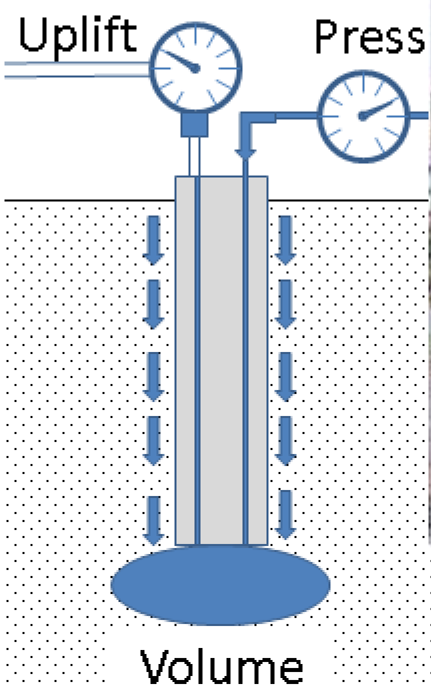
Load and Resistance Factor Design (LRFD) Resistance Factors for Tip Grouted Drilled Shafts



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GRIP 2017

UNIVERSITY OF SOUTH FLORIDA

Civil & Environmental Engineering

Outline

- Problem Statement
- Background
  - Grouting Basics
  - Grouting Systems
  - Grouting Methods
- Expected Grouting Performance
- Design Methods
- Measured vs Predicted Capacity Statistics
- Preliminary Results

Problem Statement

- Like all capacity prediction methods, the post-grouted end bearing of drilled shafts has inherent uncertainty.
- Both the design and construction practices affect reliability
- No resistance factors (or safety factors) are in place to mitigate the uncertainty associated with varying design or grouting methods

Soils and Foundations Handbook

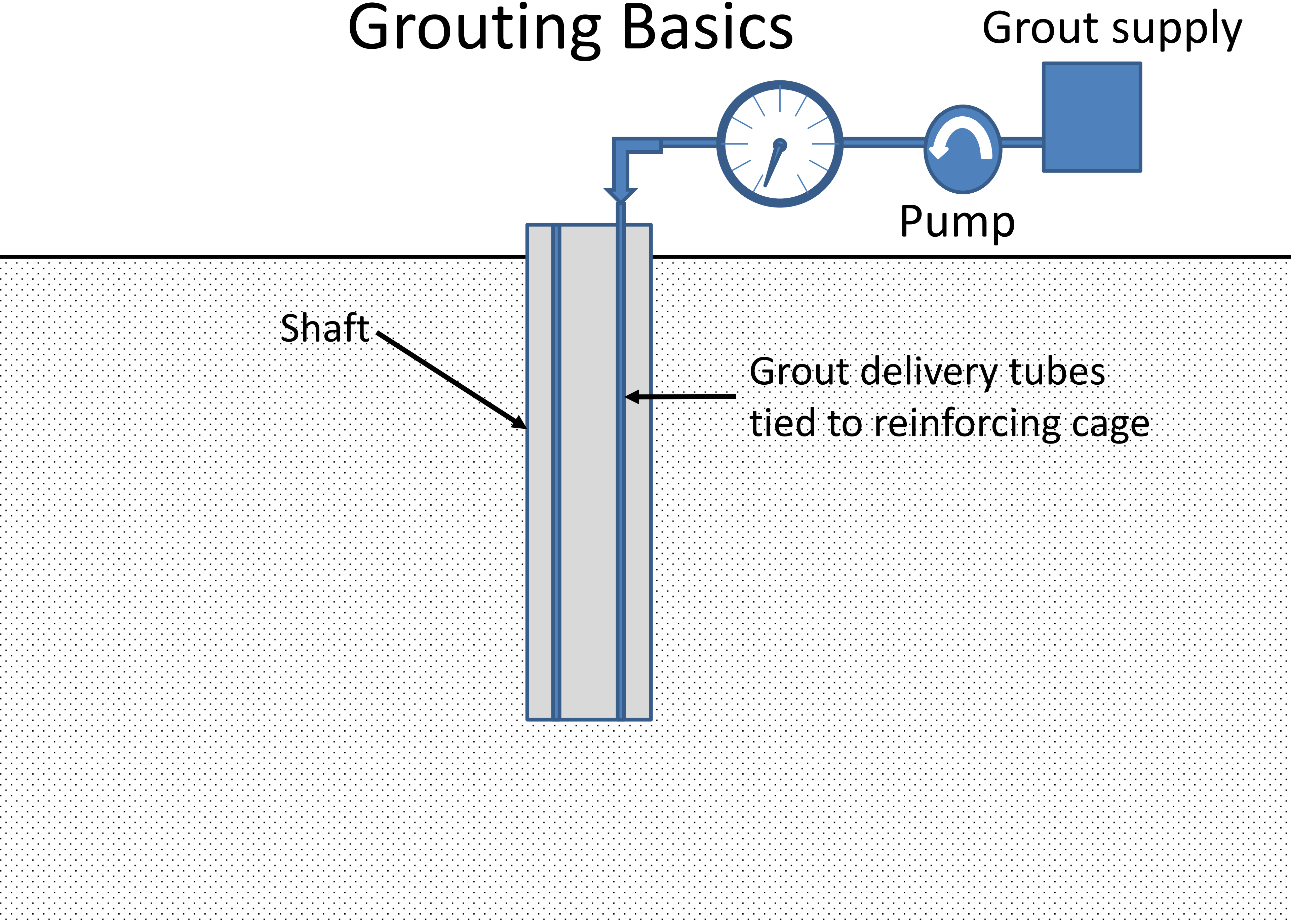
"Resistance factors and associated design methods for geotechnical resistance of drilled shafts are in SDG Table 3.6.3-1 [Table 2.3]. *It is implicitly shown in the table that the resistance factors for* ***drilled shafts tipped in sand or clay*** *are based on* ***side shear*** *design methods* ***only*** *(i.e. FHWA alpha method in clay and FHWA beta method in sand)."*

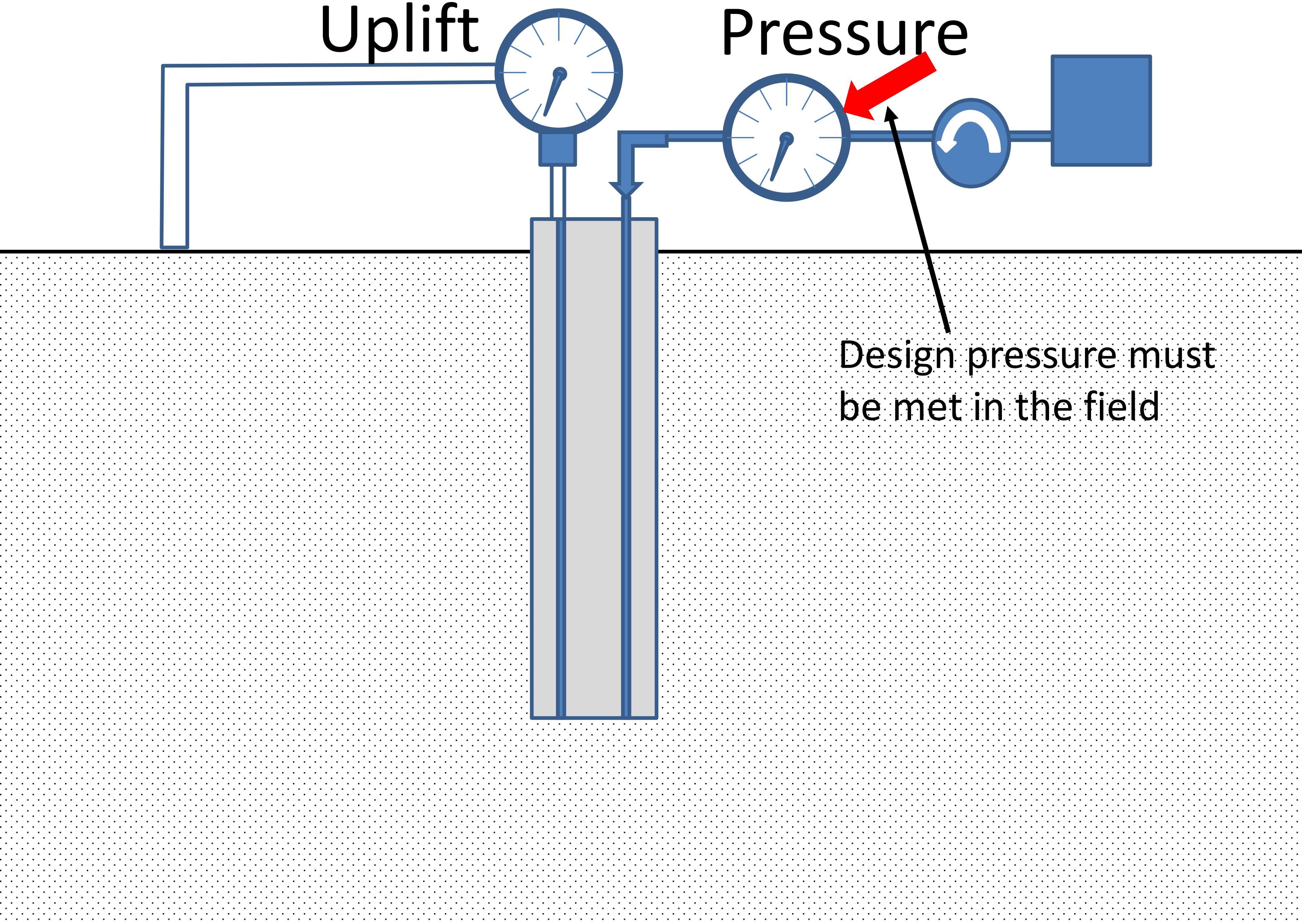
Soils and Foundations Handbook

*“**In sand, drilled shafts with pressure grouted tips should be considered.** Pressure grouted tips are most effective in loose to medium dense sands. Guidance for the design of drilled shafts with pressure grouted tips may be found in Appendix D and in Reference 9.”*

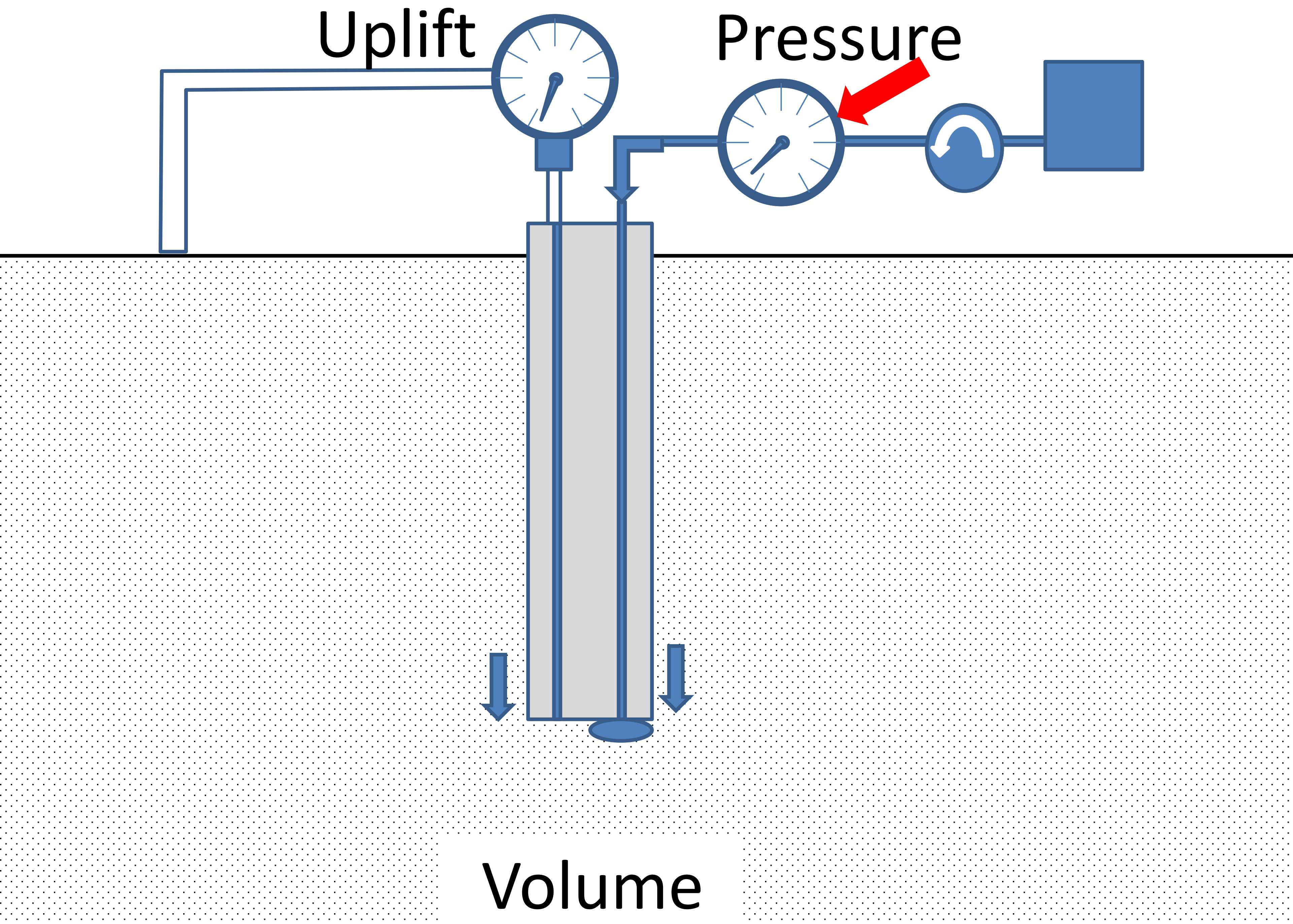
No Resistance Factor is directly associated with pressure grouted shafts; rather that from the load test method is used.

