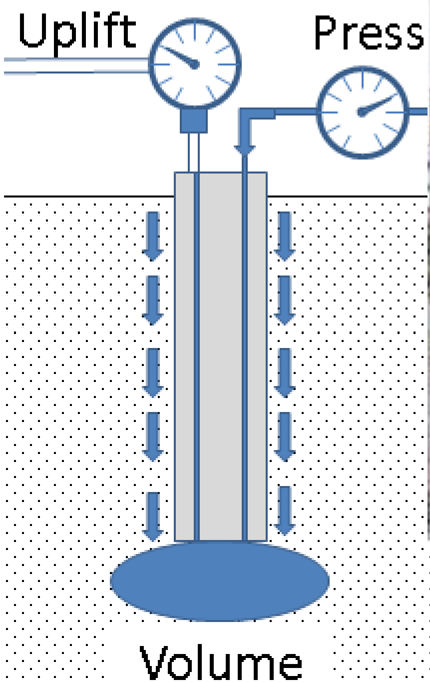
Load and Resistance Factor Design (LRFD) Resistance Factors for Tip Grouted Drilled Shafts



BDV25 TWO 977-37

GRIP 2019

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
- Results and Conclusions

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

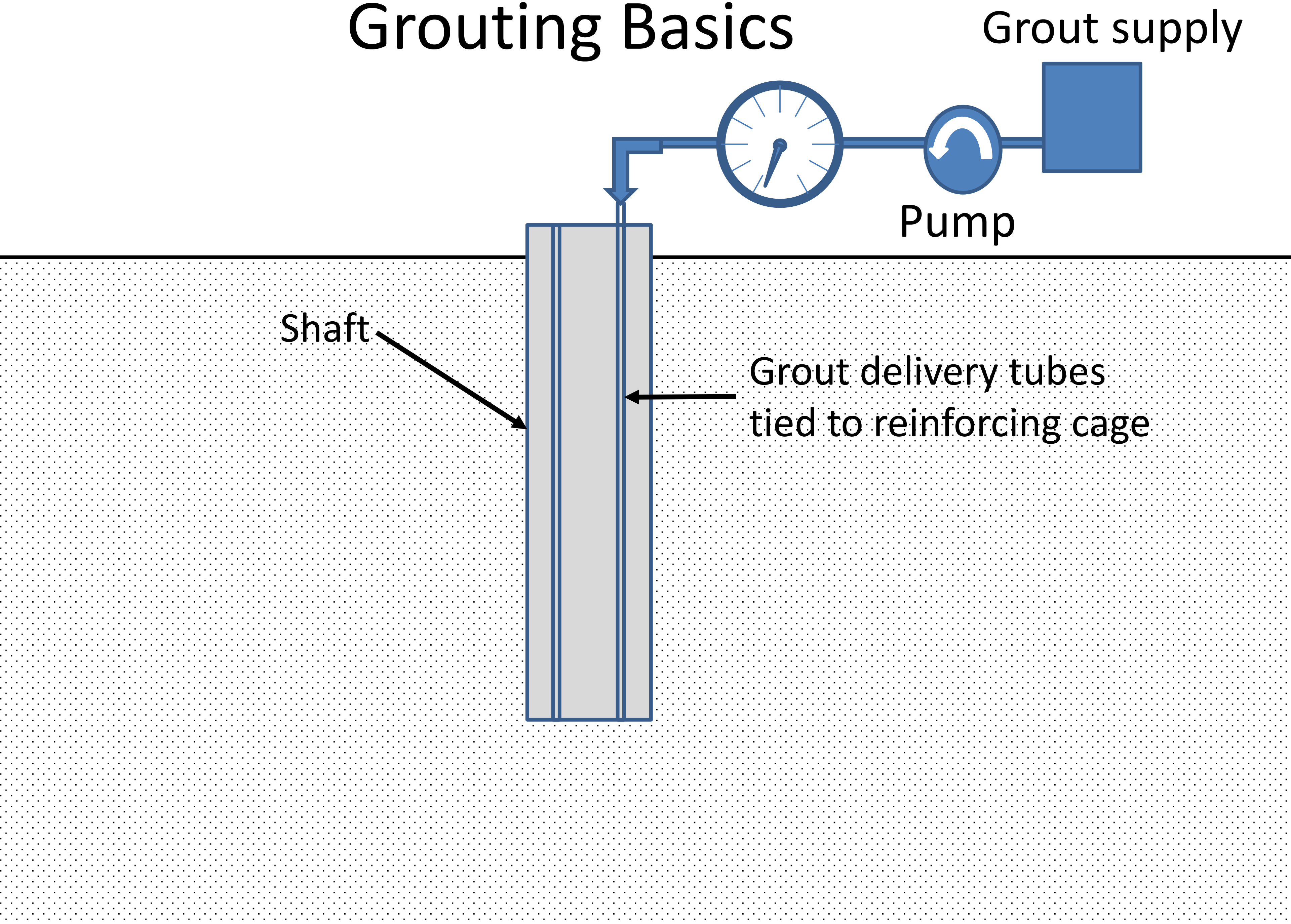
"Resistance factors and associated design methods for geotechnical resistance of drilled shafts are in SDG Table 3.6.3-1 [Table 2.3]. *It is implicitly shown in the table that the resistance factors for* ***drilled shafts tipped in sand or clay*** *are based on* ***side shear*** *design methods* ***only***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

Soils and Foundations Handbook

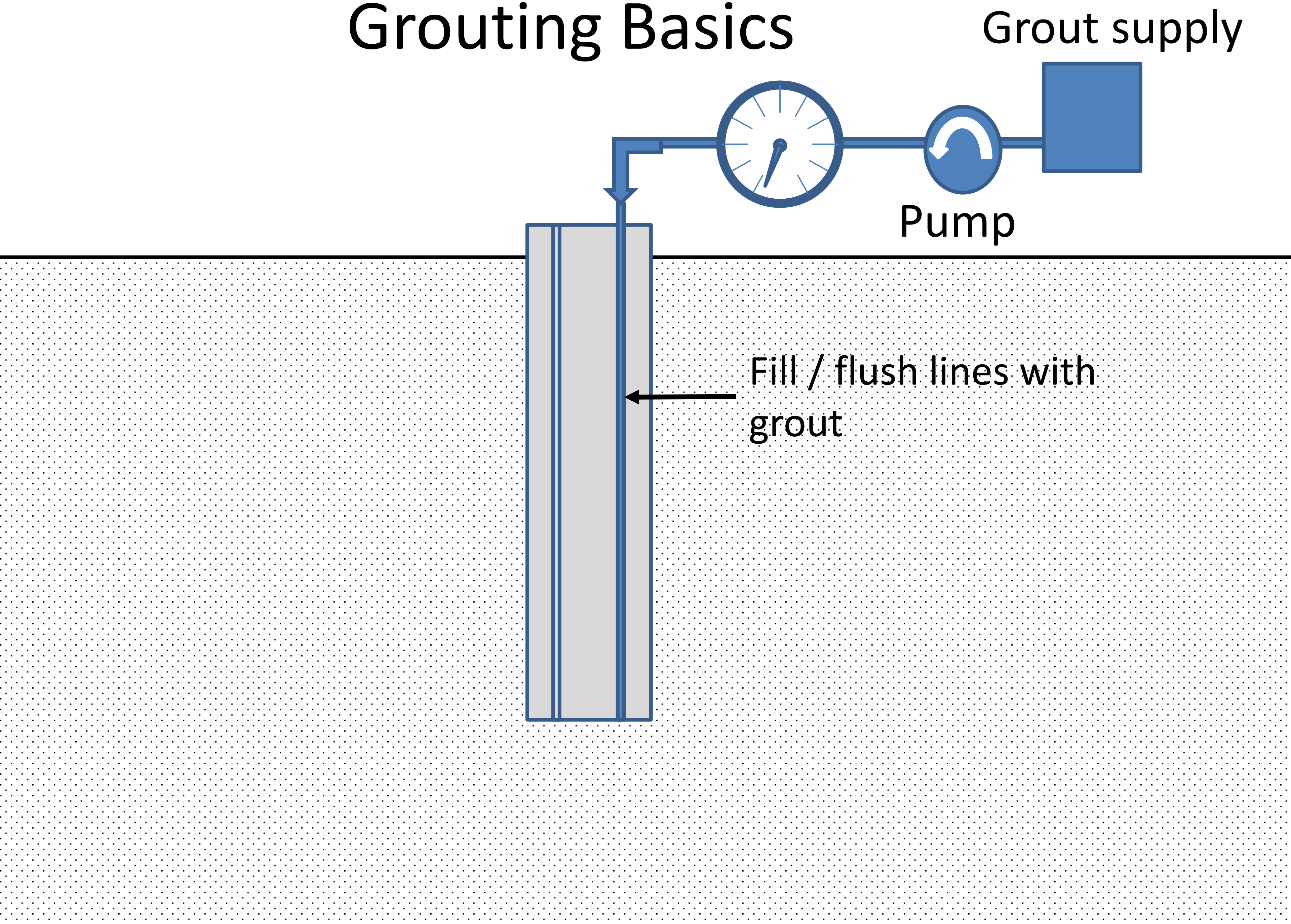
*"**In sand, drilled shafts with pressure grouted tips should be considered.** Pressure grouted tips are most effective in loose to medium dense sands. Guidance for the design of drilled shafts with pressure grouted tips may be found in Appendix D and in Reference 9."*

