Bottom Side Grouting of Drilled Shafts Prior to Tip Grouting

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

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   Sudheesh Thiyyakkandi, PhD
Presentation Overview

• 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
Previous Research

• 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
Previous Research

• 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)
FDOT Test Chamber
Design of Side Grouting System

Internal Grout Delivery System For Side Grouting
Impermeable Side Membrane
Membrane Seals
Tube-Manchette

Tip Grout System
FDOT Test Chamber
Short Shaft (3’ x 6’) - Fabrication
FDOT Test Chamber
Short Shaft (3’ x 6’) - Construction
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

No Upward Grout Flow

700 kPa $\approx 102$ psi
**FDOT Test Chamber**

**Short Shaft (3’ x 6’) - Tip Grout**

Depth of Tip Grout Zone = 6’

Initial Mean Stress, \( \sigma_m = \frac{(2*\sigma_h) + \sigma_v}{3} \approx 3 \text{psi} \)

or 20 kPa

1800 kPa \( \approx 261 \text{ psi (Max)} \)

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
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
γ ≈ 110 lb/ft³ & Φ' ≈ 33°

SPT Blow Counts:
3 – 5 at 8 ft Depth
15 – 20 at 25 ft Depth
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
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 $\approx 297$ psi

No Upward Grout Flow
FDOT Test Chamber
Long Shaft (3’ x 25’) - Side Grout

**Horizontal Soil Stress at a Depth of 21.5 Feet (Middle of Side Grout Zone)**

- **0.5’ From Shaft**
  - Gauge #15 (Red)
  - Gauge #16 (Dark Blue)
  - Gauge #17 (Light Blue)
  - Gauge #18 (Pink)

- **4’ From Shaft**
  - Gauge #9 (Orange)
  - Gauge #10 (Blue-Green)

- **2.25’ From Shaft**
  - Gauge #11 (Purple)
  - Gauge #12 (Green)

- **Average Horizontal Pressure = 70 psi**

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

**Vertical Soil Stress at a Depth of 21.5 Feet (Middle of Side Grout Zone)**

- **0.5’ From Shaft**
  - Gauge #13 (Blue)
  - Gauge #14 (Red)

- **67 psi**
0.4” Upward Shaft Movement (0.2” Differential Movement with Soil)

Depth of Tip Grout Zone = 25’
Initial Mean Stress, $\sigma_m = (2*\sigma_h) + \sigma_y$, $\frac{1}{3} \approx 12$ psi or 83 kPa

5900 kPa $\approx 856$ psi (Max)

(Salgado 2001)
FDOT Test Chamber
Long Shaft (3’ x 25’) - Tip Grout

Shaft Capacity $\geq 2 \times \text{Skin} = 1648$ Kips

(650 psi Grout Pressure & 1267 in$^2$ Tip Area)
FDOT Test Chamber
Long Shaft (3’ x 25’) - Top-Down Test
FDOT Test Chamber
Long Shaft (3’ x 25’) - Top-Down Test

- Max Applied Load, 380 Kips
- Force above Side Membrane, 335 Kips
- Force below Side Membrane (Tip), 180 kips

$\Delta \approx 0.07''$
FDOT Test Chamber
Long Shaft (3’ x 25’) - Top-Down Test

Mobilized Side Resistance

- 155 Kips Side Resistance Along Side Membrane
- 180 Kips Tip Resistance
- 45 Kips Side Resistance Above Side Membrane
- 380 Kips Maximum Applied Load

40% of Applied Load Carried by Side Grouted Zone!!!
FDOT Test Chamber
Long Shaft (3’ x 25’) - Top-Down Test

Elastic Shortening (Red)
Shaft Displacement (Blue)

Applied Load (Kips)

Average Shaft Displacement (in)

0.19% of Shaft Diameter
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}\)’ x 25’) - Site Layout

Side and Tip Grouted Drilled Shaft

SPT and CPT Near the Test Shaft
FDOT Test Site
Field Shaft (3-½’ x 25’) - Soil Layers

