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

Antonio Marinucci, Ph.D, PE
Director of Operations, ADSC
Silas Nichols, PE
Principal Geotechnical Engineer, FHWA
Benjamin S. Rivers, PE
Geotechnical Engineer, FHWA – Resource Center

U.S. Department of Transportation
Federal Highway Administration

ADSC
The International Association of Foundation Drilling

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

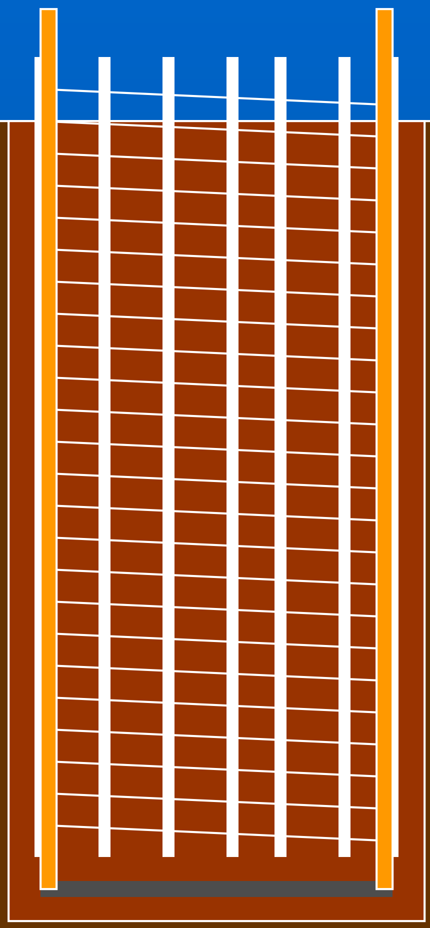
Note: Focus of this study is on base-grouted drilled shafts.

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

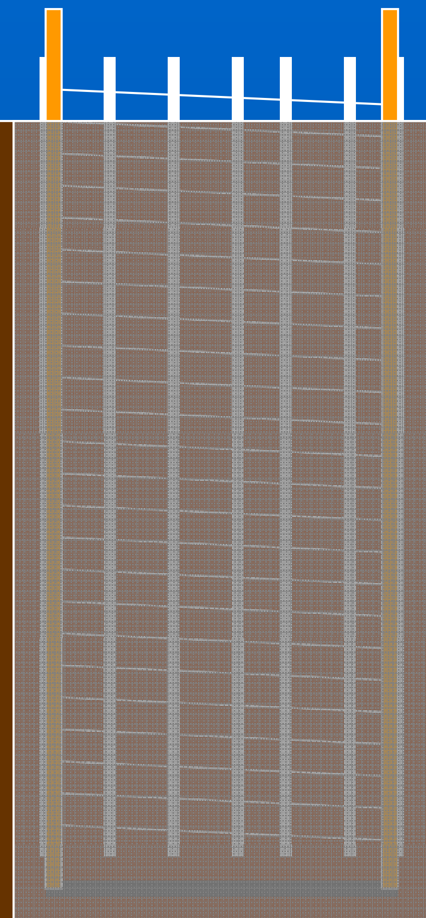
Concept

Concept



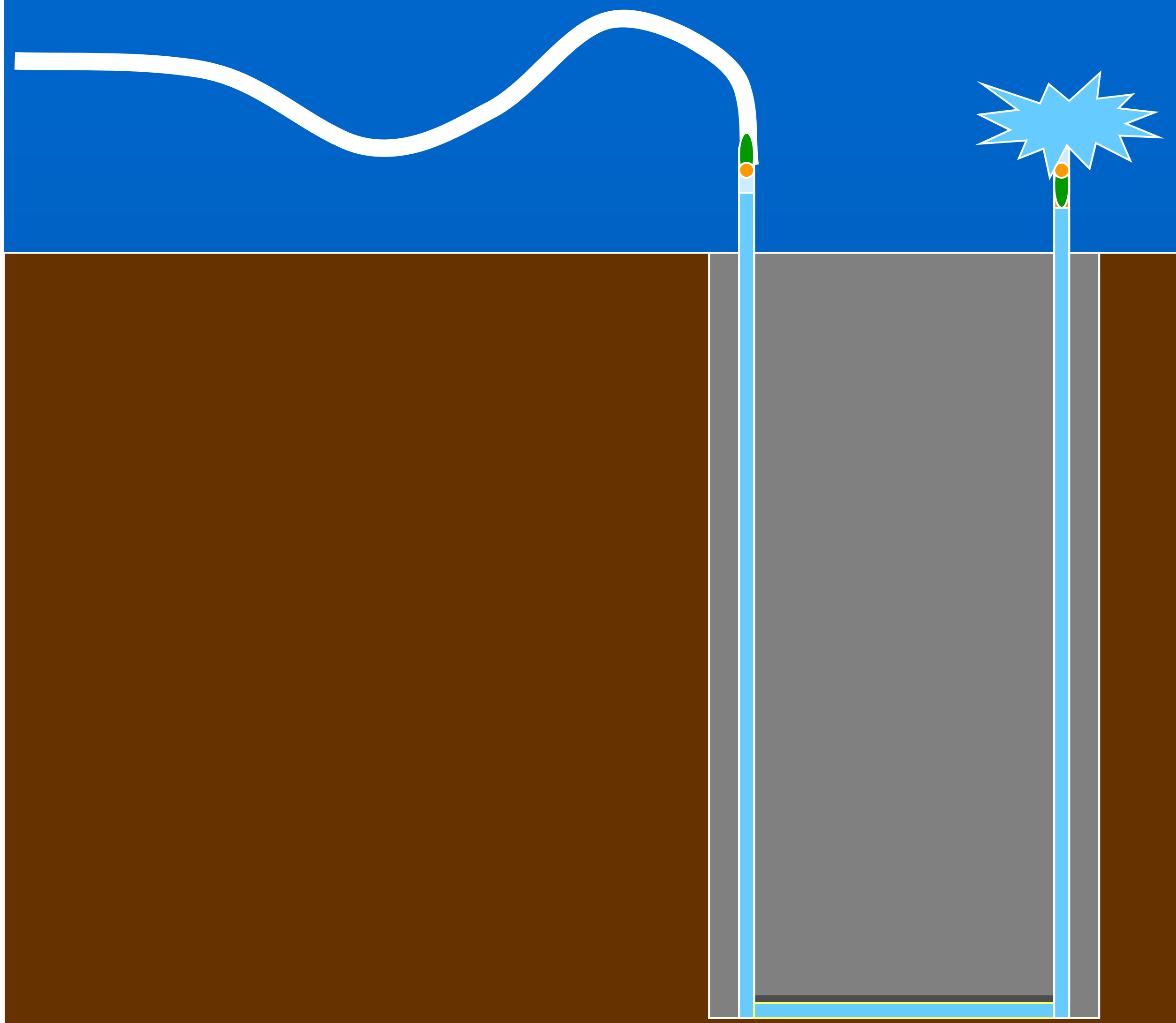
Place reinforcement, NDT tubes, and post-grouting devices

Concept



Place concrete for drilled shaft

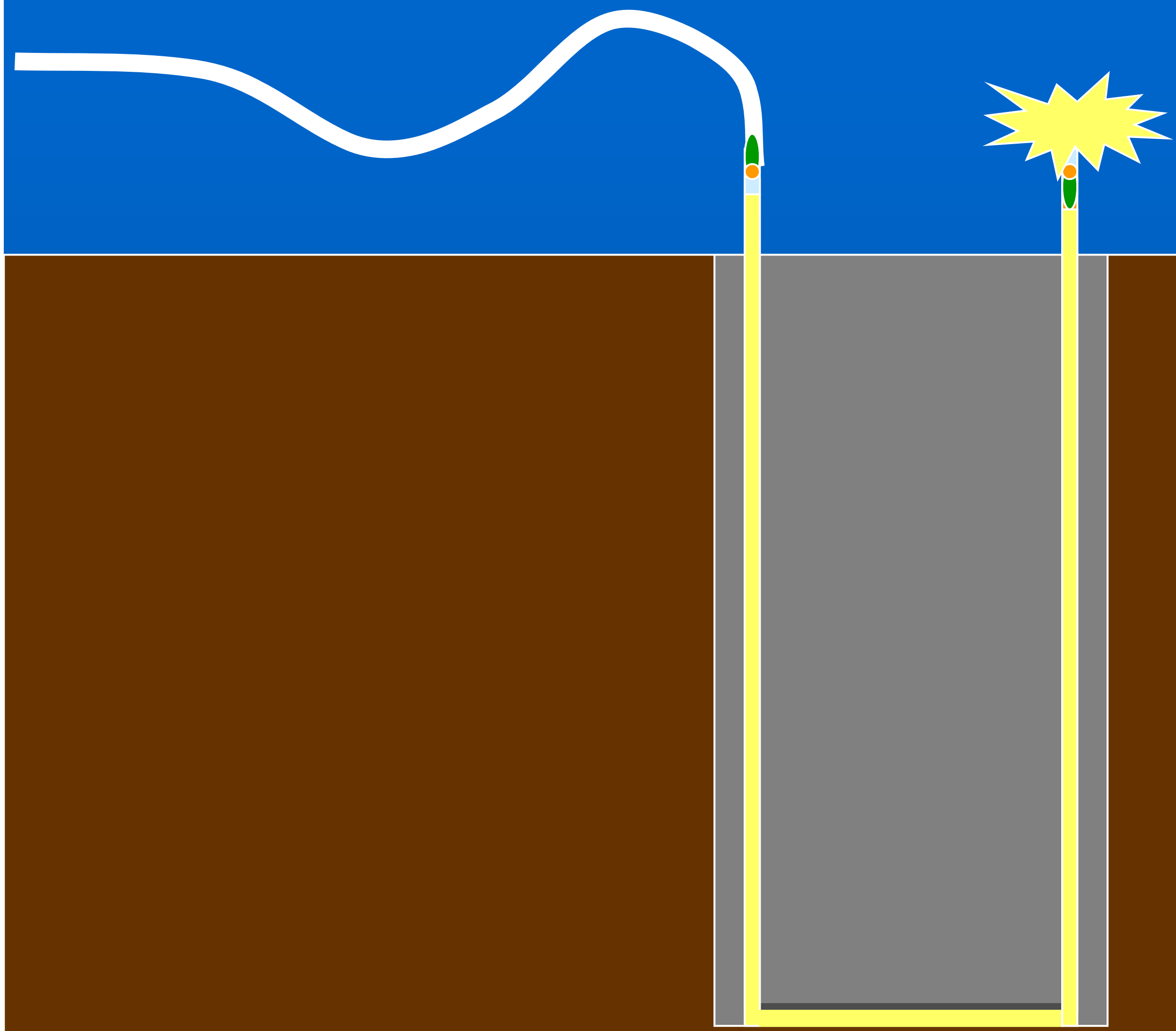
Concept



Attach grout lines and water flush the grout pipes w/in drilled shaft

(continue until return is clear)

