Evaluation and Guidance Development for Post-Grouted Drilled Shafts for Highways

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Overview

- Post-grouting Defined & Concept
- Objectives of Project
- State-of-the-Practice Summary
- Focus of Ongoing Research
Post-grouting Defined

- **What is post-grouting?**
  - "Post" = after
  - "Grouting" = placement of cementitious material

- **What and When (for our work)**
  - Injection of cementitious material, under pressure, into ground under or around drilled shaft for improvement of its performance under load
  - Performed after concrete of drilled shaft has been placed/cured, and before application of load

*Note: Focus of this study is on base-grouted drilled shafts.*
## Purpose of Post-grouting

- **Design verification**
  - Pre-mobilize tip-resistance
  - Verifying lower-bound resistance

- **Risk mitigation**
  - Reduce uncertainties with bottom cleanliness

- **Cost consideration**
  - Shorten shafts based on improved resistance
Drill borehole in soil/rock
Concept

Place reinforcement, NDT tubes, and post-grouting devices
Place concrete for drilled shaft
Attach grout lines and water flush the grout pipes w/in drilled shaft
(continue until return is clear)
After concrete has set/cured, begin post-grouting operation.

After flushing is complete, close valve at good grout return.
After concrete has set/cured, begin post-grouting operation.

After flushing is complete, close valve at good grout return.
Continue injection of grout until criteria is achieved.
Following post-grouting, base resistance has been mobilized and there is a reversal of side resistance.
### Objectives of Study

- **Develop consensus opinion**
  - Improved understanding of how it works
  - Appropriate application of post-grouting
  - Guidance documents to facilitate rational and reliable design and construction of post-grouted drilled shafts

- **Primary objectives**
  - Bound use of post-grouting for current state of knowledge
  - Quantify improvement mechanism(s) for post-grouting
  - Develop design methodology(ies) for appropriate use
  - Provide method(s) for verification
State-of-the-Practice

Overview of Post-grouting

- Post-grouting has been used worldwide for 50+ yrs
  - South America (Paraná River) – Bolognesi and Moretto (1973)

- United States
  - Early experience - Brusey (2000) described a project at the JFK airport, NY where side and tip grouting were performed
  - During last 15 years
    - Increased use mainly due to FL DOT sponsored research
    - Majority work performed by specialty geotechnical service firms

Image: From Bolognesi & Moretto (1973)
## State-of-the-Practice

<table>
<thead>
<tr>
<th>Mechanisms for Improving Performance</th>
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</table>

- 4 improvement mechanisms described in the literature

1. Due to “pre-loading” of drilled shaft
2. Due to improvement of the ground beneath the shaft tip
   - Densification of ground near tip of the shaft
   - Permeation of grout into ground at tip of the shaft
3. Due to enlarged tip area
4. Due to upward flow of grout around the perimeter of the shaft
State-of-the-Practice

Mechanisms for Improving Performance

- Fleming (1993) – Improvement due to pre-loading
  - Pre-loading effect produces no increase in ultimate capacity
  - Increases resistance mobilized at a displacement

Following post-grouting, shaft is “pre-loaded”
“negative” side resistance
“positive” tip resistance

Post-grouted shaft

Ungrounded shaft

Side resistance mobilized from “X”

Tip resistance mobilized from “Y”
State-of-the-Practice

Mechanisms for Improving Performance

- Ruiz (2005) - improvement in shaft resistance due to
  - Compression of the soil under the pile tip ("stiffer" response)
  - Redistribution of residual stresses along the shaft due to the upward movement of the shaft during grouting ("pre-loading")
  - Increase of the tip area due to the formation of a grout bulb (increased ultimate tip resistance and stiffness)
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• Muchard and Farouz (2009)
  • Improved side resistance due to migration of grout upward along and around circumference of shaft

• Side resistance
  • U.S. practice, this improvement has been largely ignored
    • Presently - study in FL on the effects of side grouting
  • In Chinese practice, this improvement has been routinely accounted for
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Grouting Mechanisms

• Tip grouting mechanisms
  • Stem (orifice) distribution system
  • Sleeve-port (tube-á-manchette) distribution system
  • Flat-jack distribution system
  • Gravel pack w/ sleeve-port or flat-jack distribution system