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

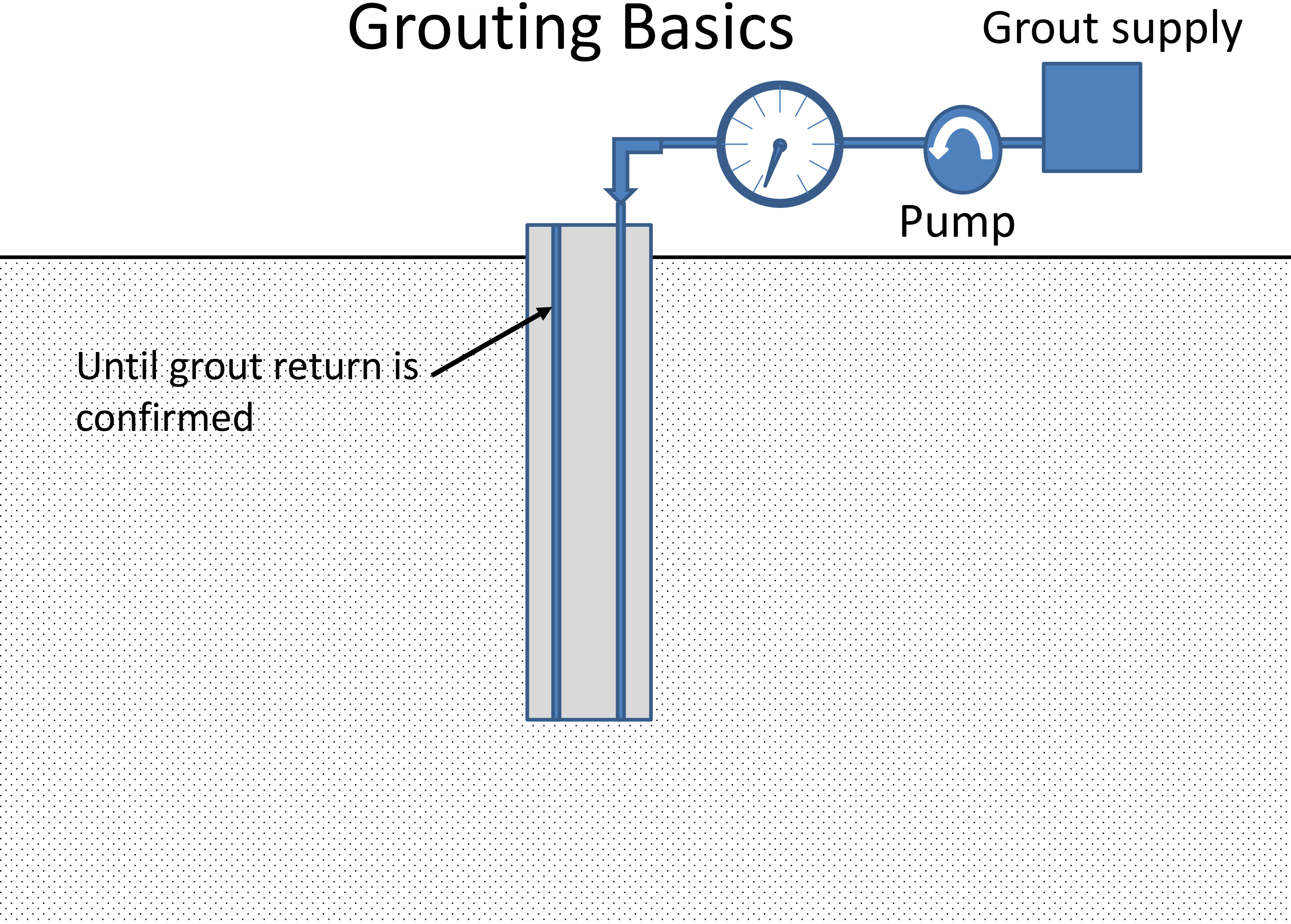
Grouting Basics

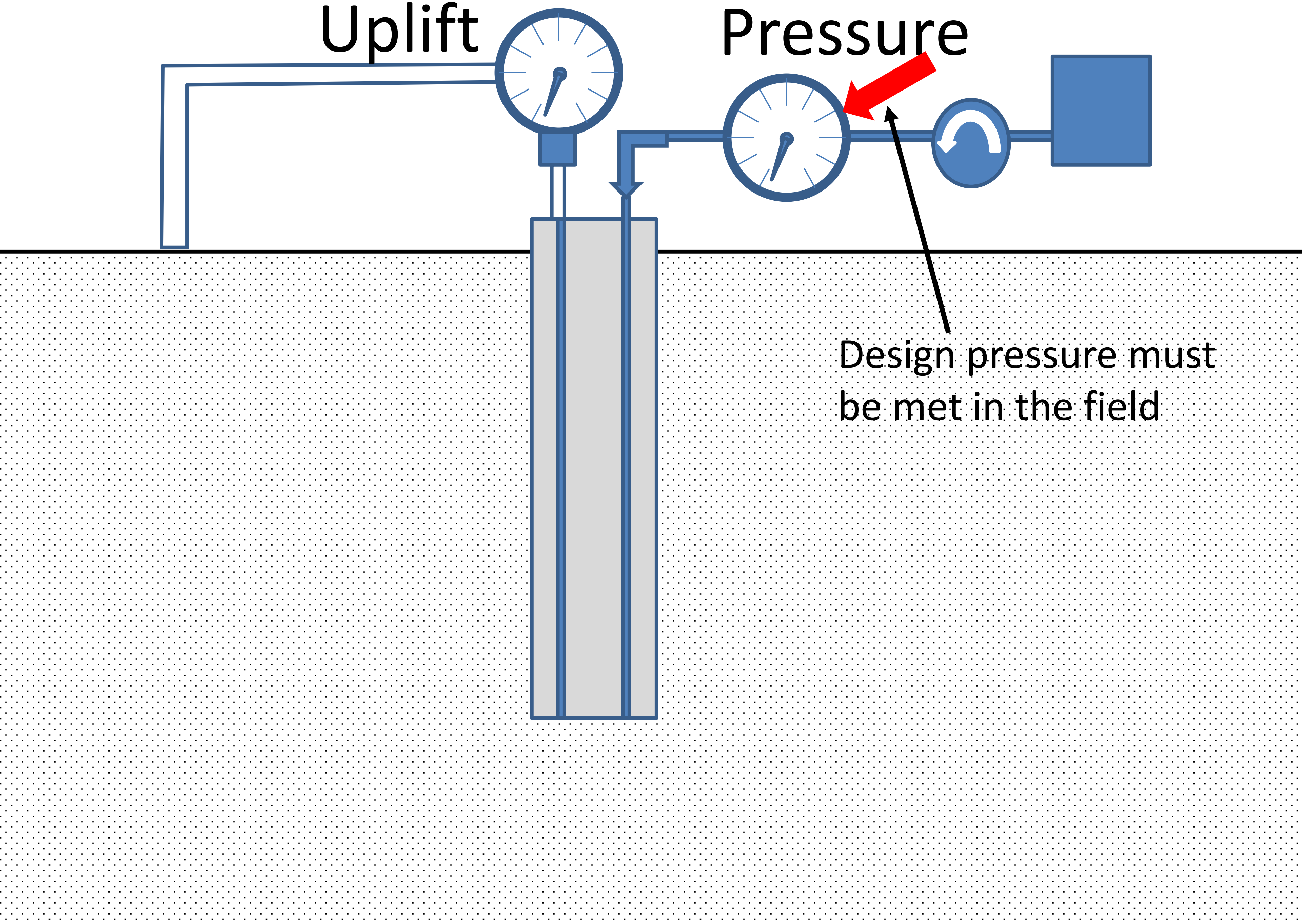


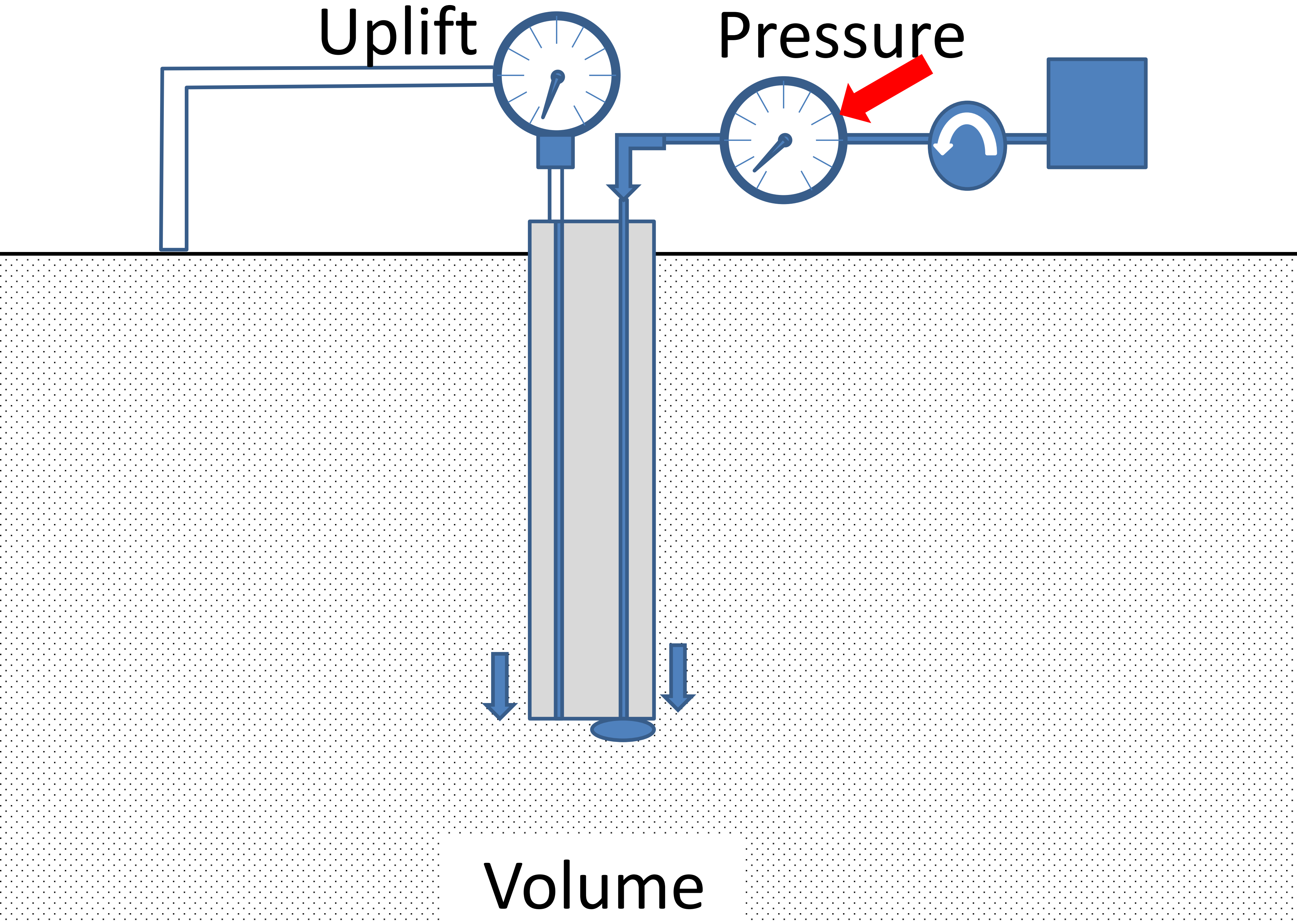
Grouting Basics

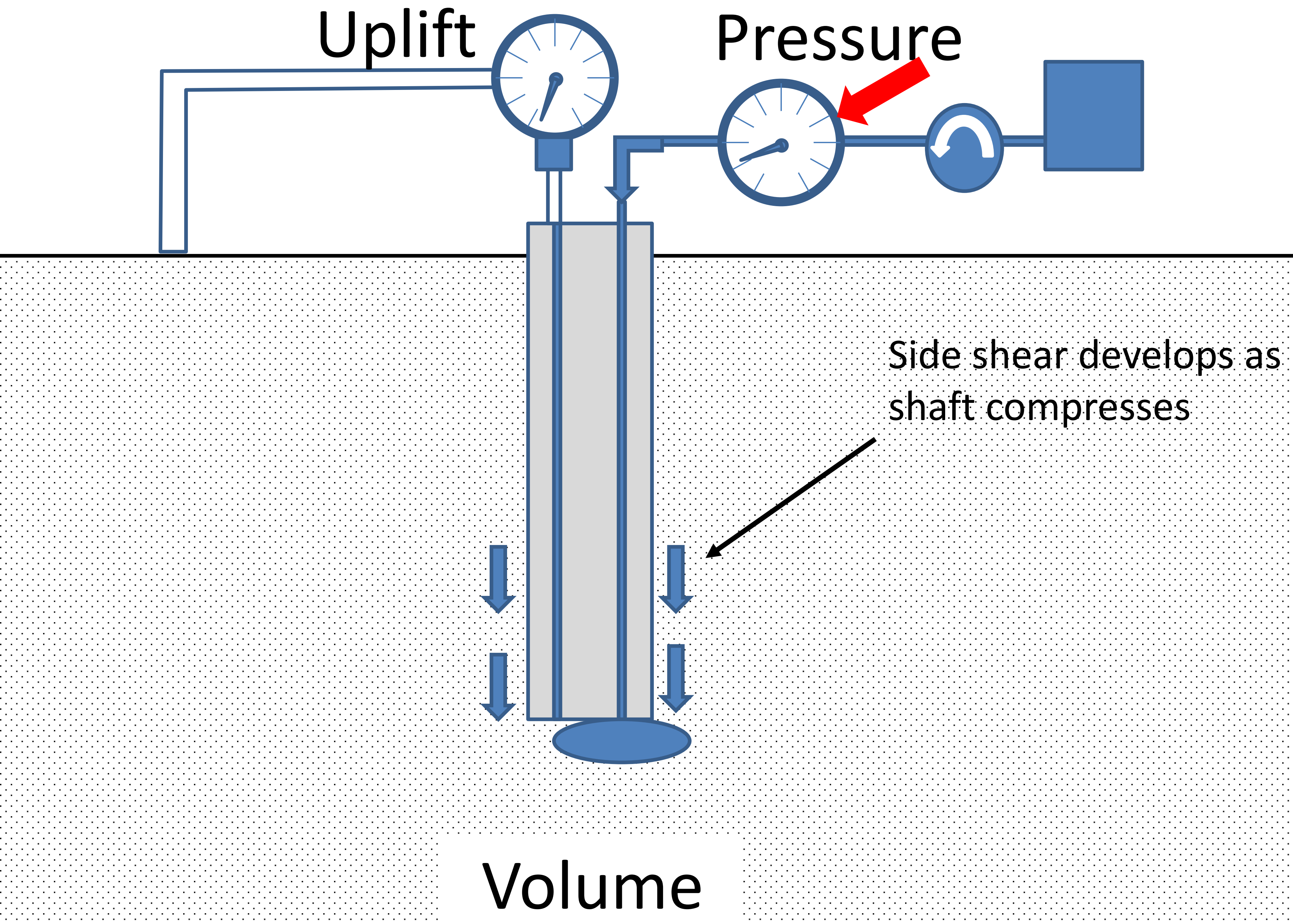


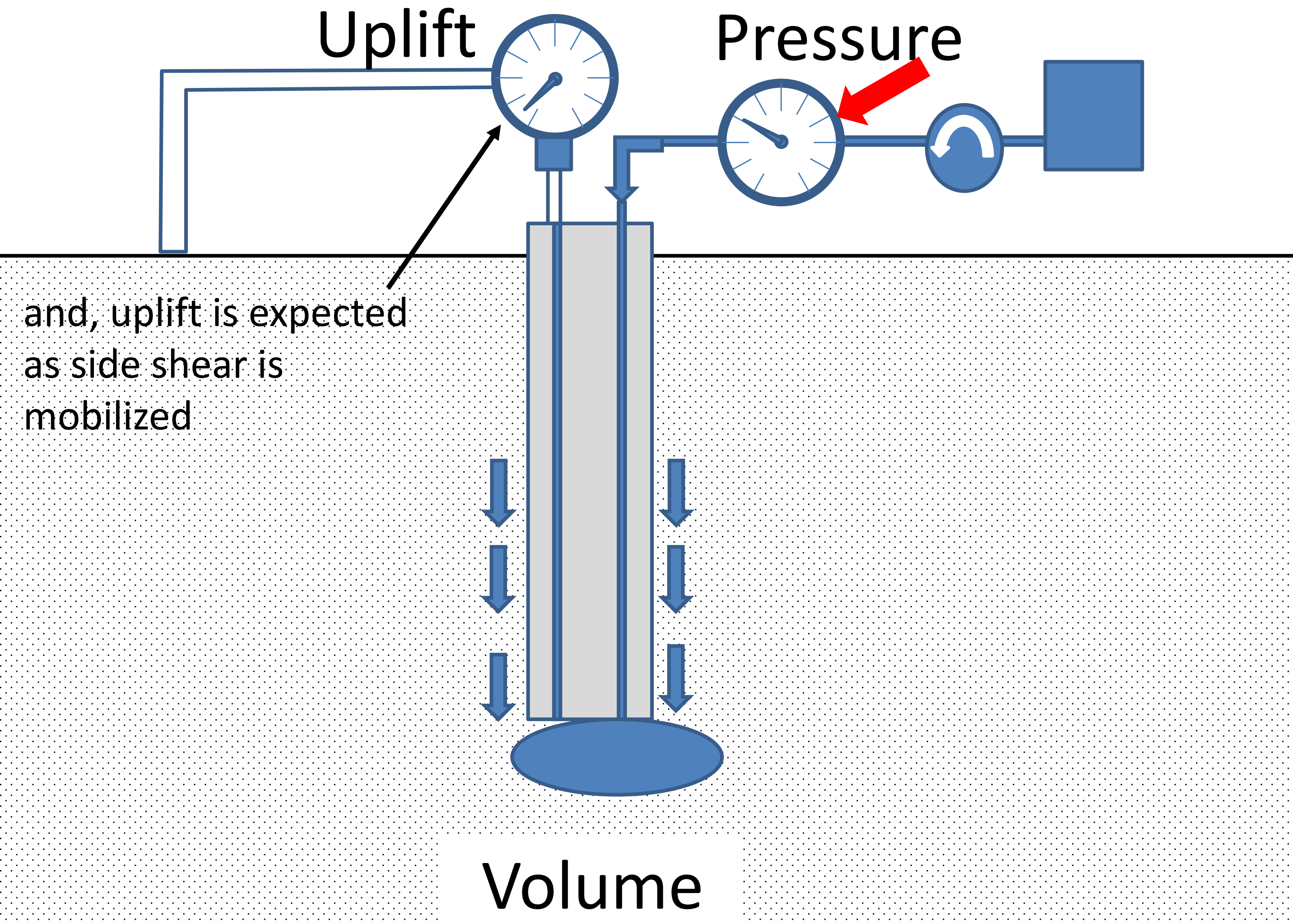
Grouting Basics

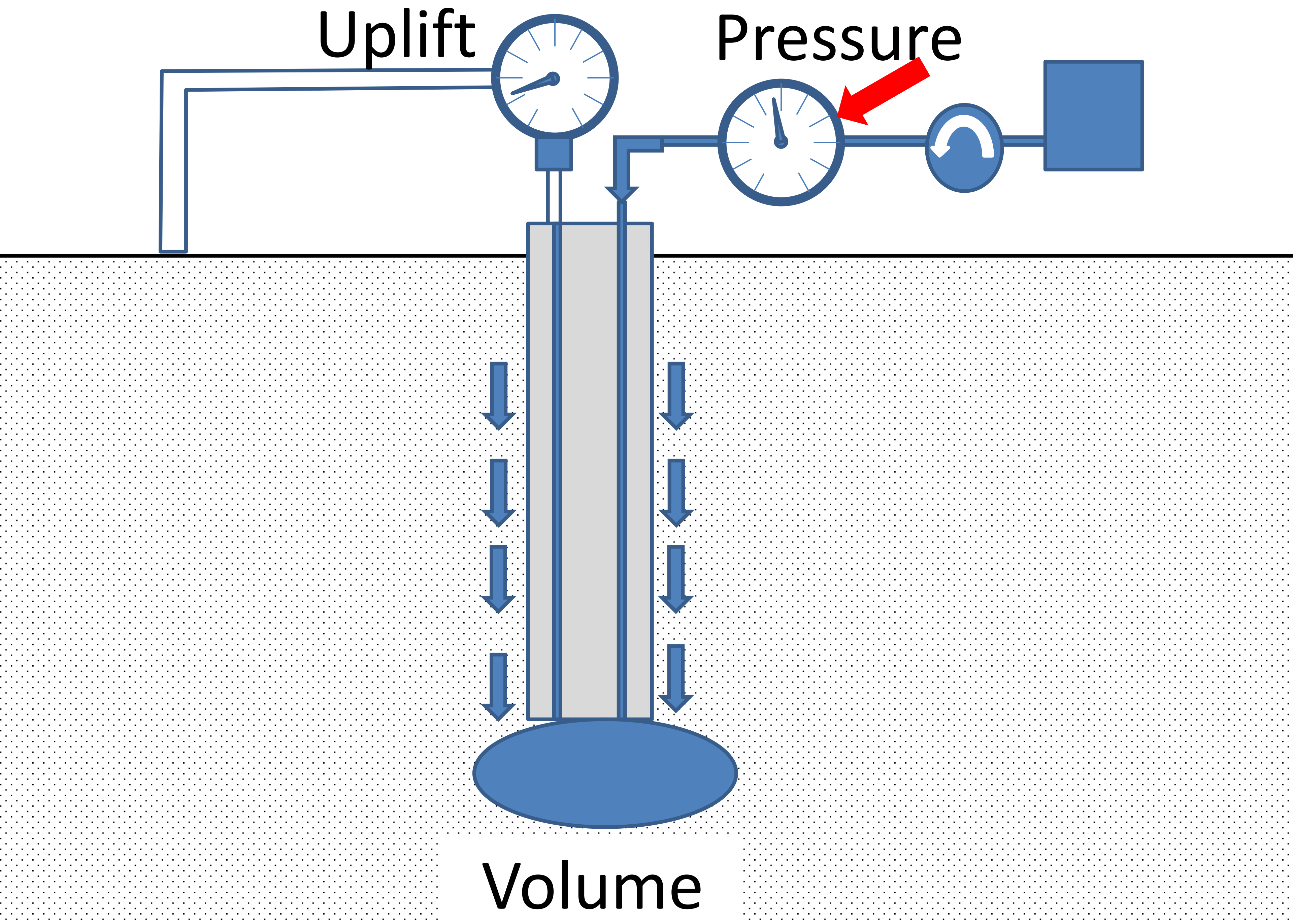


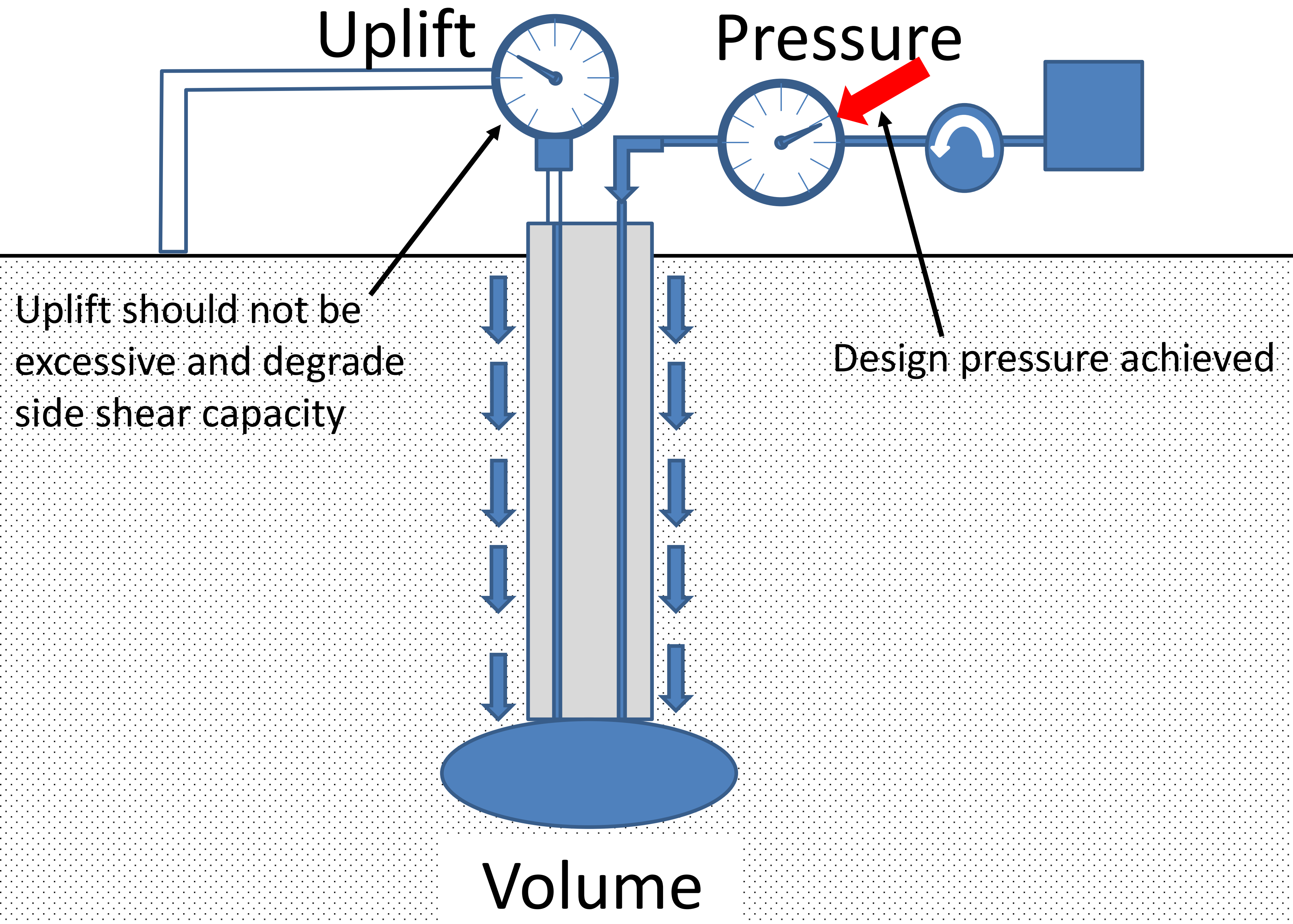

Uplift
Pressure
Design pressure must
be met in the field

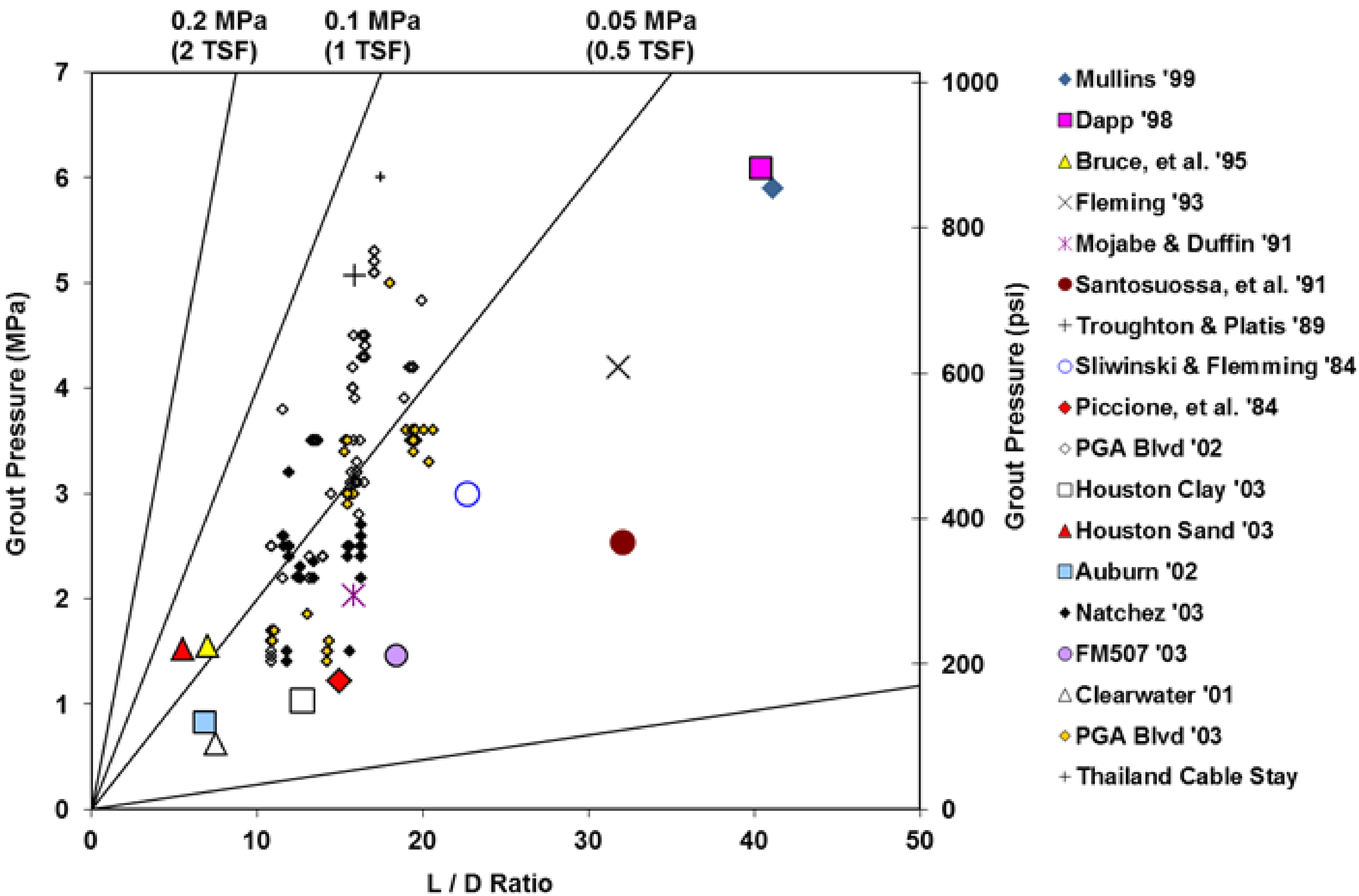

Uplift
Pressure
Volume


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



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

Grouting systems

Sutong (China)

Taipei 101 (Taiwan)

Flagler (Florida)

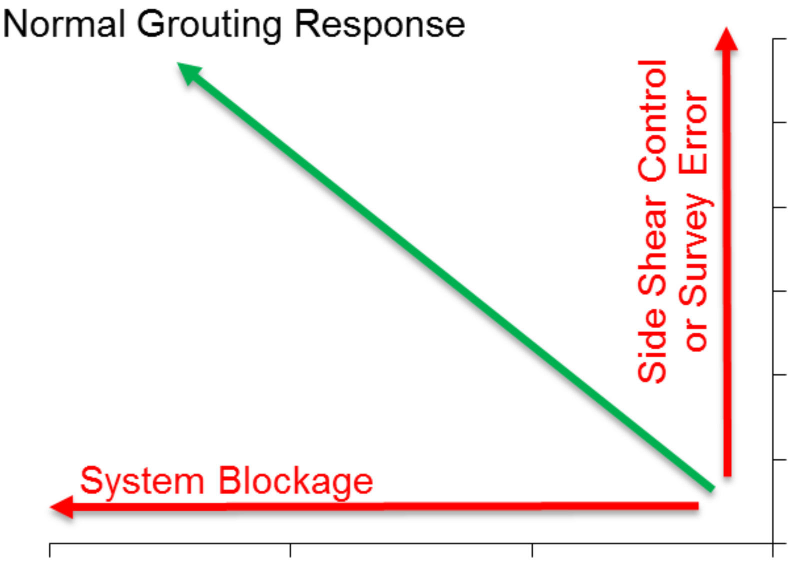
Sleeve Port (tube-a-manchette)

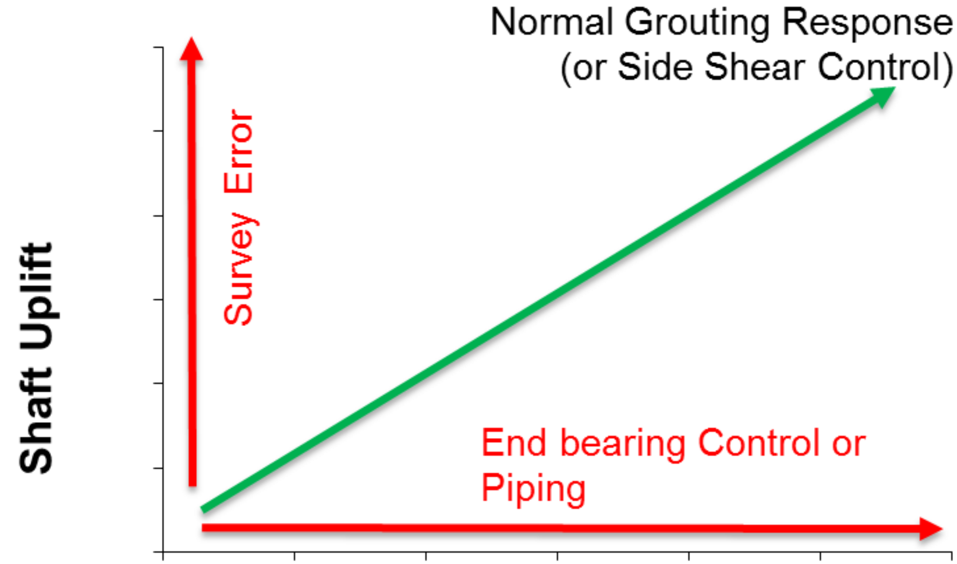
Grouting systems

Flat jack (open or closed)

Expected Results

Effectiveness Plots

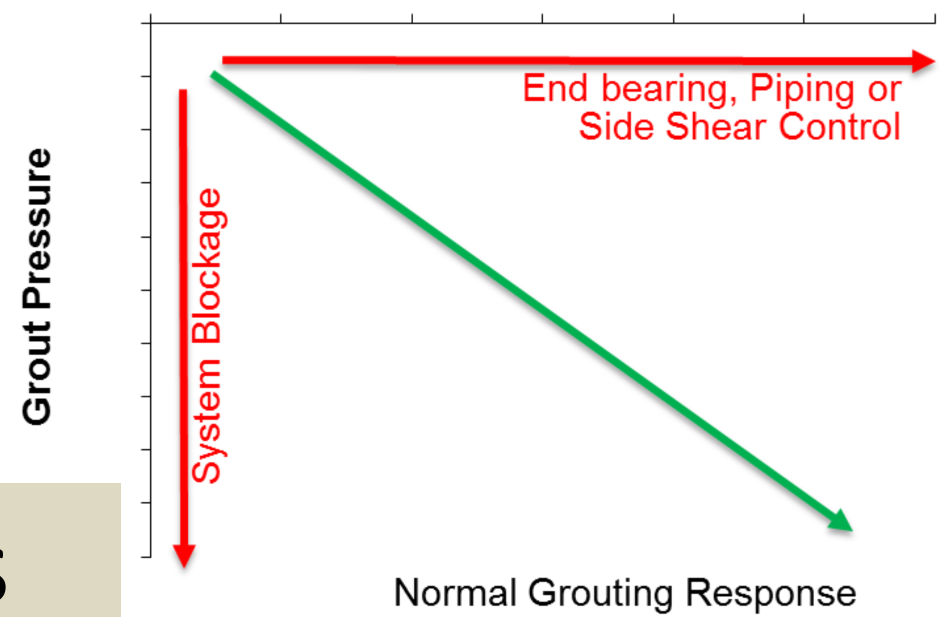




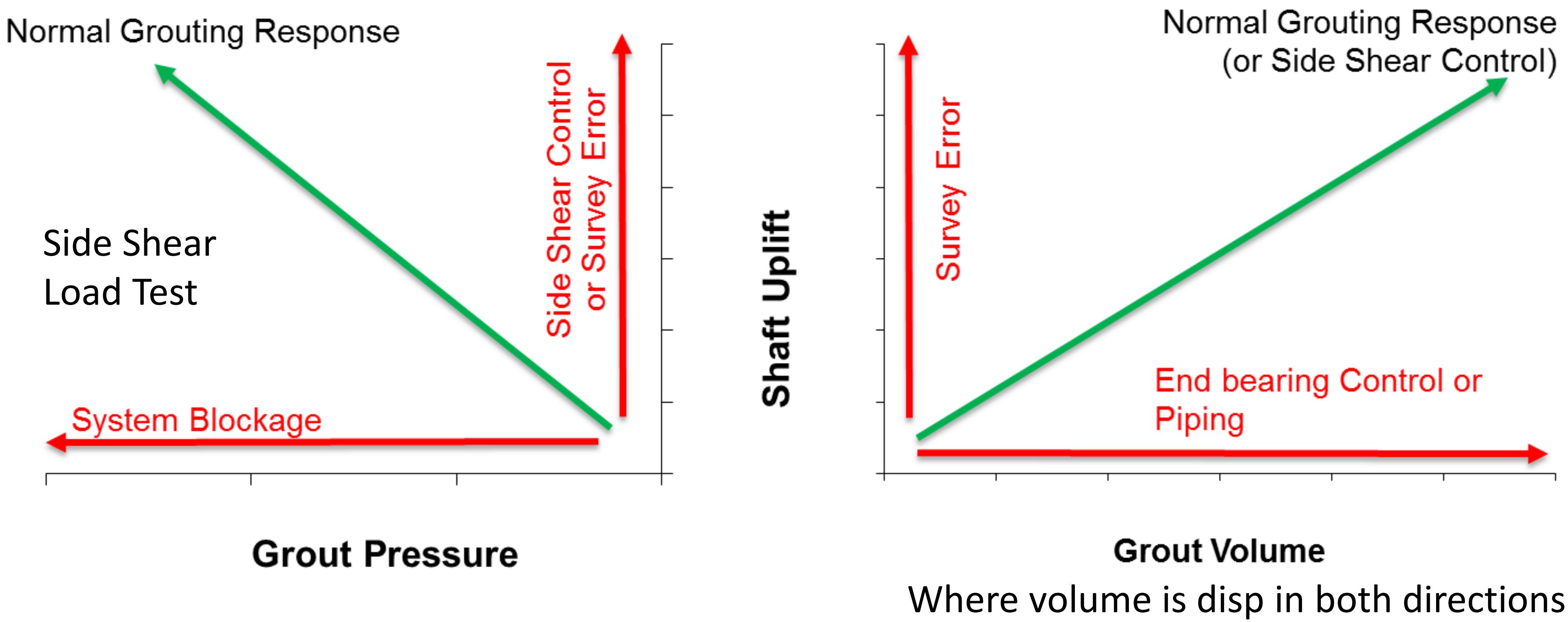
NOTE:

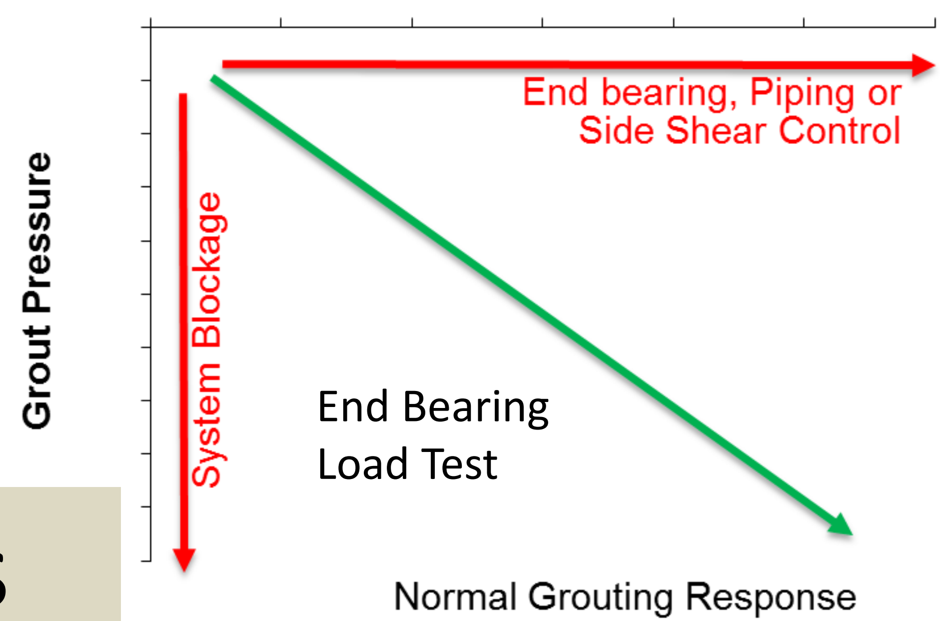
(1) All graphs should demonstrate a diagonal trend away from the center.