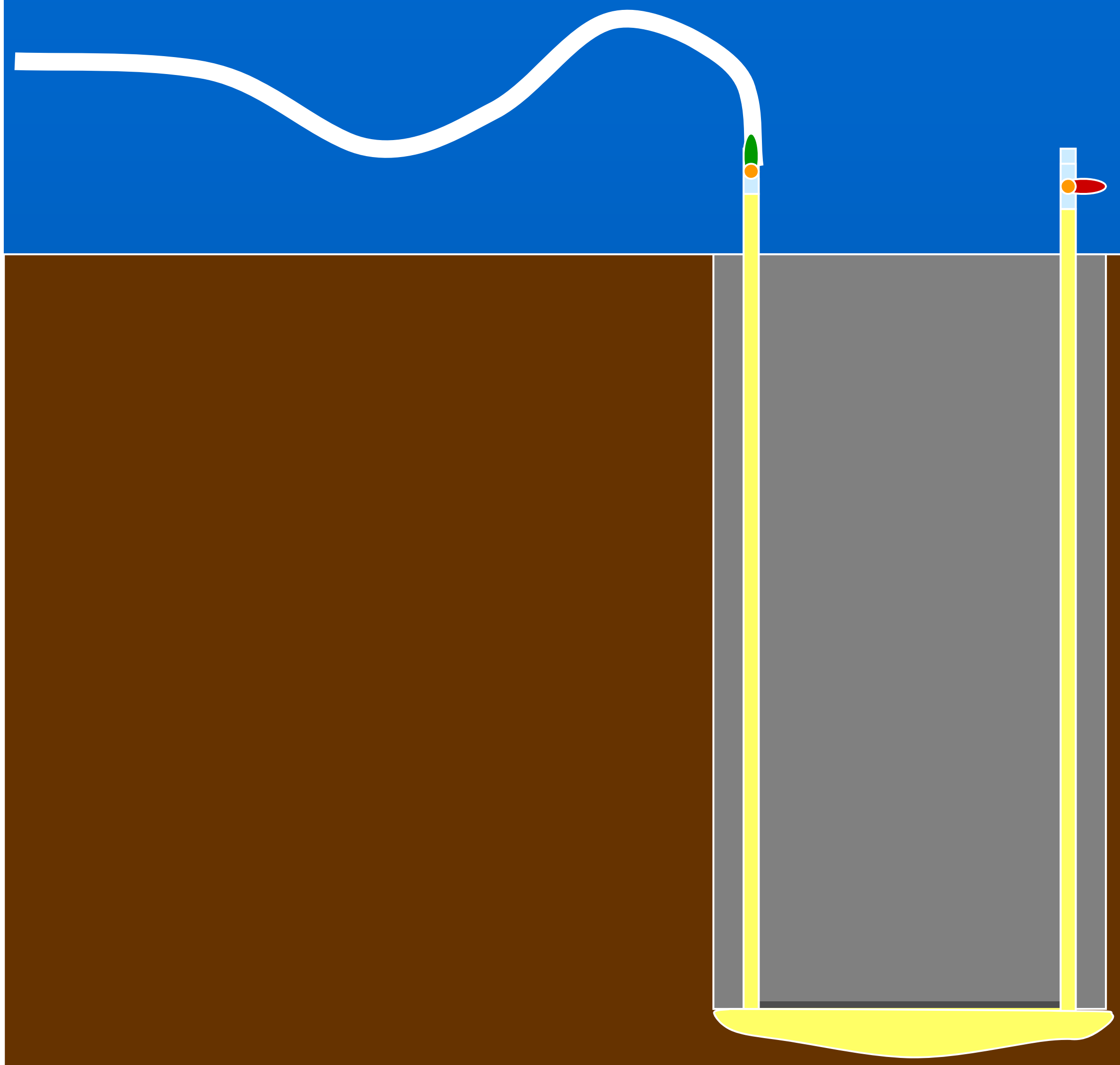
Concept



After concrete has set/cured, begin post-grouting operation

After flushing is complete, close valve at good grout return.

Concept



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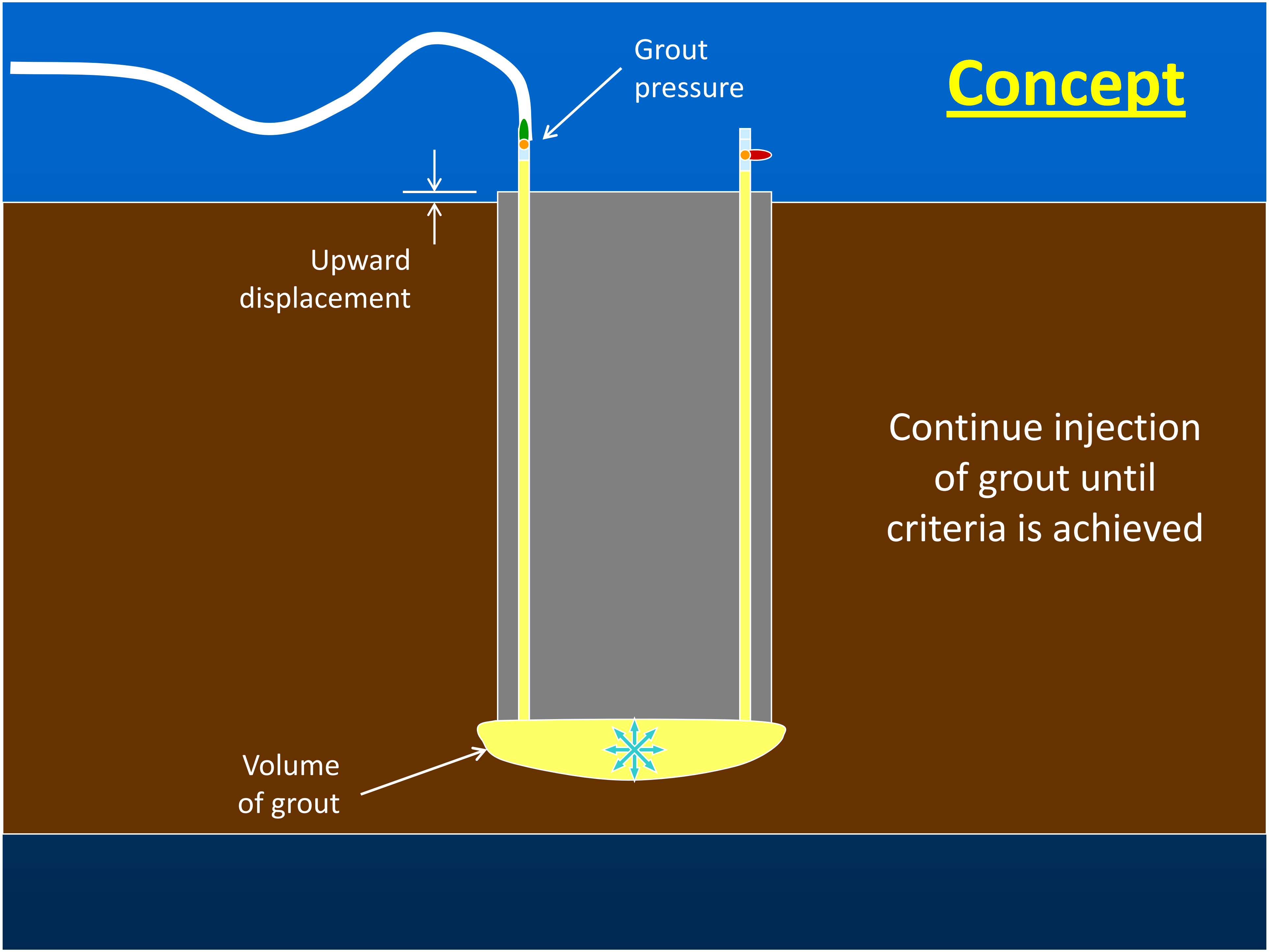
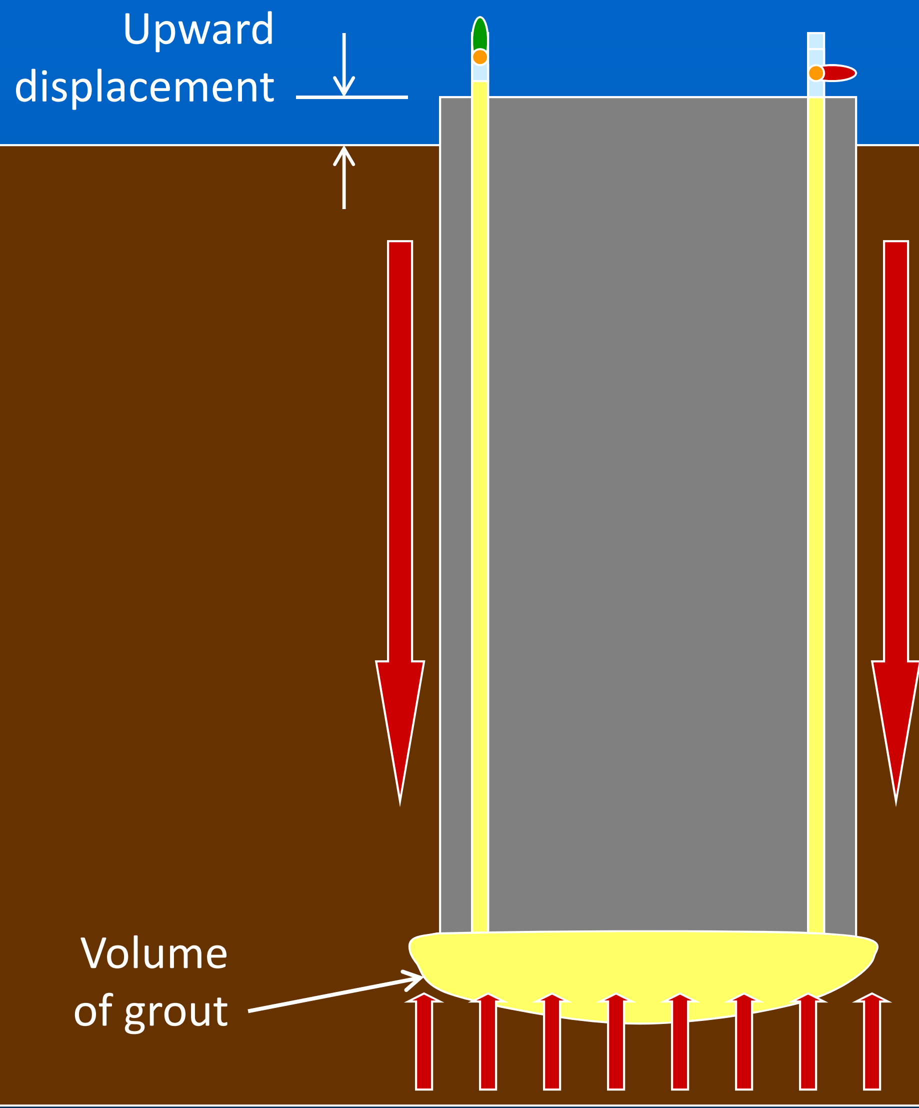

Concept
Grout pressure
Upward displacement
Continue injection of grout until criteria is achieved
Volume of grout

Concept

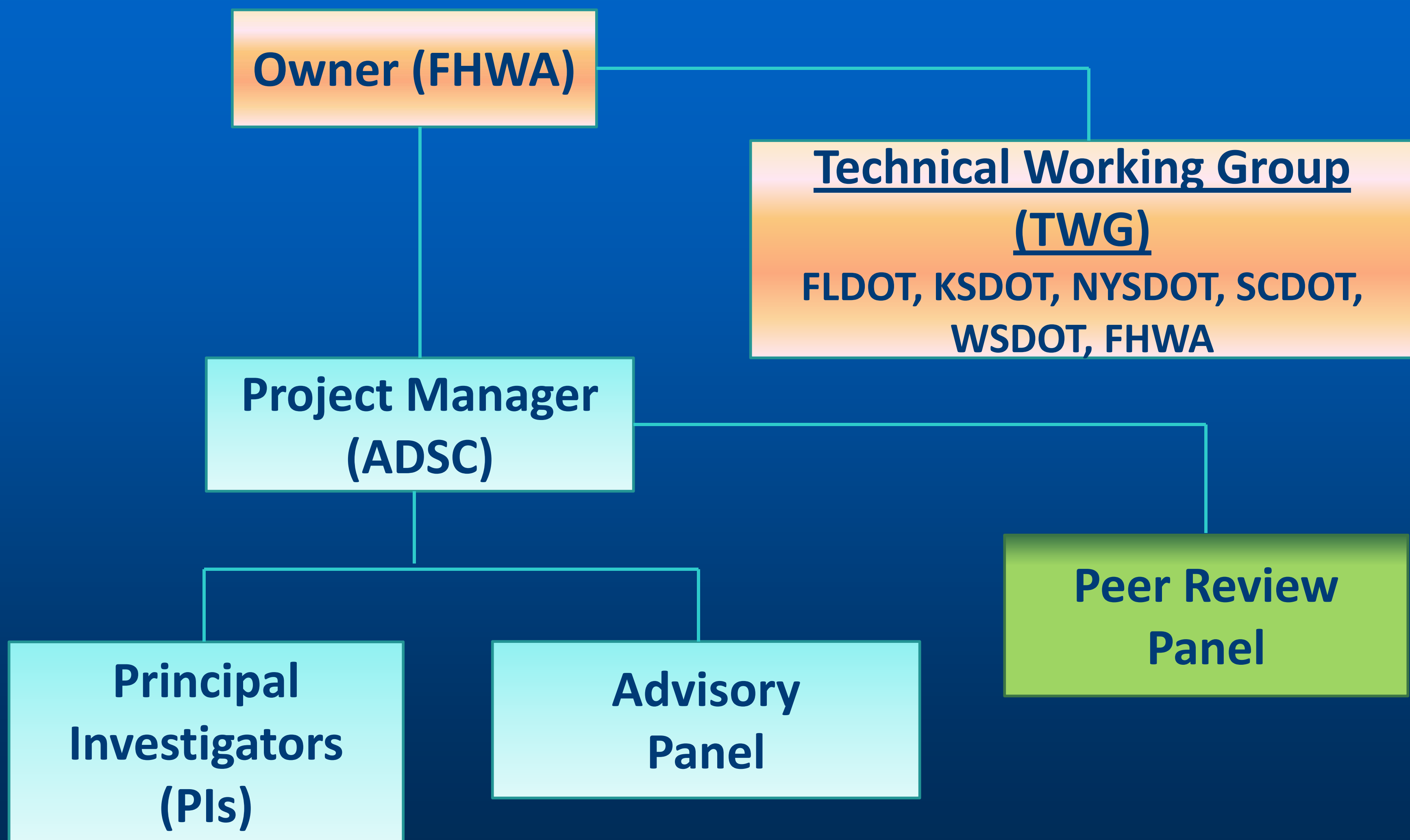


Following post-grouting, base resistance has been mobilized and there is a reversal of side resistance