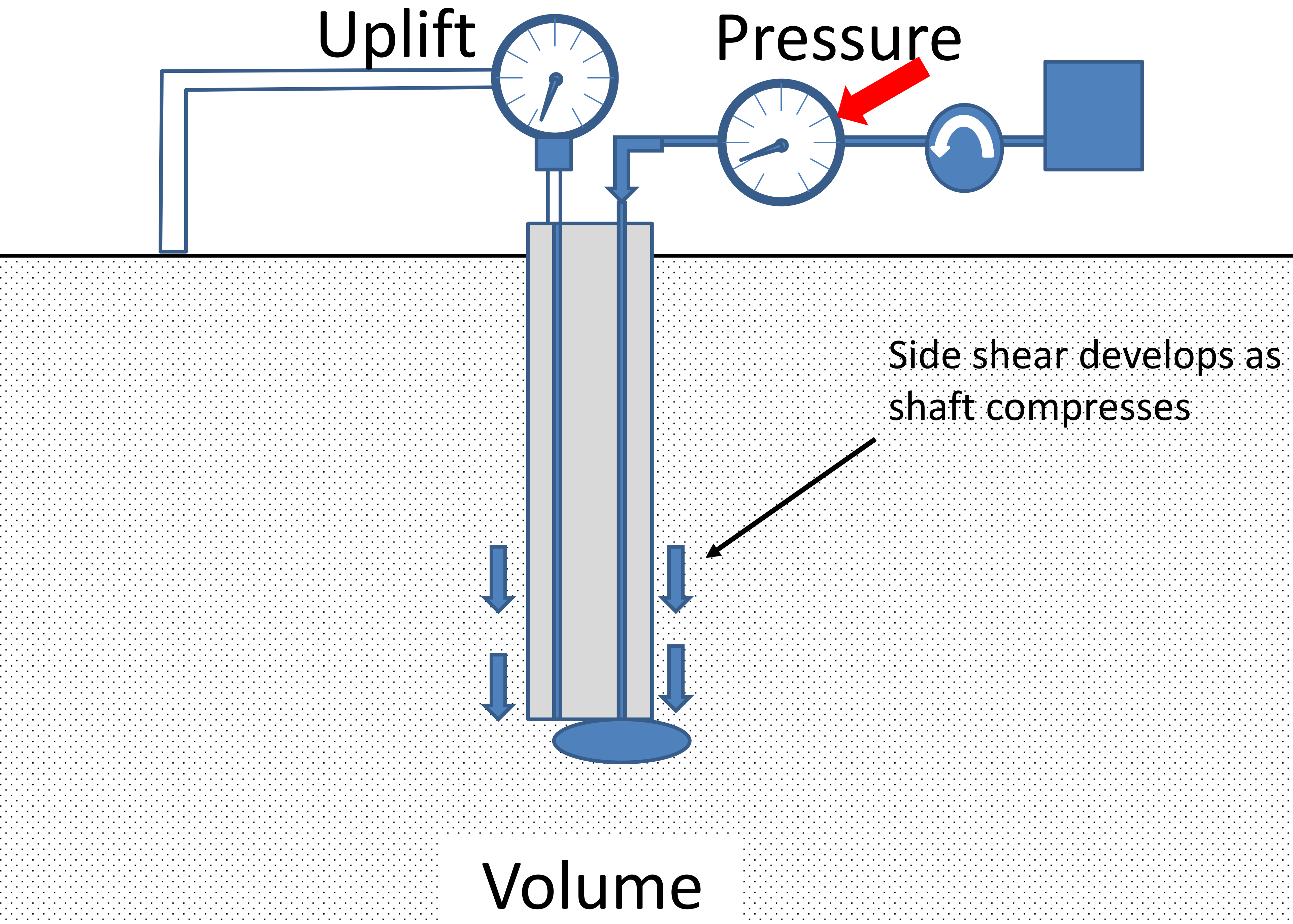
Grouting Basics

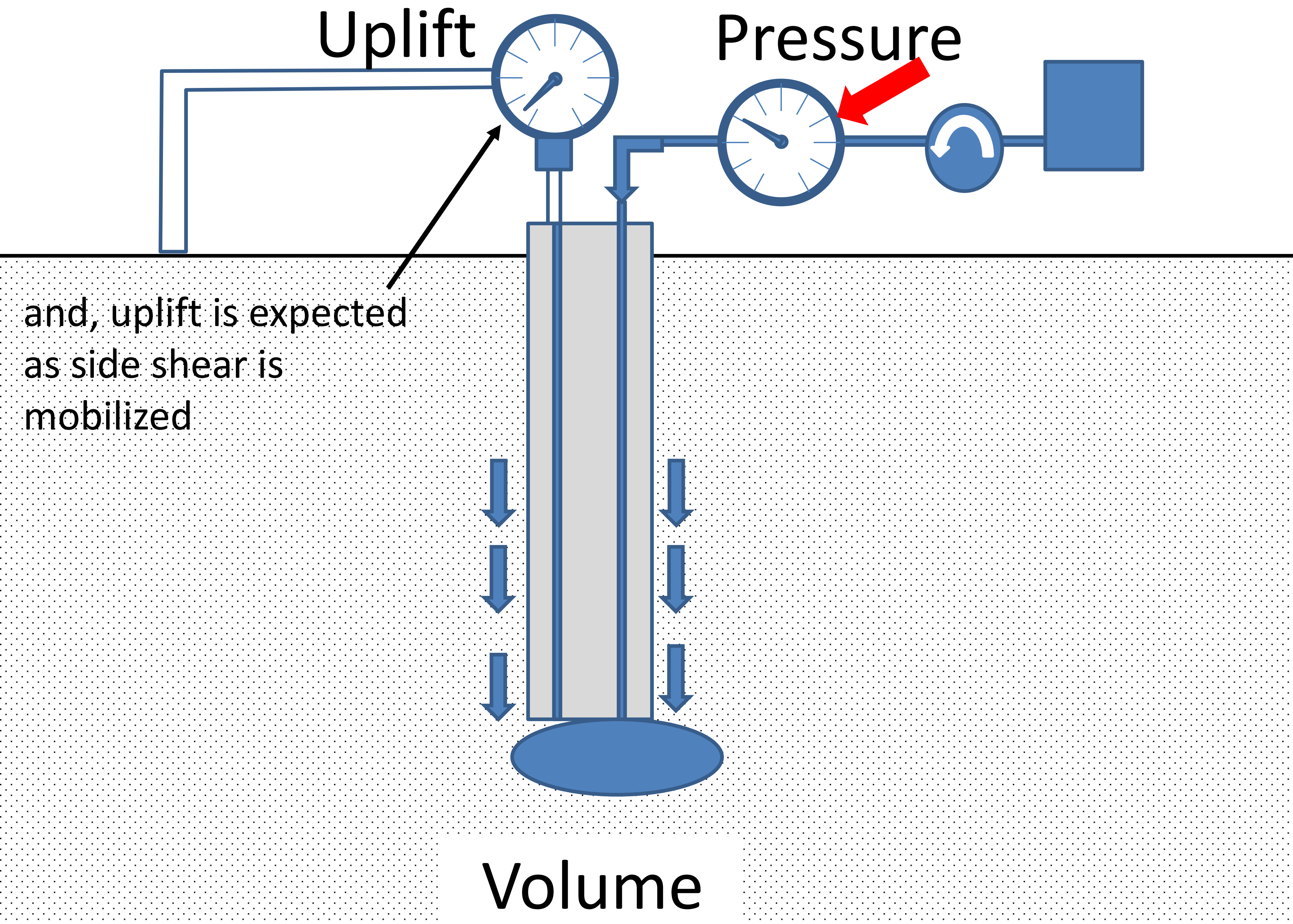




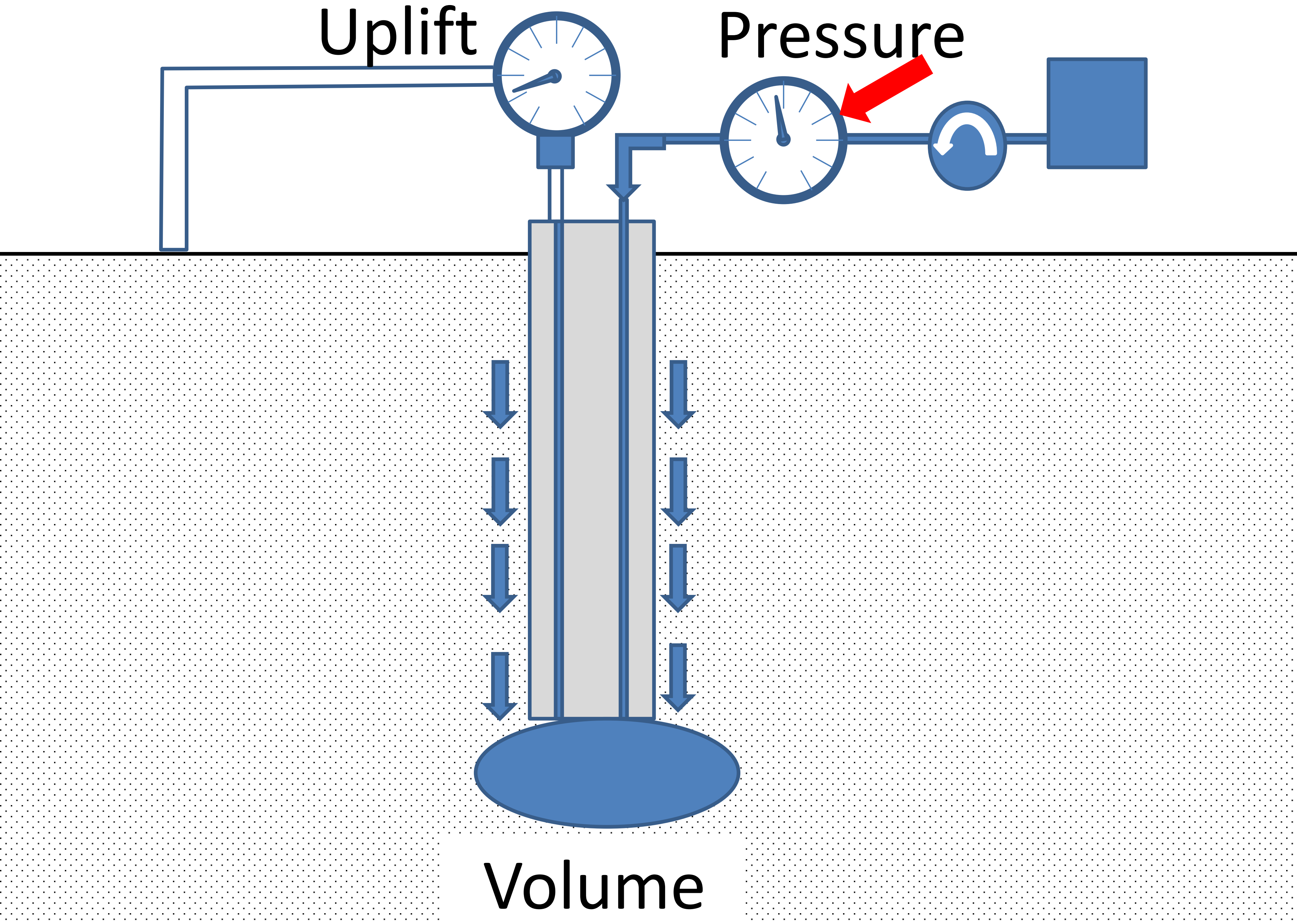
Uplift
Pressure
Design pressure must
be met in the field