(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



Expected Results





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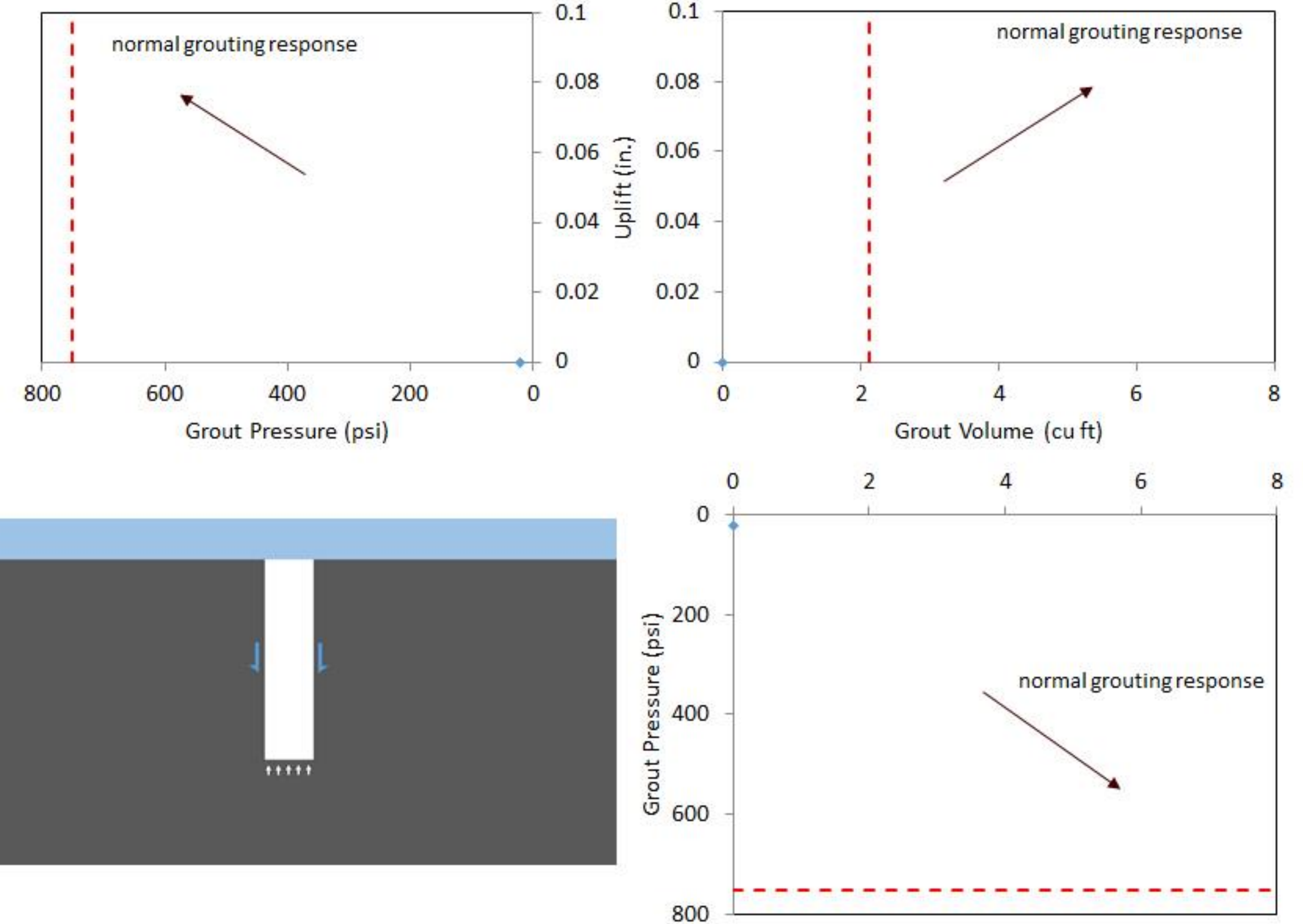
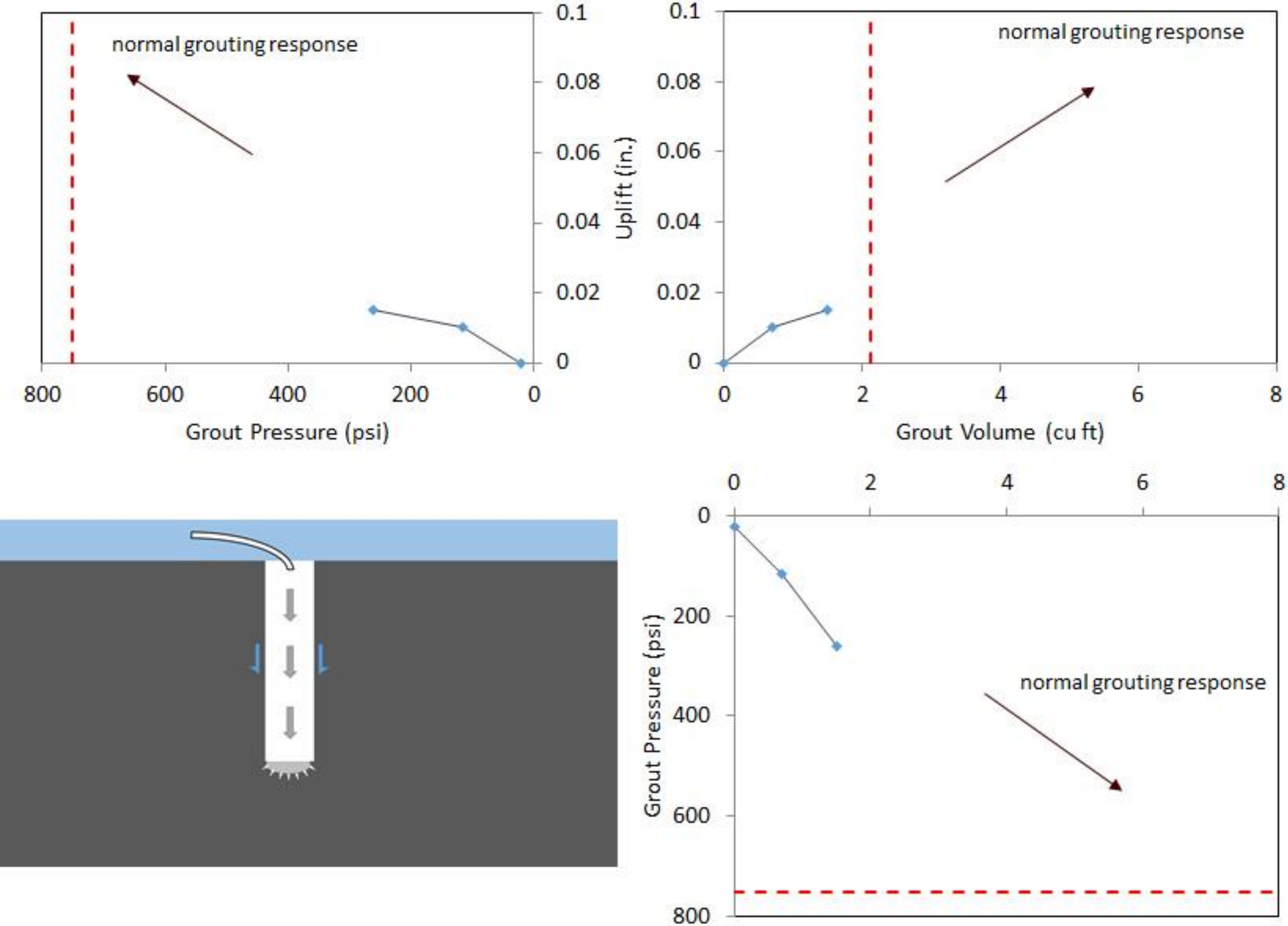
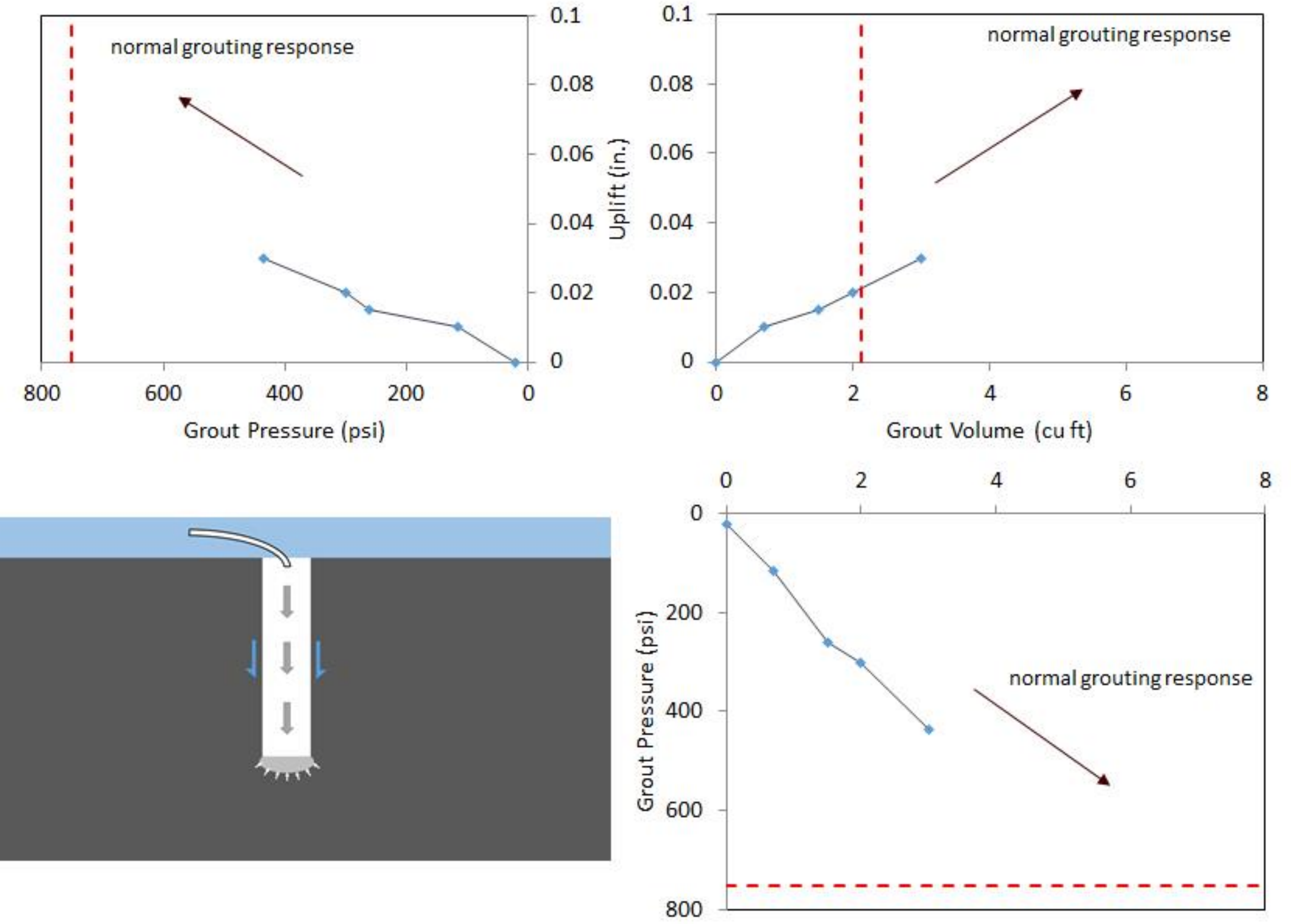


normal grouting response
Grout Pressure (psi)
Uplift (in.)
normal grouting response
Grout Volume (cu ft)
Grout Pressure (psi)
normal grouting response


normal grouting response
0.1
0.08
0.06
0.04
0.02
0
800
600
400
200
0
Grout Pressure (psi)
Uplift (in.)
normal grouting response
0
2
4
6
8
Grout Volume (cu ft)
Grout Pressure (psi)
normal grouting response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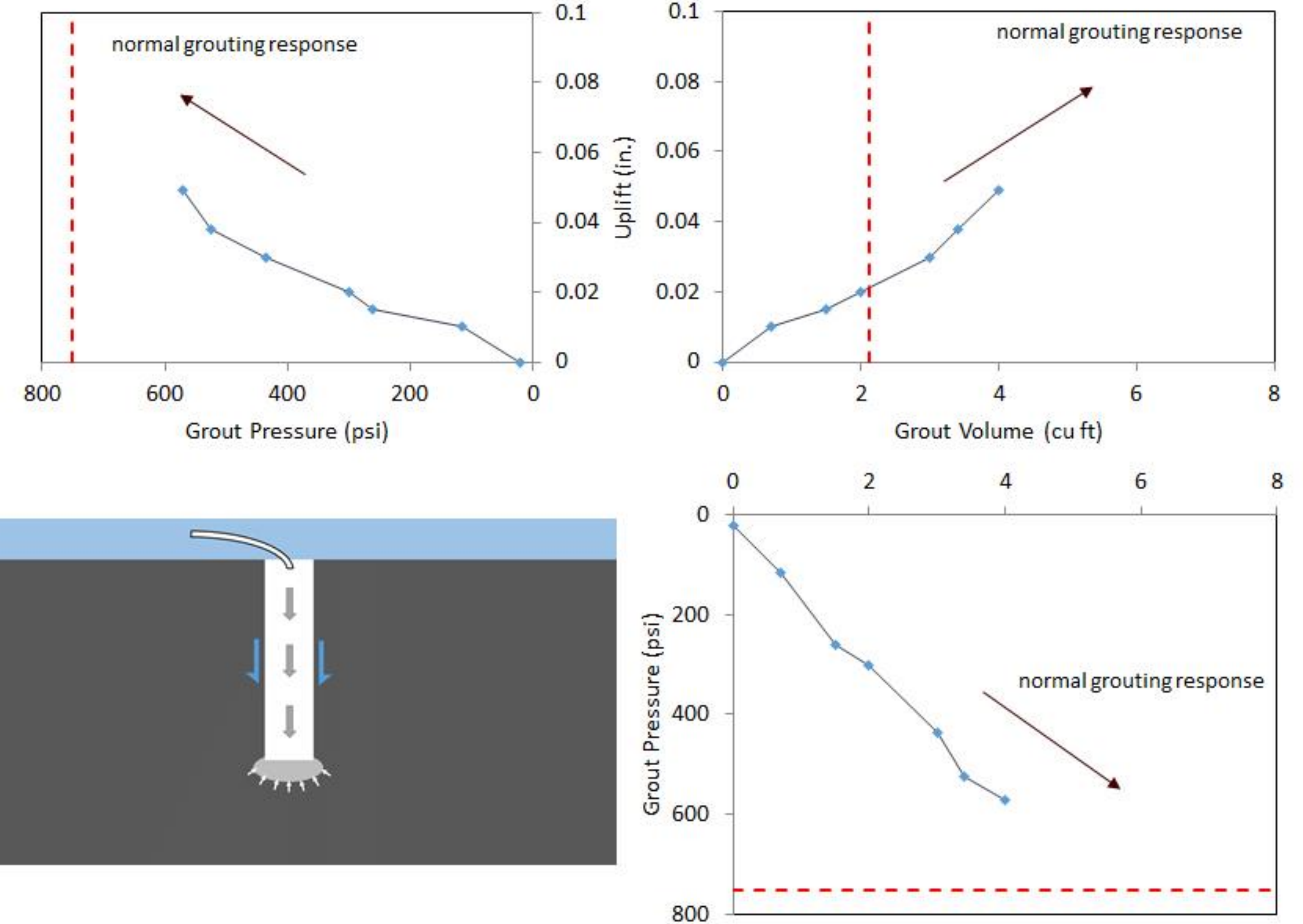
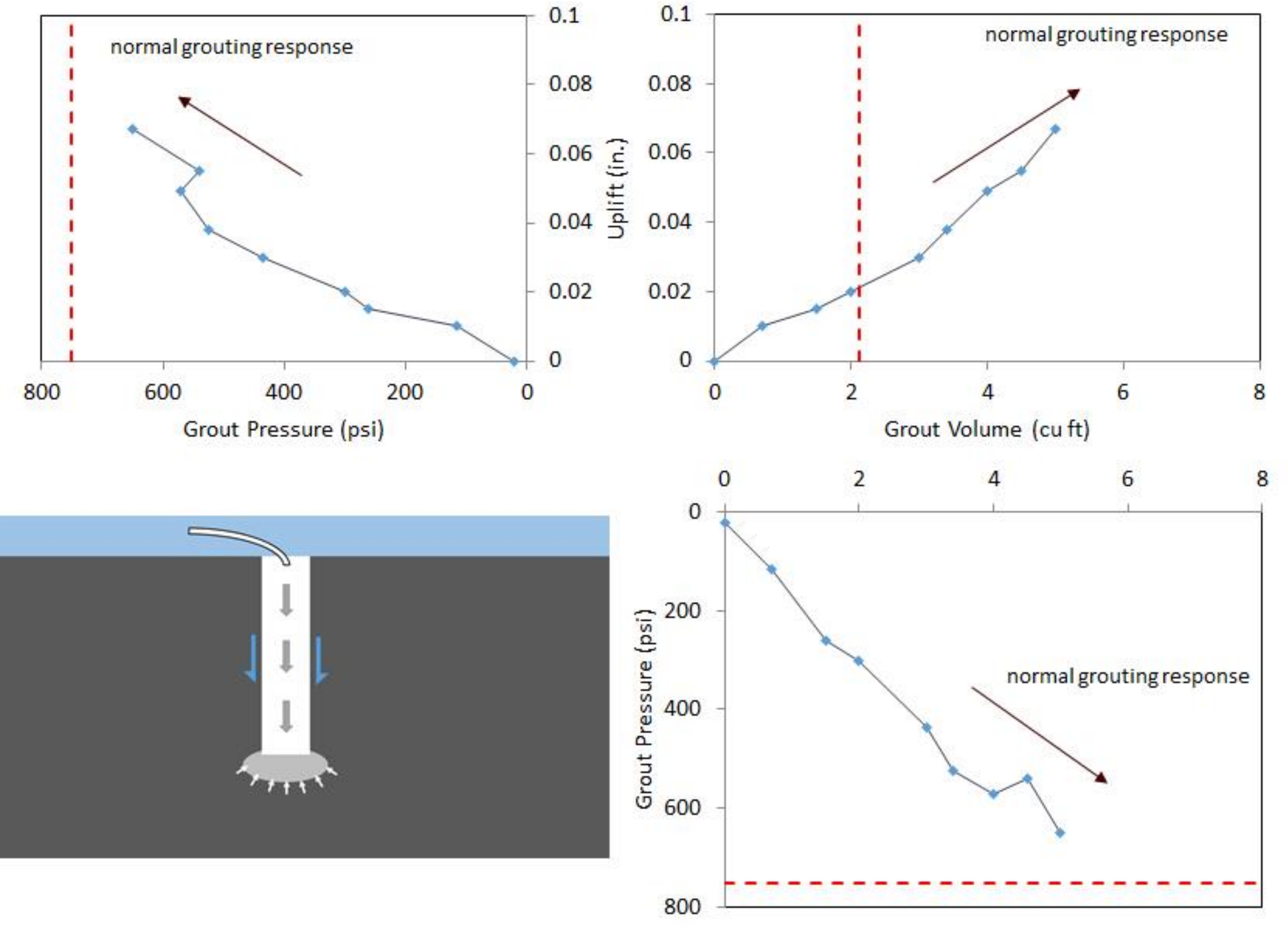
4
6
8
0
200
400
600
800
Grout Pressure (psi)
normal grouting response


normal grouting response
Grout Pressure (psi)
Uplift (in.)
normal grouting response
Grout Volume (cu ft)
normal grouting response
Grout Pressure (psi)