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

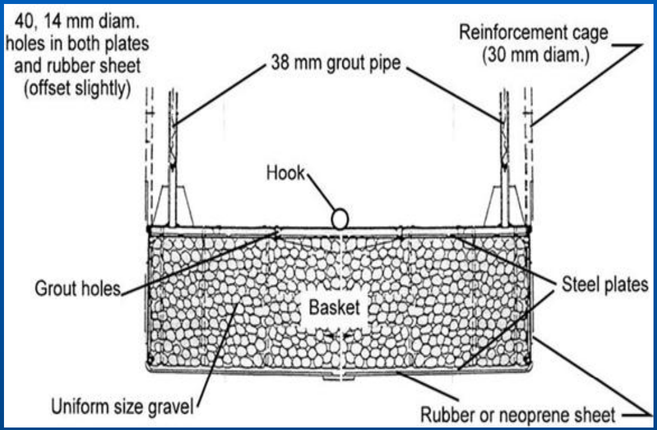
Project Structure



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)
  - England – Sliwinski and Fleming (1984)
  - Asia – Lin et al (2000)
  - Poland – Klosinski et al (2006)



- 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

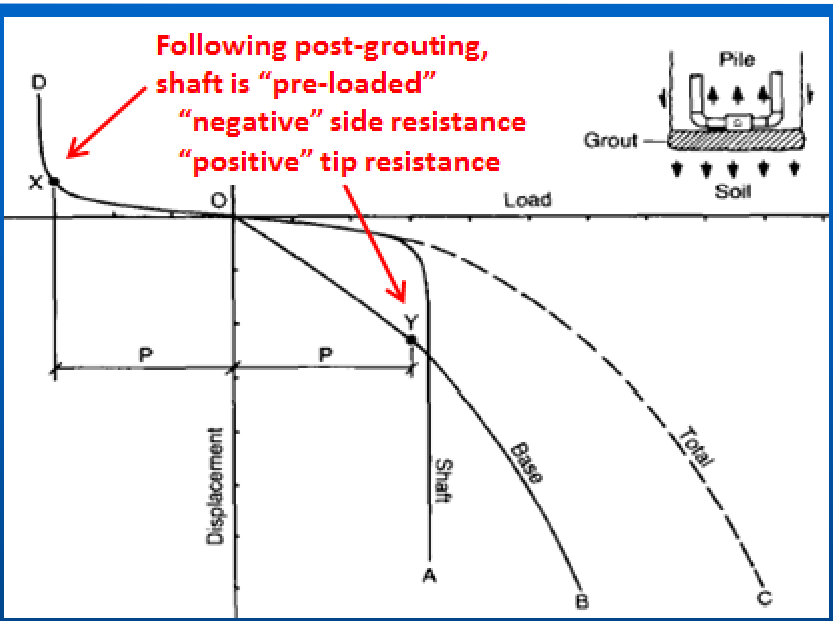
Mechanisms for Improving Performance

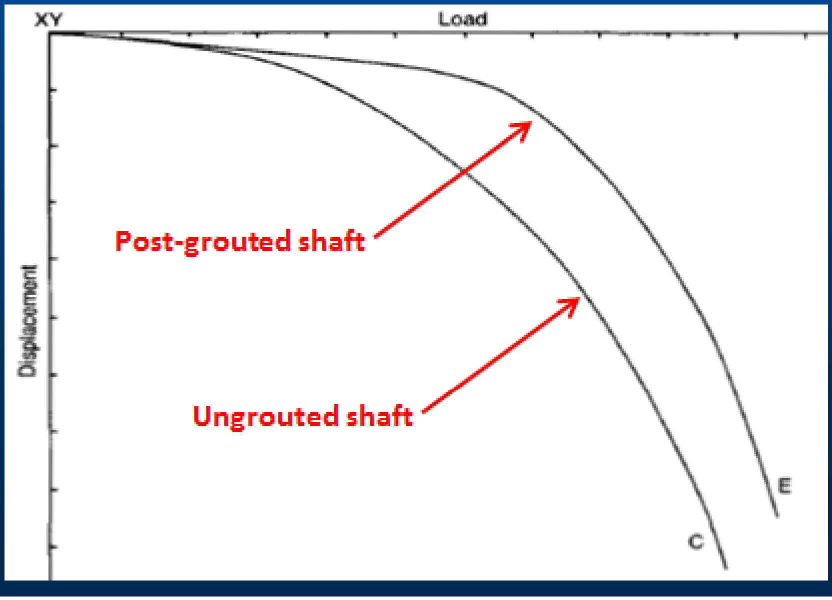
- 4 improvement mechanisms described in the literature
  1. Due to "pre-loading" of drilled shaft
  2. Due to improvement of the ground beneath the shaft tip
     - Densification of ground near tip of the shaft
     - Permeation of grout into ground at tip of the shaft
  3. Due to enlarged tip area
  4. Due to upward flow of grout around the perimeter of the shaft

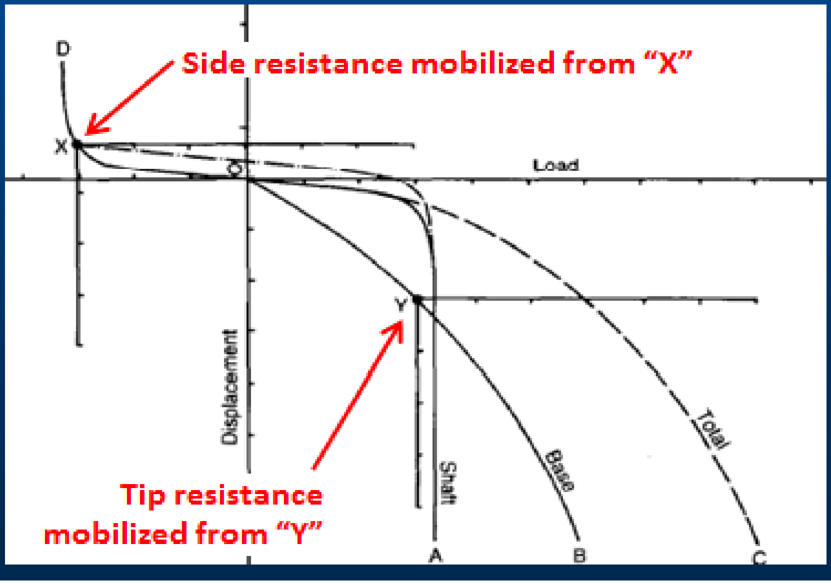
State-of-the-Practice

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





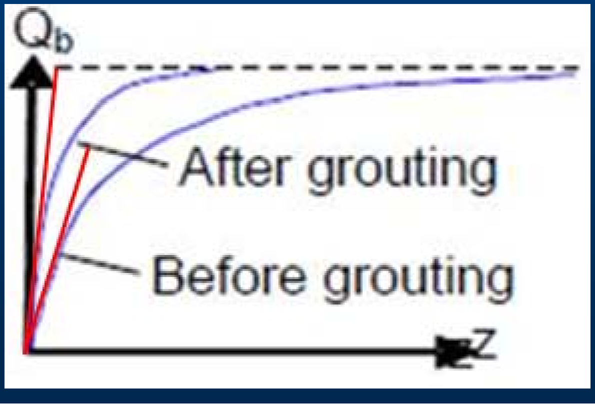


State-of-the-Practice

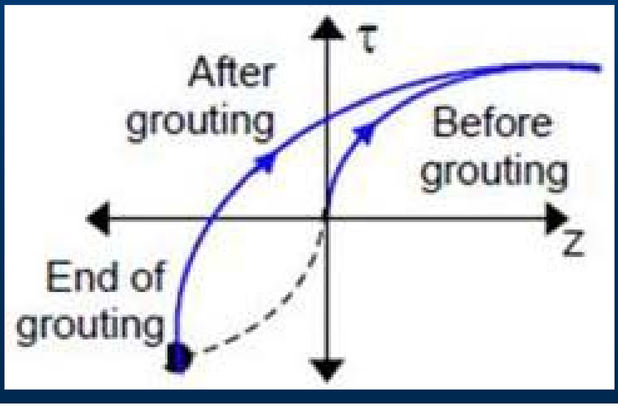
Mechanisms for Improving Performance

- 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)

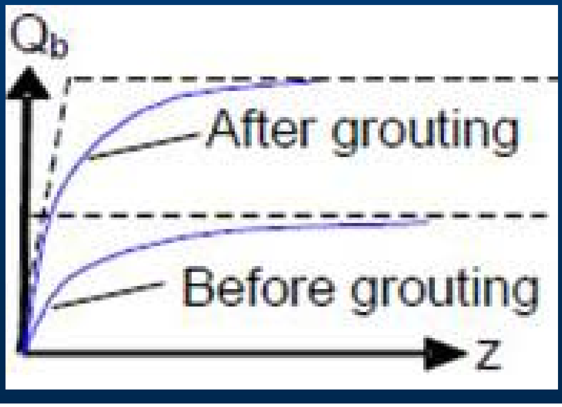
Compression of the soil under the pile tip



Redistribution of stresses along shaft due to upward movement during grouting



increase of pile tip area due to formation of grout bulb



State-of-the-Practice

Mechanisms for Improving Performance

- 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

State-of-the-Practice

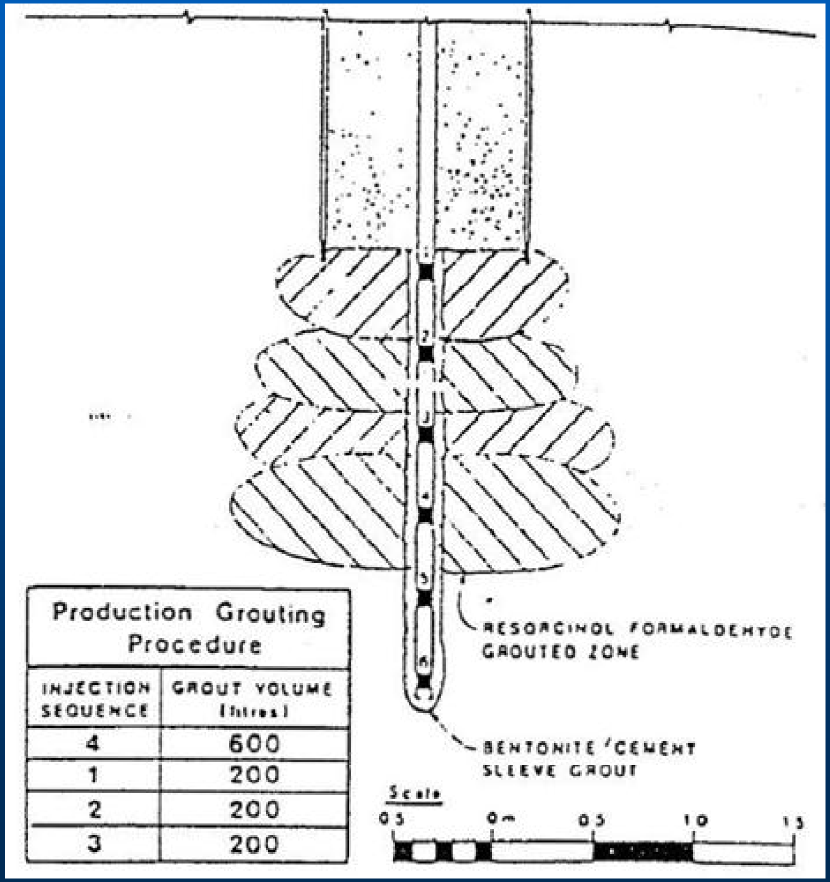
Grouting Mechanisms

- 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



Production Grouting Procedure	
INJECTION SEQUENCE	GROUT VOLUME (litres)
4	600
1	200
2	200
3	200

Source: Littlejohn et al (1983)