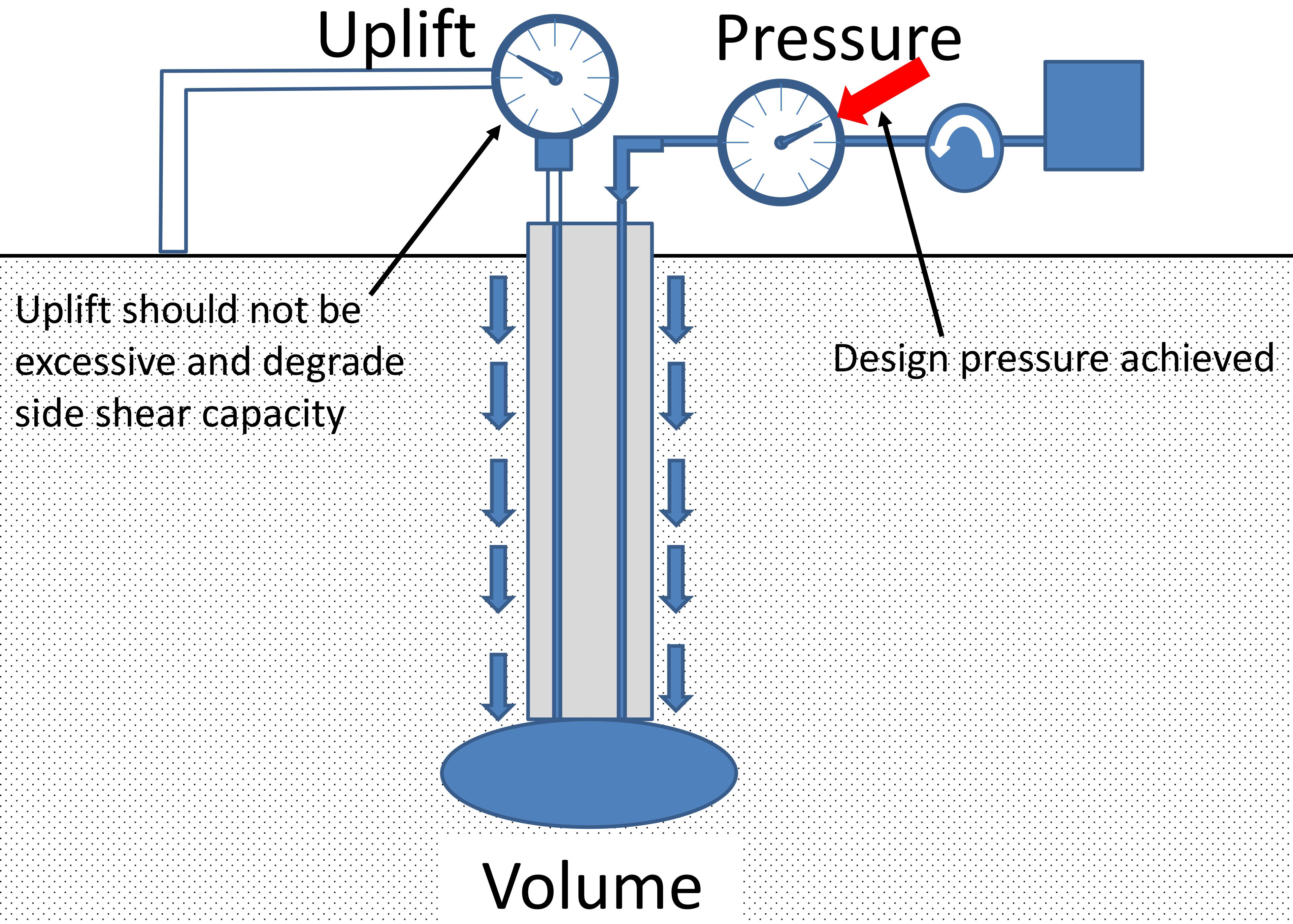

Uplift
Pressure
Volume


Uplift
Pressure
Side shear develops as
shaft compresses
Volume



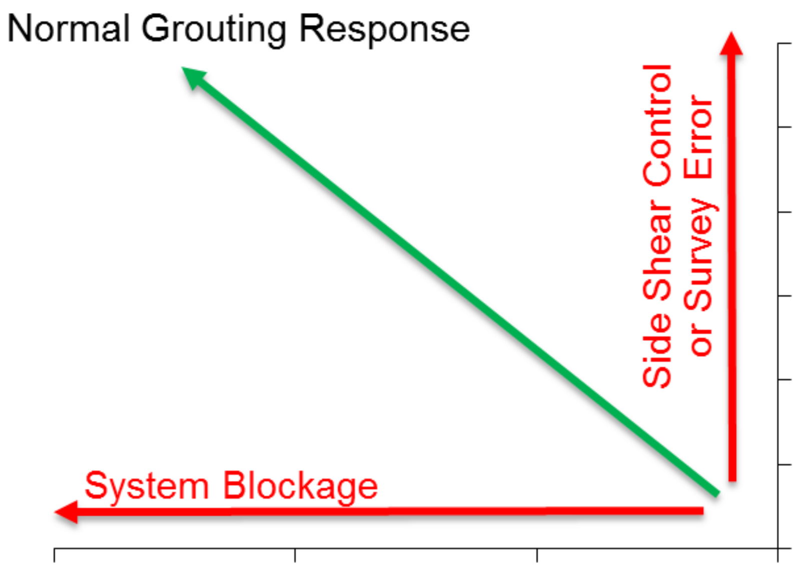
Uplift
Pressure
and, uplift is expected
as side shear is
mobilized
Volume

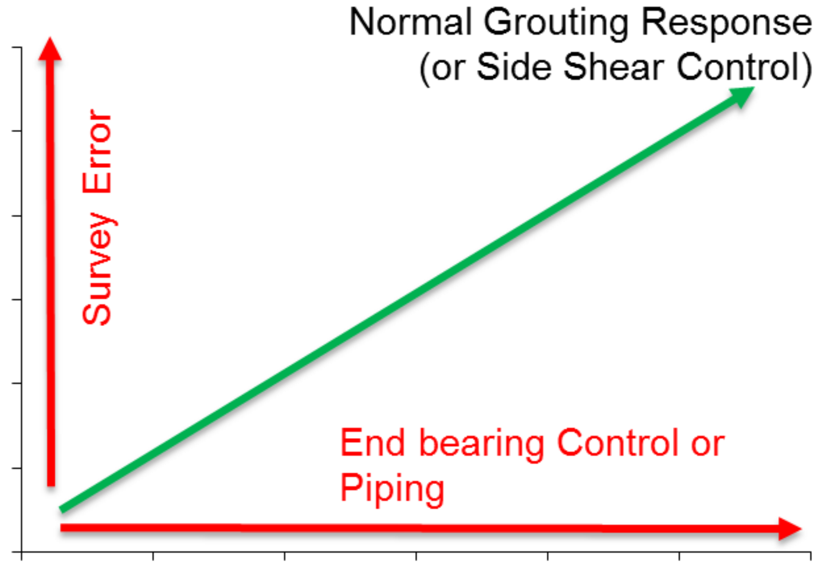

Uplift
Pressure
Volume

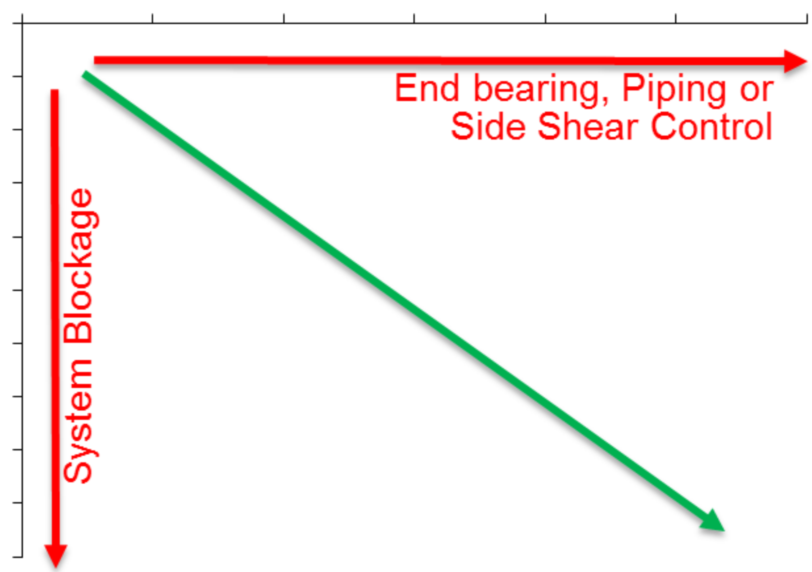

Uplift
Pressure
Uplift should not be excessive and degrade side shear capacity
Design pressure achieved
Volume

Expected Results

Effectiveness Plots



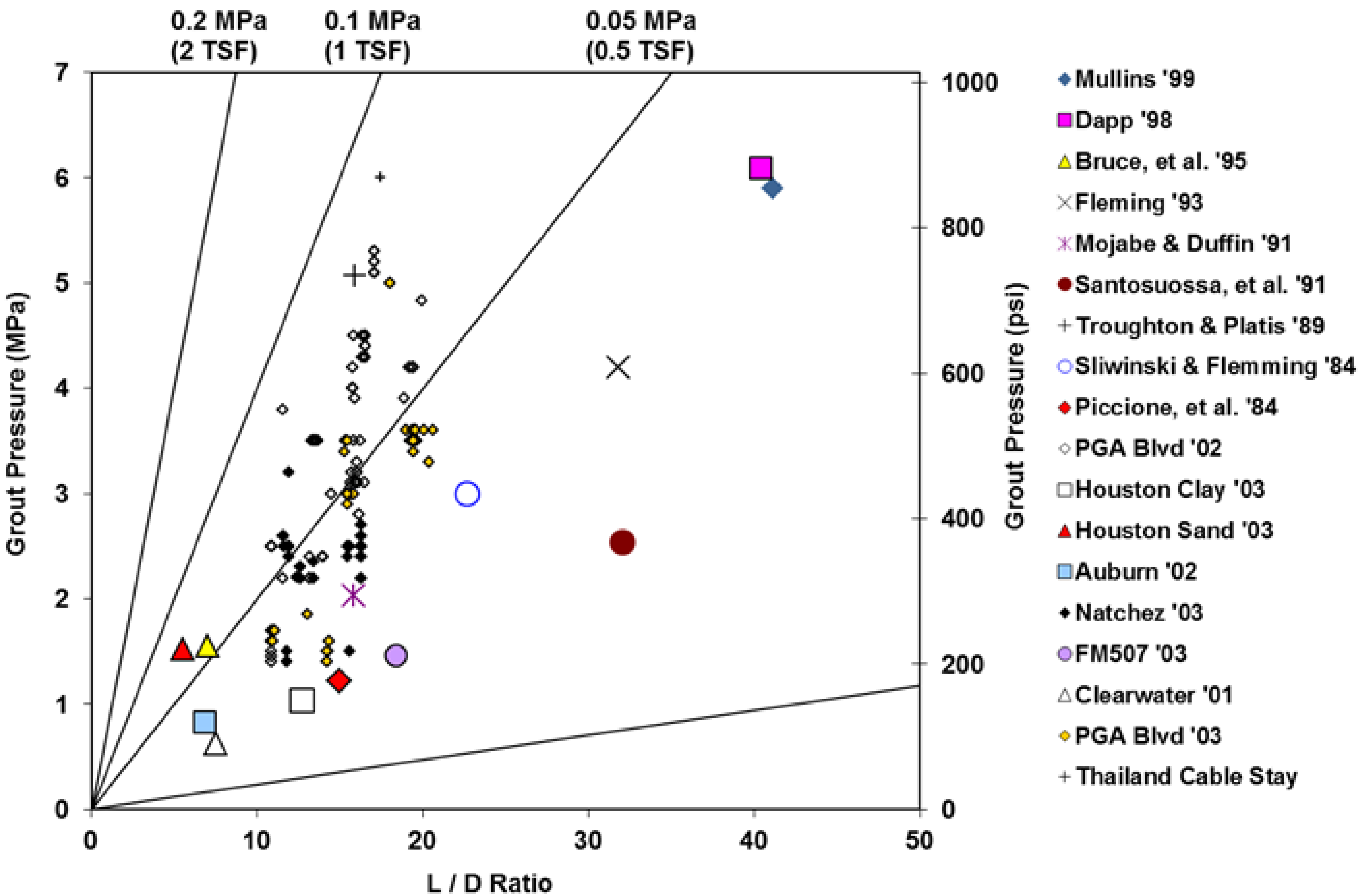




NOTE:

(1) All graphs should demonstrate a diagonal trend away from the center.

