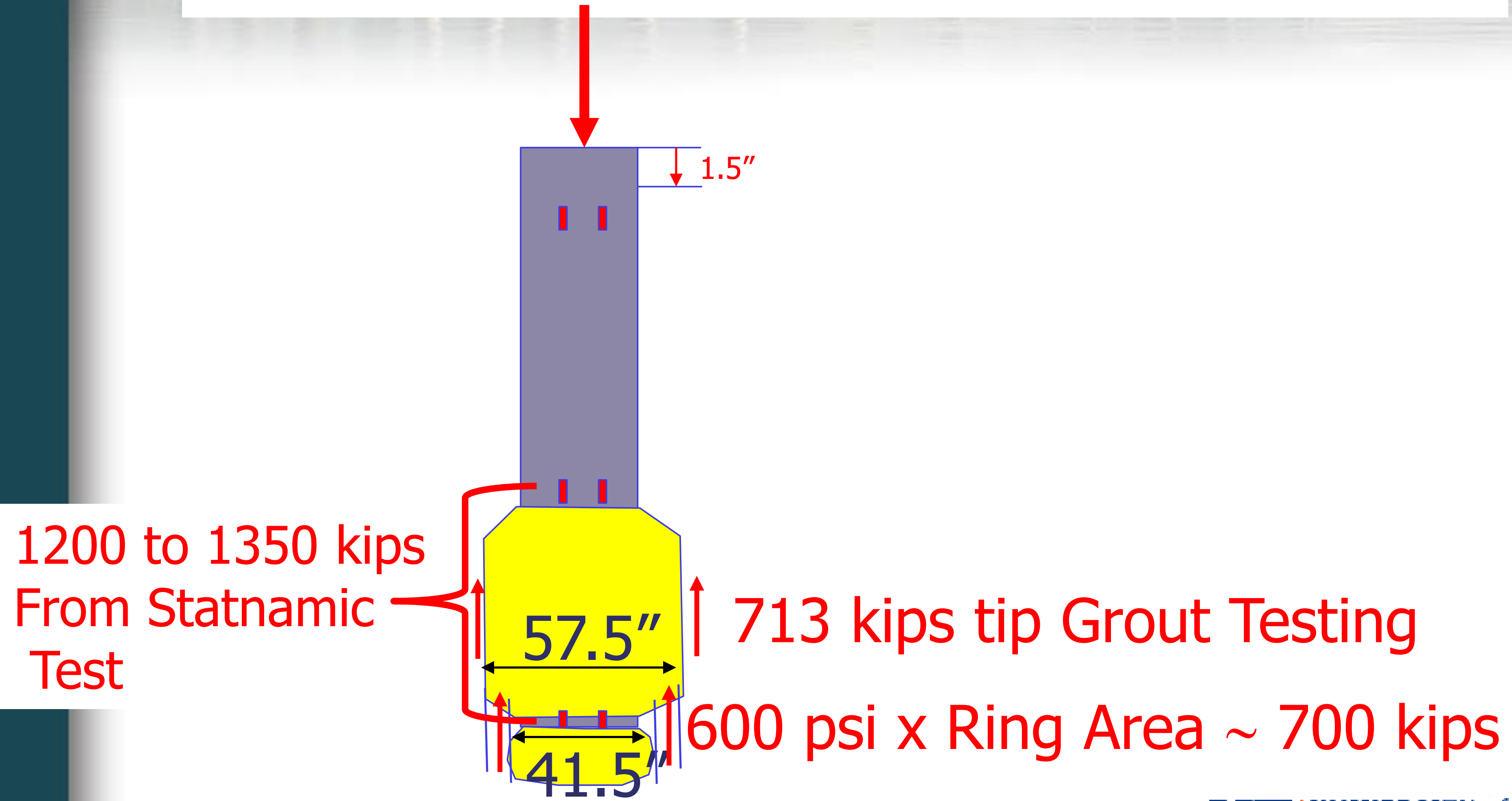
During Statnamic Test Both Skin and End Bearing on Side Grout Zone Mobilized



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Predicted Capacity

Ungrouted Drilled Shaft (42″ x 25′)

Civil & Coastal Engineering

Alpha Method

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, $f_{su} = \alpha * C_u$

Beta Method

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, $f_s = \beta*\sigma_v'$

Predicted Capacity

Ungrouted Drilled Shaft (42″ x 25′)