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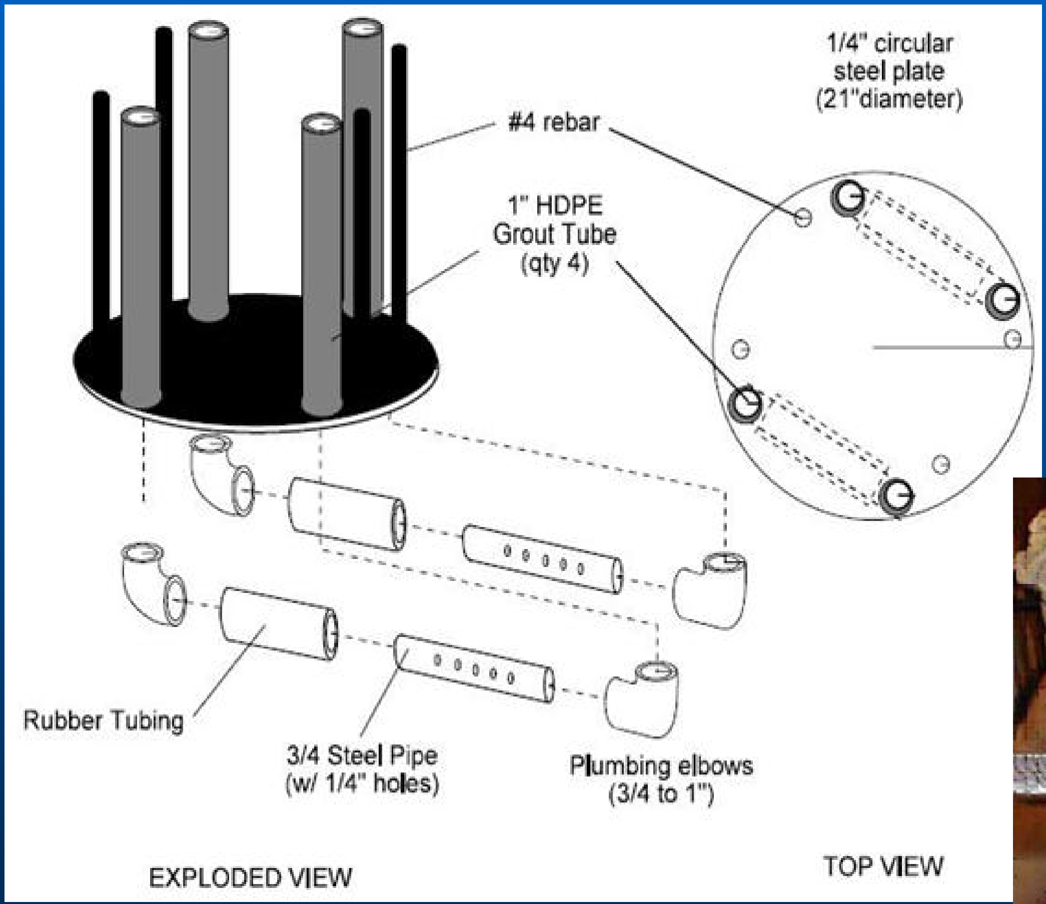
Grouting Mechanisms

- Sleeve-port (tube-á-manchette) Distribution System



Source: Mullins et al (2001)

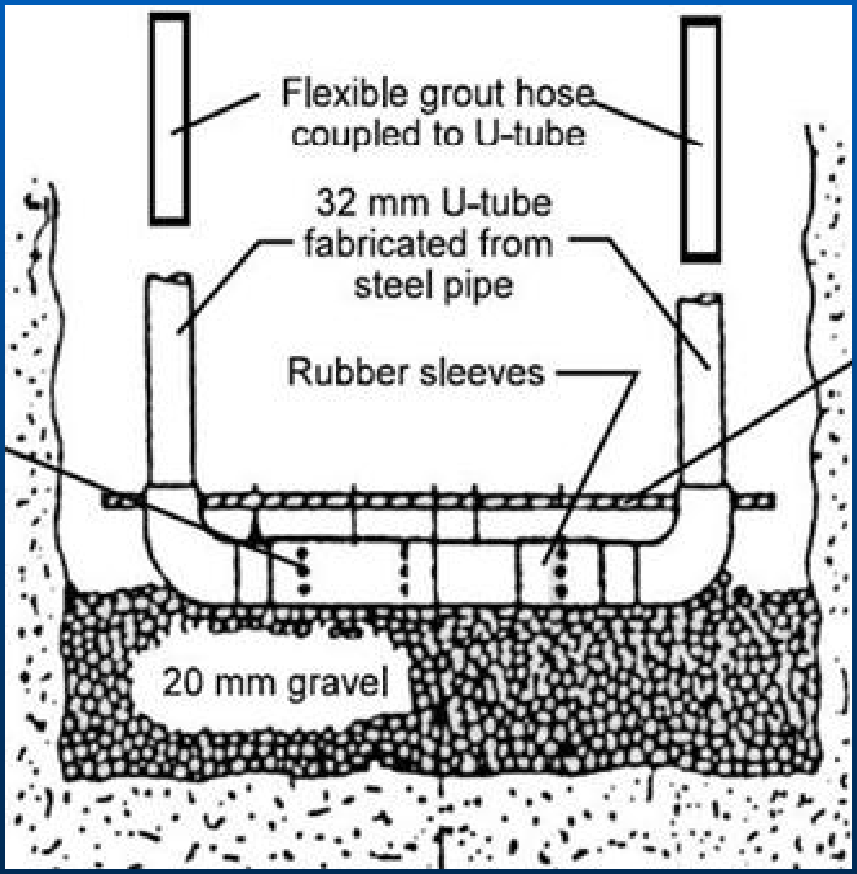
- Steel plate – separation
- Scuff ring – for strength and to "contain" grout
- Gravel Pack - to level base

Source: Mullins et al (2001)

State-of-the-Practice

Grouting Mechanisms

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



Source: Sliwinski and Fleming (1984)

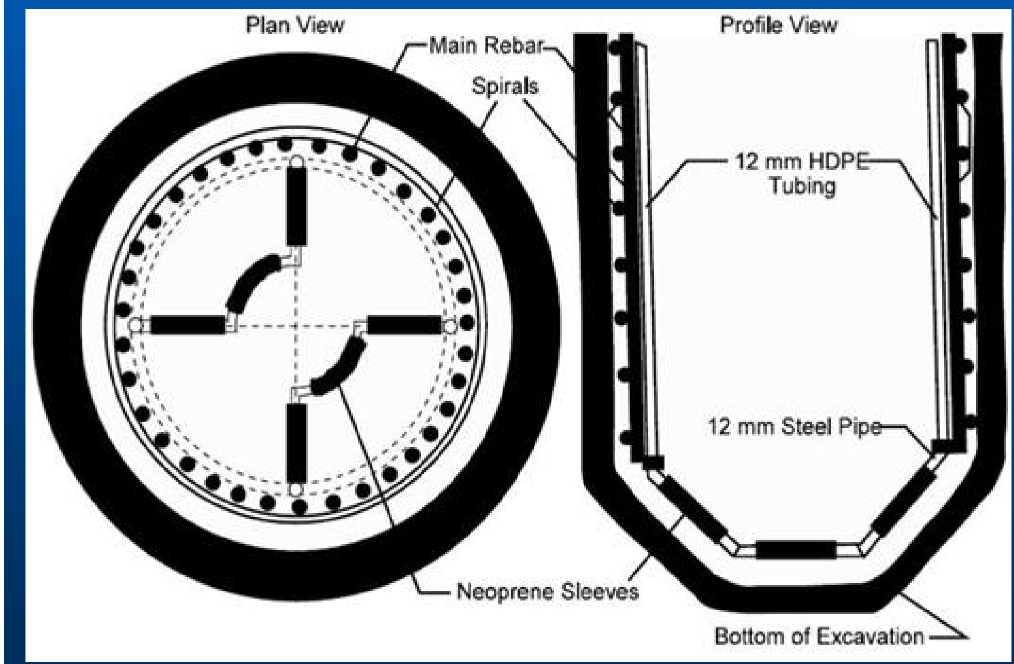
Courtesy: Applied Foundation Testing

Source: FHWA (2010)

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: Lin et al (2000)

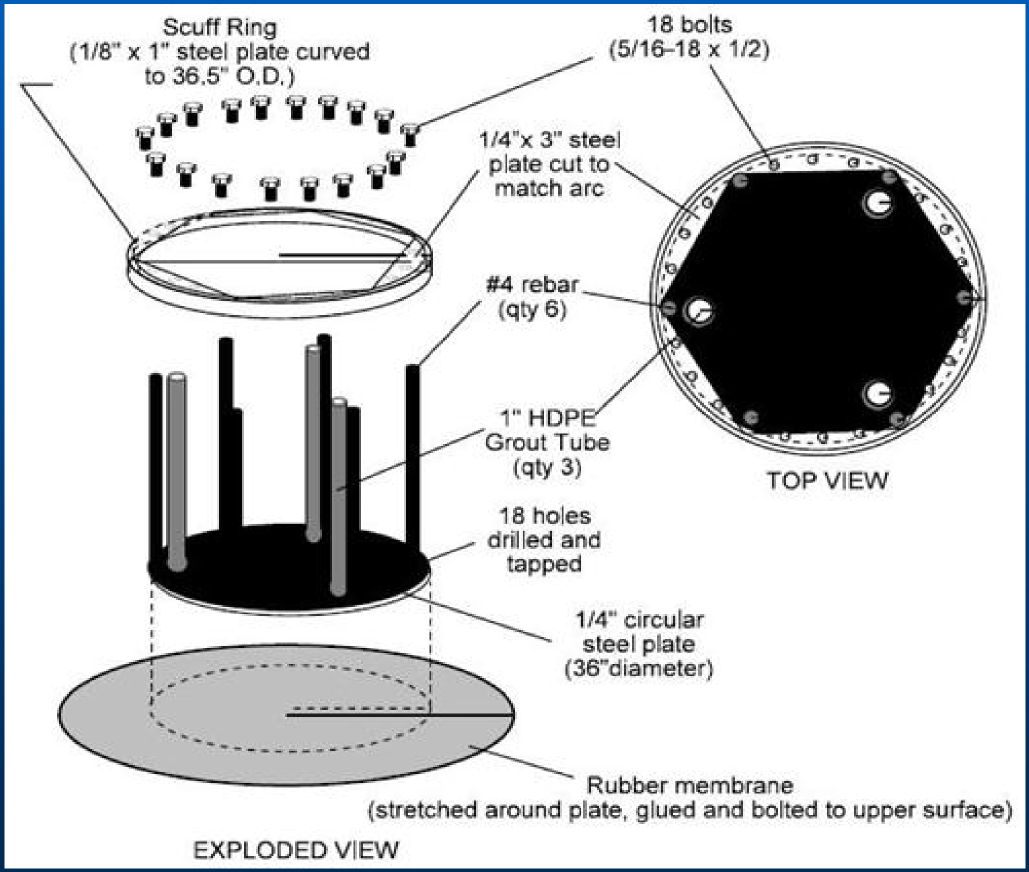
Source: Castelli (2012)

State-of-the-Practice

Grouting Mechanisms

- 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

- 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

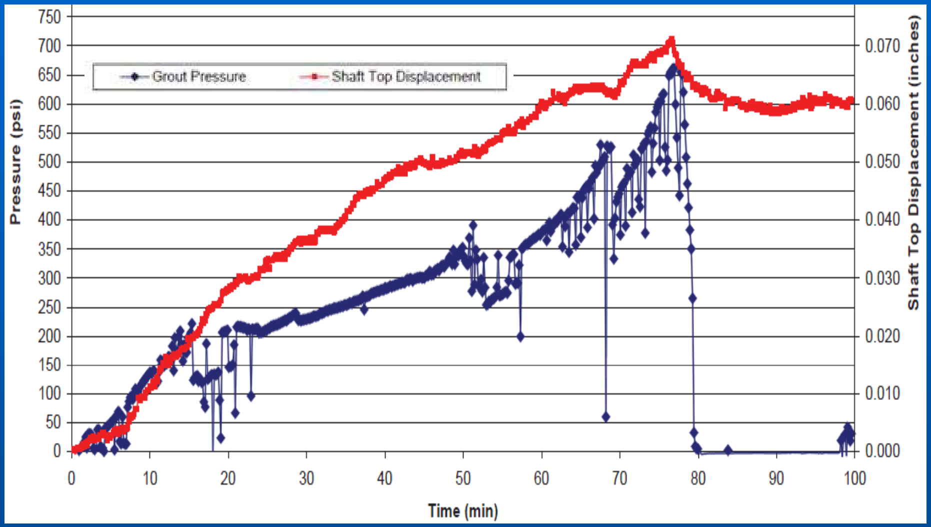
Measurements and Quality Control

- Quality Control during grouting
  - Grout Pressure
    - Measured with a bourdon gauge
    - Min. pressure is specified
    - Max. pressure is determined (ground, grouting conditions)