• Grout tubes
  • Typically - 1-inch diameter, schedule 80 PVC
  • Also - CSL tubes have been used - 2-inch diam, sched 40 steel
  • Transition to steel pipe required for segments that extend through the top of shaft
State-of-the-Practice

Grouting Mechanisms

- Stem Distribution System
  - Pipe or (single or multiple) cored hole(s) in shaft
  - Typically used as a remediation technique (not planned)
  - Not a very efficient option when compared to other distribution systems (i.e., those installed prior to concrete placement)
  - Does not lend itself to a phased grouting sequence

Source: Littlejohn et al (1983)
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**Grouting Mechanisms**

- **Sleeve-port (tube-á-manchette) Distribution System**
  - Steel plate – separation
  - Scuff ring – for strength and to “contain” grout
  - Gravel Pack - to level base

Source: Mullins et al (2001)
State-of-the-Practice

- Sleeve-port Distribution System
  - Shafts with a flat bottom

Source: Sliwinski and Fleming (1984)

Source: FHWA (2010)

Grouting Mechanisms

- Courtesy: Applied Foundation Testing
State-of-the-Practice

**Grouting Mechanisms**

- **Sleeve-port (tube-á-manchette) Distribution System**
  - Can be shaped for non-flat bottom
  - Down-hole grabs (clamshell) or reverse-circulation methods


Source: Castelli (2012)
State-of-the-Practice

• Flat-jack ("Pre-load cell") Distribution System
  • Grout is injected between steel plate and rubber membrane (expands)

Source: FHWA (2010)

Source: Mullins et al (2001)
## State-of-the-Practice

### Grout Properties

- **Most common**
  - Cement-based (simple water-cement mix)
  - Type I/II cement
  - (Admixtures - control flowability and set times)

- **Typical water/cement ratios** – 0.4 to 0.6 (high as 0.7)

- **Important properties of grout mix**
  - Flow, pumpability, viscosity, comp. strength, colloidal nature

- **Quality control (in field)**
  - Specific gravity measured using mud balance
  - Fluidity (flowability) measured with a flow cone
State-of-the-Practice

Measurements and Quality Control

- Quality Control during grouting
  - Grout Pressure
    - Measured with a bourdon gauge
    - Min. pressure is specified
    - Max. pressure is determined (ground, grouting conditions)
  - Grout Volume
    - Min. and max. volume (cubic feet or liters) is specified
  - Top-of-Shaft Displacement
    - Max. displacement is specified (typically ¼ to ½ inch)

- Phased grouting
  - Performed if desired pressure / grout volume not achieved; upward movement excessive
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Measurements and Quality Control

Pressure and Shaft Displacement vs. Time

Pressure and Volume vs. Time

Shaft Displacement vs. Grout Force
State-of-the-Practice

Measurements and Quality Control

- Quality Control during grouting - Strain gauges
  - How effectively grout has distributed across base of shaft
  - Compared to grout pressure and shaft uplift

Courtesy: Applied Foundation Testing
State-of-the-Practice

Methods

• **Tip Capacity Multiplier** (Mullins et al, 2006)
  • Predicts tip resistance at a given normalized shaft displacement
  • Sustained grout pressure is the most important factor
  • Based on 26 load tests; diam = 2-4ft; length = 25-60ft; sands
  • $GPI = \text{ratio} = \text{sustained grout pressure} / \text{ungrouted unit base resistance at a displacement of 5\%D}$
  • Mullins et al:
    \[
    TCM = \left[0.713 \cdot [GPI \cdot (%D)]^{0.364}\right] + \frac{(%D)}{0.4(%D) + 3}
    \]
  • Dapp and Brown, 2010 (Audubon Br. only – 7.5ft diam; 200ft):
    \[
    TCM = \left[0.713 \cdot [GPI \cdot (%D)]^{0.200}\right] + \frac{(%D)}{4.0(%D) + 6}
    \]
State-of-the-Practice

- **Tip Capacity Multiplier**

Source: Dapp and Brown (2010)
• **Chinese Design Method** (Hu et al, 2001; Duan & Kulhawy, 2009)
  - Empirical method based on data from 186 sites
  - Does not explicitly include sustained grout pressure
  - Presumed grouting procedures (i.e., grout pressures, grout characteristics, grouting sequence, etc.) are standardized
  - Ultimate shaft capacity predicted using
    \[
    Q_{ult} = \pi B \sum \lambda_{si} q_{si} d_i + 0.25\pi B^2 \lambda_P q_P
    \]
• **Guoliang et al (2012)**