normal grouting response
Grout Pressure (psi)
Uplift (in.)
0.1
0.08
0.06
0.04
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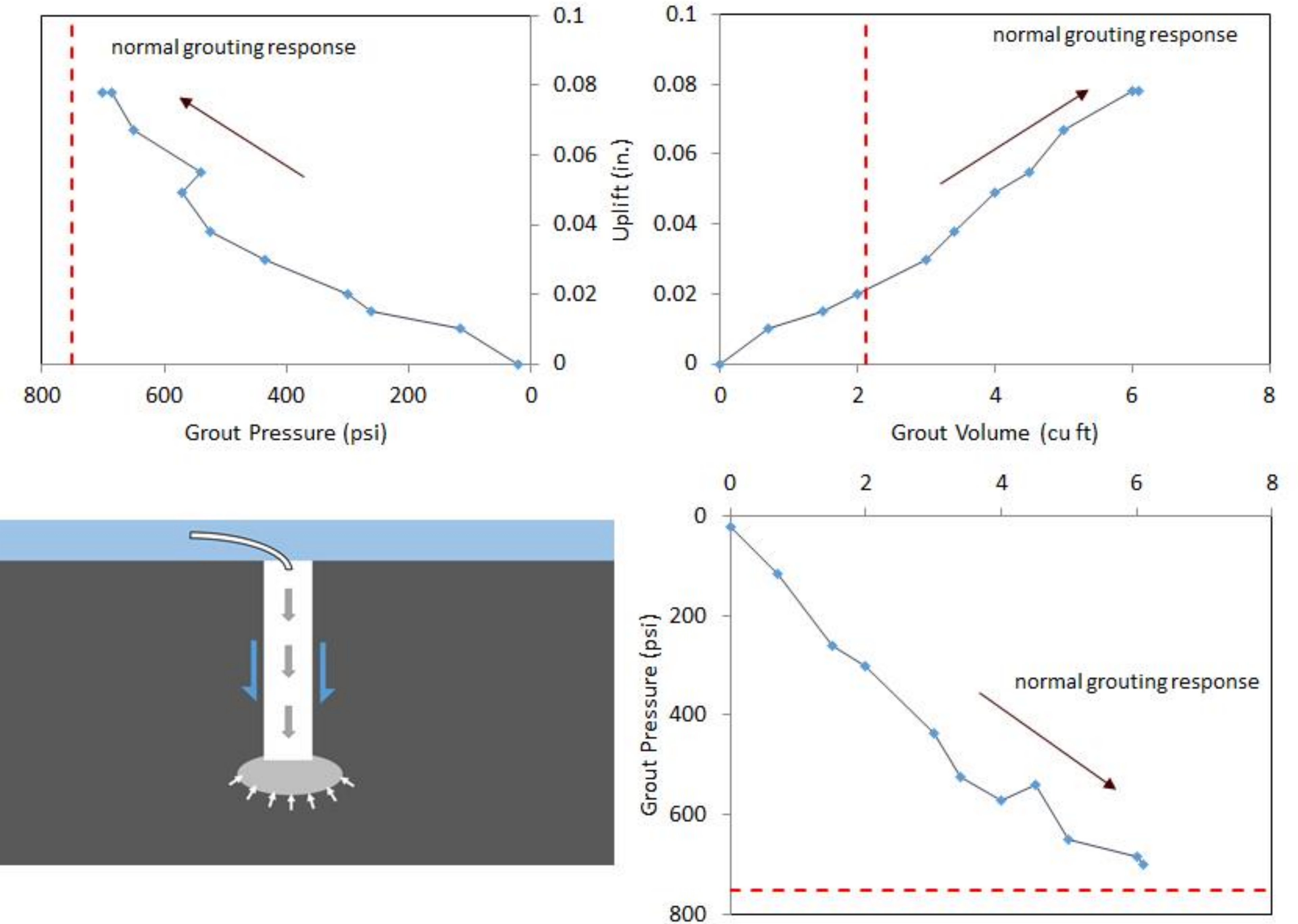
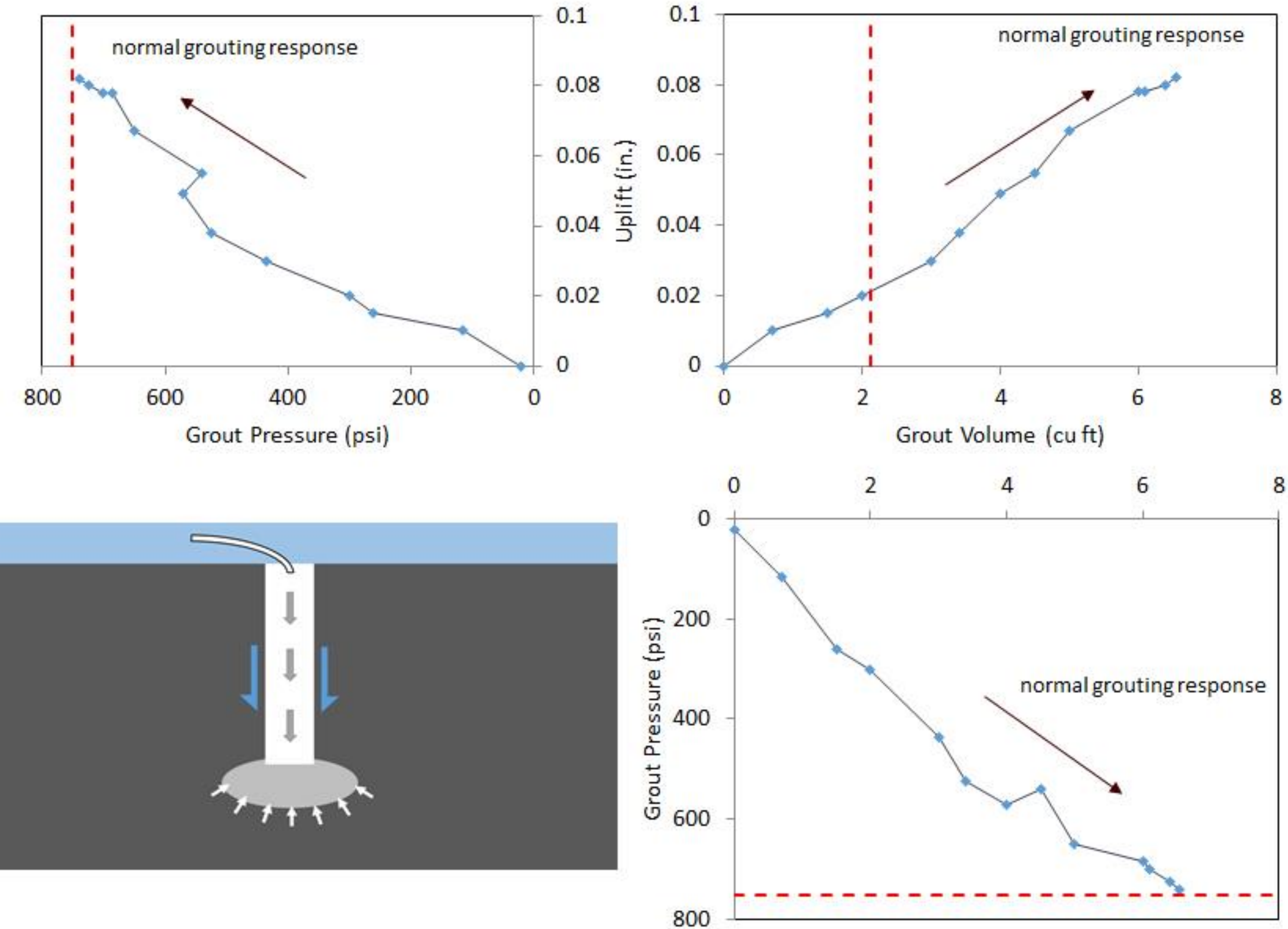
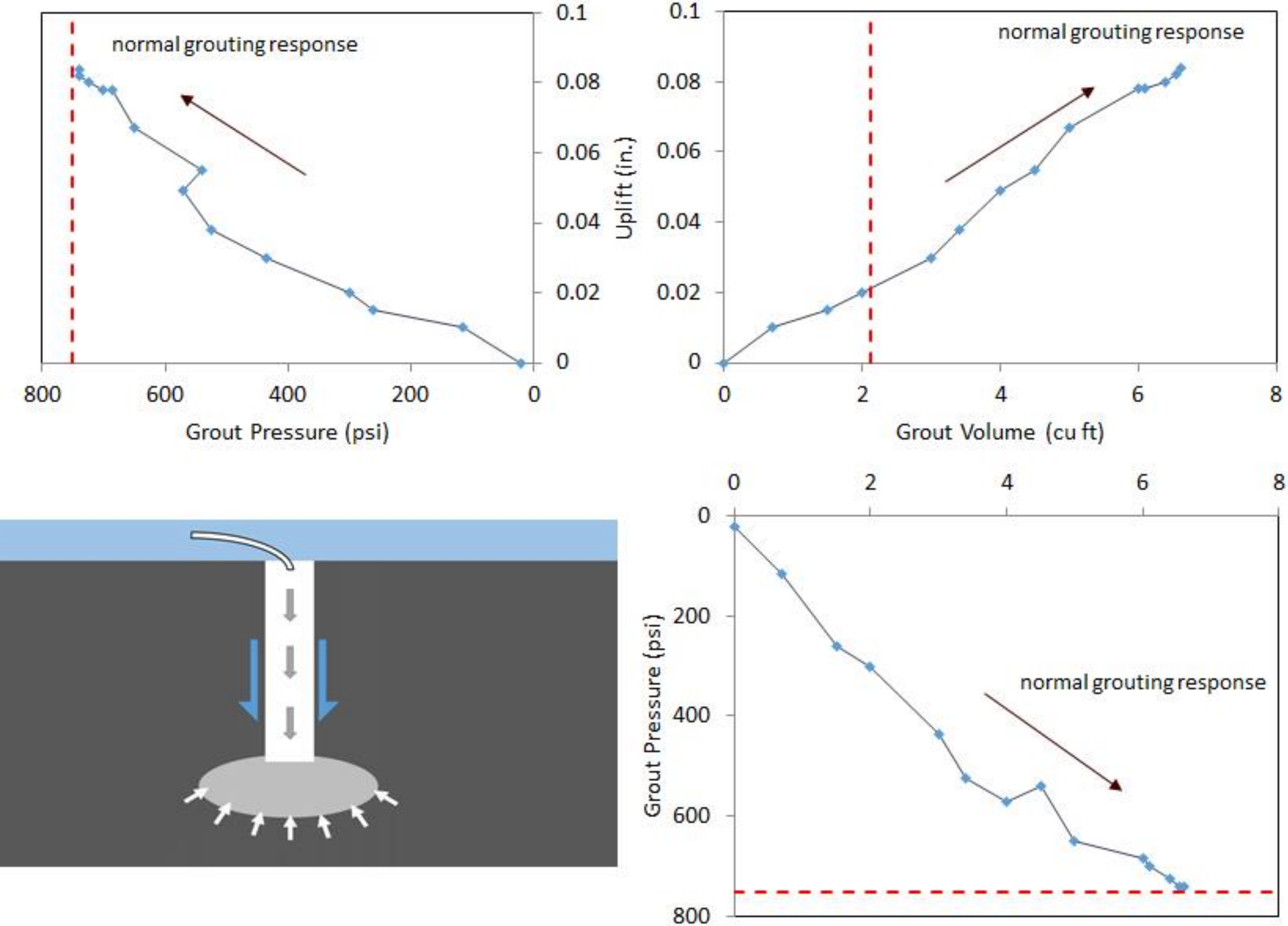
800
600
400
200
normal grouting response
Grout Volume (cu ft)
2
4
6
8
normal grouting response
Grout Pressure (psi)



normal grouting response
Grout Pressure (psi)
800
600
400
200
0
0.1
0.08
0.06
0.04
0.02
0
Uplift (in.)
normal grouting response
Grout Volume (cu ft)
0
2
4
6
8
normal grouting response
Grout Pressure (psi)
0
200
400
600
800



normal grouting response
Uplift (in.)
Grout Pressure (psi)
normal grouting response
Grout Volume (cu ft)
normal grouting response
Grout Pressure (psi)
0.1
0.08
0.06
0.04
0.02
0
800
600
400
200
0
2
4
6
8

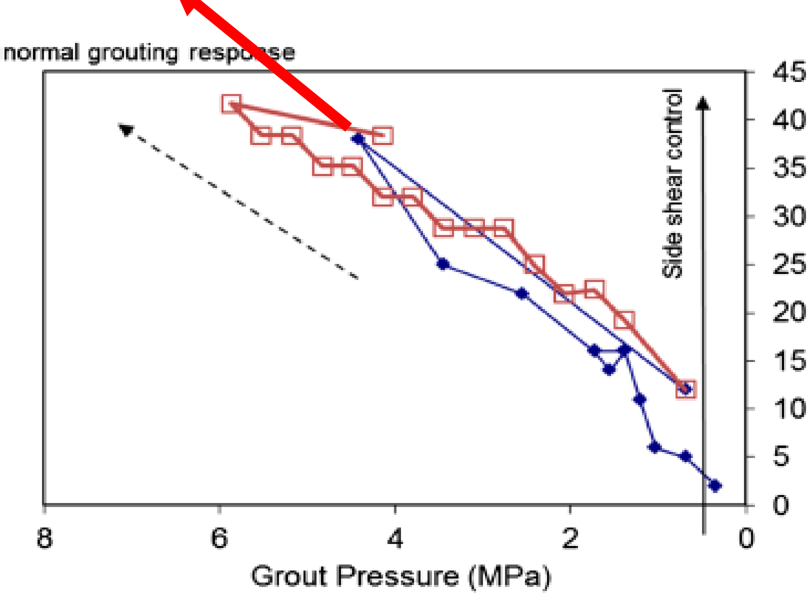


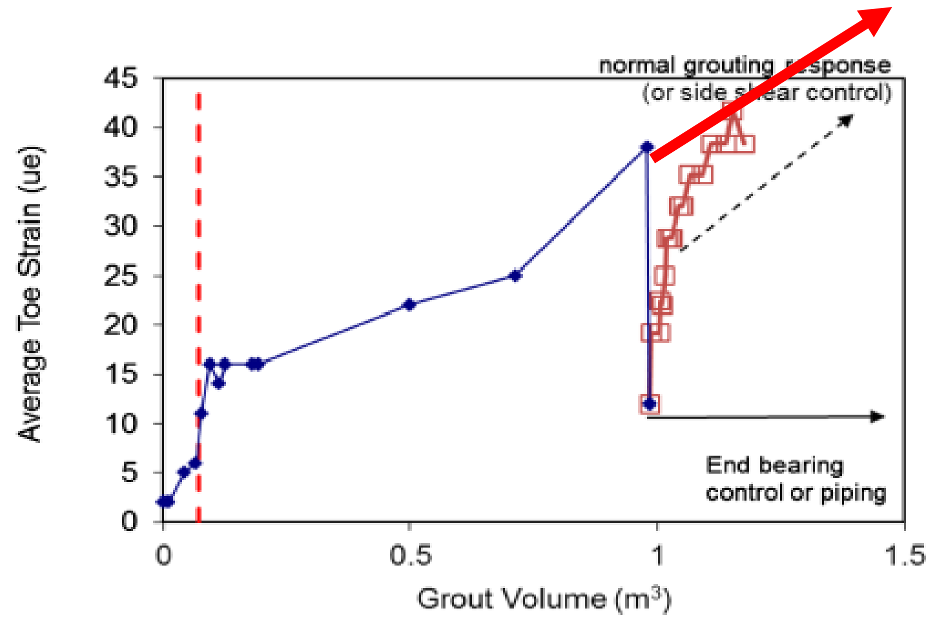
normal grouting response
Grout Pressure (psi)
800
600
400
200
0
Uplift (in.)
0.1
0.08
0.06
0.04
0.02
0
normal grouting response
Grout Volume (cu ft)
0
2
4
6
8
Grout Pressure (psi)
200
400
600
800
normal grouting response

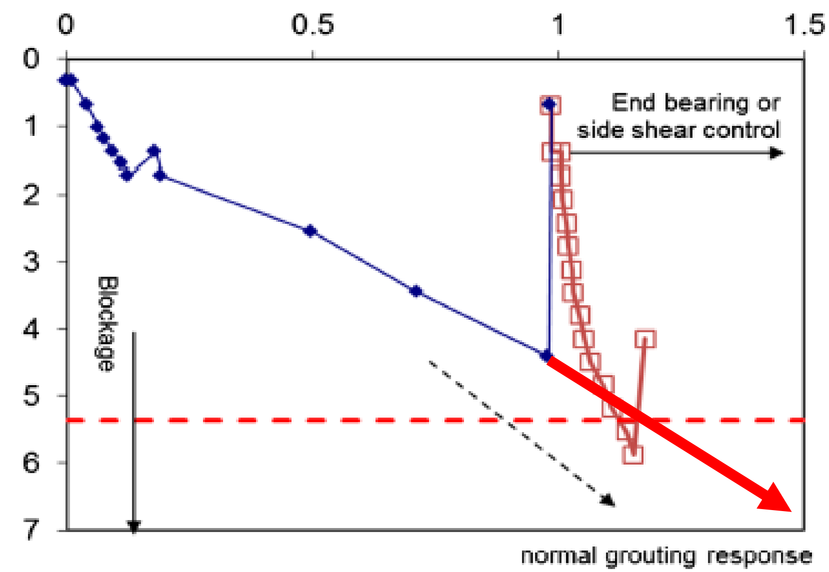
Field Practice / Design Expectation

- 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 may reduce the size of the active/liquid grout pressure area and does not always 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







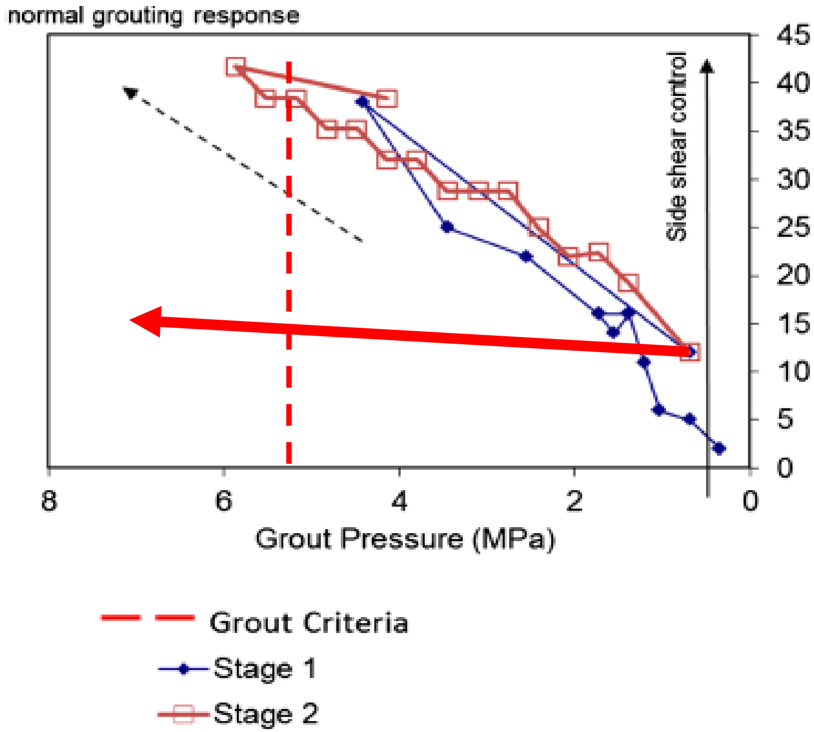
Grout Criteria

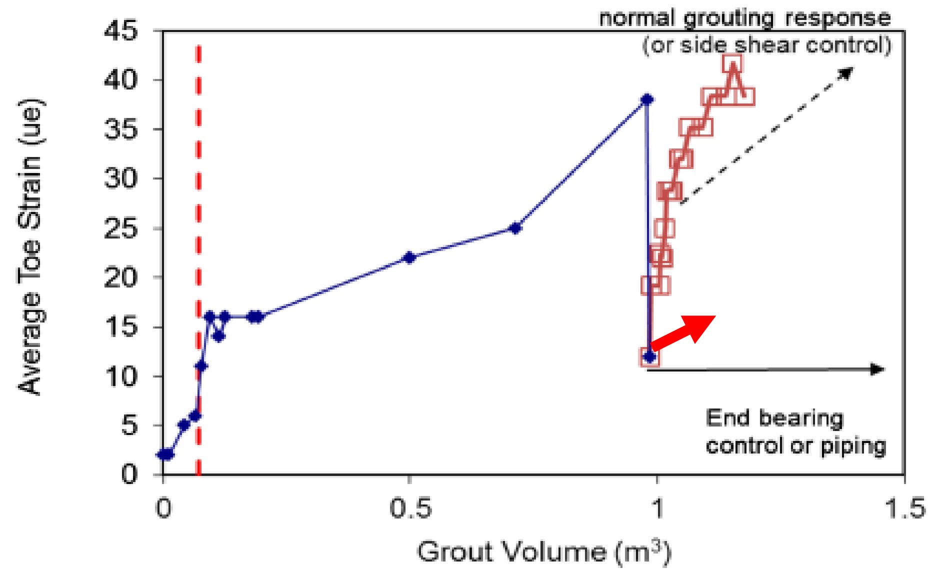
Stage 1

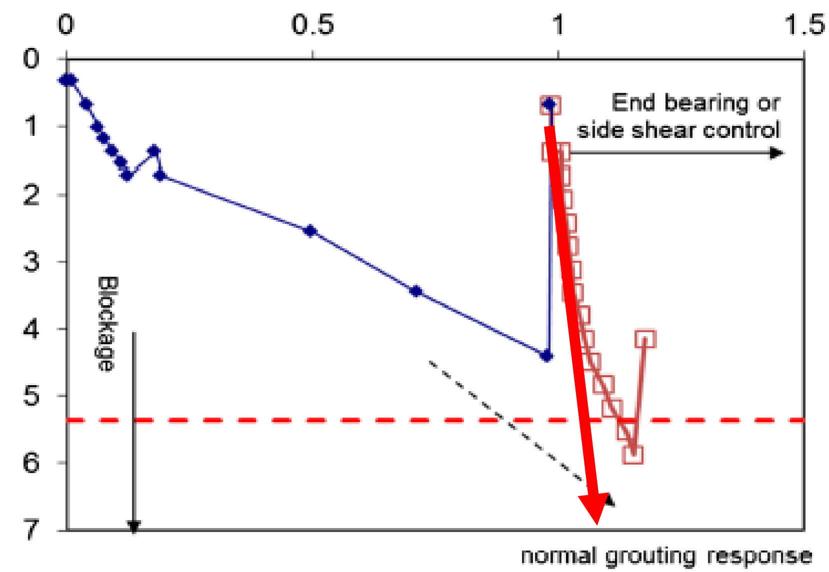
Stage 2

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

Undesired Result of Stage Grouting

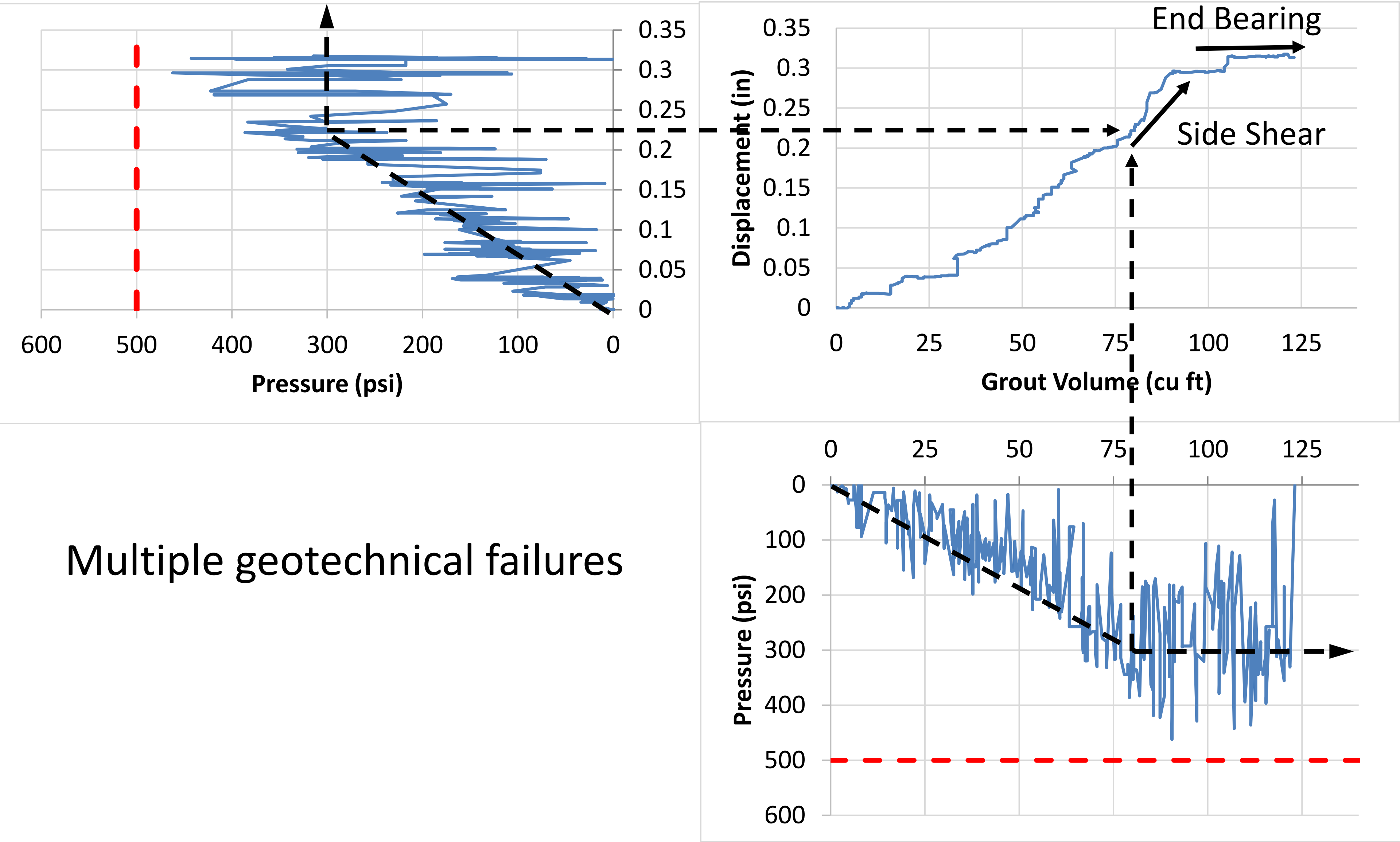






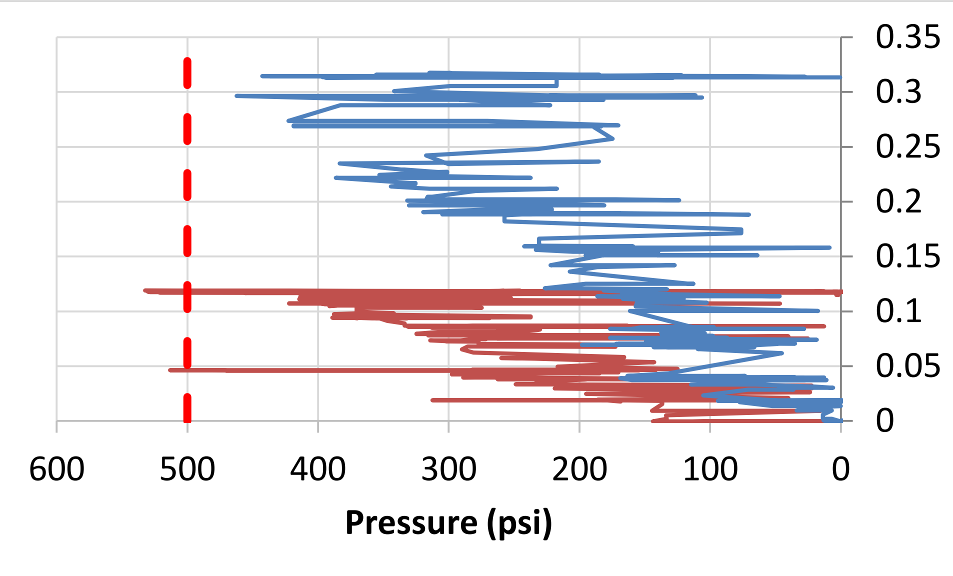
- Grouting effective but terminated early
- Met net volume criterion
- Design pressure met in second stage
- Exhibited normal / anticipated response