(2) If any one of the graphs demonstrates a horizontal or vertical trend, the post grouting process has become ineffective for one of the reasons shown



$$Max\ Grout\ Pressure = 4\,(unit\ side\ shear)\ L/D$$

Grouting systems

Sutong (China) Taipei 101 (Taiwan) Flagler (Florida)

Sleeve Port (tube-a-manchette)

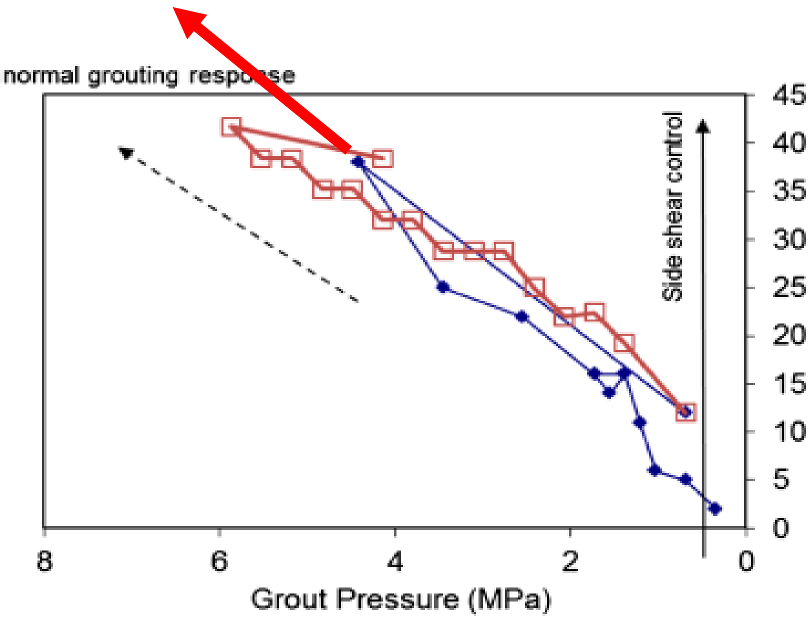
Grouting systems

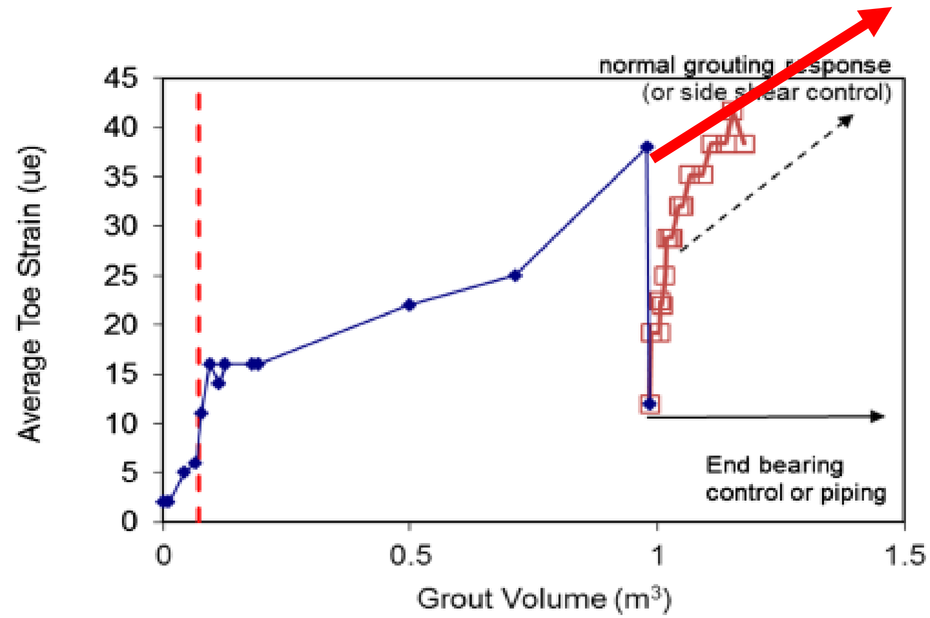
Flat jack (open or closed)

Field Practice / Design Expectation

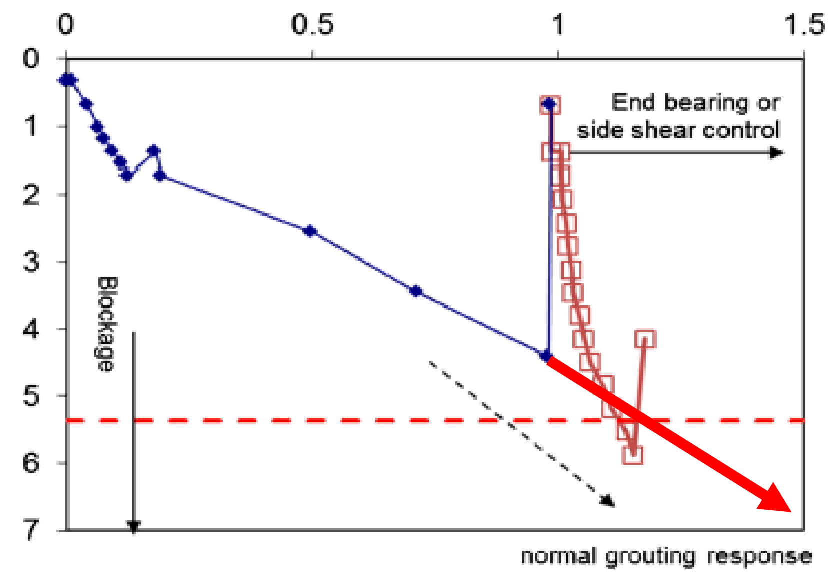
- Grout pressure is intended to create an expanding bulb of grout where pressure increases with size of bulb
- If pressure is not achieved, stage grouting is often suggested
- Stage grouting reduces the size of the active/liquid grout pressure area and does not continue to increase soil improvement in the same way
- Design methods implicitly assign capacity gains on a combination of increases in tip area and soil strength
- Designer must be aware of this global effect

Best Case Effect of Stage Grouting

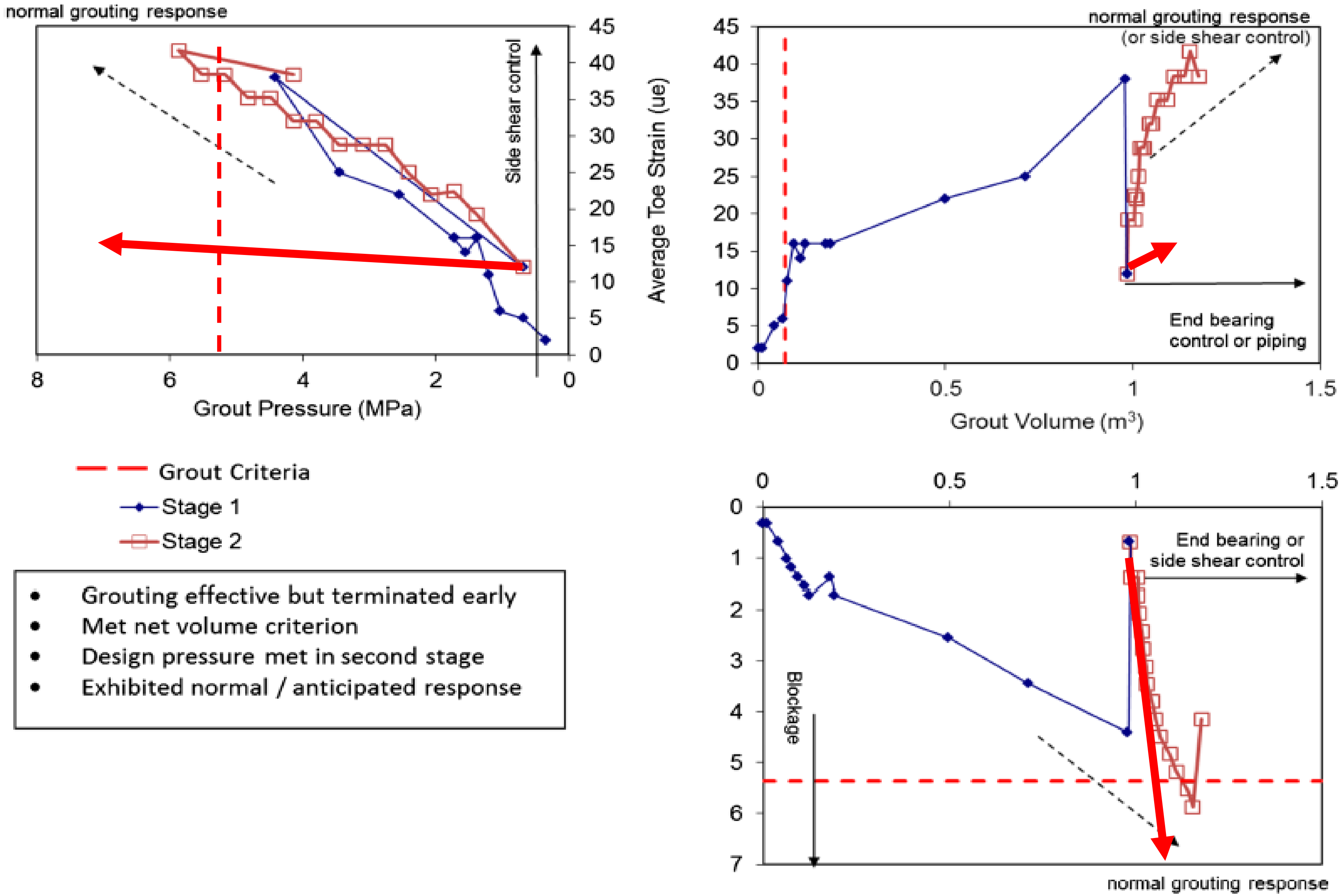




- Grouting effective but terminated early
- Met net volume criterion
- Design pressure met in second stage
- Exhibited normal / anticipated response



Undesired Result of Stage Grouting



- Grouting effective but terminated early
- Met net volume criterion
- Design pressure met in second stage
- Exhibited normal / anticipated response

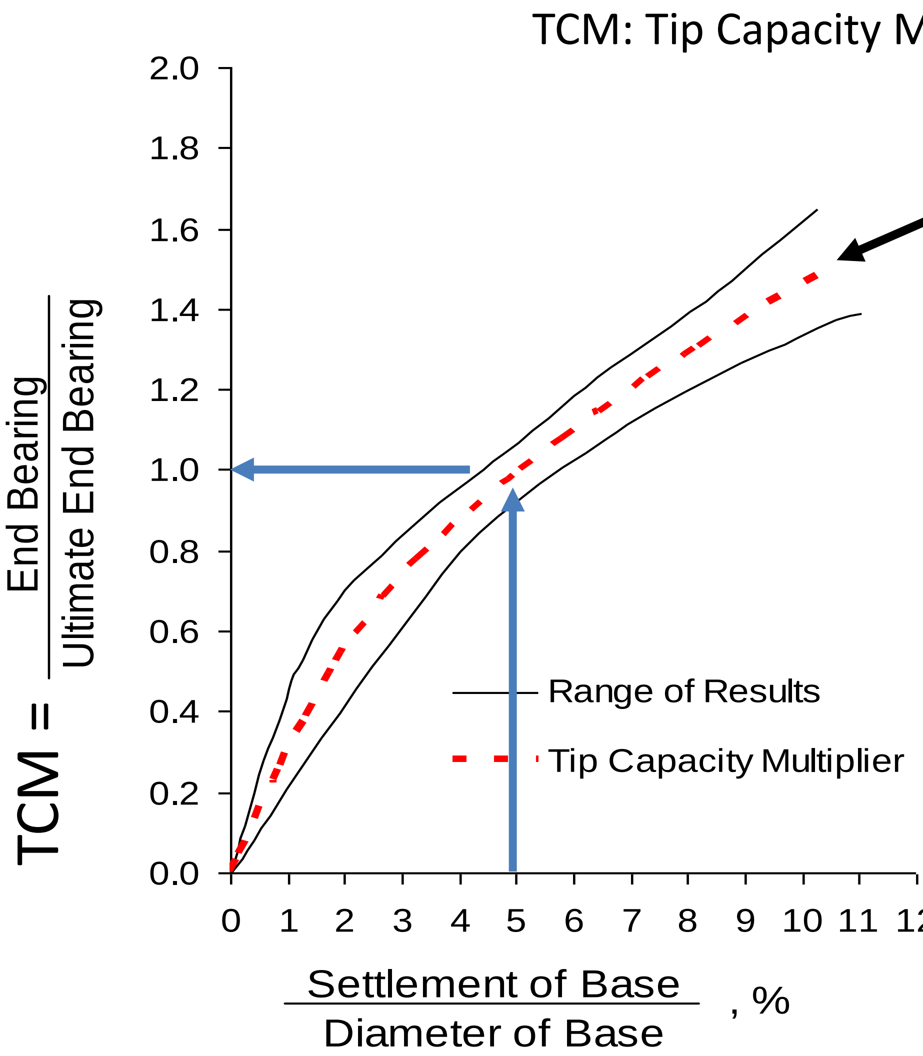
Design Methods

Three Basic Approaches

- End bearing $\propto$ grout volume (circa 1970s not used)
- End bearing = Grout pressure
- End bearing function of grout pressure <u>and displacement</u>
  - – Single stage grouting *Mullins et al. 2006*
  - – Multi-stage grouting *Dapp and Brown, 2010*

Ungrouted End Bearing Capacity

(O'Neill in AASHTO)



$$TCM = \frac{\%D}{0.4(\%D)+3.0}$$

q_b = TCM $\underline{0.6N}$ (tsf)

End bearing @ 5%D = 1.0 x 0.6N

Design Methods

- q = $(0.713(GPI)(\%D^{0.364}) + \frac{\%D}{0.4(\%D)+3.0})$ 0.6N

  Mullins et al. 2006 single stage grouting

- q = $(0.713(GPI)(\%D^{0.2}) + \frac{\%D}{0.4(\%D)+6.0})$ 0.6N

  Dapp and Brown 2010 multi stage grouting

Design Methods

- q = $\left(0.713(GPI)(\%D^{0.364}) + \frac{\%D}{0.4(\%D)+3.0}\right)$ 0.6N

Mullins et al. 2006 single stage grouting

- q = $\left(0.713(GPI)(\%D^{0.2}) + \frac{\%D}{0.4(\%D)+6.0}\right)$ 0.6N

Dapp and Brown 2010 multi stage grouting

TCMs for grouted end bearing capacity

Design Methods

- $q = \left(0.713(GPI)(\%D^{0.364}) + \frac{\%D}{0.4(\%D)+3.0}\right)0.6N$

Mullins et al. 2006 single stage grouting

- $q = \left(0.713(GPI)(\%D^{0.2}) + \frac{\%D}{0.4(\%D)+6.0}\right)0.6N$

Dapp and Brown 2010 multi stage grouting

Same TCM as O'Neill for ungrouted end bearing capacity

FDOT Method

- $q_{gb} = [(0.713(GPI)(\%D^{0.364}) + (\frac{\%D}{0.4(\%D)+3.0})]\ q_b$
- $q_{gb} \leq$ grout pressure