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

36 ft
FDOT Test Site
Field Shaft (3-1/2’ x 25’) - Soil Properties

<table>
<thead>
<tr>
<th>Soil Layer (#)</th>
<th>Depth (ft)</th>
<th>Depth to Mid-Point of Soil Layer (ft)</th>
<th>Peak Friction Angle, $\phi_p$</th>
<th>Ultimate Friction Angle, $\phi_u$</th>
<th>Moist Unit Weight (lb/ft$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 8</td>
<td>4</td>
<td>35</td>
<td>---</td>
<td>115</td>
</tr>
<tr>
<td>2</td>
<td>8 - 15</td>
<td>11.5</td>
<td>35</td>
<td>---</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>15 - 25</td>
<td>20</td>
<td>41.2</td>
<td>36.2</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>25 - 40</td>
<td>32.5</td>
<td>41.2</td>
<td>---</td>
<td>130</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Layer (#)</th>
<th>Depth (ft)</th>
<th>Vert. Effective Stress, $\sigma_v$ (lb/ft$^2$)</th>
<th>Vert. Effective Stress, $\sigma_v'$ (lb/in$^2$)</th>
<th>(1) Lateral Earth Pressure Coef., $K_0$ (lb/ft$^2$)</th>
<th>Horiz. Effective Stress, $\sigma_h$ (lb/ft$^2$)</th>
<th>Horiz. Effective Stress, $\sigma_h'$ (lb/in$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 8</td>
<td>460</td>
<td>3.2</td>
<td>0.43</td>
<td>196.2</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>8 - 15</td>
<td>1122</td>
<td>7.8</td>
<td>0.43</td>
<td>478.3</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>15 - 25</td>
<td>1636</td>
<td>11.4</td>
<td>0.34</td>
<td>558.5</td>
<td>3.9</td>
</tr>
<tr>
<td>4</td>
<td>25 - 40</td>
<td>2456</td>
<td>17.1</td>
<td>0.34</td>
<td>838.3</td>
<td>5.8</td>
</tr>
</tbody>
</table>

(1) Lateral Earth Pressure Coefficient (Jaky 1960), $K_0 = 1 - \sin(\phi_p)$
FDOT Test Site
Field Shaft (3-½’ x 25’) - Push-In Pressure Cells
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}'\) x 25') - Fabrication
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}\)’ x 25’) - Construction
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}\)’ x 25’) - Grouting

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.)
FDOT Test Site
Field Shaft (3-1/2′ x 25′) - Side Grouting

Average Depth of Side Grout Zone = 20′
Initial Lateral Stress, \( \sigma_h \approx 3.9 \text{ psi} \)
or 26.7 kPa

Grout Pump Recirculating back into Reservoir at the End of Stroke

2500 kPa \( \approx \) 363 psi
375 psi
FDOT Test Site
Field Shaft (3-1/2’ 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 (3-1/2’ x 25’) - Tip Grouting

Depth of Tip Grout Zone = 25’
Initial Mean Stress, $\sigma_m = \frac{(2*\sigma_h) + \sigma_v}{3}$
$\approx 7.6$ psi or $52.4$ KPa

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

8000 kPa $\approx 1160$ psi (Max)
Observed: 620 psi (Max)
FDOT Test Site
Field Shaft (3-½’ x 25’) - Tip Grouting

Clean Grout Pump (10 min)
Changed Tip-Manchette (25 min)

Internal Force during Tip Grouting Phase

<table>
<thead>
<tr>
<th>Force (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-900</td>
</tr>
<tr>
<td>-800</td>
</tr>
<tr>
<td>-700</td>
</tr>
<tr>
<td>-600</td>
</tr>
<tr>
<td>-500</td>
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<tr>
<td>-400</td>
</tr>
<tr>
<td>-300</td>
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<tr>
<td>-200</td>
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<tr>
<td>-100</td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>100</td>
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<tr>
<td>200</td>
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<tr>
<td>300</td>
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<tr>
<td>400</td>
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<tr>
<td>500</td>
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<tr>
<td>600</td>
</tr>
<tr>
<td>700</td>
</tr>
<tr>
<td>800</td>
</tr>
<tr>
<td>900</td>
</tr>
</tbody>
</table>

Shaft Capacity ≥ 2 x Skin = 1542 Kips

(620 psi Grout Pressure & 1243 in² Tip Area)
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}'\) x 25') - Top-Down Test
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}\)’ x 25’) - Top-Down Test

Internal Forces during Top-Down Test

Failed Reaction Shafts (4’ x 55’)

Maximum Upward Displacements
- South Shaft – 0.58”
- North Shaft – 0.37”
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}\)’ x 25’) - Top-Down Test

Mobilized Resistance during Top-Down Test

- **Applied Load (Jack)**
- **Skin Above Side Grouted Zone**
- **Skin Along Side Grouted Zone**
- **Tip Resistance**

- **241 Kips**
- **523 Kips**
- **86 Kips**
- **850 Kips**

\(\Delta \approx 0.18\)”

61% of Applied Load Carried by Side Grouted Zone!!!
FDOT Test Site
Field Shaft (3-\(\frac{1}{2}\)’ x 25’)- Top-Down Test

Fully Mobilized above Side Grouted Zone

Not Fully Mobilized along Side Grouted Zone
## Ungrouted Drilled Shafts
### Predicted Capacity – Skin (Alpha & Beta)
(FHWA/AASHTO, 2007)

<table>
<thead>
<tr>
<th>Layer (#)</th>
<th>Soil Type</th>
<th>Depth (ft)</th>
<th>Depth to Mid-Point of Zone, ( z ) (ft)</th>
<th>Avg. Cone Tip Resist., ( Q_c ) (ton/ft²)</th>
<th>Vertical Stress, ( \sigma_v ) (lb/ft²)</th>
<th>Undrained Shear Strength, ( C_u ) (kip/ft²)</th>
<th>(1) Alpha Value, ( \alpha )</th>
<th>(2) Unit Side Resistance, ( f_{su1} ) (kip/ft²)</th>
<th>Surface Area (Top 8 ft), ( A_{side1} ) (ft²)</th>
<th>Side Resistance (Top 8 ft), ( q_{s1} ) (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clay</td>
<td>0 - 8</td>
<td>4</td>
<td>18.06</td>
<td>460</td>
<td>1</td>
<td>0.55</td>
<td>0.55</td>
<td>87.96</td>
<td>48</td>
</tr>
</tbody>
</table>