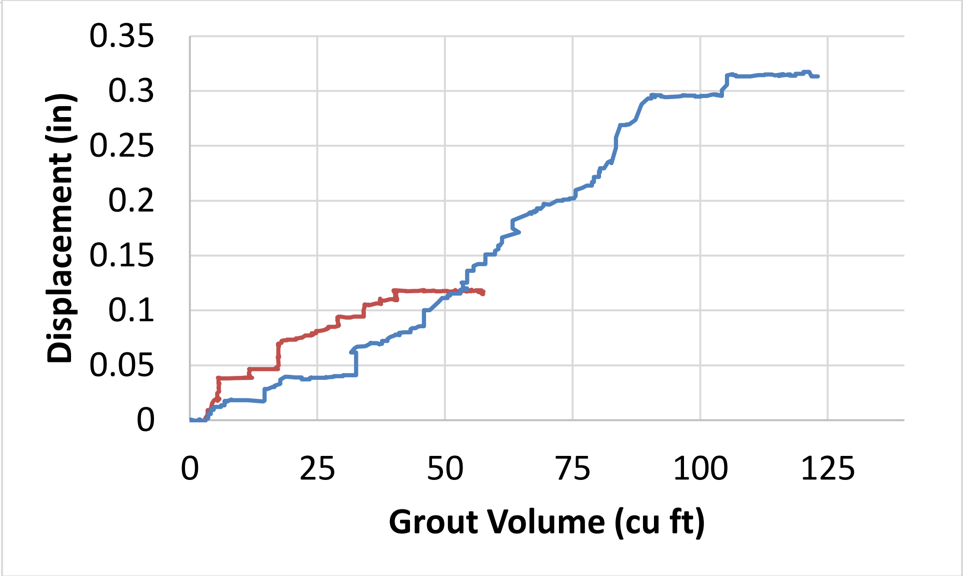
Case Study: design pressure was not met



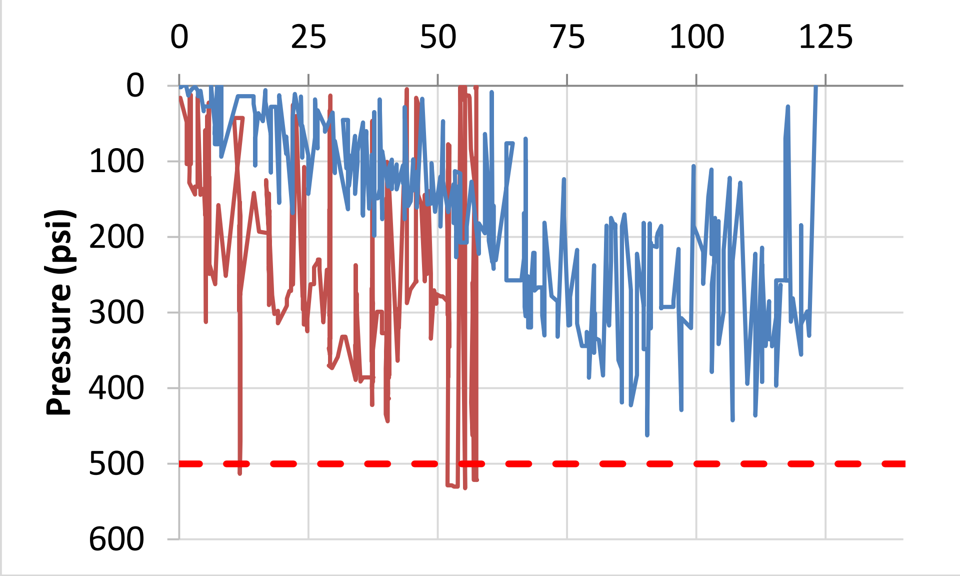
Multiple geotechnical failures

Stage 2 with Grouting Parameter Reset

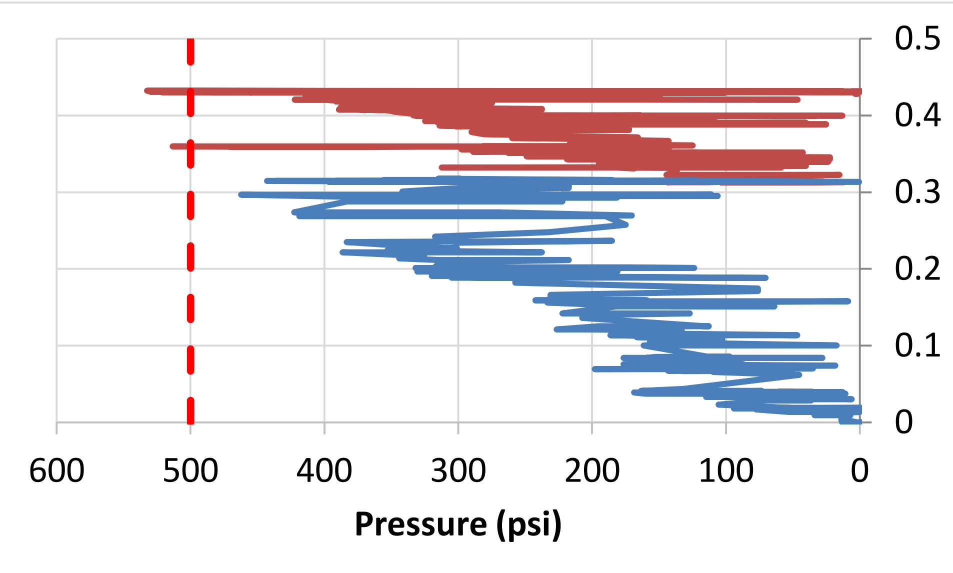


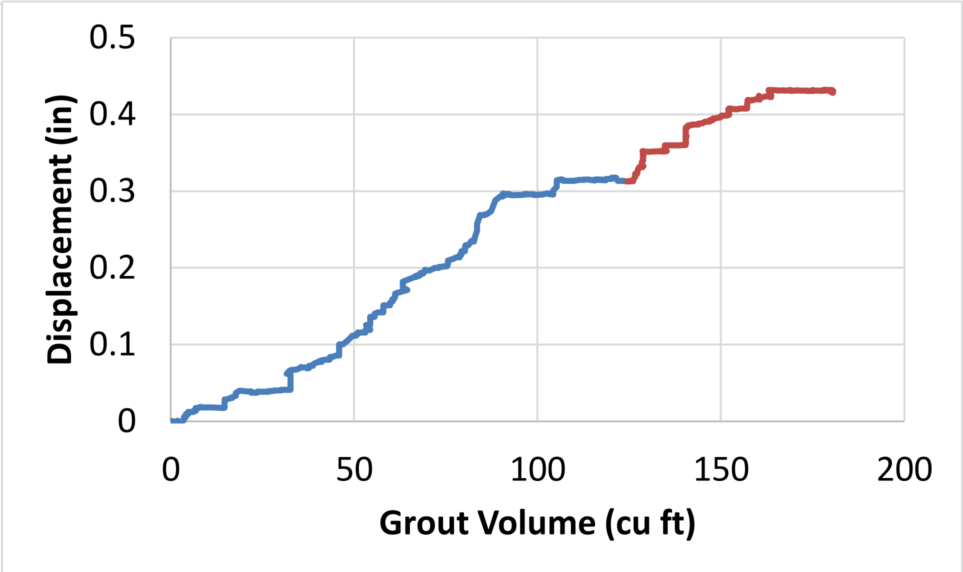


Data collected every 30 sec



Stage 2 without Grouting Parameter Reset





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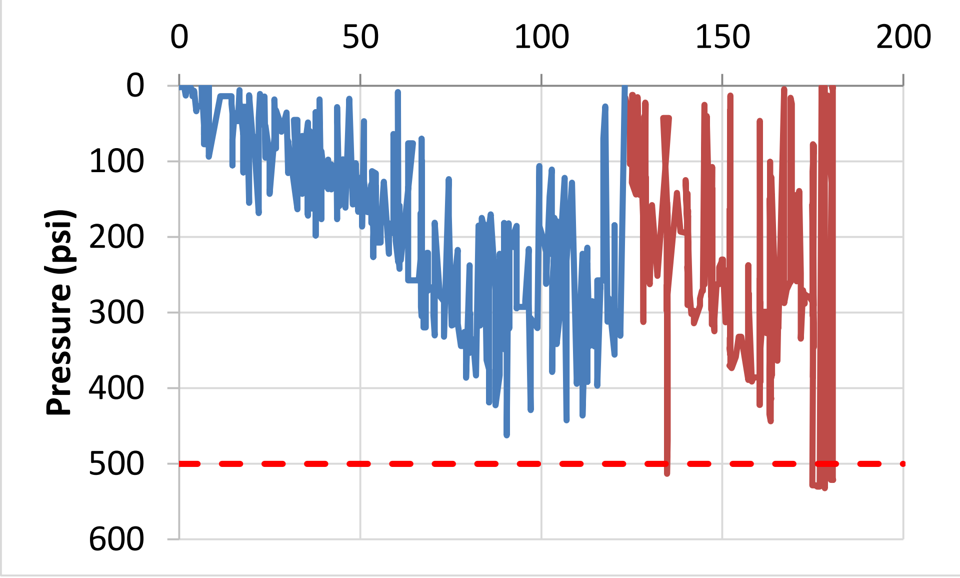

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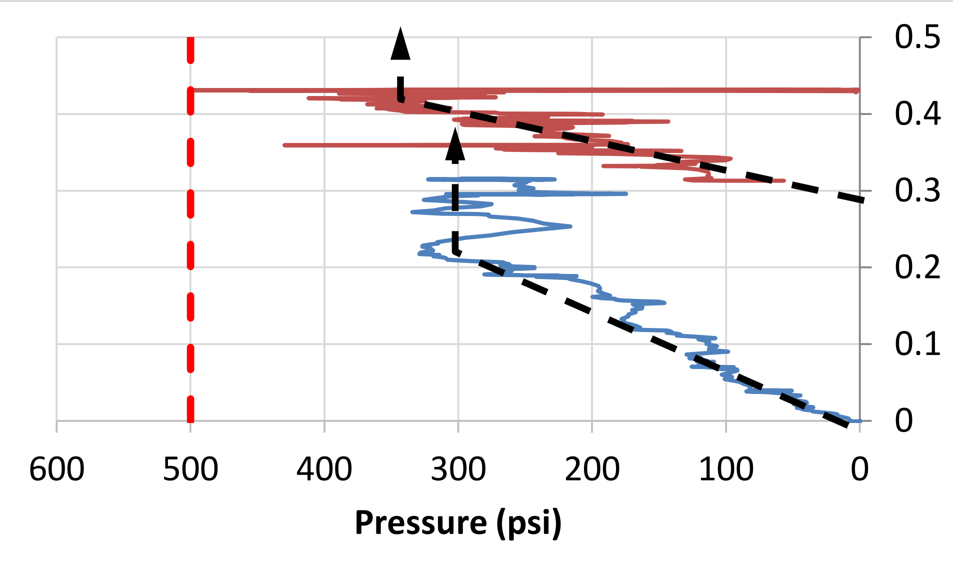
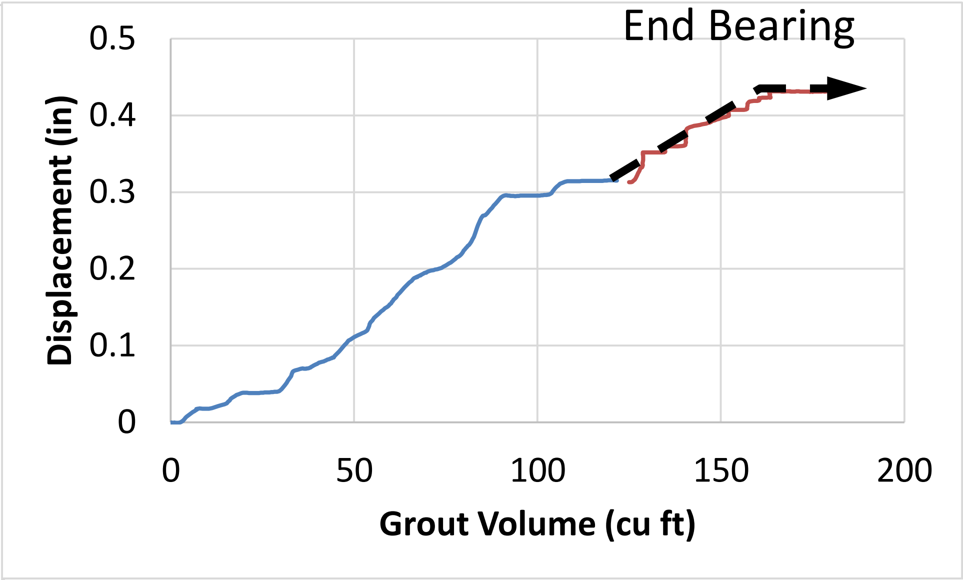
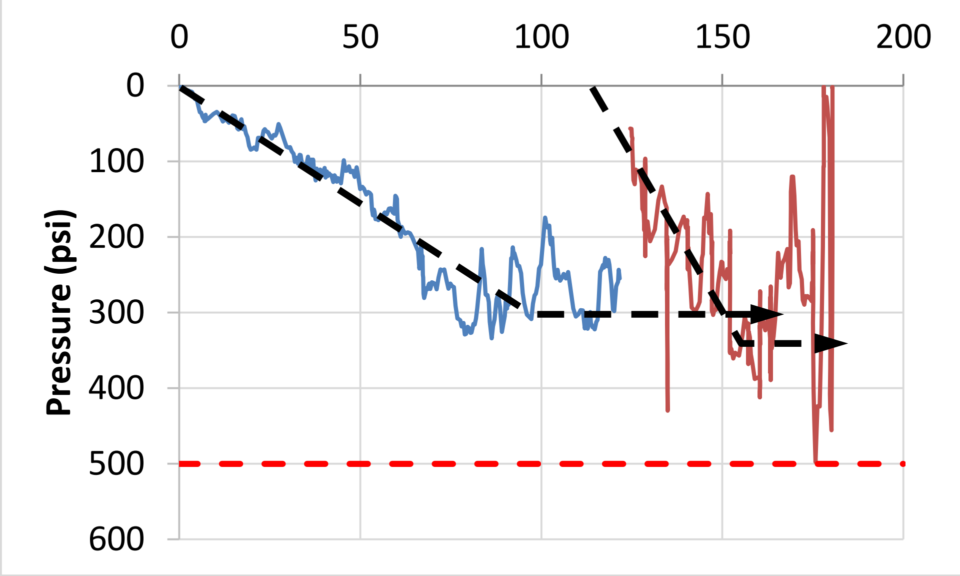




Two minute moving average



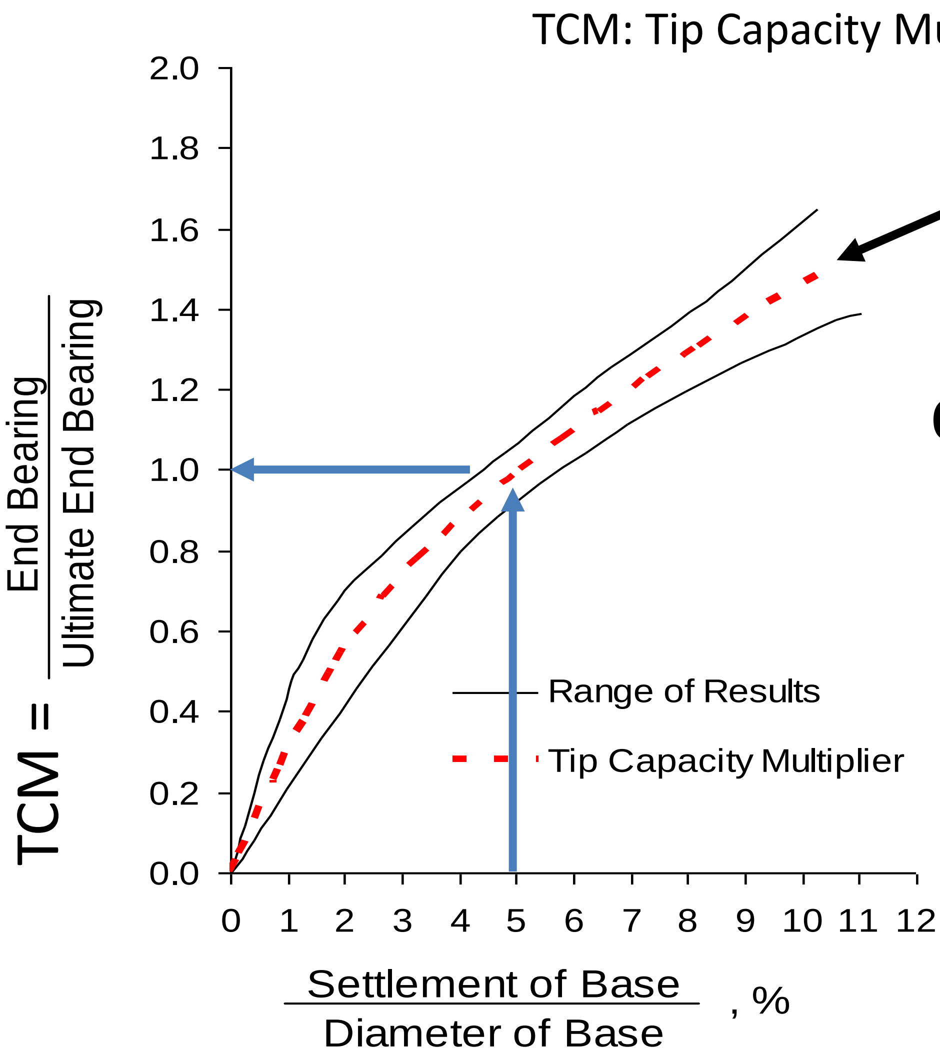
Design Methods

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

Post Grouted 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

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

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

TCMs for grouted end bearing capacity

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

Same TCM as O'Neill for ungrouted end bearing capacity

FDOT Method (with limit)

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

- $q_{gb} \leq$ grout pressure

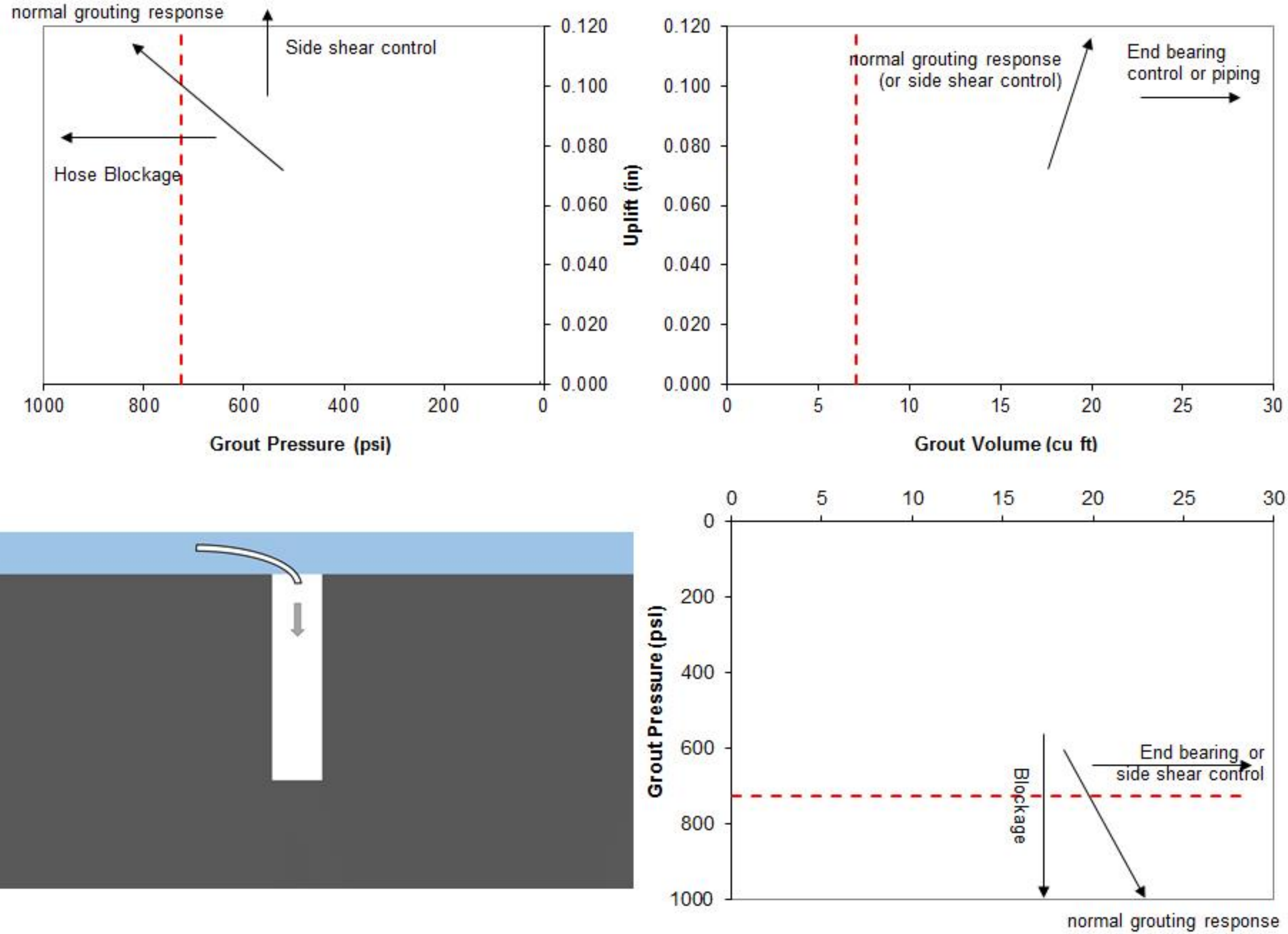
- GPI = grout pressure / q_b ; where q_b is from O'Neill