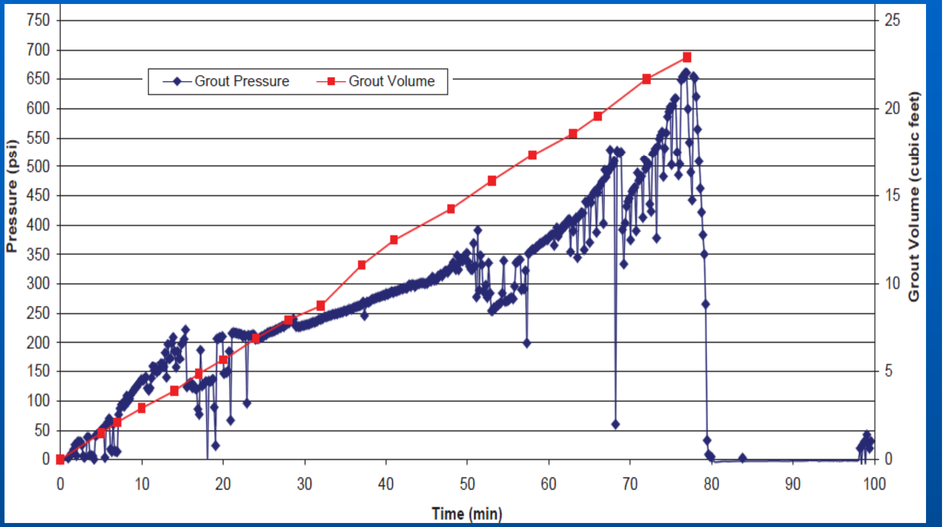
  - Grout Volume
    - Min. and max. volume (cubic feet or liters) is specified
  - Top-of-Shaft Displacement
    - Max. displacement is specified (typically ¼ to ½ inch)
- Phased grouting
  - Performed if desired pressure / grout volume not achieved; upward movement excessive

State-of-the-Practice

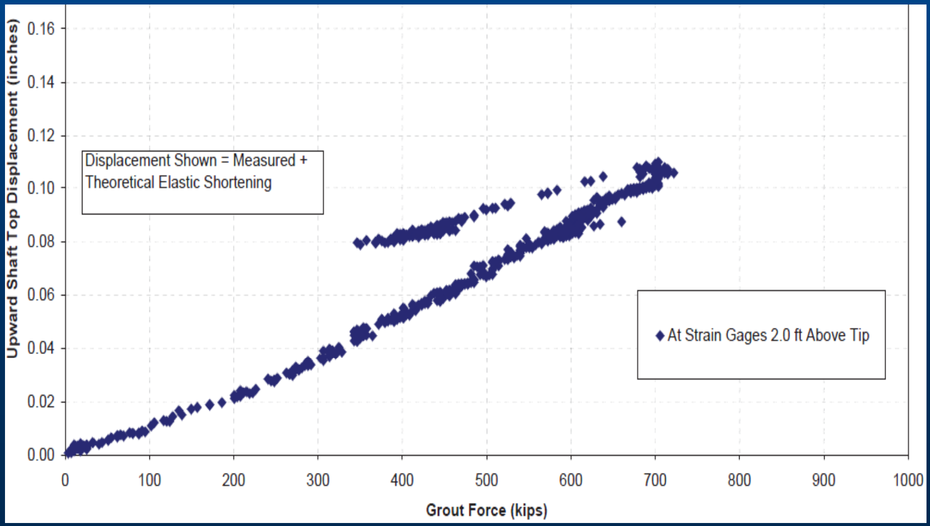
Measurements and Quality Control



Pressure and Shaft Displacement *vs.* Time



Pressure and Volume *vs.* Time

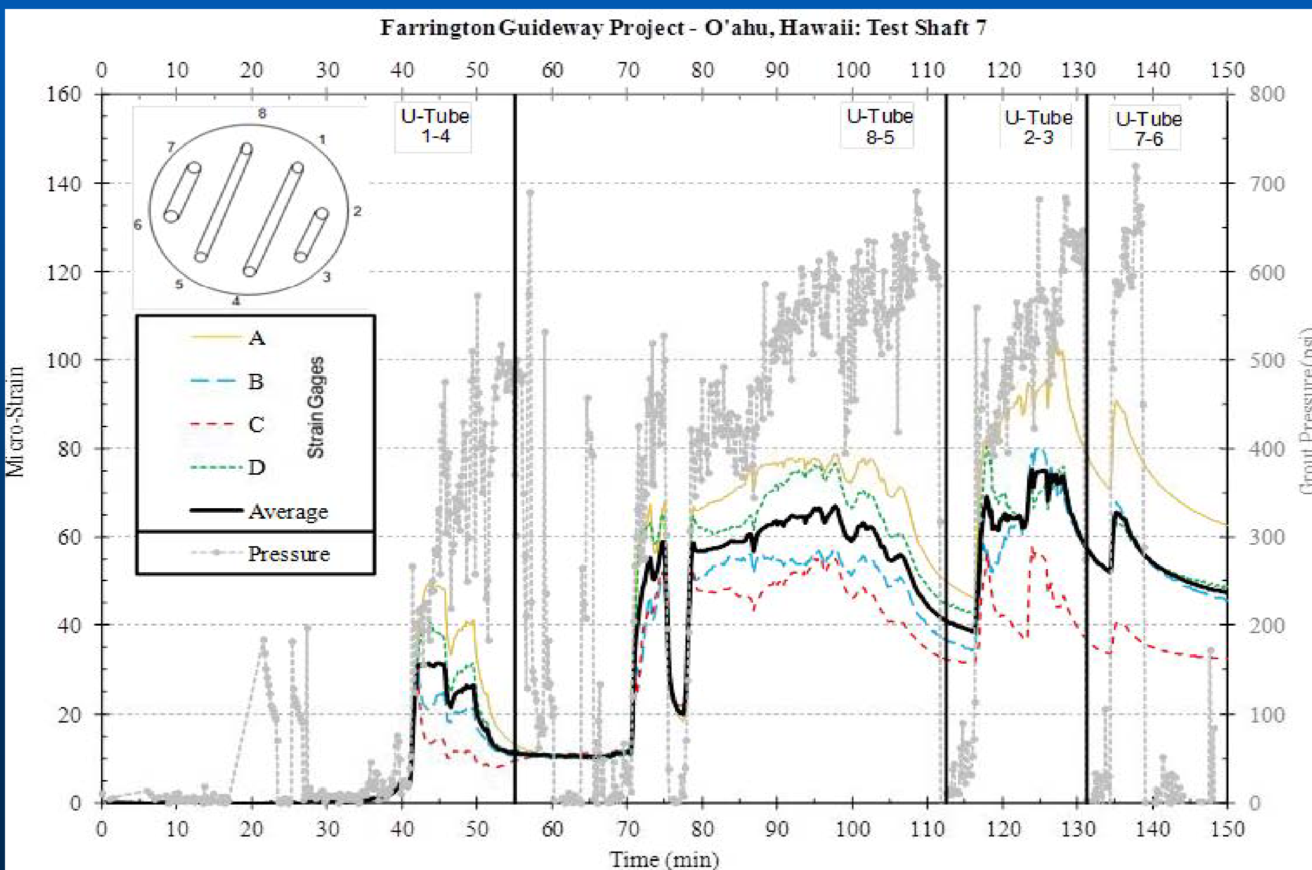


Shaft Displacement *vs.* Grout Force

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

Design 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 = ratio = sustained grout pressure / ungrouted unit base resistance at a displacement of 5%D
  - Mullins et al:

$$TCM = \left[0.713 \cdot [GPI \cdot (\%D)]^{0.364}\right] + \frac{(\%D)}{0.4(\%D) + 3}$$

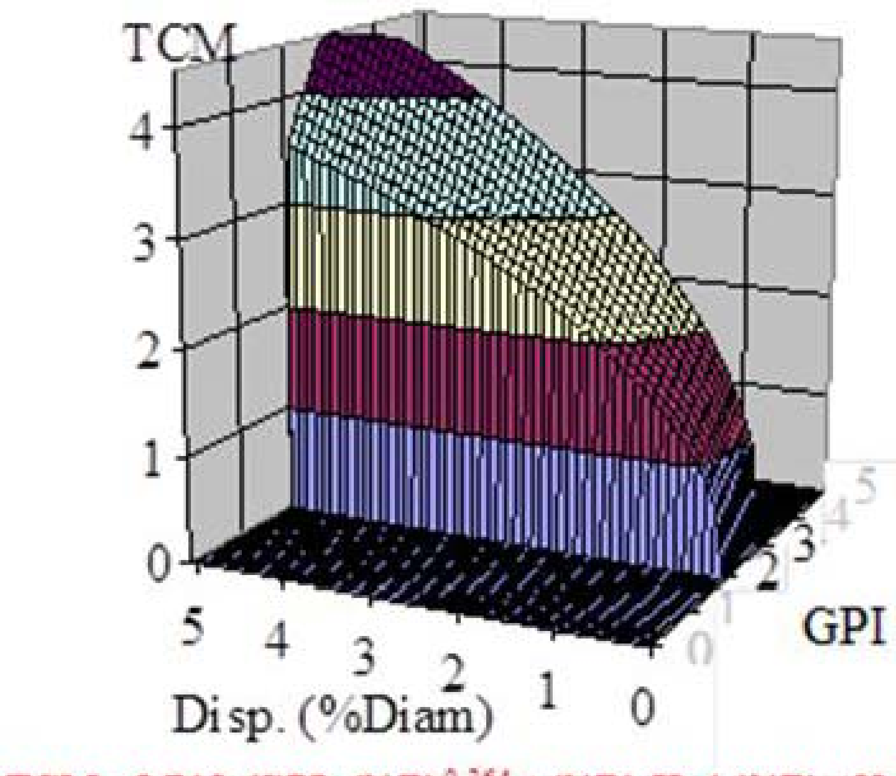
  - Dapp and Brown, 2010 (Audubon Br. only – 7.5ft diam; 200ft):

$$TCM = \left[0.713 \cdot [GPI \cdot (\%D)]^{0.200}\right] + \frac{(\%D)}{4.0(\%D) + 6}$$

State-of-the-Practice

Design Methods

- <u>Tip Capacity Multiplier</u>



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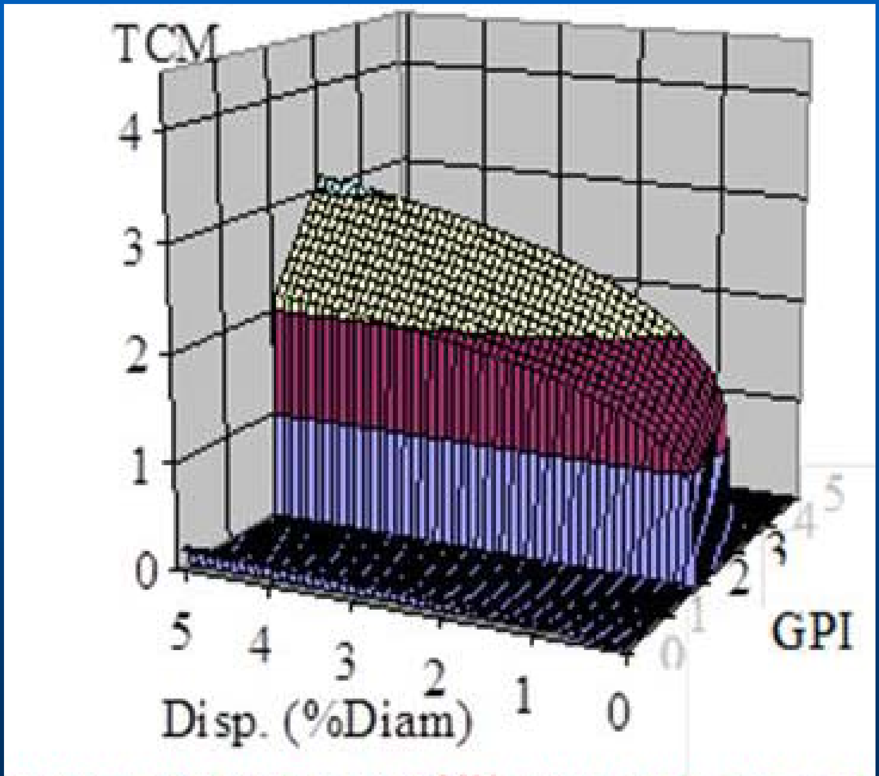
Source: Mullins et al (2006)