- GPI = grout pressure / q_b ; where q_b is from O'Neill
- In original study q_b was determined from ungrouted shaft on-site and not assumed from O'Neill
- So there is an imposed bias when 0.6N is used to estimate the ungrouted capacity

Approach

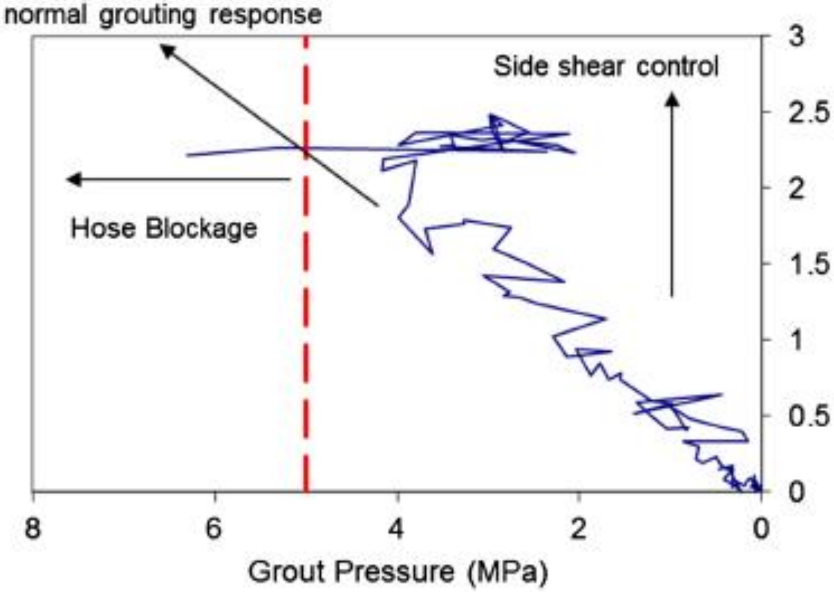
- Collect end bearing data from load tests conducted on post grouted shafts
- Compare measured to predicted end bearing
- Compute resistance factor based on bias statistics

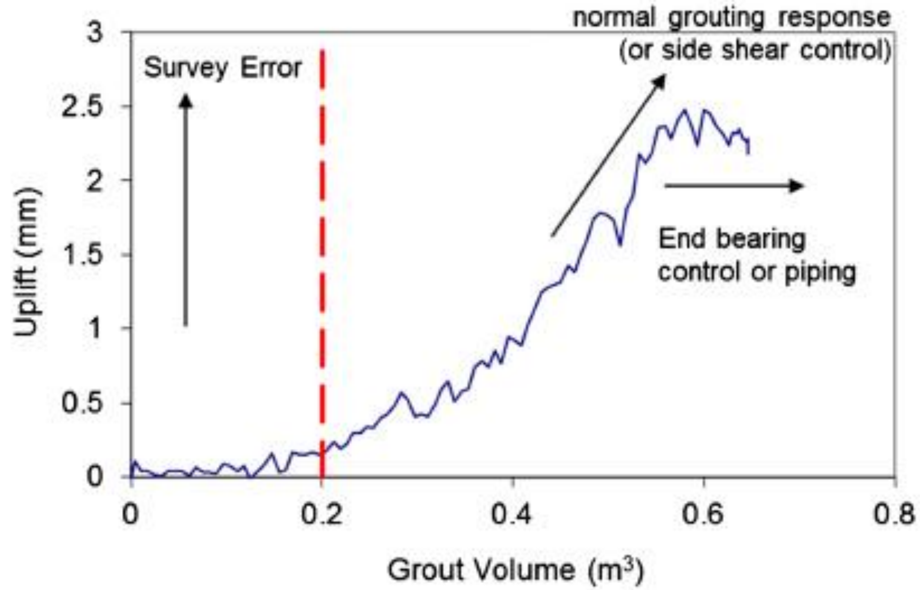
- Required information includes:
  - Field grouting logs
  - Load test end bearing vs disp data
  - Boring logs
- Check grouting effectiveness and determine:
  - Max field recorded grout pressure
  - Side shear predicted grout pressure
  - Effective grout pressure from tri-axis plots

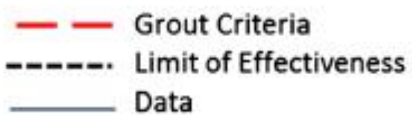
Factors Affecting Resistance Factor

- Predicted End Bearing depends on grout pressure
  - Side shear prediction of grout pressure
  - Field measurements of grout pressure
- Grouting Effectiveness
  - Effectiveness plot verification
- Displacement
  - Davisson method not applicable
  - Not a single bias from a given load test
- Frequency of Load Testing (or in this case grouting)

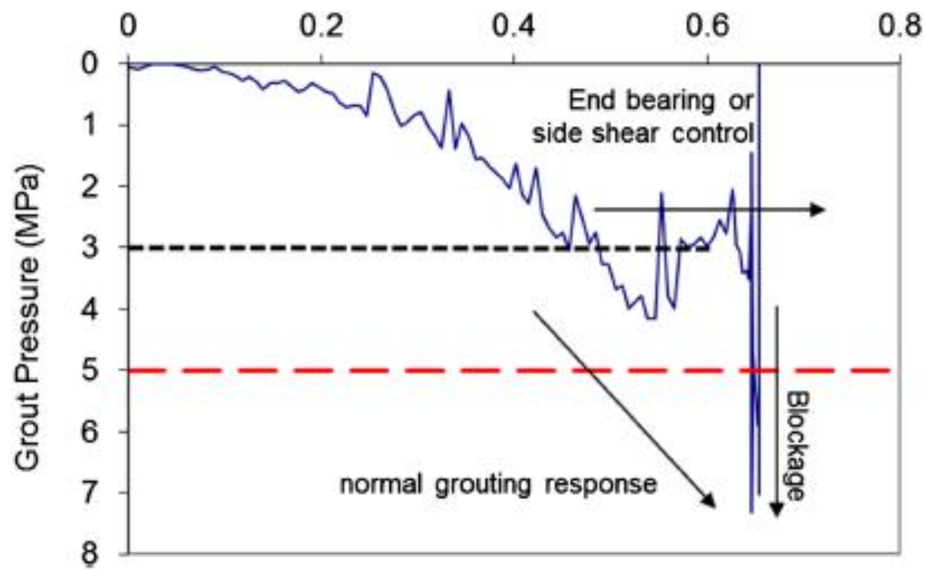
Grout pressure determination



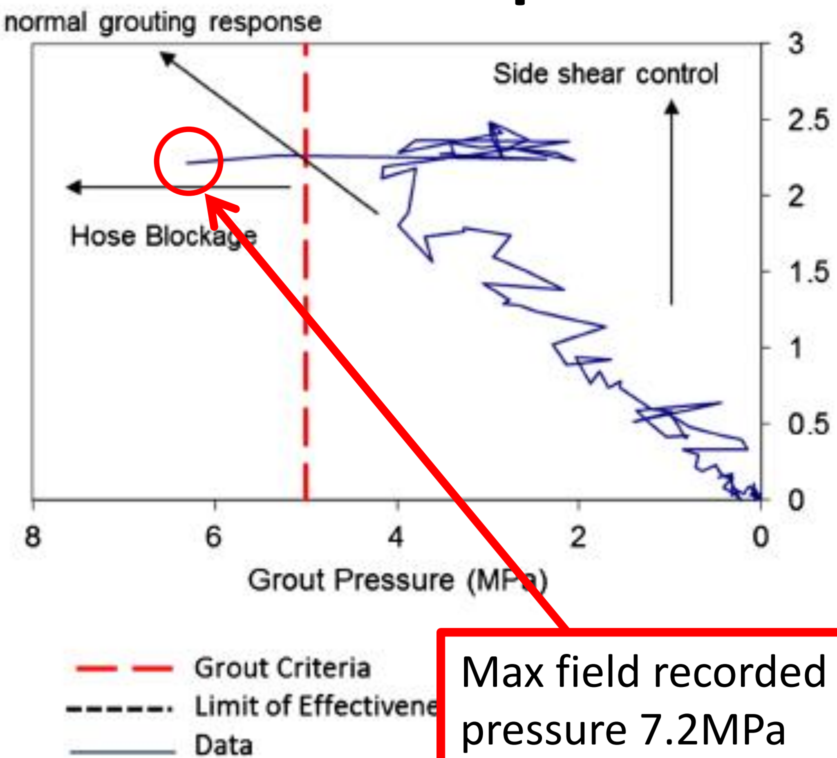


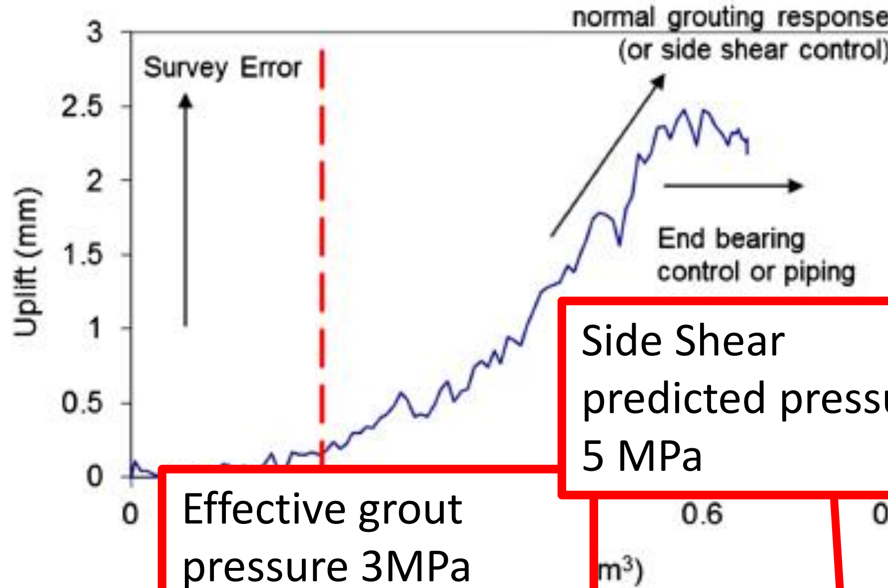


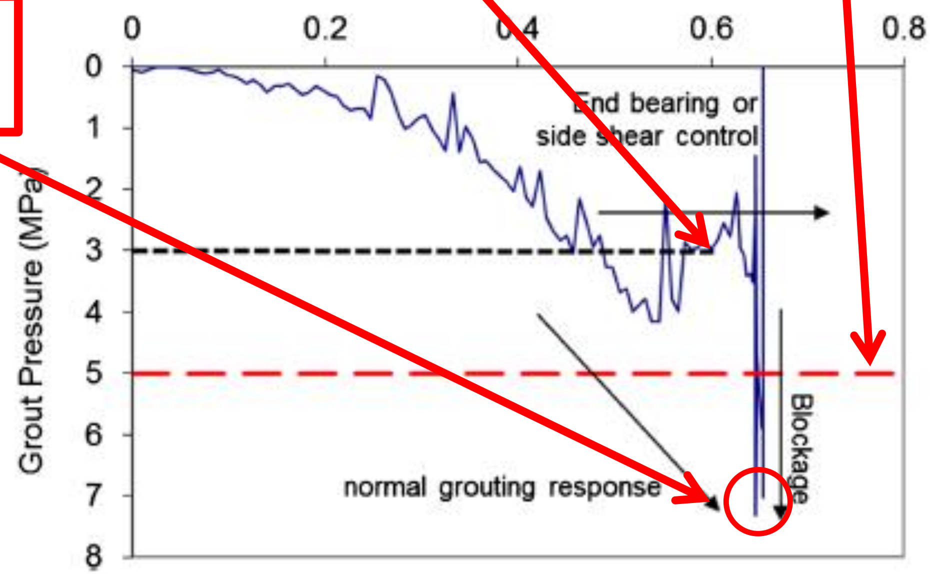
- Grouted normally up to 4MPa
- Exceeded net volume criterion
- Exhibited end bearing failure
- Followed by system blockage
- Met both pressure and volume criterion, but not actually
- Effectively ended at 3MPa