Civil & Coastal Engineering

Side Resistance above Side Grouted Zone, $Q_{s\text{-}above}$ (kip)	81	$= q_{s1} + q_{s2}$
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) = $A_T(ft^2) * q_T(ton/ft^2) * 2(kip/ton)$

Recall Measured above Side Grouted Zone

- **87 kip during Tip Grouting**
- **86 kip during Top-Down test**

566 kip

Total Axial Resistance

Conventional Drilled Shaft at 2.1″ Settlement (5% of Shaft Diameter)

Recall Mobilized Resistance of Side & Tip Grouted Shaft:

Side Grouted Zone: 713 kip Mobilized during Tip Grouting vs. 161 kip

End Bearing: 1,300 kip Mobilized during Statnamic Test vs. 323 kip

Predicted Capacity

Conventional Base Grouted Drilled Shaft (FDOT Soils & Foundations Handbook)

Civil & Coastal Engineering

Tip Area, A_T (ft^2)	9.62
(1) Grouted Tip Area, $A_{T\text{-}Grouted}$ (ft^2)	8.30
Avgerage Tip N-Value	28
(2) Unit Tip Resistance, q_{tip} (ton/ft^2)	16.8
Side Resistance, Q_s (ton)	121.5
(3) Maximum Grout Pressure, GP_{max} (ton/ft^2)	12.6
(4) Grout Pressure Index, GPI	0.75
Maximum Displacement, %D (%)	3.6
(5) Tip Capacity Multiplier, TCM	1.67
(6) Grouted Unit Tip Resist., $q_{grouted}$ (ton/ft^2)	27.97
(7) Grouted Tip Resistance Q_t (ton)	232.07
(8) Unltimate Resistance (ton)	**353.57**

464 kip Total End Bearing
Conventional Base Grouted Drilled Shaft (2x Grouted Tip Resistance)

Recall Mobilized Resistance of Side & Tip Grouted Shaft:

End Bearing: 1,300 kip Mobilized during Statnamic Test vs. 464 kip

Total Resistance: ~ 2,700 kip Mobilized during Statnamic Test vs. 707 kip

Predicted Capacity

Side & Tip Grouted Drilled Shaft

Resistance of Side Grouted Zone - K_g Method (Thiyyakkandi & McVay, 2013)

Civil & Coastal Engineering

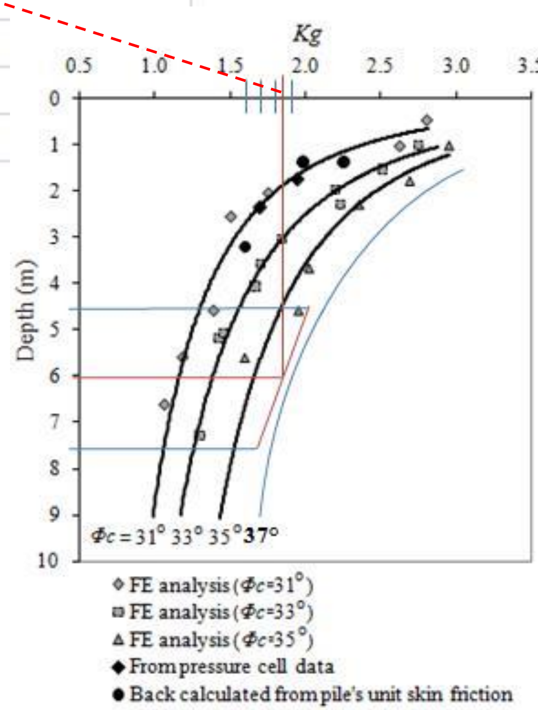
Soil Layer (#)	Depth (ft)	Depth to Mid-Point of Soil Layer (ft)	Peak Friction Angle, ϕ_p	Post Grout Surface Area, A_{sg} (ft^2)	Vertical Effective Stress, σ_v' (lb/ft^2)	(1) K_g	(2) Post Grout Vertical Stress, σ_{vg}' (lb/ft^2)	(3) Post Grout Unit Side Resist., f_{s3-Kg} (kip/ft^2)	(4) Post Grout Side Resist., q_{s3-Kg} (kip)	
3	15 - 25	20	41.2	156.69	1636	1.85	3027	4.40	689	$= q_{s3-Kg}$
(1) Use $\phi_c = \phi_u = 36.2°$ (See Plot Below)				(5) Total Side Resistance (Post Side Grout), $Q_{sg-Total-Kg}$ =					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, $f_{s3-Kg} = \sigma_{vg}' * [\sin\phi_p/(1-\sin\phi_p)] * \sin(90-\phi_p)$