(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) Ultimate Unit Load Transfer in Side Resistance, \( f_{su} = \alpha C_u \)

<table>
<thead>
<tr>
<th>Layer (#)</th>
<th>Soil Type</th>
<th>Depth (ft)</th>
<th>Depth to Mid-Point of Zone, ( z ) (ft)</th>
<th>Avg. Uncorrected Blow Count (N-Value)</th>
<th>Vertical Effective Stress, ( \sigma_v' ) (lb/ft²)</th>
<th>(1) Beta Value (( \beta ))</th>
<th>(2) Corrected Beta Value (( \beta ))</th>
<th>(3) Unit Side Resistance, ( f_s ) (kip/ft²)</th>
<th>Surface Area, ( A_{side} ) (ft²)</th>
<th>Side Resist., ( q_s ) (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Sand</td>
<td>8 - 15</td>
<td>11.5</td>
<td>5.5</td>
<td>1122</td>
<td>1.0422</td>
<td>0.3821</td>
<td>0.43</td>
<td>77</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>Sand</td>
<td>15 - 25</td>
<td>20</td>
<td>16</td>
<td>1636</td>
<td>0.8963</td>
<td>0.8963</td>
<td>1.47</td>
<td>110</td>
<td>161</td>
</tr>
<tr>
<td>4</td>
<td>Sand</td>
<td>25 - 40</td>
<td>32.5</td>
<td>55</td>
<td>2456</td>
<td>0.7304</td>
<td>0.7304</td>
<td>1.79</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

(1) \( \beta_0 = 1.2 \) (if \( z < 5 \) ft); \( \beta_0 = 1.5 - 0.135v(z) \) (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, \( f_s = \beta \sigma_v' \)
### Ungrutoted Drilled Shafts

**Predicted Capacity - Skin & Tip**

*(FHWA/AASHTO, 2007)*

| 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, $A_T$ (in²) | 1385.44 |
| Tip Area, $A_T$ (ft²) | 9.62 |
| (1) Average Tip N-Value | 28 |
| (2) Unit Tip Resistance, $q_T$ (ton/ft²) | 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/ft²) = 0.6*N
(3) Tip Resistance, $Q_T$ (kip) = $A_T$(ft²)*$q_T$(ton/ft²)*2(kip/ton)

**566 Kips** Total Axial Resistance before Grouting (Conventional Drilled Shaft)
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
Estimated Total Capacity = Skin + Tip

Since,
Total Skin < Tip Spherical Expansion Pressure \times Tip Area

Total Capacity > 2 \times Skin = 2 \times 824
= 1648 \text{ Kips}

\[ \text{Total Capacity} > 2 \times \text{Skin} = 2 \times 824 = 1648 \text{ Kips} \]
## Side and Tip Grouted Shafts
### Predicted & Measured Capacities

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

<table>
<thead>
<tr>
<th></th>
<th>Above Side Grouted Zone (Top 15 ft of Shaft)</th>
<th>Along Side Grouted Zone (Bottom 10 ft of Shaft)</th>
<th>Total Side Resistance (Kip)</th>
<th>Tip Resistance (Kip)</th>
<th>Ultimate Load (Kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit Side Resistance (ksf)</td>
<td>Side Resistance (Kip)</td>
<td>Unit Side Resistance (ksf)</td>
<td>Side Resistance (Kip)</td>
<td></td>
</tr>
<tr>
<td>Ungrooved Drilled Shaft (Neglect Tip Resist.)</td>
<td>0.49</td>
<td>81</td>
<td>1.47</td>
<td>161</td>
<td>243</td>
</tr>
<tr>
<td>Ungrooved Drilled Shaft (Include Tip Resist.)</td>
<td>0.49</td>
<td>81</td>
<td>1.47</td>
<td>161</td>
<td>243</td>
</tr>
<tr>
<td>Side &amp; Tip Grouted Drilled Shaft, Kg Method</td>
<td>---</td>
<td>---</td>
<td>4.40</td>
<td>689</td>
<td>770</td>
</tr>
<tr>
<td>Side &amp; Tip Grouted Drilled Shaft, PMT Method</td>
<td>---</td>
<td>---</td>
<td>4.74</td>
<td>743</td>
<td>824</td>
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<tr>
<td>*Mobilized during Tip Grouting (Max)</td>
<td>0.53</td>
<td>87</td>
<td>4.37</td>
<td>684</td>
<td>771</td>
</tr>
<tr>
<td>**Mobilized during Top-Down Test (Max)</td>
<td>0.52</td>
<td>86</td>
<td>3.34</td>
<td>523</td>
<td>609</td>
</tr>
</tbody>
</table>

*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
References:


Thank You

Questions?