Grout pressure determination







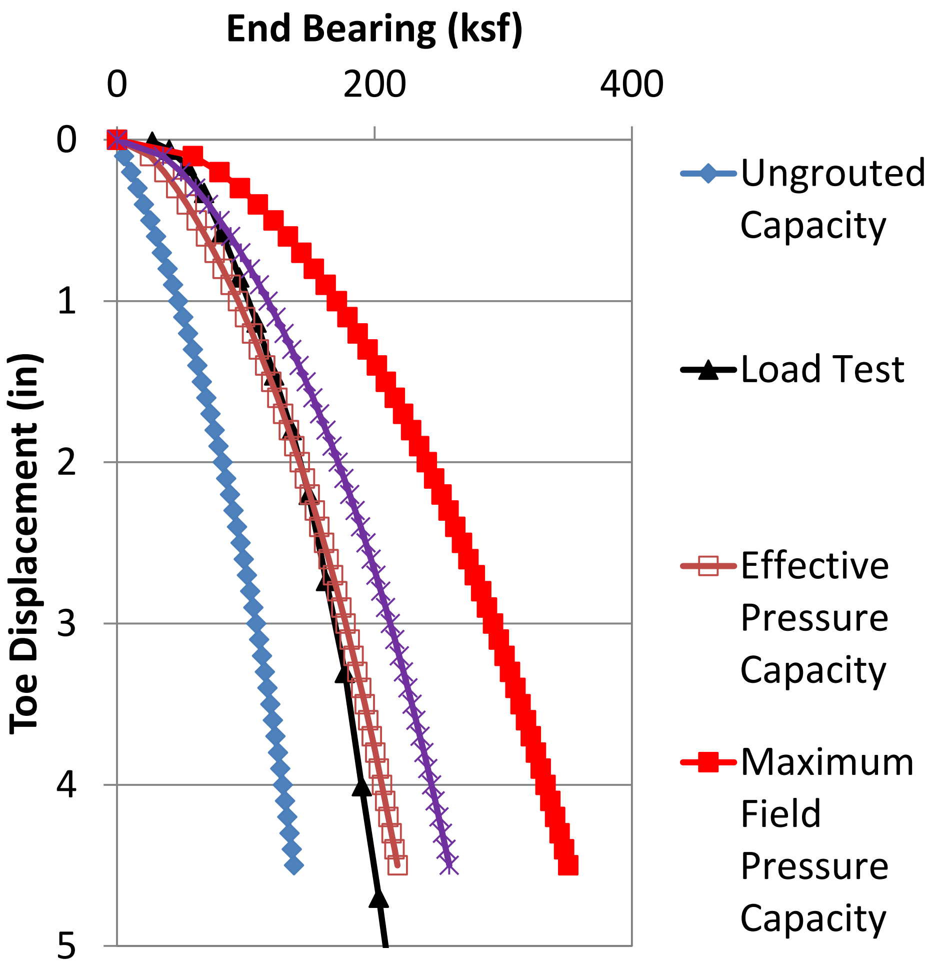
Side Shear predicted pressure 5 MPa

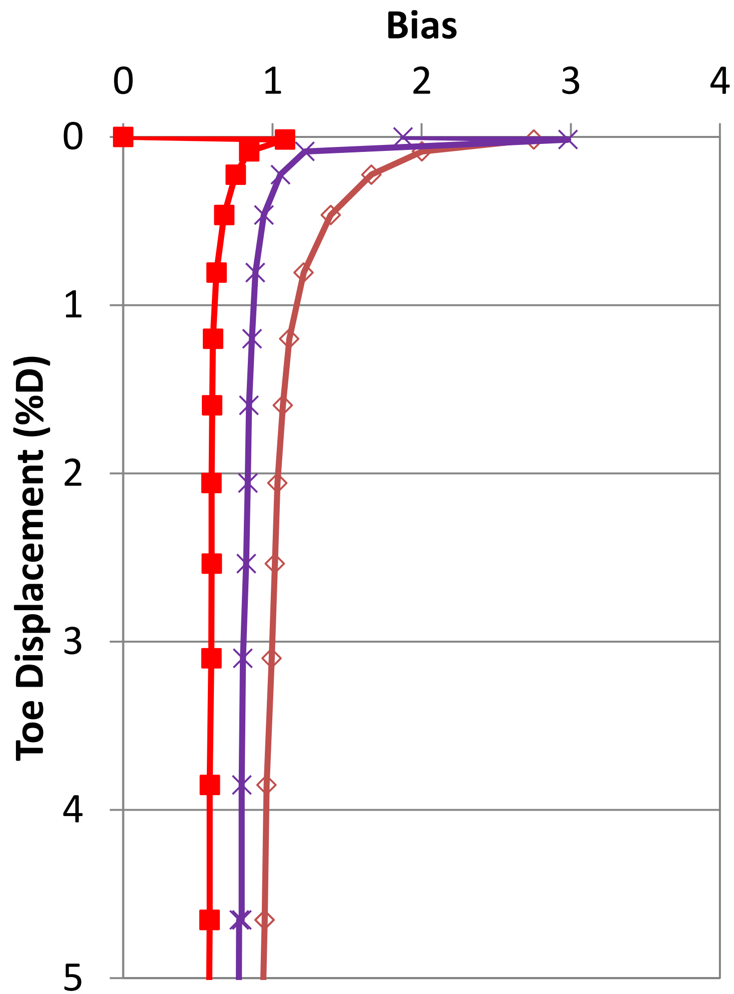
Effective grout pressure 3MPa

Max field recorded pressure 7.2MPa

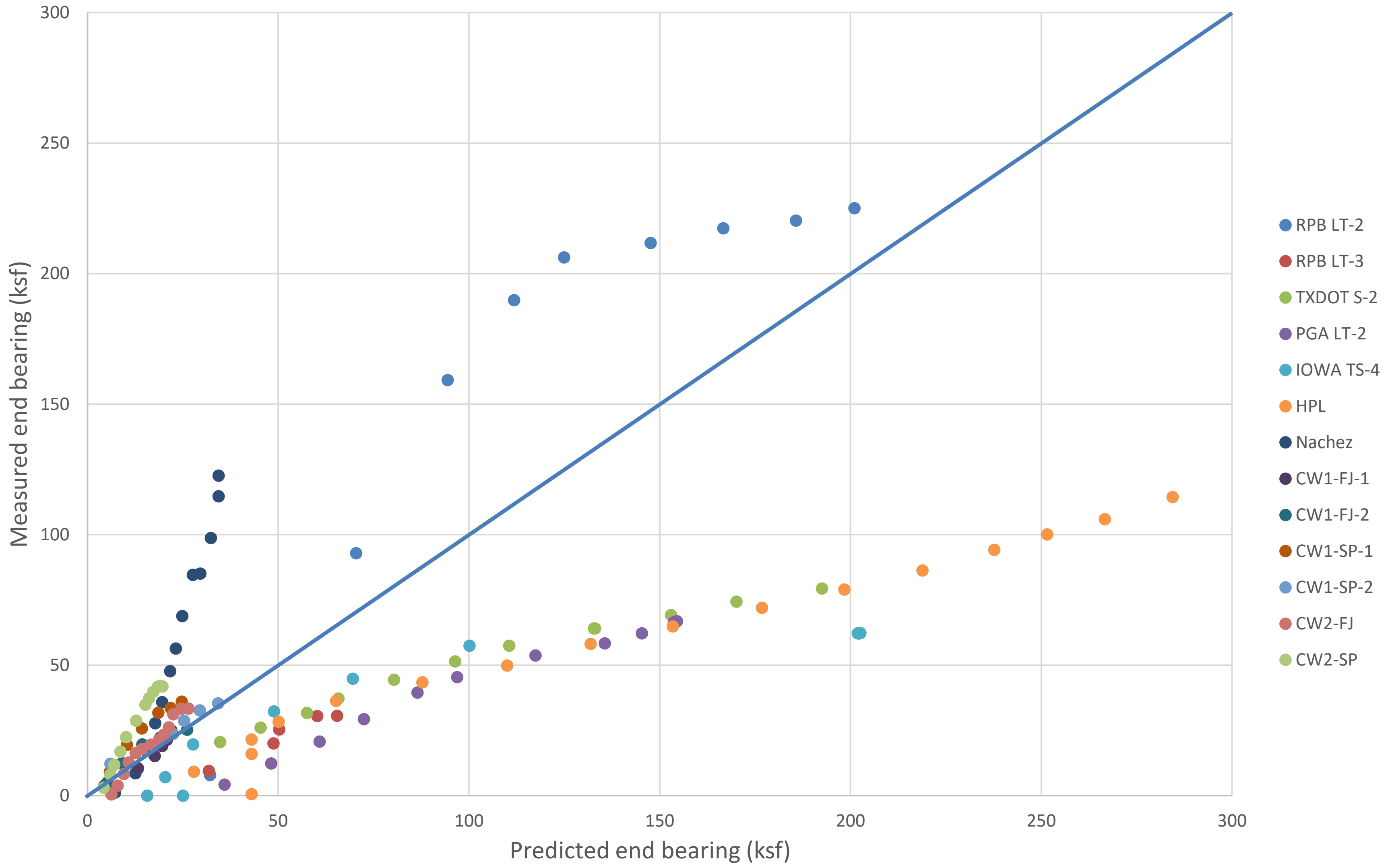
- Grouted normally up to 4MPa
- Exceeded net volume criterion
- Exhibited end bearing failure
- Followed by system blockage
- Met both pressure and volume criterion, but not actually
- Effectively ended at 3MPa