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

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



Recall Mobilized Side Resistance along Side Grouted Zone during Tip Grouting:

713 kip Observed vs. 686 kip Predicted

Predicted Capacity

Side & Tip Grouted Drilled Shaft

Resistance of Side Grouted Zone - PMT Method (FDOT BDK-545 #31, 2009)

Civil & Coastal Engineering

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

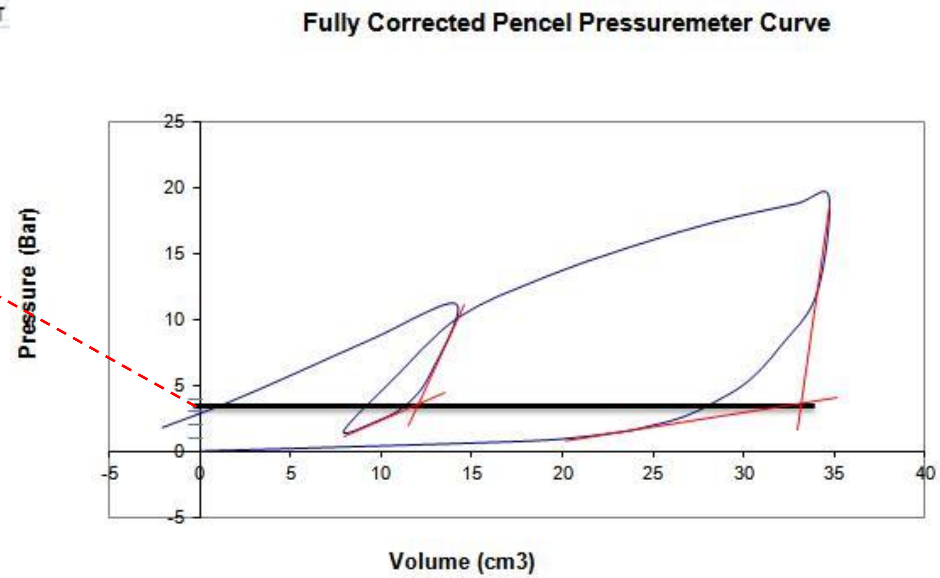
= 743 + 81 kips

(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, $Q_{sg\text{-}Total\text{-}PMT} = Q_{s\text{-}above} + q_{s3\text{-}PMT}$

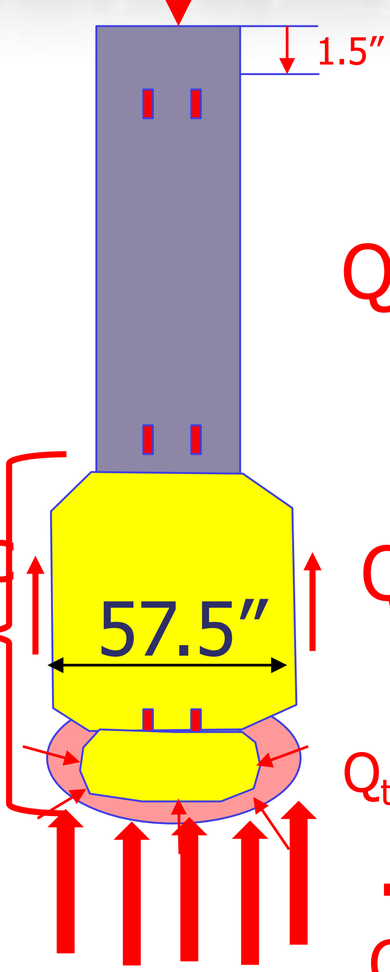


Recall Mobilized Side Resistance along Side Grouted Zone during Tip Grouting:

713 kip Observed vs. 743 kip Predicted

Predicting skin, Tip and Total Capacity of Side and Tip Grouted Shaft

Static from Statnamic 2600 to 2800 kips



Qs_{shaft} ~ 100 kips

Static Statnamic 2300 to 2500kips

Qs_{grout} ~ 700 kips

Q_{tip} ~ 600psi π $(57.5)^2/(4\text{x}1000)$ =1560 kips

Q_{total} ~ 2360 kips

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Summary & Conclusions

- Drilled Shafts Constructed in Cohesionless Soils have much Lower Side Resistance & End bearing than Driven Piles
- Side Grouting with Membrane Seals & Impermeable Side Membrane allows for the Development of Cylindrical Cavity Expansion Stresses during Side Grouting Processes
  - Increasing both Lateral and Vertical Stresses around the Side Grouted Zone as Side Membrane Expands Outwards
  - Significantly Increasing the Mobilized Side Resistance along the Side Grouted Zone
    - Increased Unit Skin Friction
    - Increased Surface Area

Summary & Conclusions

Civil & Coastal Engineering

- Required Side & Tip Grout Pressures may be Easily Estimated from Cavity Expansion Charts (Salgado, 2001)
- Estimated Axial Side Resistance along the Side Grout Zone from K_g or PMT Method(s) (Thiyyakkandi & McVay, 2012)
- Maximum Tip Grout Pressure is Limited by available Shaft Resistance to Upwards Movement during Tip Grouting
  - (1) Side Resistance of the Side Grouted Shaft (FHWA Side Resistance along Un-Grouted Portion; K_g or PMT Method along Grouted Portion; Weight of Side Grouted Shaft)
  - (2) Spherical Cavity Expansion Limit Pressure (Salgado, 2001)

***Use Smaller of (1) or (2)**

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Summary & Conclusions

Civil & Coastal Engineering

- Design Estimated Capacity of Side & Tip Grouted Drilled Shafts in Cohesionless Soils is the Sum of:
  - FHWA Side Resistance along Un-Grouted Portion of Shaft
  - K_g or PMT Method for Side Resistance along Side Grouted Zone
  - Estimated Tip Grout Pressure x Cross-Sectional Area of Side Grouted Zone

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References

Civil & Coastal Engineering

- American Association of State Highway and Transportation Officials [AASHTO] (2010). *LRFD bridge design specifications*, 5th Edition, AASHTO.
- American Society for Testing and Materials [ASTM] D 1143/D 1143M (2007). Standard test methods for deep foundations under static axial compression load, ASTM.
- Bruce, D.A. (1986). "Enhancing the performance of large diameter piles by grouting," Parts 1 and 2, *Ground Engineering*, May and July, respectively.
- Florida Department of Transportation [FDOT] (2012). *Soils and Foundations Handbook*. FDOT State Materials Office Gainesville, Florida
- Kulhawy, F.H., and Mayne, P.H. (1990). "Manual on Estimating Soil Properties for Foundation Design." Report EL-6800, Final Rep. Submitted Electric Power Research institute [EPRI], August 1990.
- Holtz, R. D. and Kovacs, W. D. (1981). *An Introduction to Geotechnical Engineering*. Prentice Hall, N.J.
- Lai, P., McVay, M., Bloomquist, D., & Forbes, H. (2010). "An Innovative Prefabricated Pile Installation Method Utilizing Jetting and Pressure grouting." Proc., GeoFlorida 2010: Advances in Analysis, Modeling, & Design, ASCE, Reston, VA, 1592-1601

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References

- Marchetti, S., and Craps, D. (1981). "Flat dilatometer manual," Internal report of G.P.E. Inc.
- Marchetti, S. (1997). "The flat dilatometer: design applications." Proc. Third International Geotechnical Engineering Conference, Keynote lecture, Cairo University, Jan., 421-448.
- Mayne, P.W., and Kulhawy, F.H. (1982). "K0-OCR relationships in soil." *Journal of Geotechnical Engineering*, Vol. 108 (GT6), pp.851-872.
- Mayne, P.W. (2007). "National Cooperative Highway Research Program [NCHRP] Synthesis 368: Cone Penetration Testing." Transportation Research Board, National Research Council, Washington, D.C., 117 pages.
- McVay, M., Bloomquist, D., Forbes, H., and Johnson, J. (2009). "Prestresses Concrete Pile Installation – Utilized Jetting and Pressure Grouting." Final Rep. Submitted Florida Department of Transportation, Fla.
- McVay, M. C. and Thiyyakkandi, S. (2010). "Group Efficiencies of Grout-Tipped Drilled Shafts and Jet-Grouted Piles." Final Rep. Submitted Florida Department of Transportation, Fla.
- Meyerhof, G.G. (1957). "Discussion on Research on determining the density of sands by penetration testing." Proc. 4th Int. Conf. on Soil Mech. and Found. Eng., Vol. 1: 110.