$TCM = 0.713 \cdot (GPI) \cdot (\%D)^{0.200} + (\%D)/[4.0 \cdot (\%D)+6]$

Source: Dapp and Brown (2010)

State-of-the-Practice

Design Methods

- 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)

Increase Coefficient	Clayey Soil or Silt	Silty Sand	Fine Sand	Medium Sand	Coarse Sand	Gravel Sand	Detritus Soil
λ_{si}	1.3-1.4	1.5-1.6	1.5-1.7	1.6-1.8	1.5-1.8	1.6-2.0	1.5-1.6
λ_p	1.5-1.8	1.8-2.0	1.8-2.1	2.0-2.3	2.2-2.4	2.2-2.4	2.2-2.5

State-of-the-Practice

Design Methods

- 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)

$$Z = \frac{\tau_o r_o}{G_o g} \cdot \ln\left\{\frac{\left(\frac{r_m}{r_o}\right)^g - f \cdot \left(\frac{\tau_o}{\tau_{max}}\right)^g}{1 - f \cdot \left(\frac{\tau_o}{\tau_{max}}\right)^g}\right\}$$

  - Q-z curve (base resistance)

$$Z_{base} = \frac{Q_b \cdot (1-\gamma)}{4 G_o r_o \cdot \left\{\frac{Q_b \cdot (1-\gamma)}{1 - f \cdot \left(\frac{Q_b}{Q_{b-max}}\right)^g}\right\}}$$

State-of-the-Practice

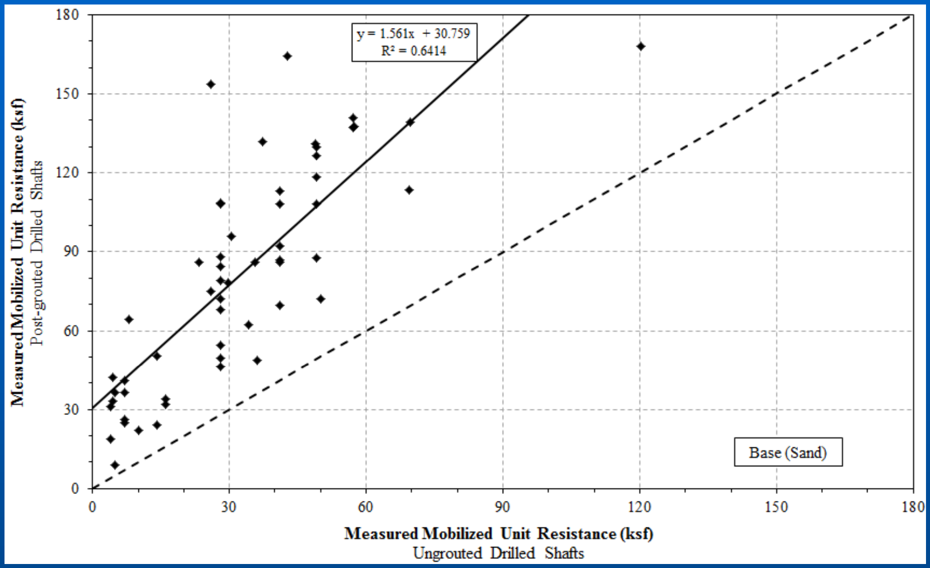
- Simplified Design Approach (McVay et al, 2010)
  - Based on tests on reduced scale individual shafts & groups of shafts in a test chamber
  - Conservative approach
    - Neglects contributions from increased side resistance
    - Neglects contributions from increased base resistance due to formation of an enlarged tip
    - Accounts for increased capacity due to preloading

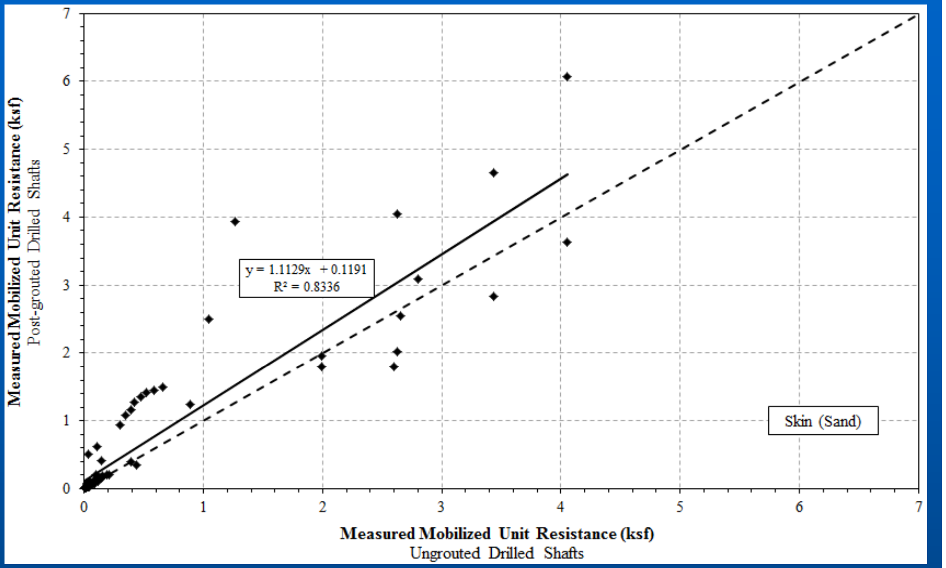
$$Q_{ult} = 2F_s + F_p$$

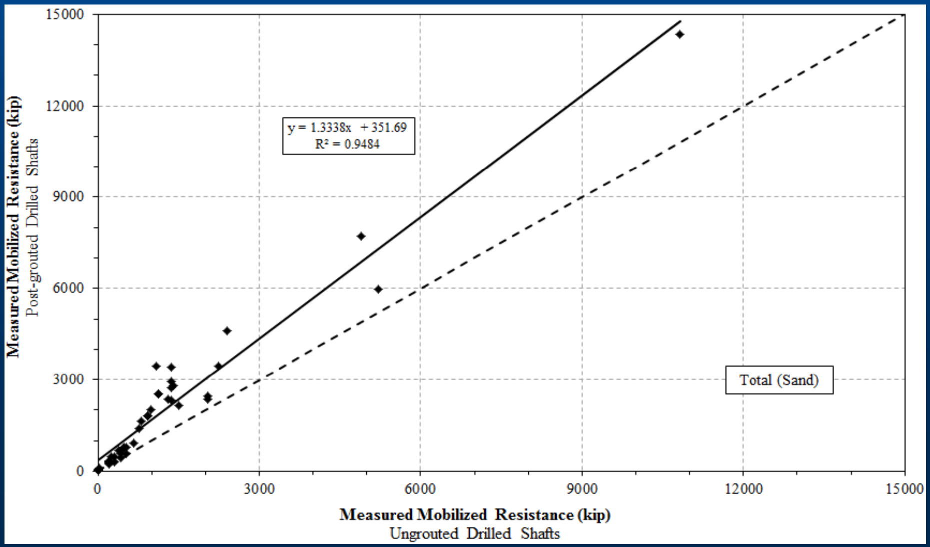
  - Rationale follows that the shaft has been upwardly pre-loaded so that this load must first be overcome prior to mobilizing "downward" side resistance