Measured vs Predicted

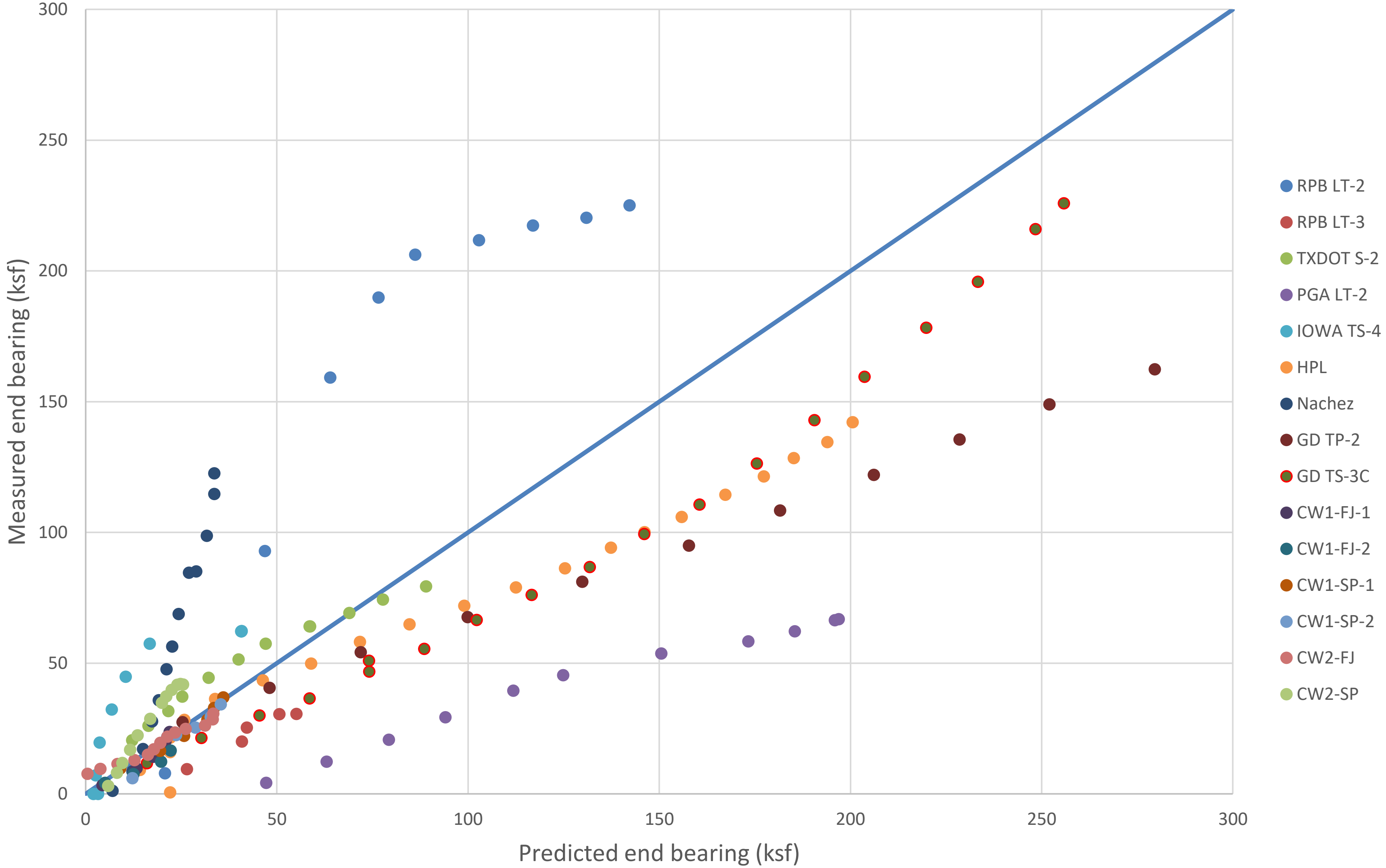




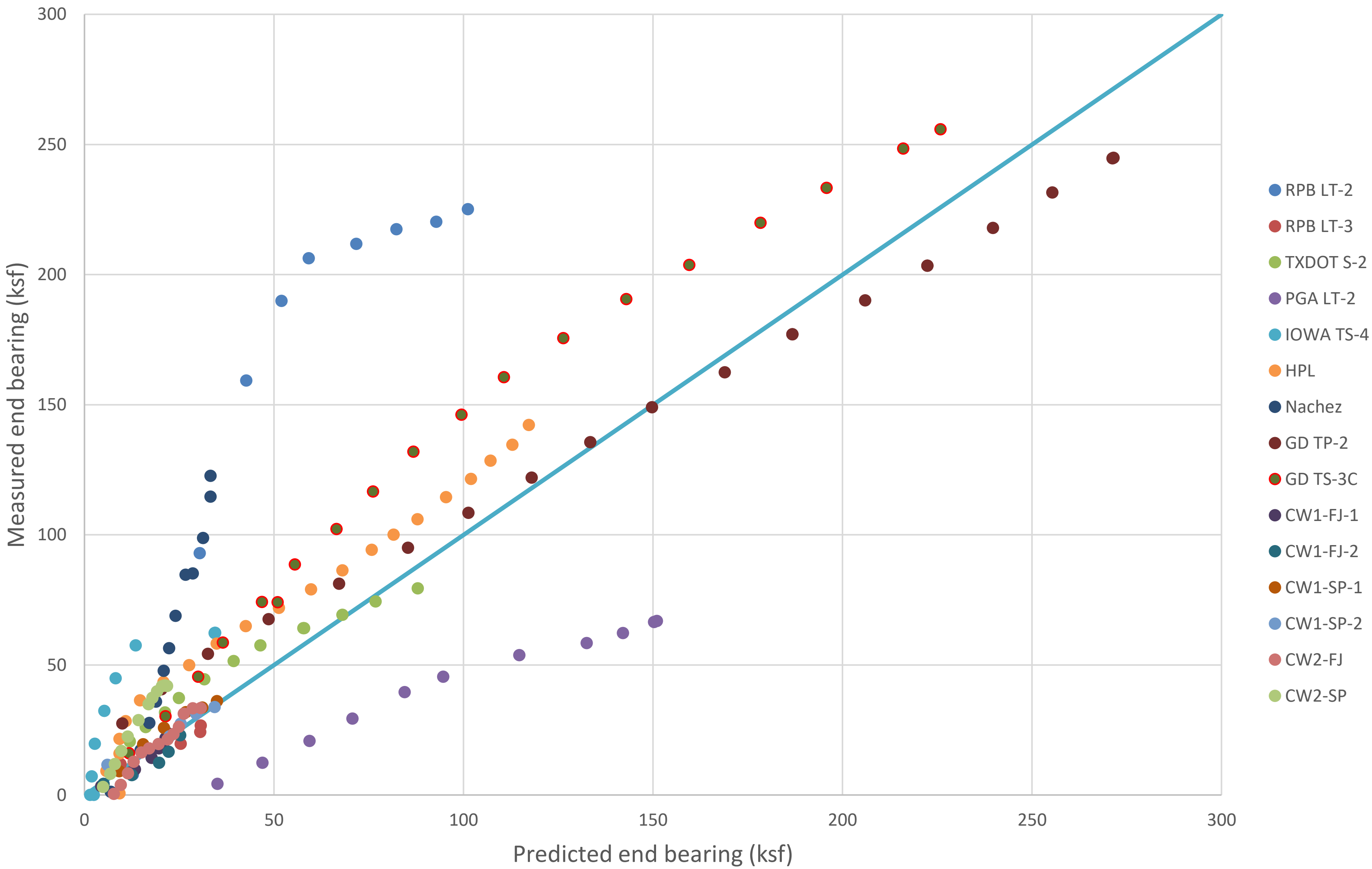
Measured vs Predicted (side shear predicted pressure)



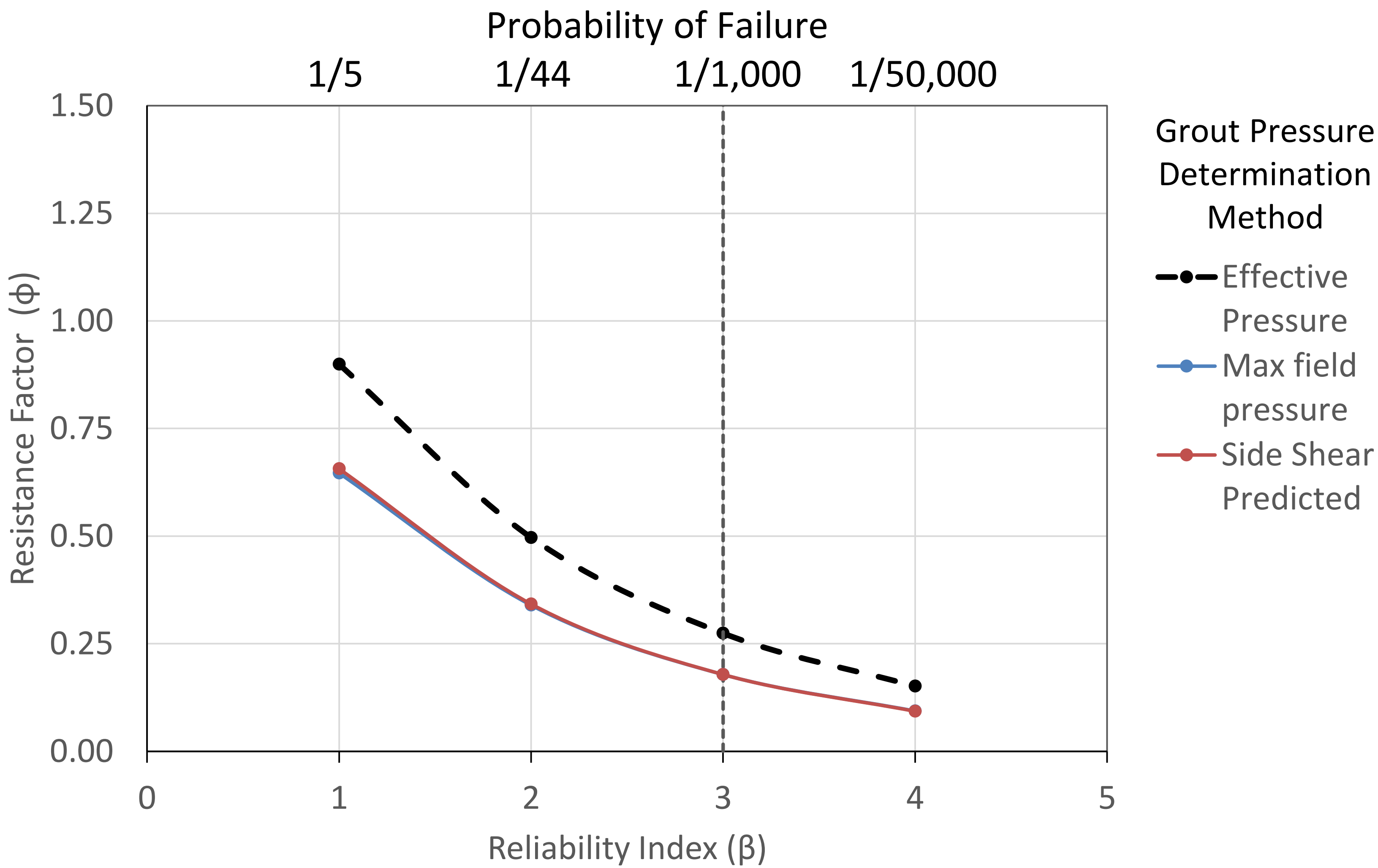
Measured vs Predicted
(max field recorded pressure)



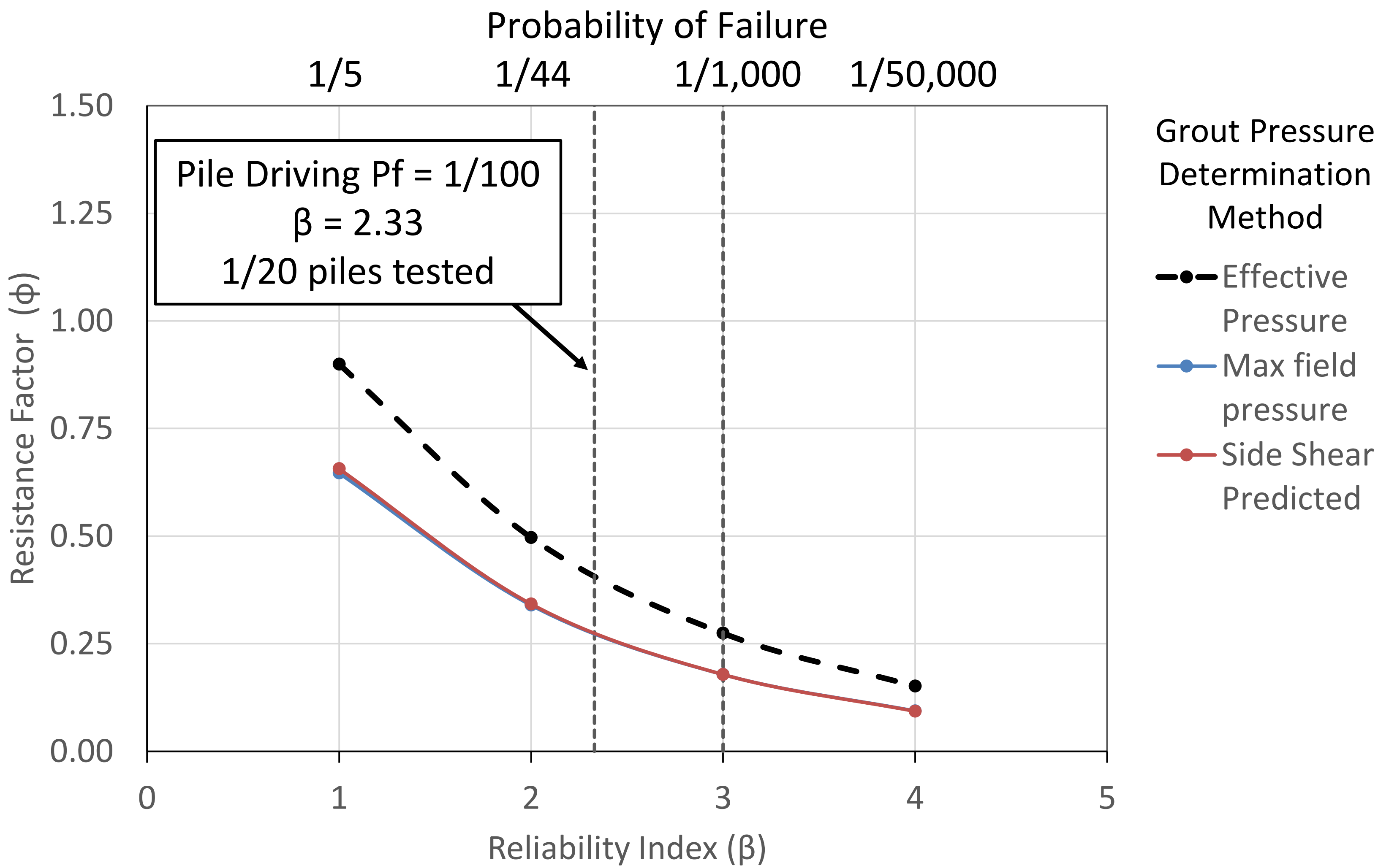
Measured vs Predicted (effective grout pressure)



Preliminary Results



Preliminary Results



Preliminary Results

Bias Criteria	Resistance Factor (φ)			
	$\beta = 1.00$	$\beta = 2.00$	$\beta = 2.33$	$\beta = 3.00$
Effective pressure (field verified / inspection plots)	0.90	0.50	0.41	0.27
Maximum field pressure	0.65	0.34	0.27	0.18
Side shear predicted pressure	0.66	0.34	0.28	0.18

Future Work

- Half of the available data has not been included (missing one or more required items). Will continue to fill in the missing pieces.
- Grout pressure predictions based on side shear predictions apply no resistance factor. Will check the effects of using uplift side shear resistance factor (e.g. 0.45 for sand)
- Need to establish criteria for selecting proper reliability index for 100% post grout (proof test)

Effects of Slurry on Rebar Bond
(FHWA Drilled Shaft Manual 2010)

"The current state of knowledge on this topic suggests that the use of mineral and polymer slurries for drilled shaft construction does not reduce the bond resistance between concrete and reinforcing bars. There is currently no reason to account for the use of drilling fluids when considering development length of rebar in drilled shafts."