References

- Middendorp, P., Bermingham, P., and Kuiper, B. (1992). "Statnamic Load Testing of a Foundation Pile." Proceedings, 4th International Conference on Application of Stress-Wave Theory to Piles, The Hague, pp. 581-588
- Mullins, G., Dapp, S., Fredrerick, E., and Wagner, R. (2001). "Pressure grouting drilled shaft tips - Phase I final report." Final Rep. Submitted Florida Department of Transportation, Fla.
- Mullins, G., Dapp, S., and Lai, P. (2000). "Pressure-grouting drilled shaft tips in sand." New technological and design developments in deep foundations, N. D. Dennis, R. Castelli, and M. W. O'Neill, eds., ASCE, Reston, Va.
- Mullins, G., Lewis, C. L. & Justason, M. D (2002). "Advancements in Statnamic data regression techniques." Proceedings of the ASTM International Deep Foundations Congress, ASTM Geotechnical Special Publication No. 116, Vol. 2, pp. 915–930. West Conshohocken, PA: ASTM International.
- Mullins, G., and Winters, D. (2004). "Post grouting drilled shaft tips - Phase II final report." Final Rep. Submitted Florida Department of Transportation, Fla.
- Mullins, G., Winters, D., and Dapp, S. (2006). "Predicting End Bearing Capacity of Post Grouted Drilled Shafts in Cohesionless Soils." ASCE *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 4. pp. 478-487

References

- O’Neil, M. W., and Reese, L. C. (1999). “Drilled shafts: Construction procedures and design methods.” FHWA, Publication No. FHWA-IF-99-025.
- Reese, L. C., and O’Neill, M. W. (1988). “Drilled shafts: Construction and design.” FHWA, Publication No. HI-88-042.
- Robertson, P.K., and Campanella, R.G., (1983). “Interpretation of cone penetration tests - part I: sand.” *Canadian Geotechnical Journal*, 20(4); 718-733.
- Schmertmann, J. H., (1975). “Measurement of in-situ shear strength.” Proceedings of the Specialty Conference on in-situ Measurement of Soil Properties, ASCE, Raleigh, Vol. 2 pp. 57-138.
- Salgado, R., and Prezzi, M. (2007). “Computation of Cavity Expansion Pressure and Penetration Resistance in Sands.” *International Journal of Geomechanics*, Vol. 7, No. 4, pp. 251-265.
- Salgado, R. and Randolph, M. (2001). “Analysis of Cavity Expansion in Sands.” *The International Journal of Geomechanics*, Vol. 1, No. 2, p. 175-192

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References

- Thiyyakkandi, S., McVay, M., Bloomquist, D., Lai, P. (2013a). "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.
- Thiyyakkandi, S., McVay, M., Bloomquist, D., Lai, P. (2013b). "Experimental study, numerical modeling of and axial prediction approach to base grouted drilled shafts in cohesionless soils." *Acta Geotechnica*, Springer. DOI: 10.1007/s11440-013-0246-3.
- Tran K. T, McVay M., Herrera R., and Lai P. (2011a). "A New Method for Estimating Driven Pile Static Skin Friction with Instrumentation at the Top and Bottom of the Pile." *Soil Dynamics and Earthquake Engineering*, Vol. 31, pp. 1285-1205.
- Tran K. T, McVay M., Herrera R., and Lai P. (2011b). "Estimating Static Tip Resistance of Driven Piles with Bottom Pile Instrumentation." *Canadian Journal of Geotechnical Engineering*, Vol. 49, pp. 381-393.
- U.S. Department of Transportation Federal Highway Administration [FHWA] (2010). *Drilled Shafts: Construction Procedures and LRFD Design Methods*. FHWA-NHI-10-016, FHWA GEC 010

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Thank You

Questions?

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