Project Approach

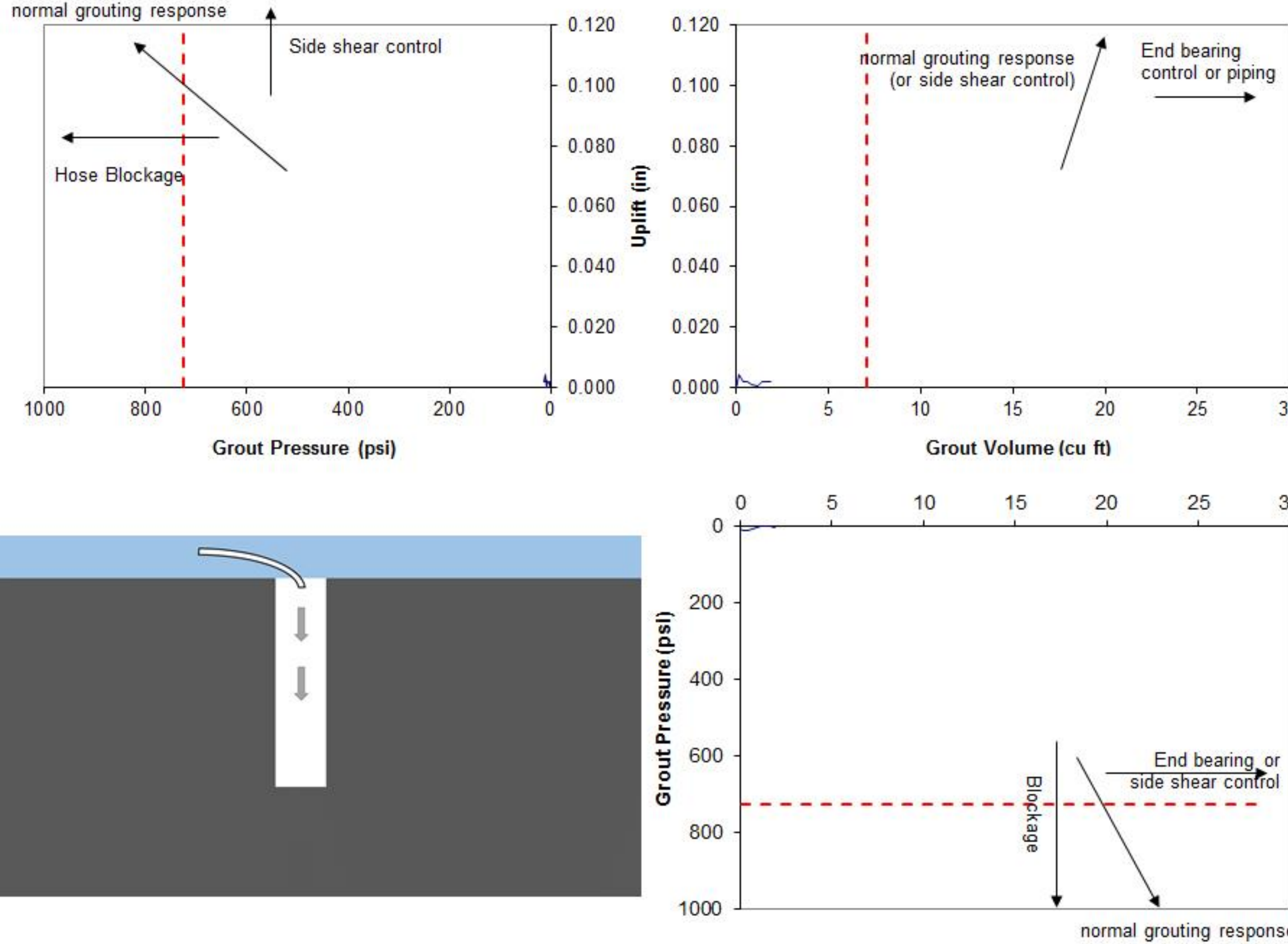
- Collect end bearing data from load tests conducted on post grouted shafts
- 31 shafts from 17 projects were evaluated
- Compare measured to predicted end bearing
- Compute resistance factor based on bias statistics
- Required information includes:
  - Field grouting logs
  - Load test end bearing vs 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



normal grouting response
Side shear control
Hose Blockage
0.120
0.100
0.080
0.060
0.040
0.020
0.000
1000
800
600
400
200
0
Grout Pressure (psi)
Uplift (in)
normal grouting response
(or side shear control)
End bearing
control or piping
0
5
10
15
20
25
30
Grout Volume (cu ft)
Grout Pressure (psi)
End bearing or
side shear control
Blockage
normal grouting response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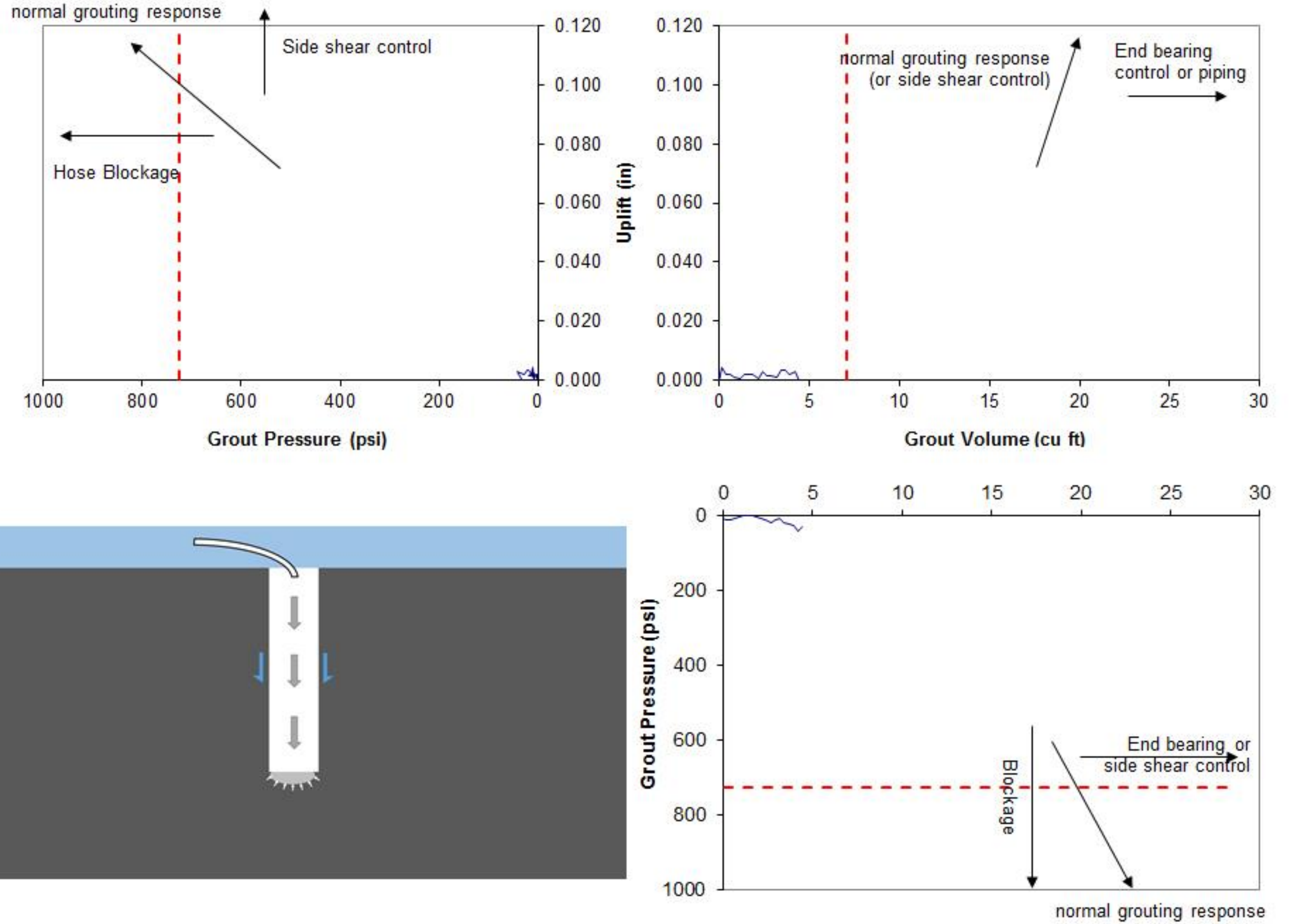
normal grouting response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Grout Volume (cu ft)
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Blockage
End bearing or
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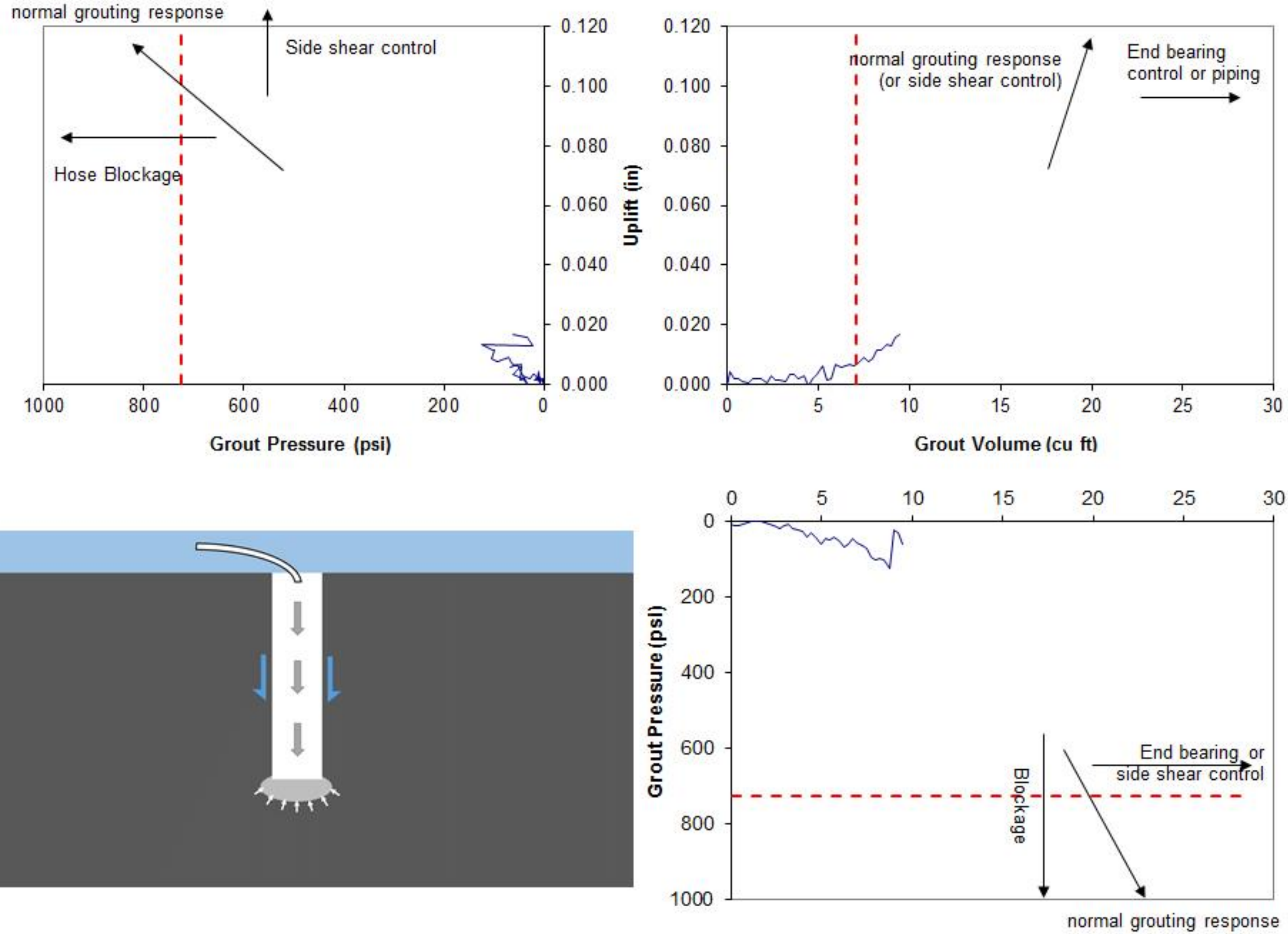
normal grouting response



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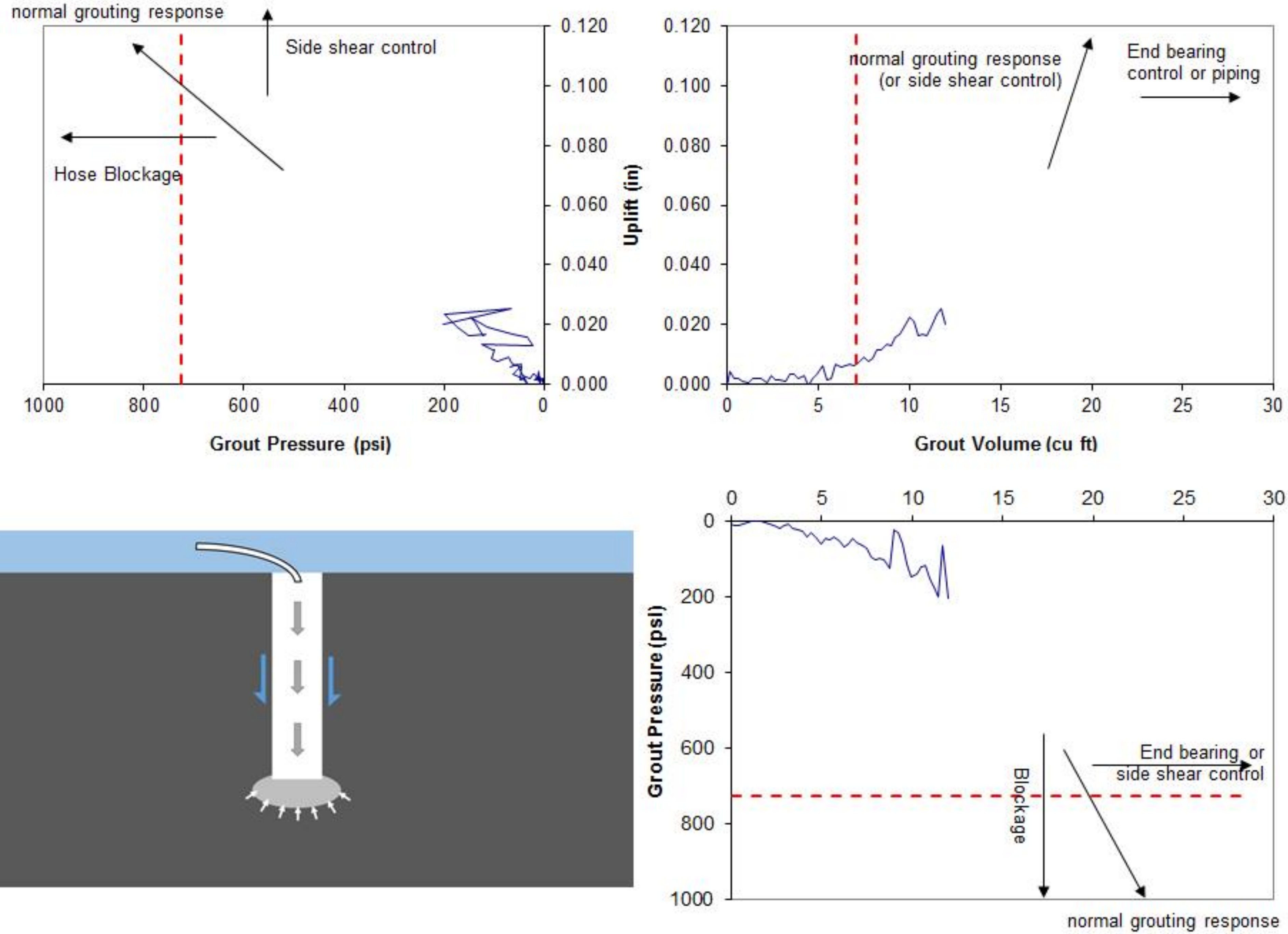
normal grouting response



normal grouting response
Side shear control
Hose Blockage
Grout Pressure (psi)
1000
800
600
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0.120
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0.020
0.000
Uplift (in)
normal grouting response
(or side shear control)
End bearing
control or piping
Grout Volume (cu ft)
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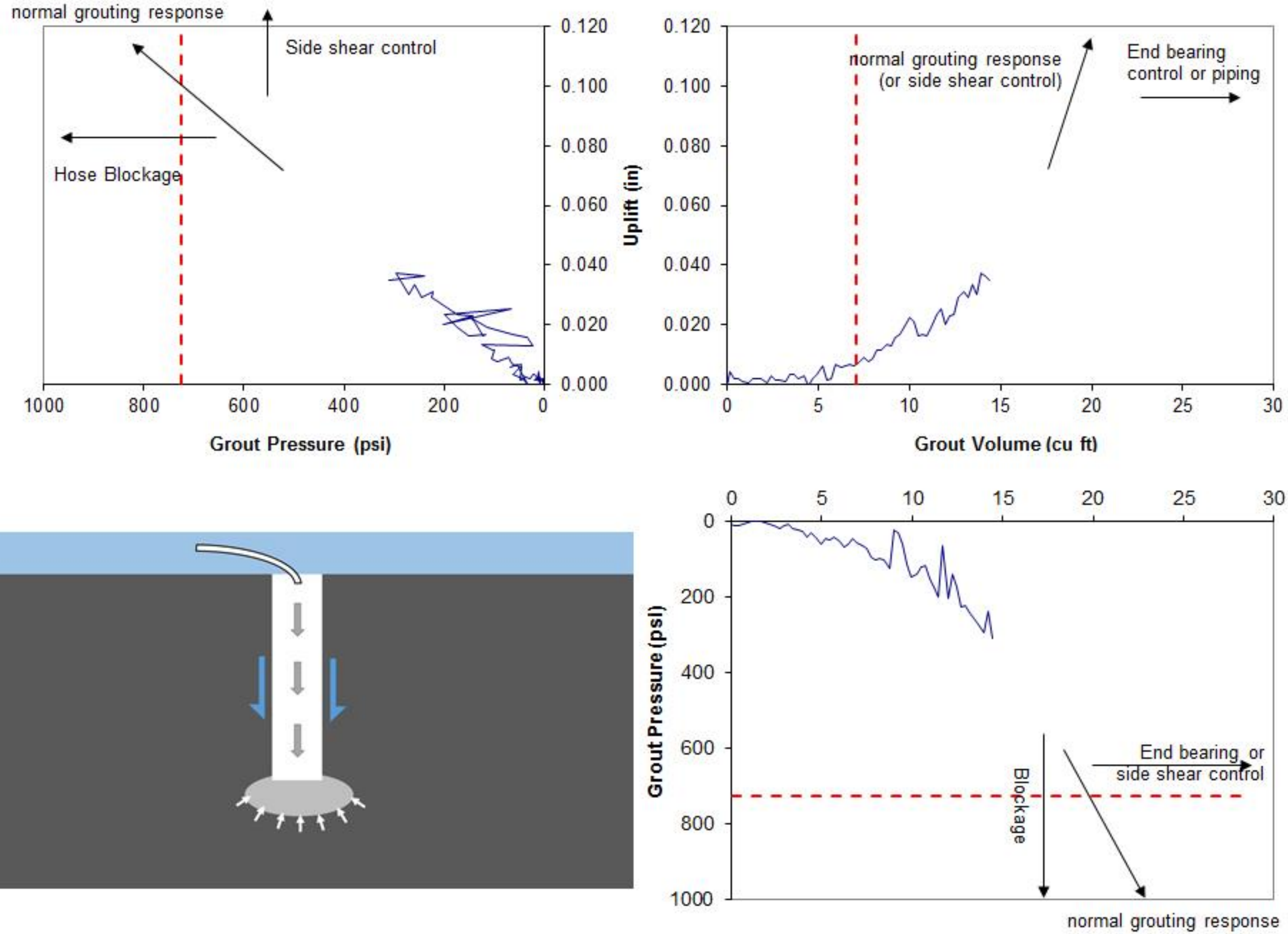
Grout Pressure (psi)
Blockage
End bearing or
side shear control
normal grouting response



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Side shear control
Hose Blockage
Grout Pressure (psi)
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Uplift (in)
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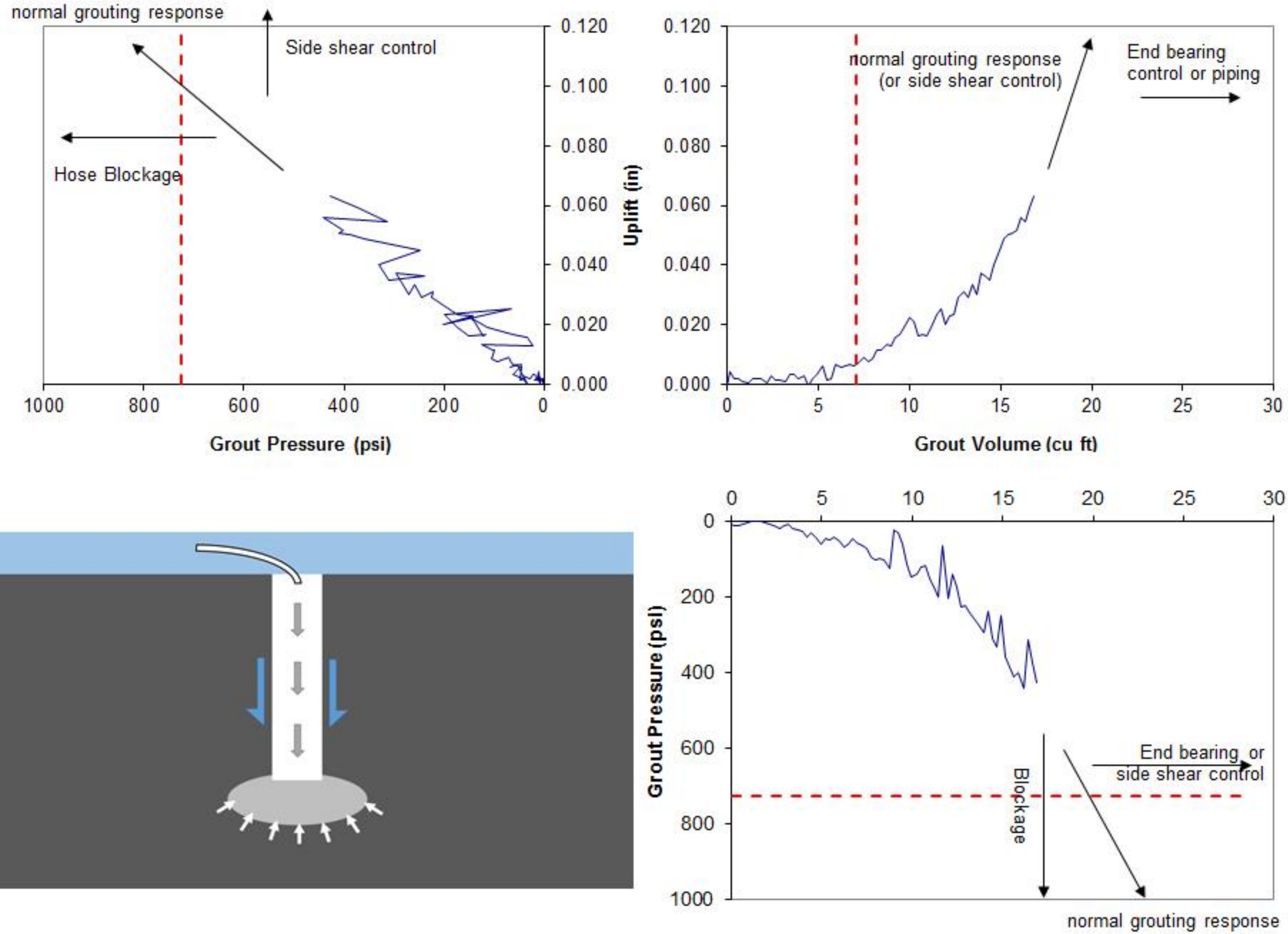