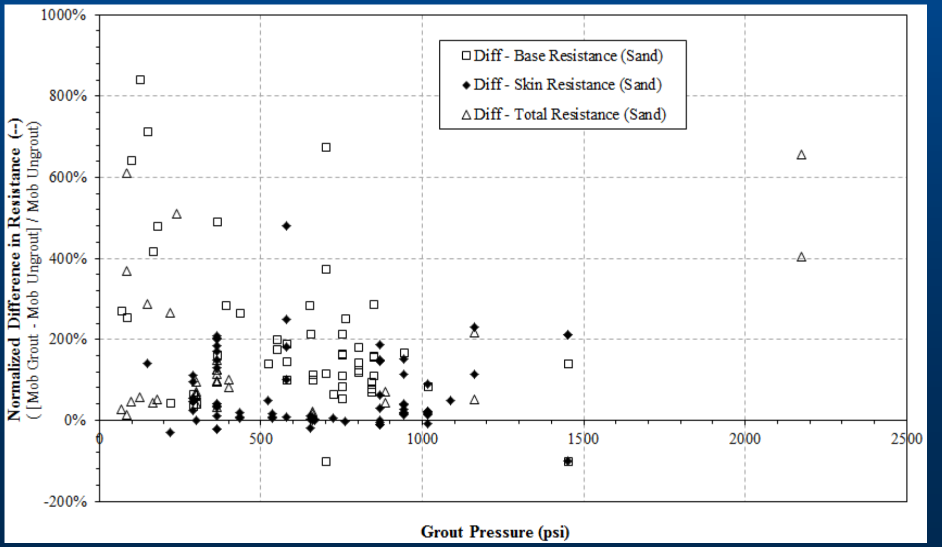
State-of-the-Practice

Preliminary Findings - Data in Sands



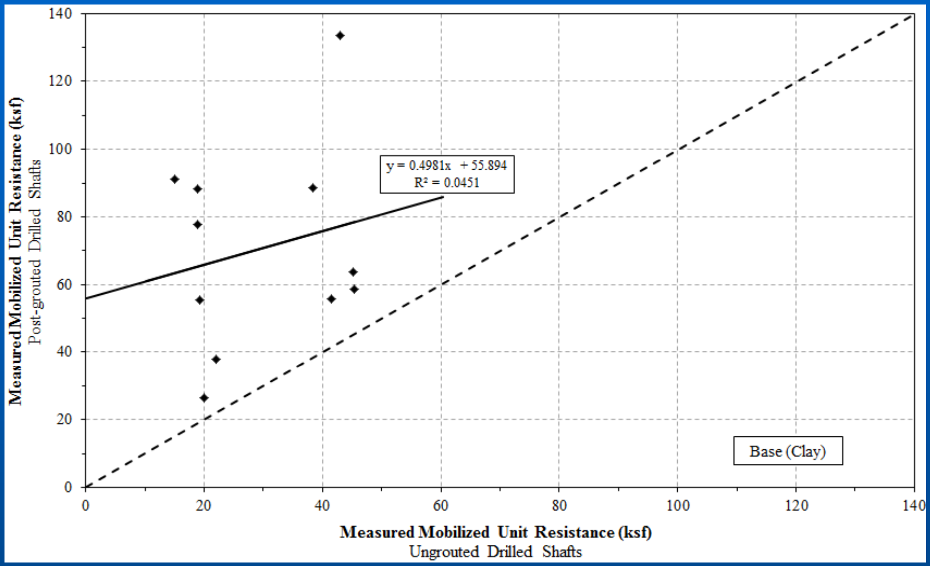


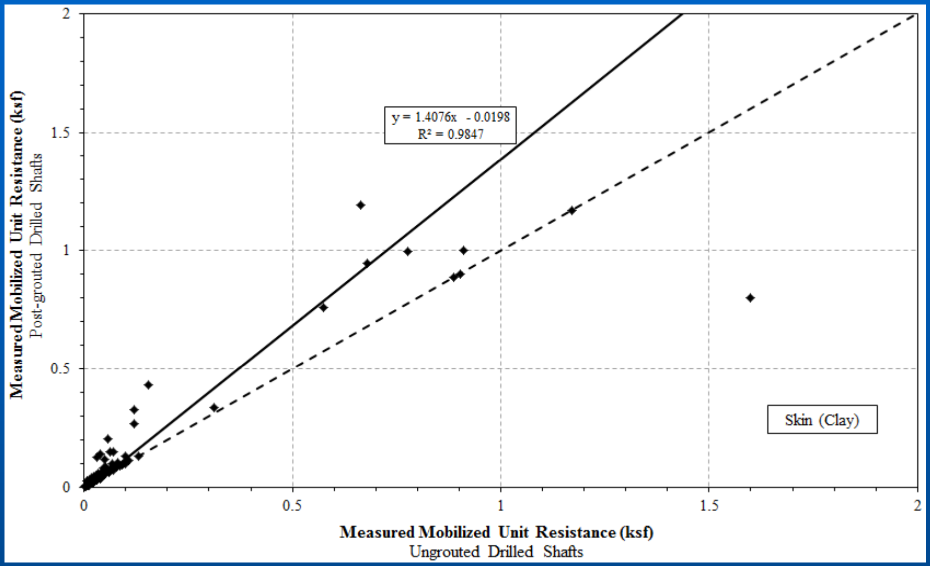


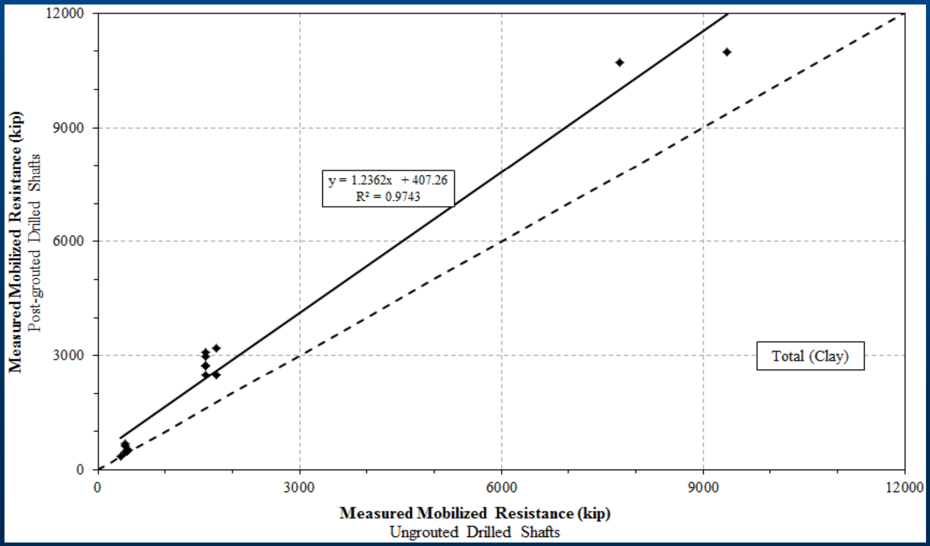


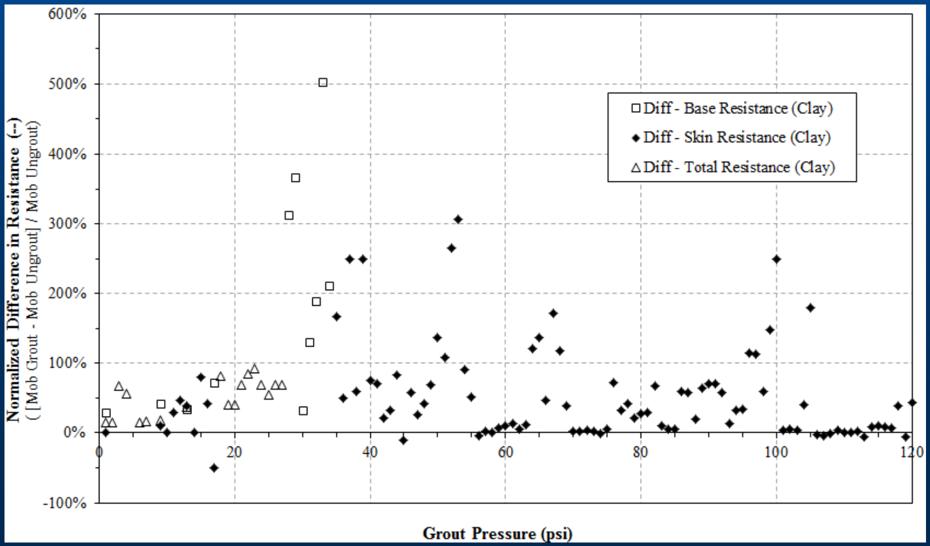
State-of-the-Practice

Preliminary Findings
- Data in Clays



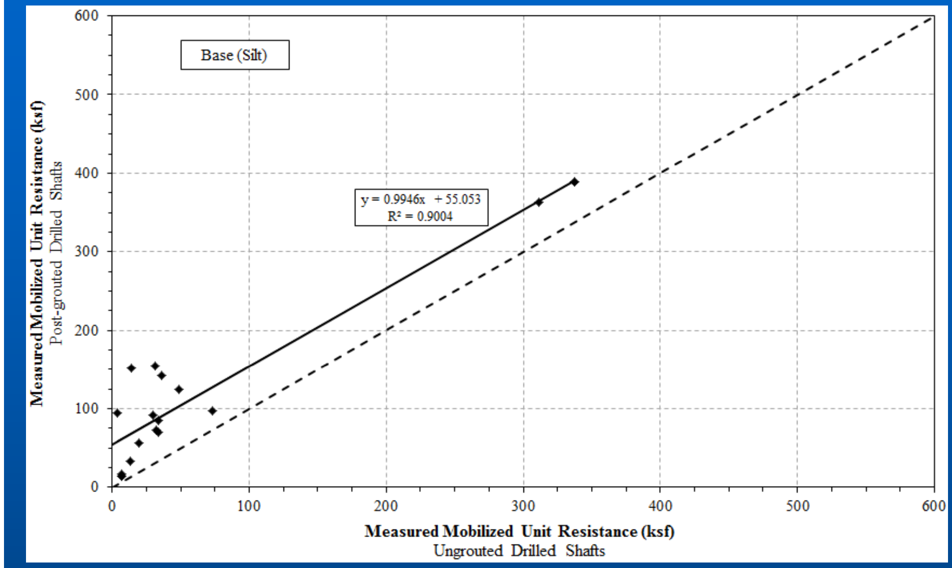


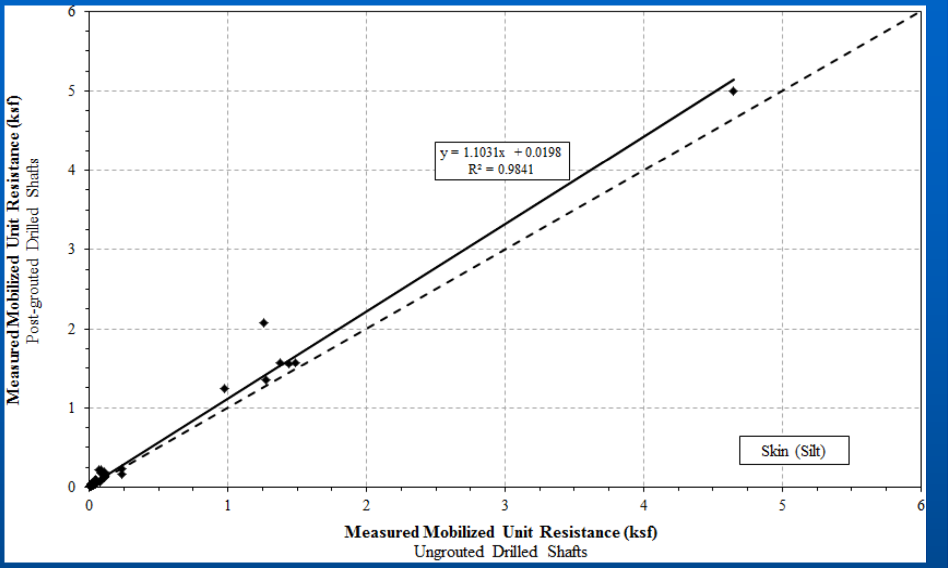


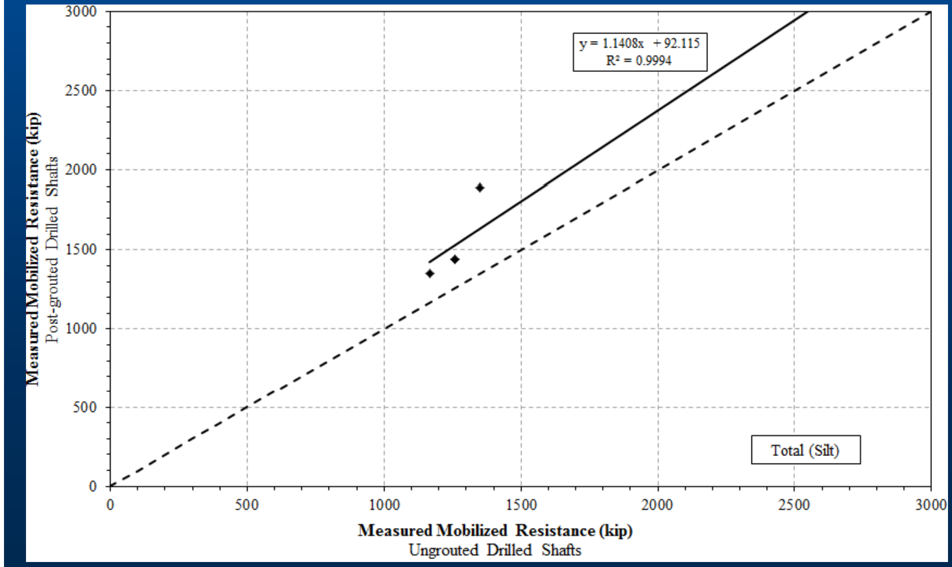


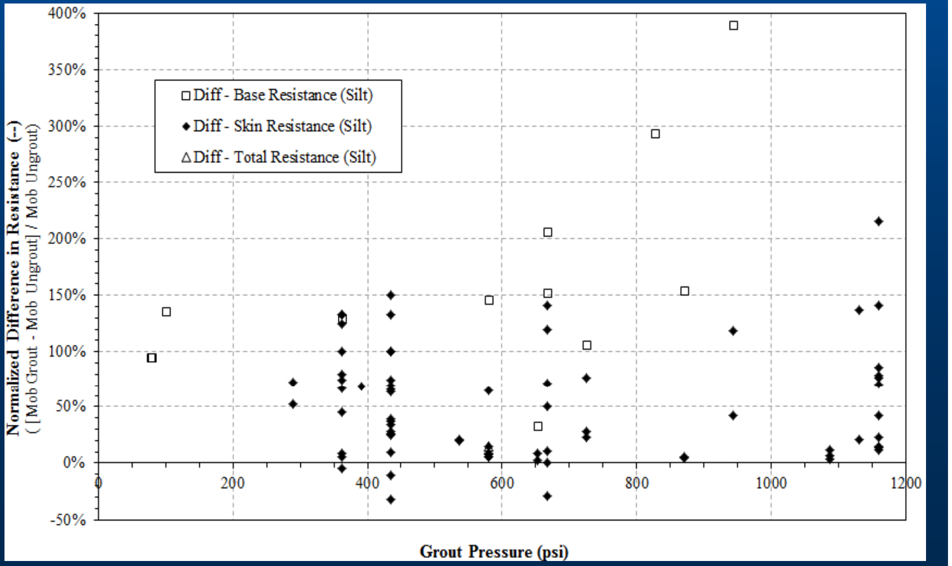
State-of-the-Practice

Preliminary Findings - Data in Silts



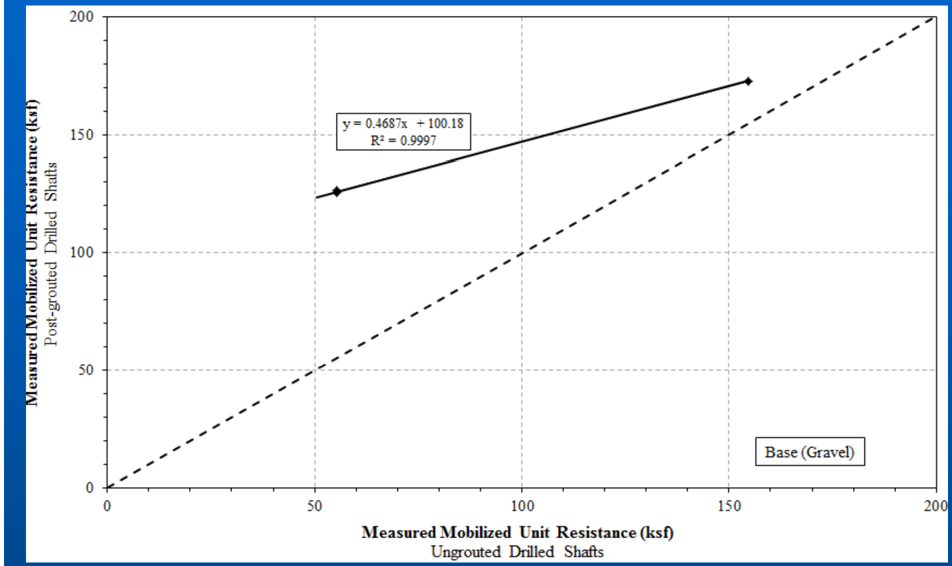


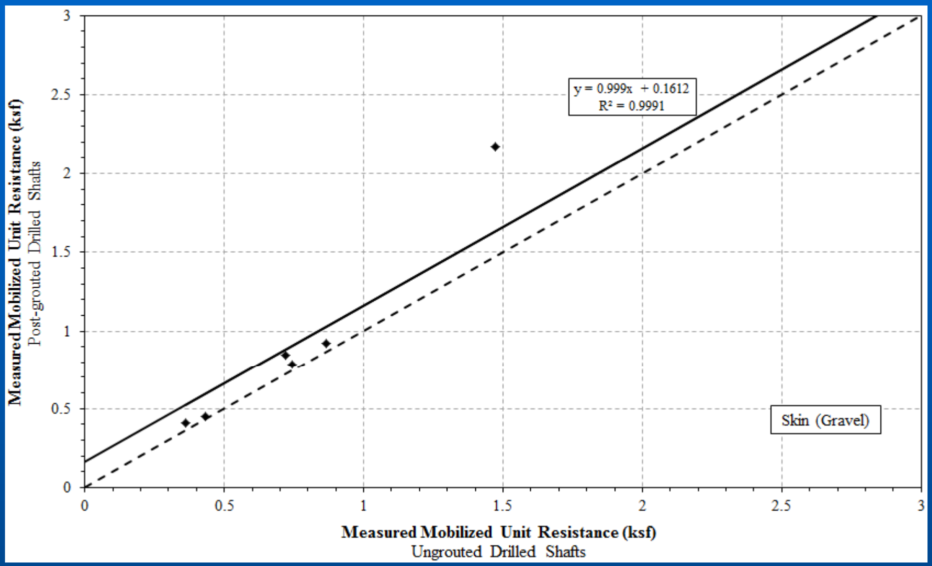


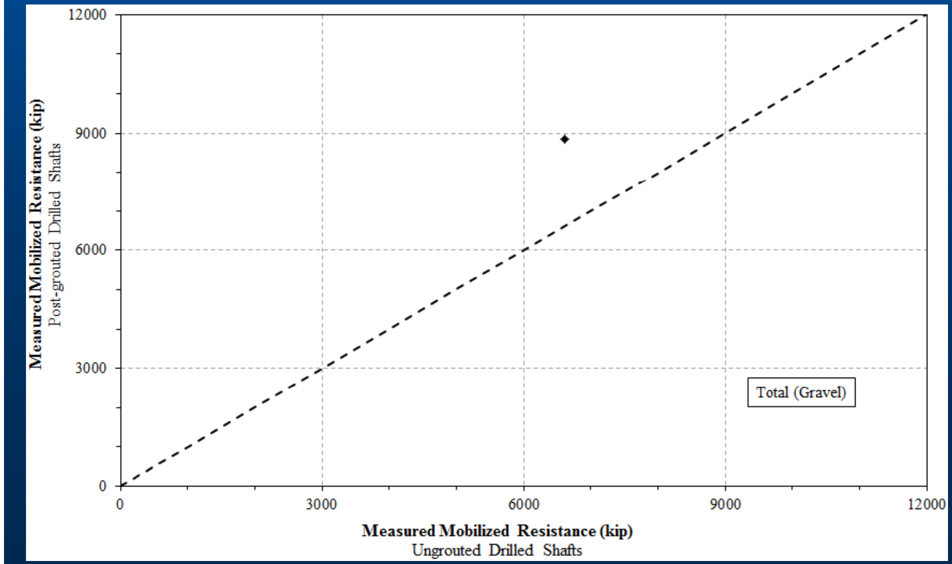


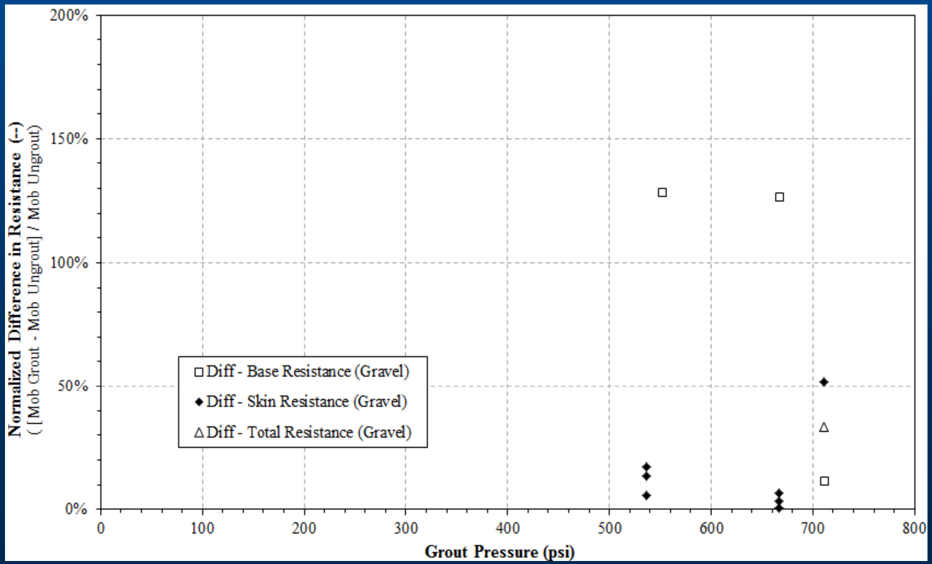
State-of-the-Practice

Preliminary Findings
- Data in Gravels