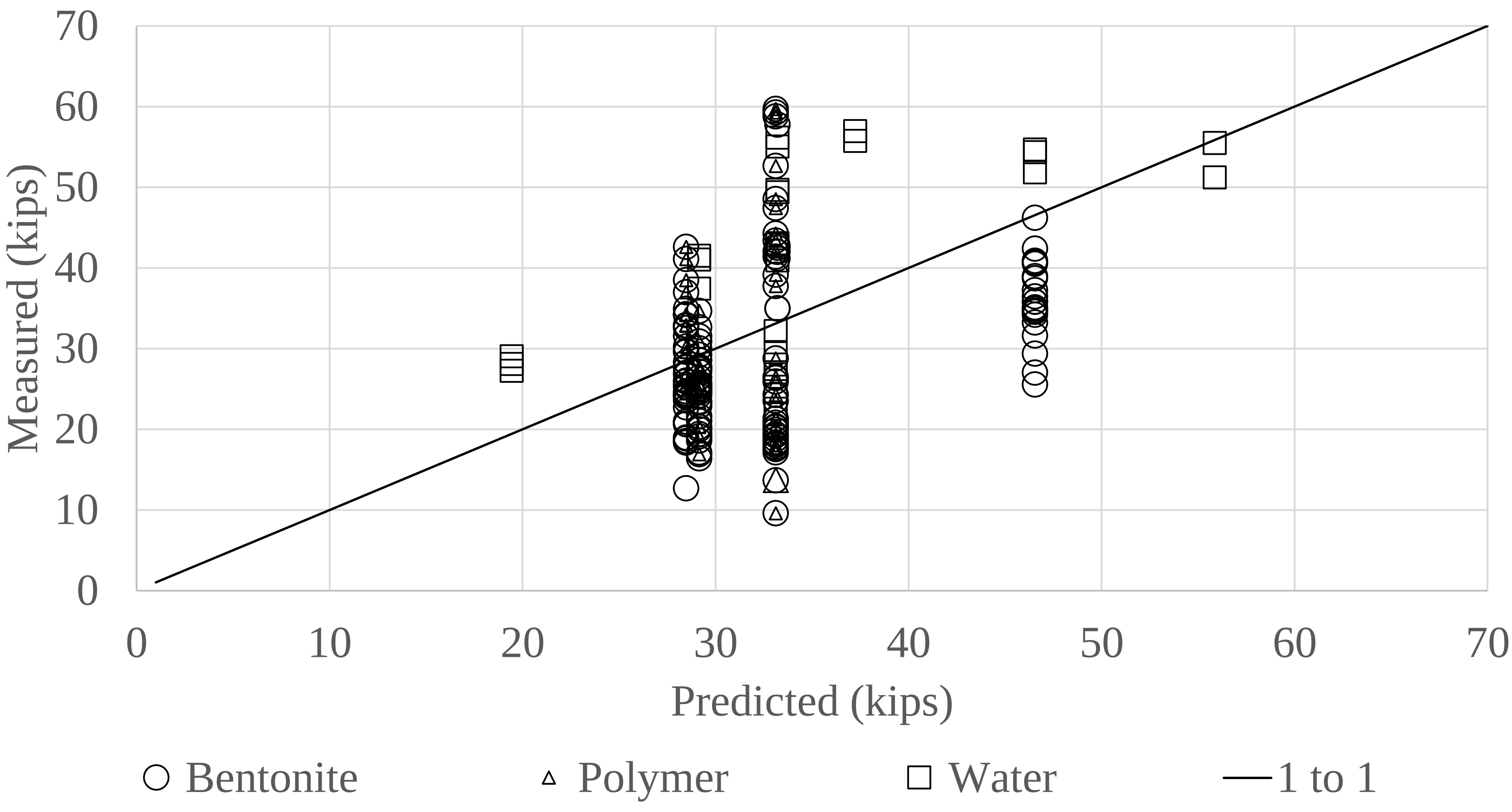
Effects of Slurry on Rebar Bond
(FDOT 455 Specifications 2018)

For new slurry products

"demonstrate the bond between the bar reinforcement and the concrete is not materially affected by exposure to the slurry under typical construction conditions, over the typical range of slurry viscosities to be used."

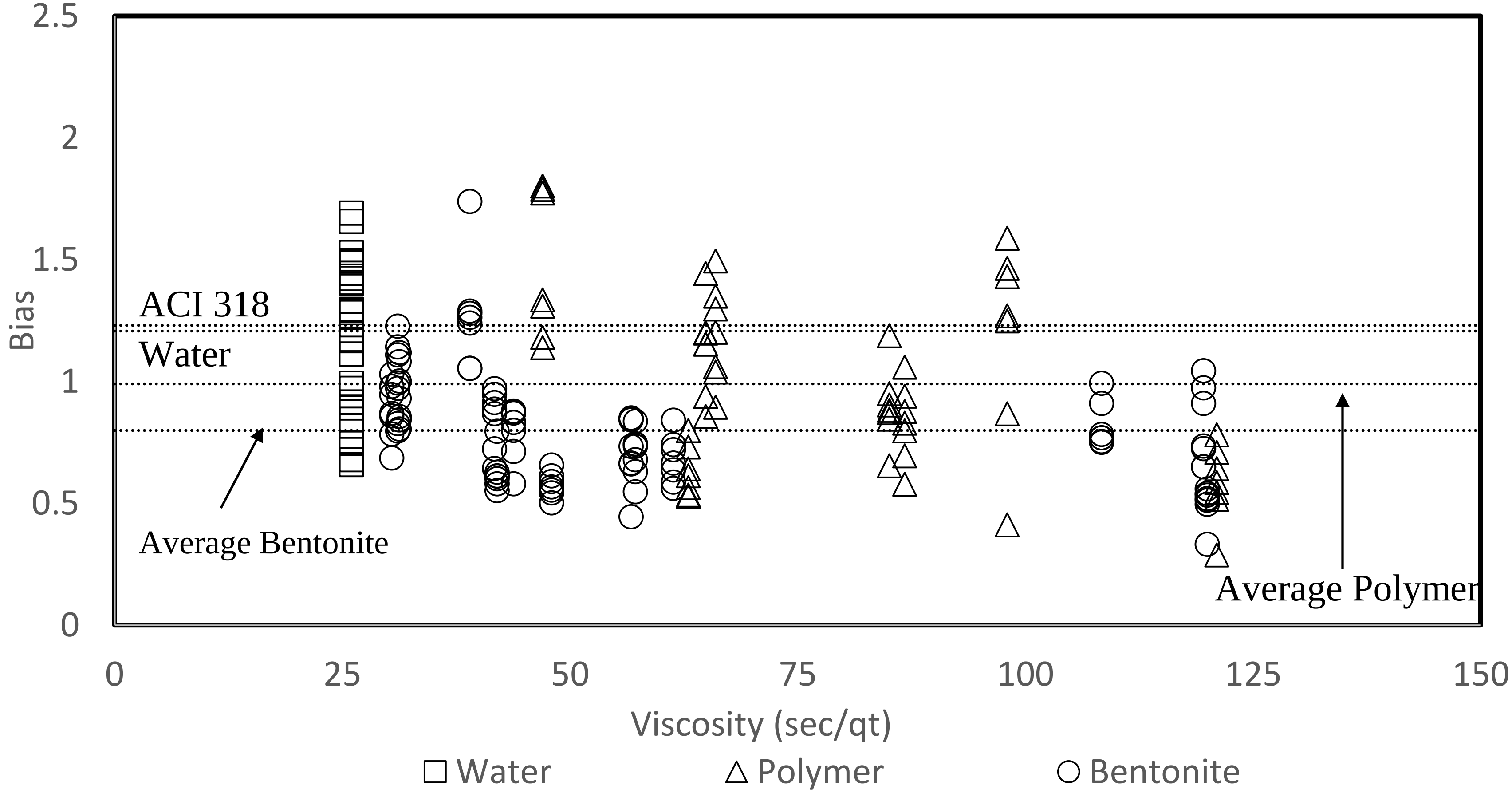
Effects of Slurry on Rebar Bond

(227 rebar pullout tests)



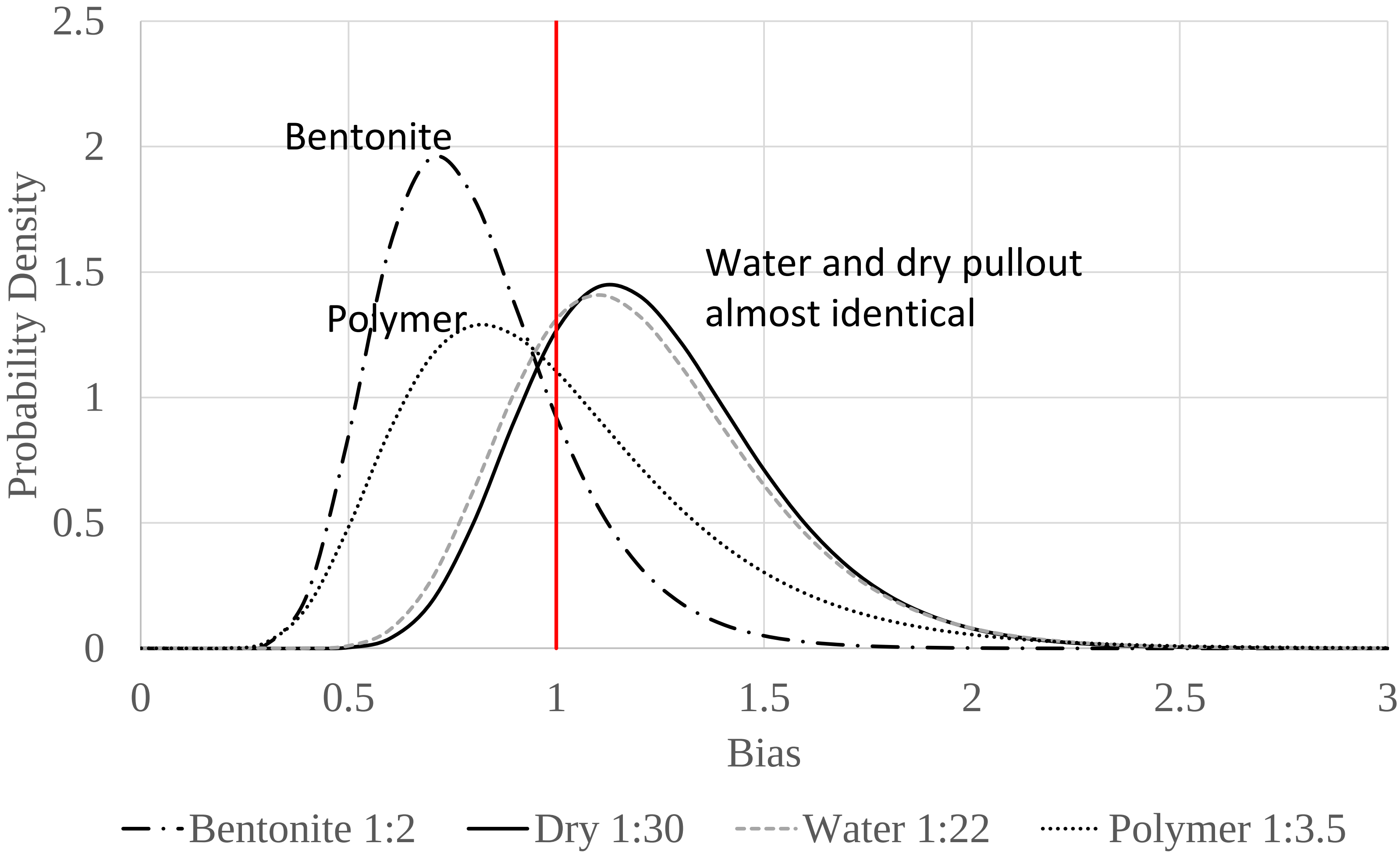
Effects of Slurry on Rebar Bond

(227 rebar pullout tests)



Effects of Slurry on Rebar Bond

(227 rebar pullout tests)



Effects of Slurry on Rebar Bond

(development length)

$$l_d = \left(\frac{3}{40} \frac{f_y}{\lambda \varnothing_d \sqrt{f_c'}} \frac{\Psi_t \Psi_e \Psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b$$

Present ACI 318 Code limits this expression to ≤ 2.5

Water – 0/1,000,000
Bentonite – 1/3074
Polymer – 1/2040

Required Reliability Index
β = 3.5 or Pf ≤ 1/4149

Effects of Slurry on Rebar Bond
(development length)

$$l_d = \left(\frac{3}{40}\frac{f_y}{\lambda \emptyset_d \sqrt{f_c'}}\frac{\Psi_t \Psi_e \Psi_s}{\left(\frac{c_b + K_{tr}}{d_b}\right)}\right) d_b$$

New ACI 408 Committee recommendations use resistance factors to unify reliability

Dry – 1/4629
Water – 1/4694
Bentonite – 1/4166
Polymer – 1/4219

Present ACI 318 Code limits this expression to ≤ 2.5

Water – 0/1,000,000
Bentonite – 1/3074
Polymer – 1/2040

Required Reliability Index
β = 3.5 or Pf ≤ 1/4149

Effects of Slurry on Rebar Bond

$\emptyset_{\text{dry}}$	0.65
$\emptyset_{\text{water}}$	0.61
$\emptyset_{\text{bentonite}}$	0.37
$\emptyset_{\text{polymer}}$	0.35
Ψ_{water}	1.1
$\Psi_{\text{bentonite}}$	1.8
Ψ_{polymer}	1.9

Present ACI 318 Code recognizes effects of rebar coatings like epoxy (1.0 bare steel; 1.5 epoxy coated) but does not use resistance factors

$$l_d = \left(\frac{3}{40} \frac{f_y}{\lambda \cancel{\phi_d} \sqrt{f'_c}} \frac{\Psi_t \Psi_e \Psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b$$

So an additional factor for slurry should be used to maintain the same level of reliability as dry conditions

$$\Psi_{\text{slurry}} = \frac{\emptyset_{\text{dry}}}{\emptyset_{\text{slurry}}}$$

Effects of Slurry on Rebar Bond

$\varnothing_{dry}$	0.65
$\varnothing_{water}$	0.61
$\varnothing_{bentonite}$	0.37
$\varnothing_{polymer}$	0.35
Ψ_{water}	1.1
$\Psi_{bentonite}$	1.8
$\Psi_{polymer}$	1.9

Future use of resistance factors

$$l_d = \left(\frac{3}{40} \frac{f_y}{\lambda \varnothing_d \sqrt{f_c'}} \frac{\Psi_t \Psi_e \Psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b$$

Present ACI should use slurry factors

$$l_d = \left(\frac{3}{40} \frac{f_y}{\lambda \sqrt{f_c'}} \frac{\Psi_t \Psi_e \Psi_s \Psi_{slurry}}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b$$

Conclusion

- Mineral and polymer slurry affect rebar bond
- New product testing has compared new slurry to bentonite and have been similar
- Most rebar splices in shafts do not occur in high moment regions requiring full development so failures are not likely to occur (?)
- However, to maintain same reliability some allowance should be made by increasing development lengths for slurry casting conditions

Questions