normal grouting response
Side shear control
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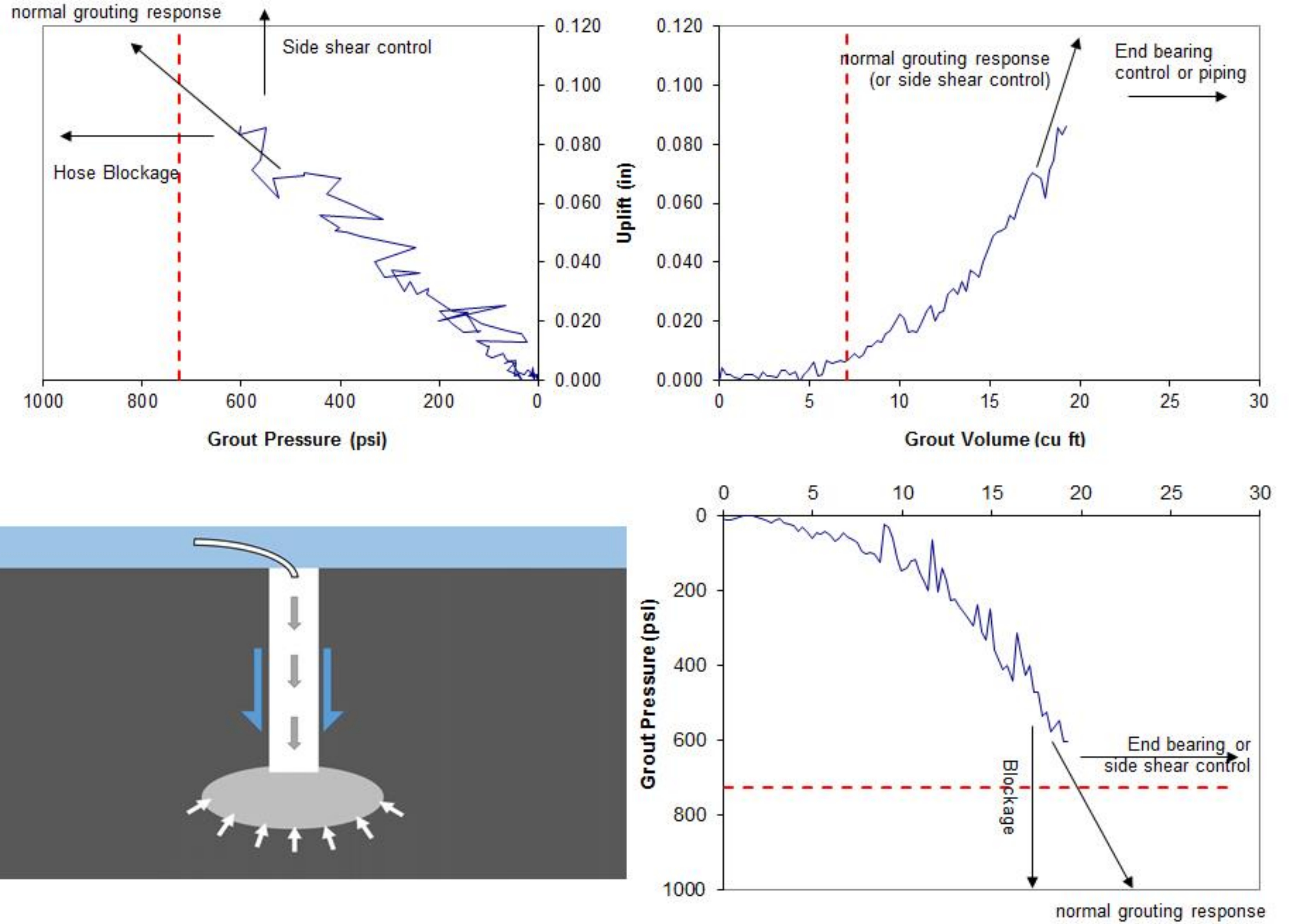

normal grouting response
Side shear control
Hose Blockage
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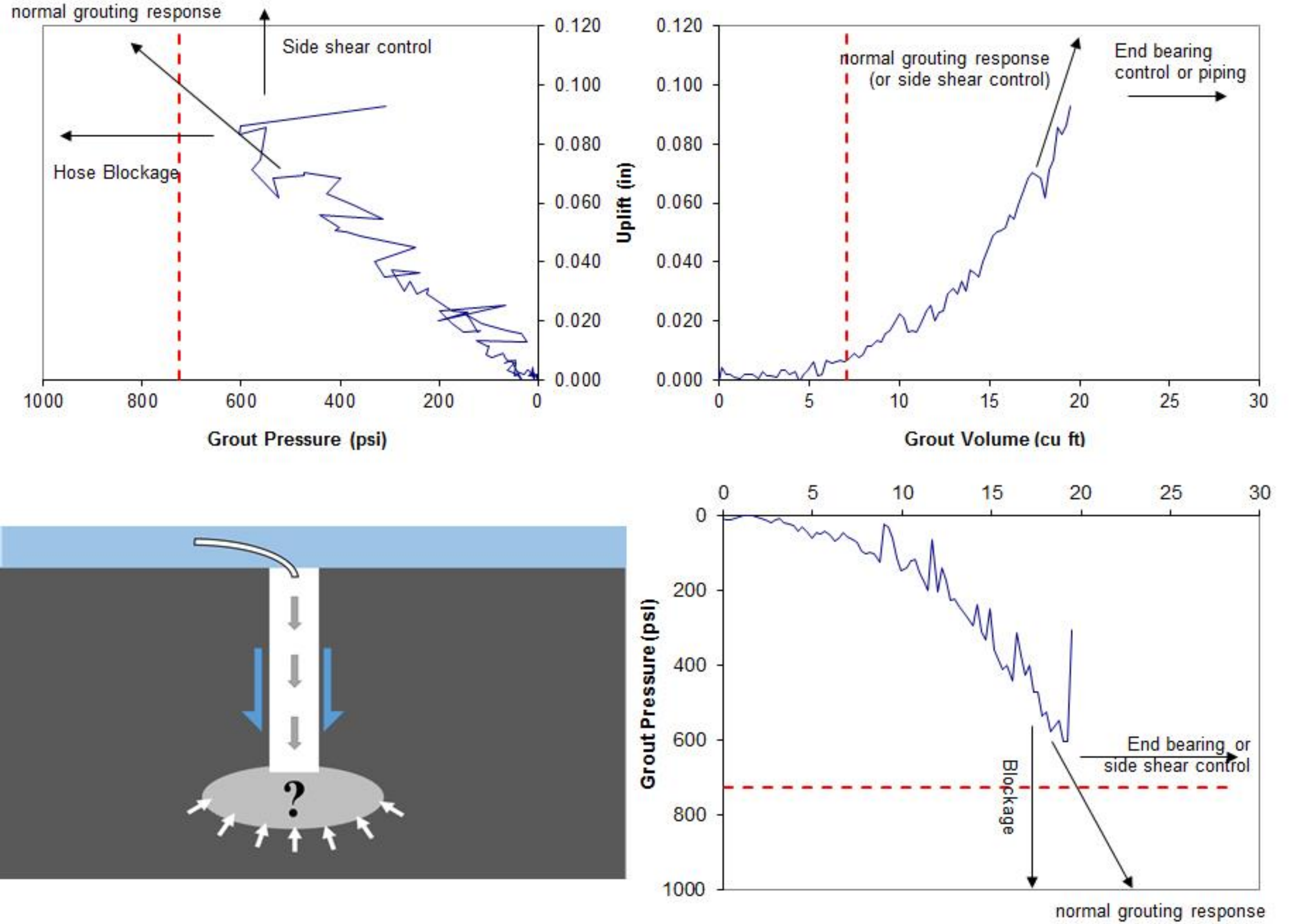
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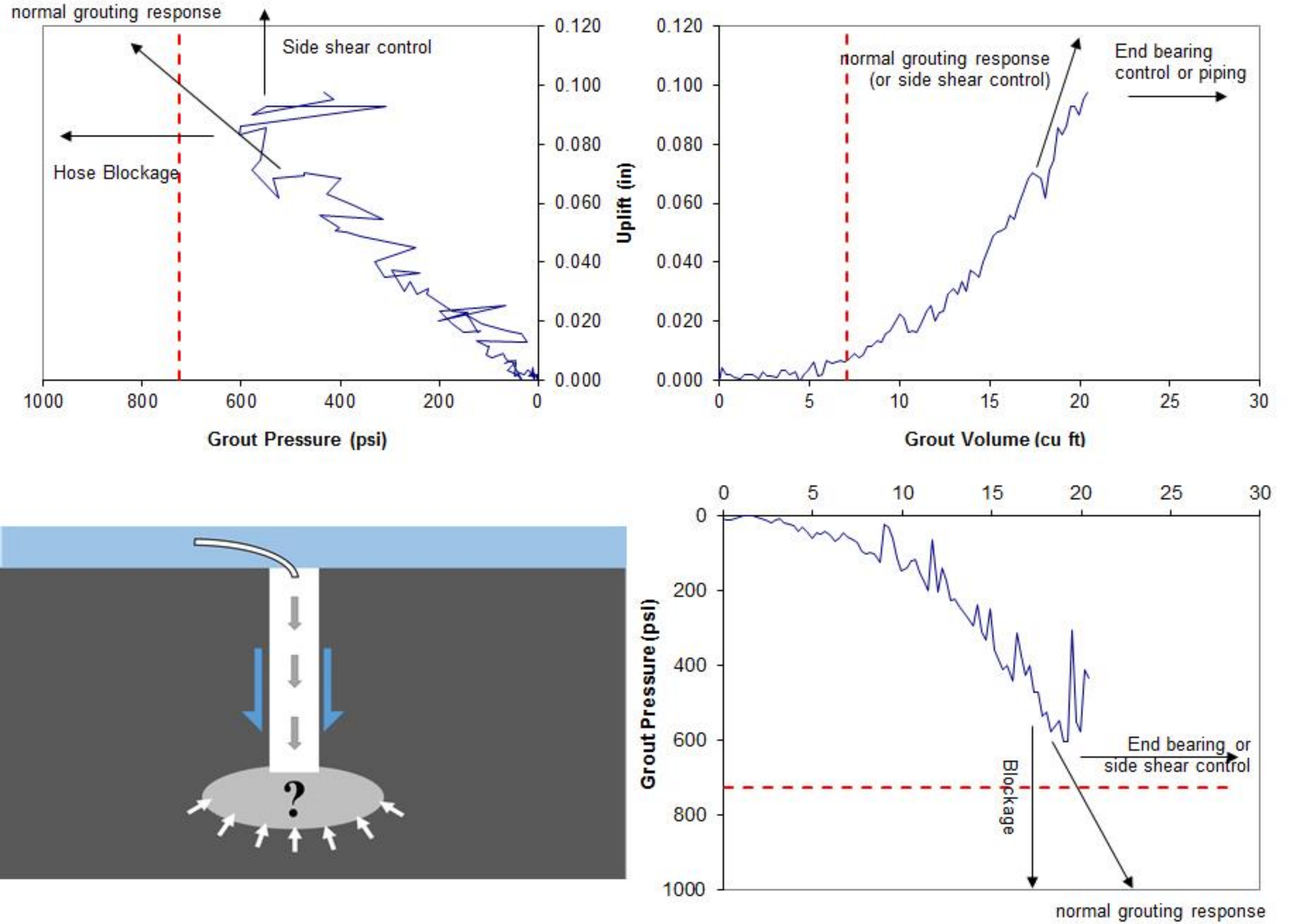
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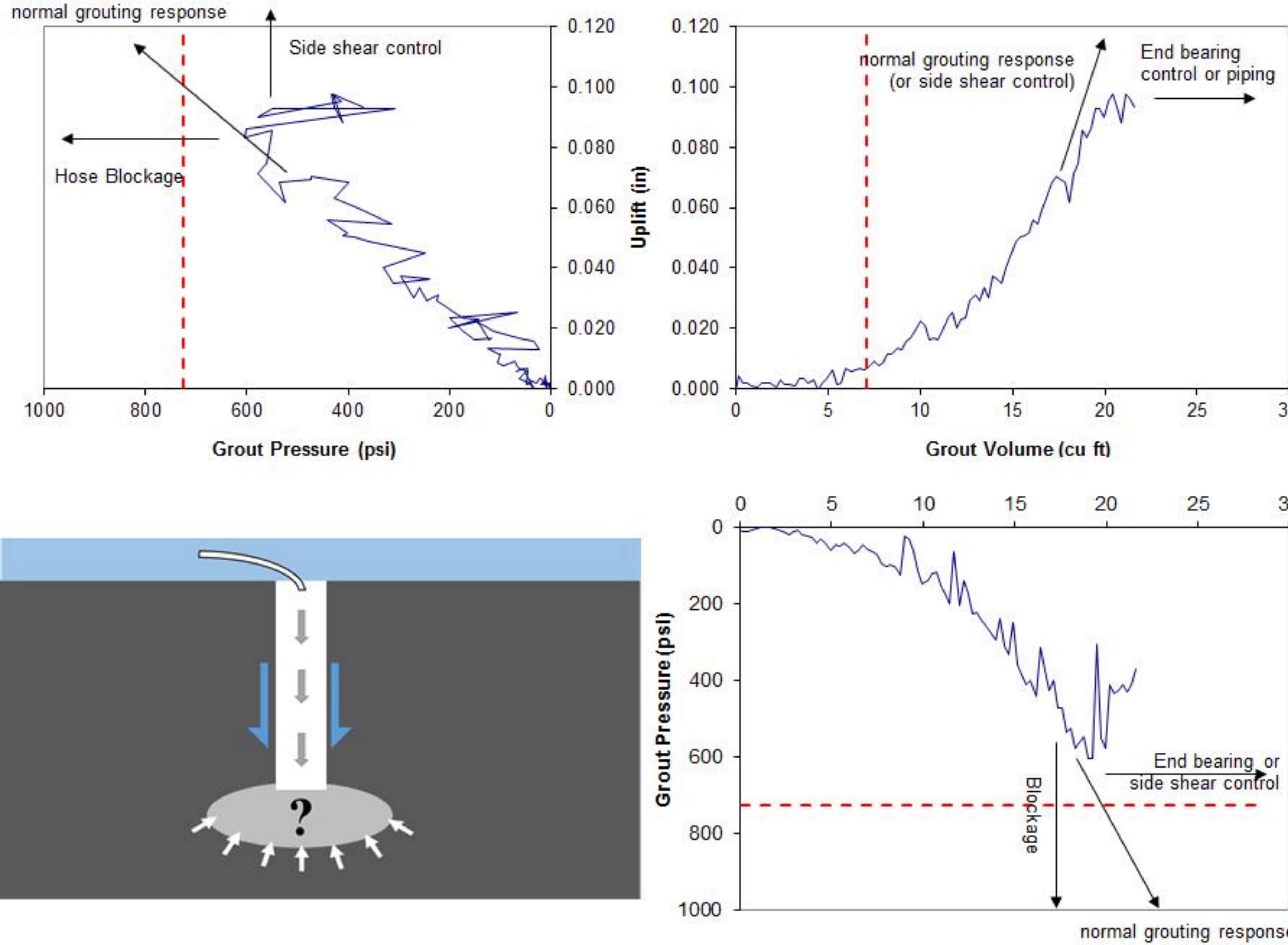
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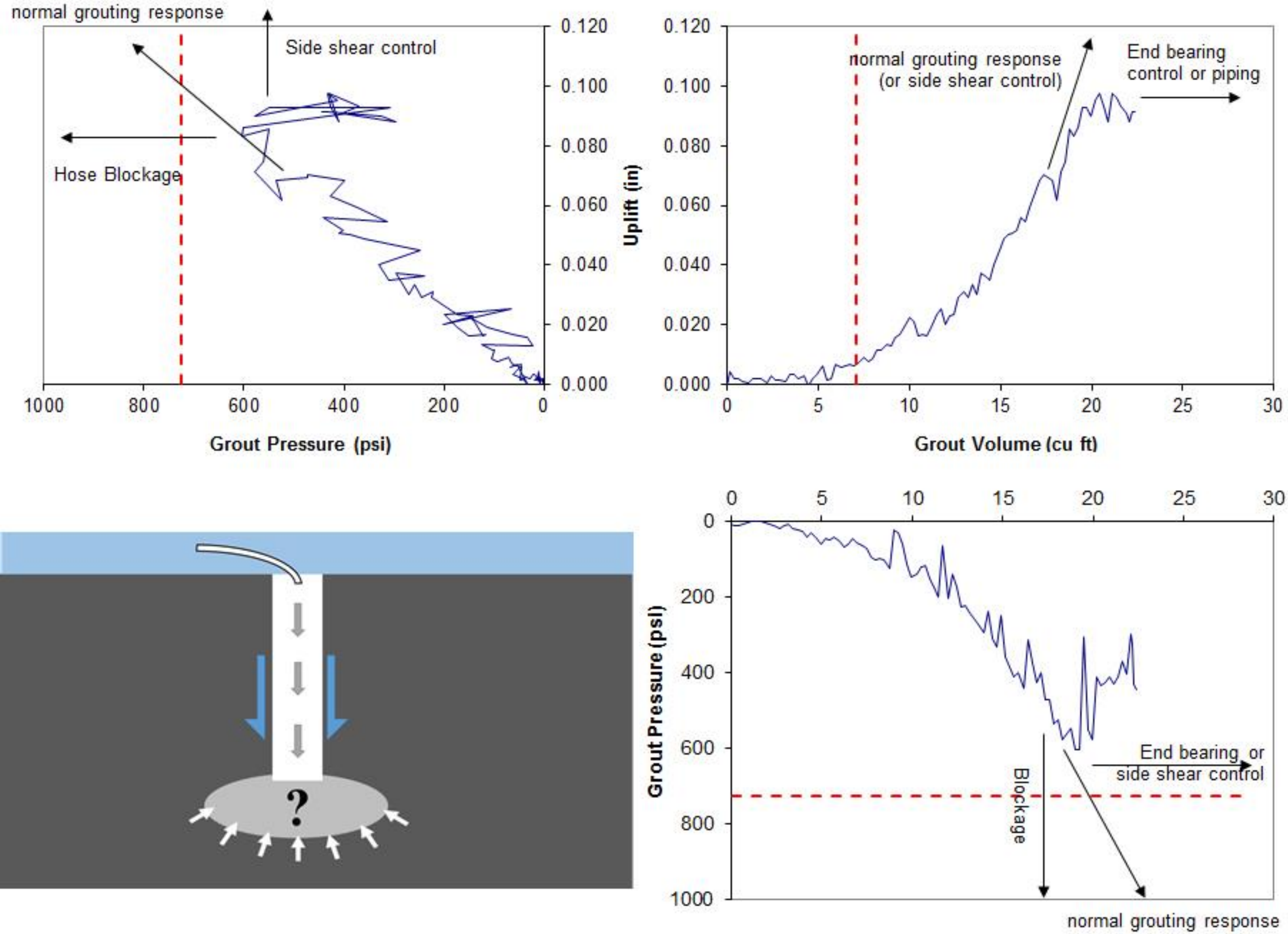
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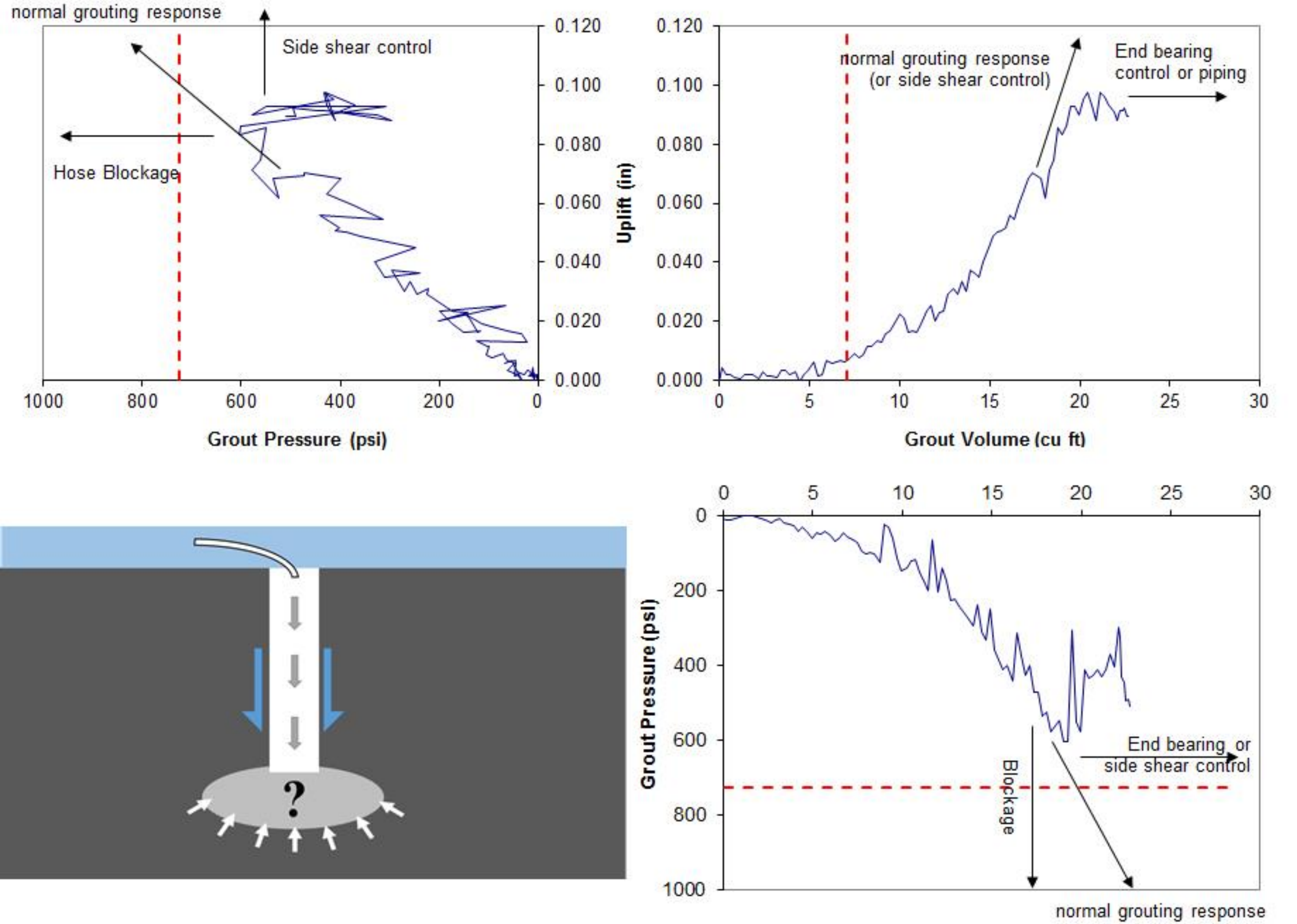
normal grouting response
Side shear control
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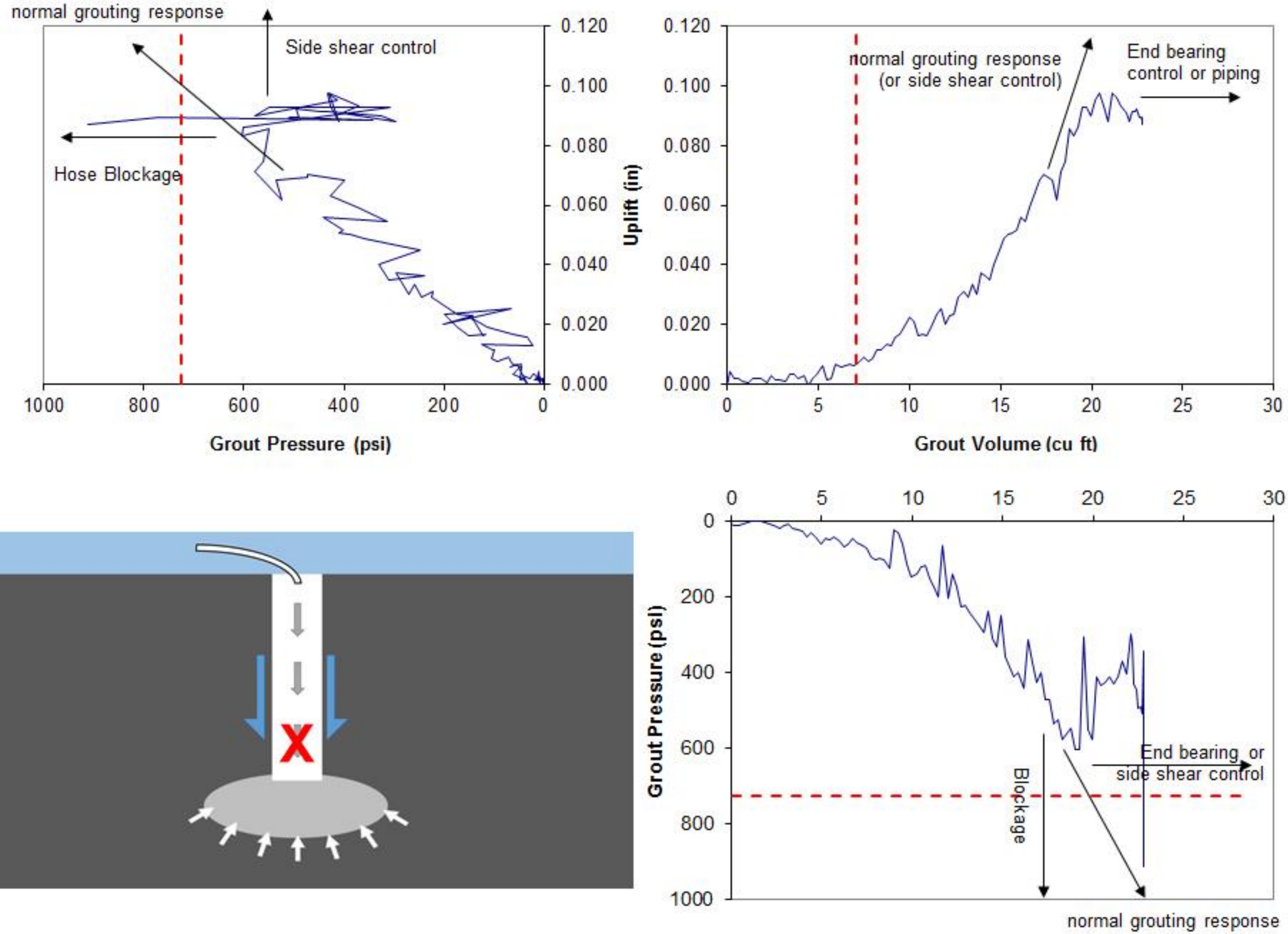
normal grouting response