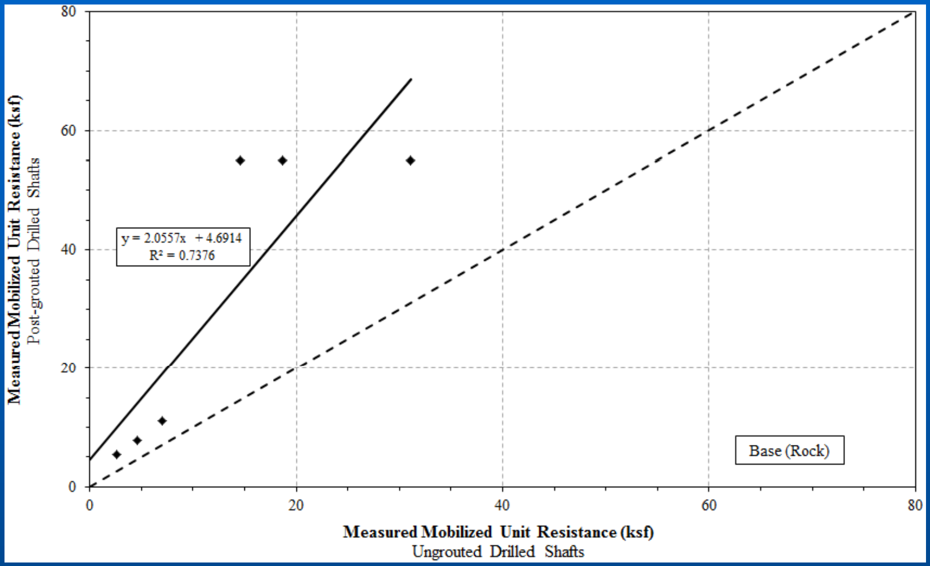


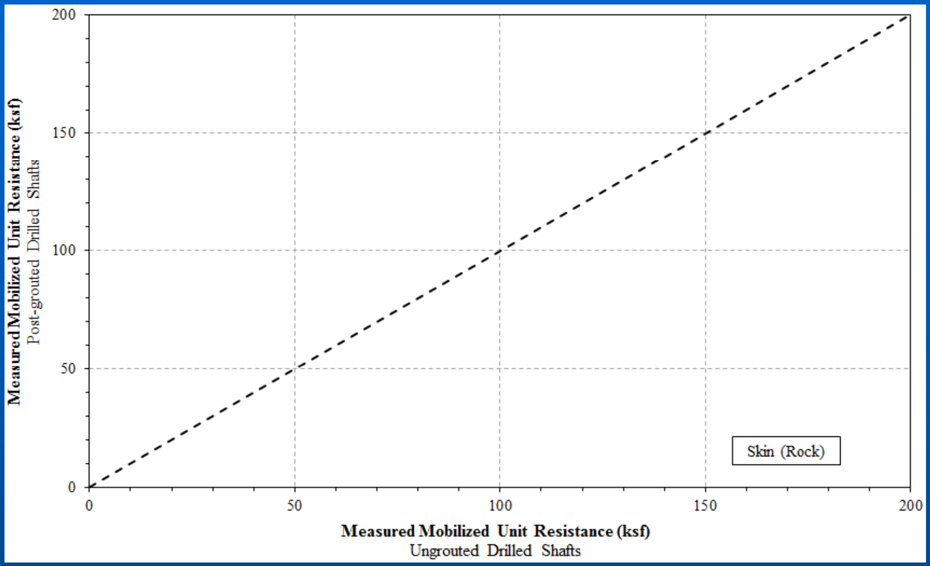


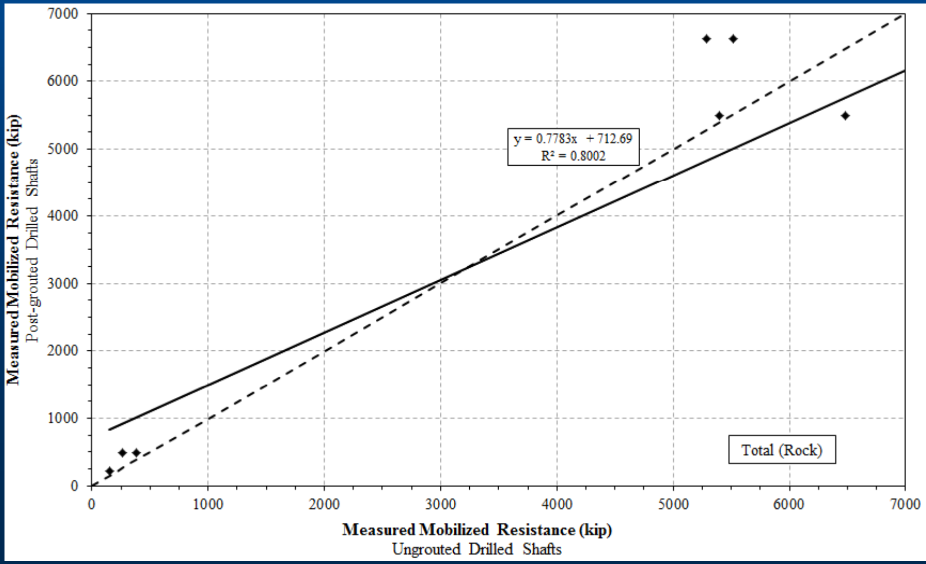


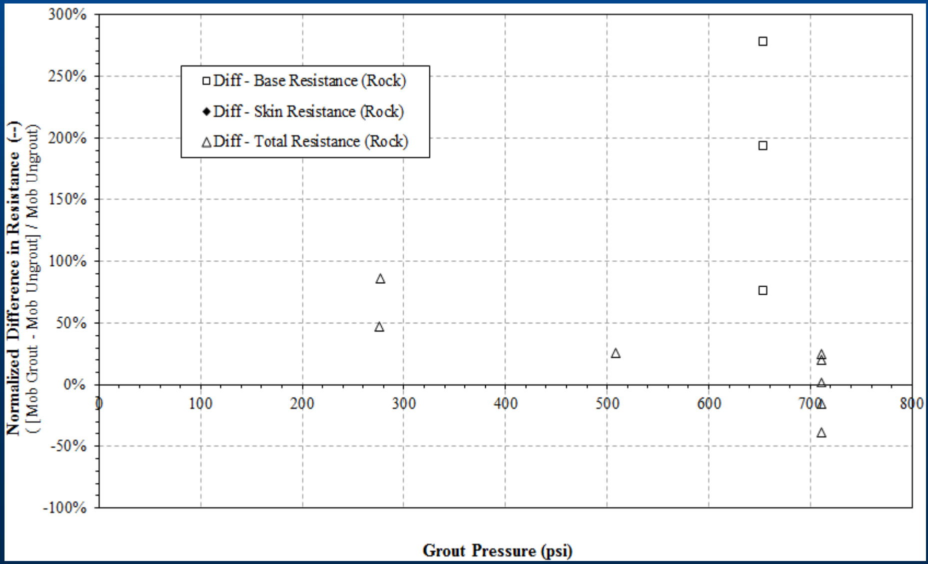
State-of-the-Practice

Preliminary Findings - Data in Rock









State-of-the-Practice

Research Needs

- Focus of ongoing research
  - More detailed analysis on existing data
  - Analyzing improvement mechanisms
    - Pre-loading
    - Side resistance effects
    - Ground improvement at tip
    - Enlargement of shaft tip
  - Design methods
  - Effects of soil conditions
  - Grouting delivery mechanisms, characteristics, and process
  - Shaft Performance – Stiffness vs. Resistance vs. Capacity
  - Quality control / quality assurance assessment methods
  - Pre-loading and stress reversal during post-grouting

Thank you for your attention!!

Questions??