<table>
<thead>
<tr>
<th>Increase Coefficient</th>
<th>Clayey Soil or Silt</th>
<th>Silty Sand</th>
<th>Fine Sand</th>
<th>Medium Sand</th>
<th>Coarse Sand</th>
<th>Gravel Sand</th>
<th>Detritus Soil</th>
</tr>
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<tbody>
<tr>
<td>(\lambda_{si})</td>
<td>1.3-1.4</td>
<td>1.5-1.6</td>
<td>1.5-1.7</td>
<td>1.6-1.8</td>
<td>1.5-1.8</td>
<td>1.6-2.0</td>
<td>1.5-1.6</td>
</tr>
<tr>
<td>(\lambda_P)</td>
<td>1.5-1.8</td>
<td>1.8-2.0</td>
<td>1.8-2.1</td>
<td>2.0-2.3</td>
<td>2.2-2.4</td>
<td>2.2-2.4</td>
<td>2.2-2.5</td>
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</tbody>
</table>
• **Load Transfer Approach** (Ruiz, 2005)
  - Theoretically-derived nonlinear curves (follows Fleming, 1993)
  - Load transfer attributed to three phenomena
    - Compression of soil under shaft tip
    - Redistribution of residual stresses due to upward movement
    - Increase in shaft tip area due to formation of grout bulb
  - t-z curve (side resistance)
    \[
    Z = \frac{\tau_o r_o}{G_o G} \cdot \ln \left\{ \frac{\left(\frac{r_m}{r_o}\right)^g - f \cdot \left(\frac{\tau_o}{\tau_{\text{max}}}\right)^g}{1 - f \cdot \left(\frac{\tau_o}{\tau_{\text{max}}}\right)^g} \right\}
    \]
  - Q-z curve (base resistance)
    \[
    Z_{\text{base}} = \frac{Q_b \cdot (1 - \gamma)}{4G_o r_o} \cdot \frac{Q_b \cdot (1 - \gamma)}{1 - f \cdot \left(\frac{Q_b}{Q_{b-\text{max}}}\right)^g}
    \]
**State-of-the-Practice**

- **Simplified Design Approach** (McVay et al, 2010)
  - Based on tests on reduced scale individual shafts & groups of shafts in a test chamber
  - Conservative approach
    - Neglects contributions from increased side resistance
    - Neglects contributions from increased base resistance due to formation of an enlarged tip
    - Accounts for increased capacity due to preloading
      \[ Q_{ult} = 2F_s + F_p \]
  - Rationale follows that the shaft has been upwardly pre-loaded so that this load must first be overcome prior to mobilizing “downward” side resistance
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Preliminary Findings - Data in Sands

Graphs showing the relationship between measured mobilized unit resistance and other variables, with linear regression lines and correlation coefficients.
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Preliminary Findings
- Data in Clays

Graphs showing measured mobilized unit resistance and normalized difference in resistance against various parameters.
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Preliminary Findings - Data in Silts

1. **Base (SR)**
   - Equation: $y = 0.944x + 53.033$
   - $R^2 = 0.9944$

2. **Skin (SR)**
   - Equation: $y = 1.010x - 0.0199$
   - $R^2 = 0.9841$

3. **Total (SR)**
   - Equation: $y = 1.148x + 33.115$
   - $R^2 = 0.9994$

4. **Normalized Difference in Resistance**
   - Symbols used: Diff - Base Resistance (SR), Diff - Skin Resistance (SR), ΔDiff - Total Resistance (SR)
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Preliminary Findings - Data in Gravels

- Data in Gravels

- Findings

- Preliminary

- Practice

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Preliminary Findings - Data in Rock

- Data in Rock

- Preliminary Findings

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<td>Focus of ongoing research</td>
<td>Ground improvement at tip</td>
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<tr>
<td>• More detailed analysis on existing data</td>
<td>• Enlargement of shaft tip</td>
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<td>• Analyzing improvement mechanisms</td>
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<td>• Grouting delivery mechanisms, characteristics, and process</td>
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<td>• Shaft Performance – Stiffness vs. Resistance vs. Capacity</td>
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<tr>
<td>• Quality control / quality assurance assessment methods</td>
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<tr>
<td>• Pre-loading and stress reversal during post-grouting</td>
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Thank you for your attention!!

Questions??