normal grouting response
Side shear control
Hose Blockage
Grout Pressure (psi)
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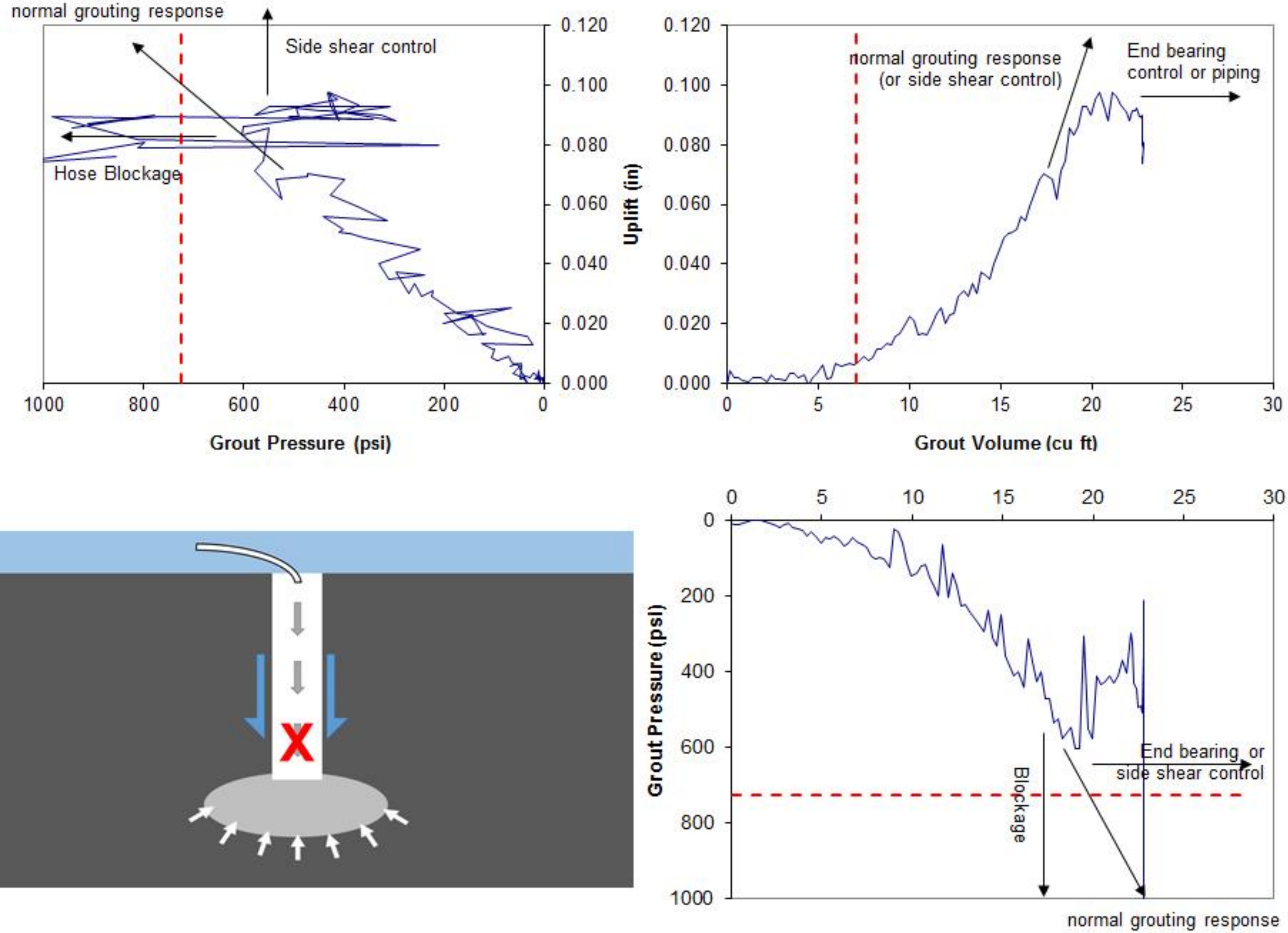
Grout Pressure (psi)
End bearing or
side shear control
Blockage
normal grouting response
X



normal grouting response
Side shear control
Hose Blockage
Grout Pressure (psi)
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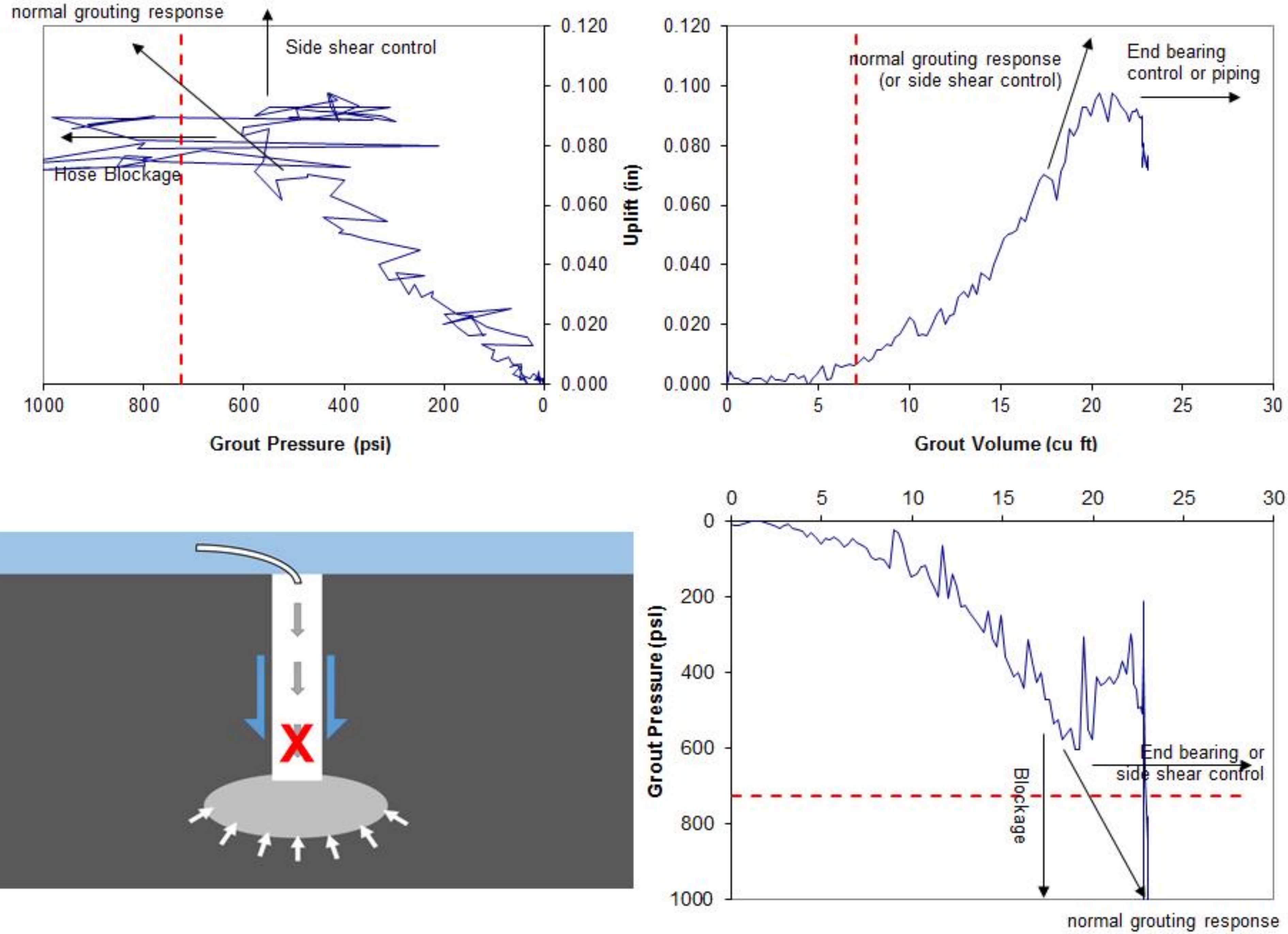
600
800
1000
Blockage
End bearing or
side shear control
normal grouting response
X



normal grouting response
Side shear control
Hose Blockage
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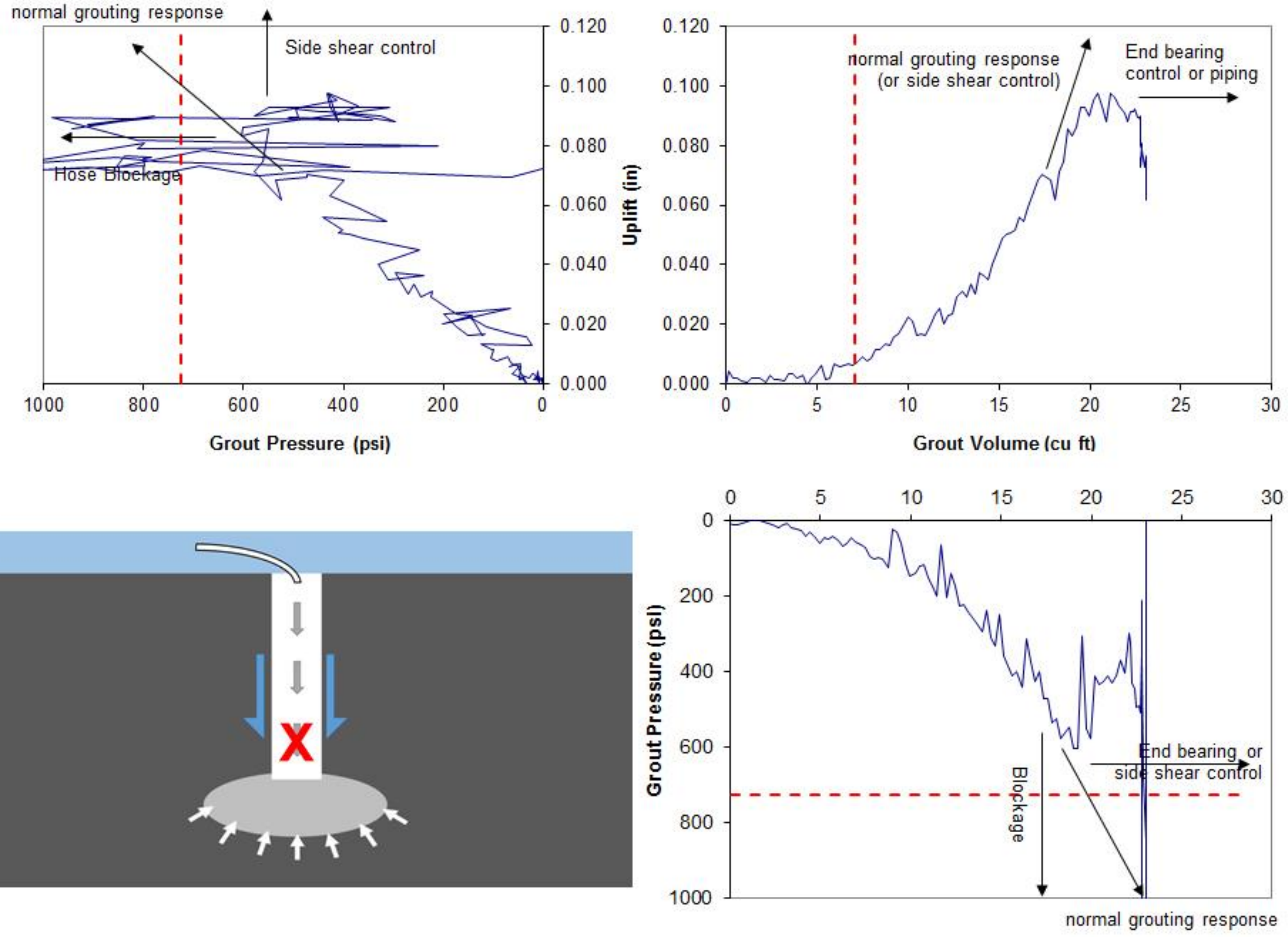
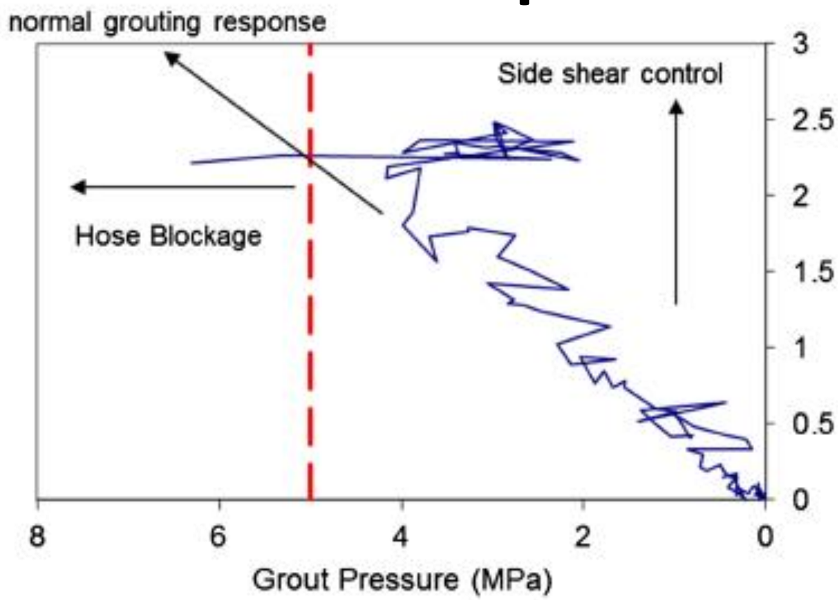
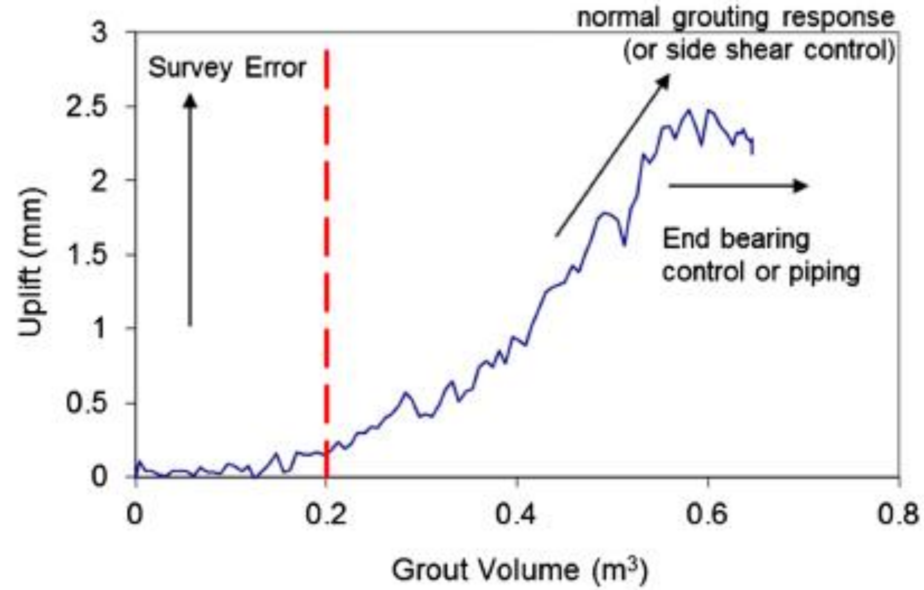
X



normal grouting response
Side shear control
Hose Blockage
Grout Pressure (psi)
Uplift (in)
normal grouting response
(or side shear control)
End bearing
control or piping
Grout Volume (cu ft)
Grout Pressure (psi)
Blockage
End bearing or
side shear control
normal grouting response

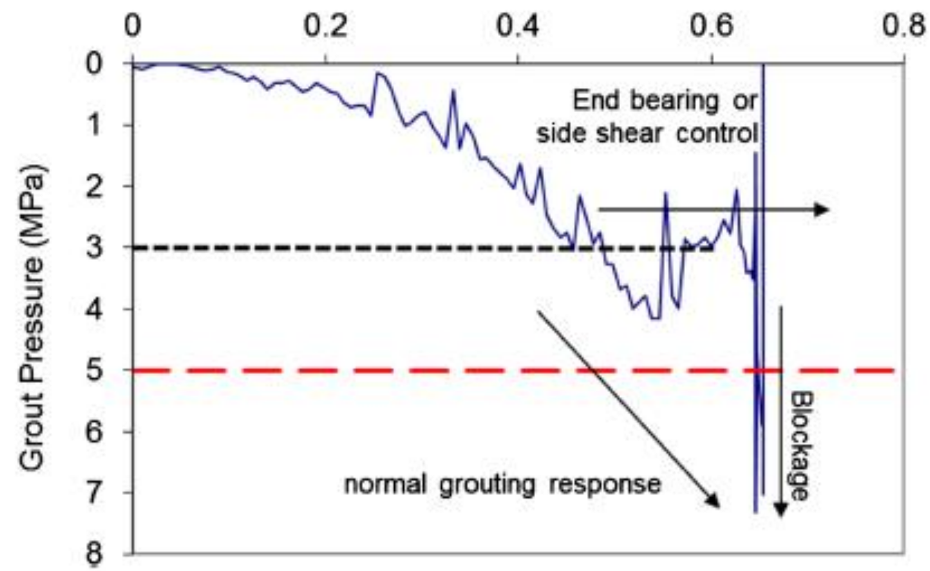
Grout pressure determination



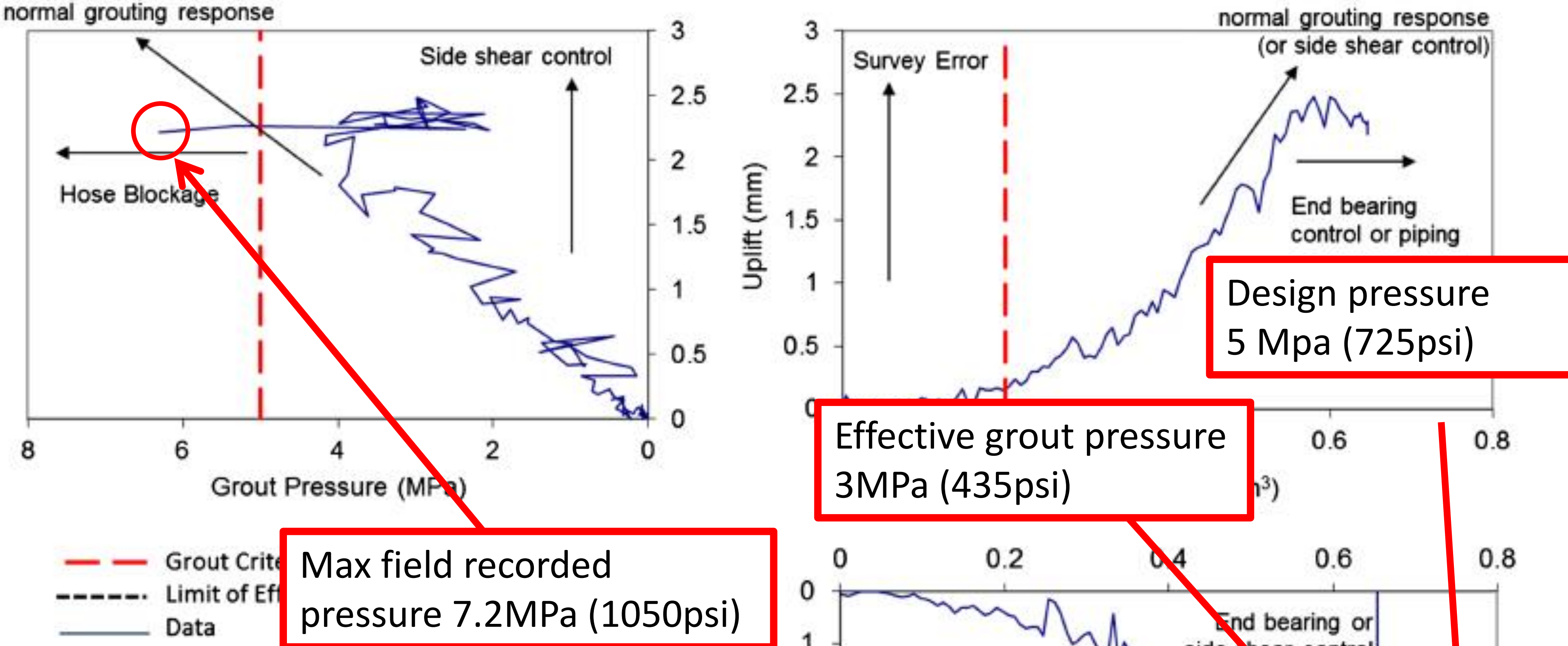


— — Grout Criteria
- - - - Limit of Effectiveness
—— Data

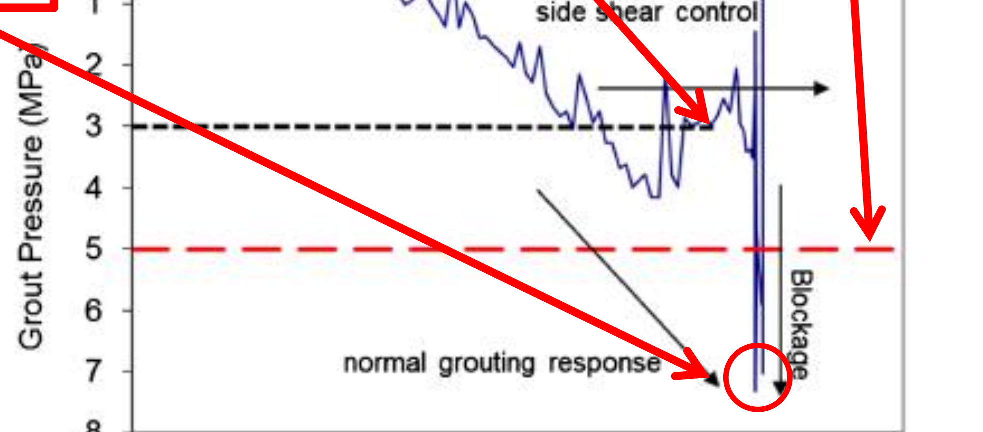
- Grouted normally up to 4MPa **(580psi)**
- Exceeded net volume criterion
- Exhibited end bearing failure
- Followed by system blockage
- Met both pressure and volume criterion, but not actually
- Effectively ended at 3MPa **(435psi)**



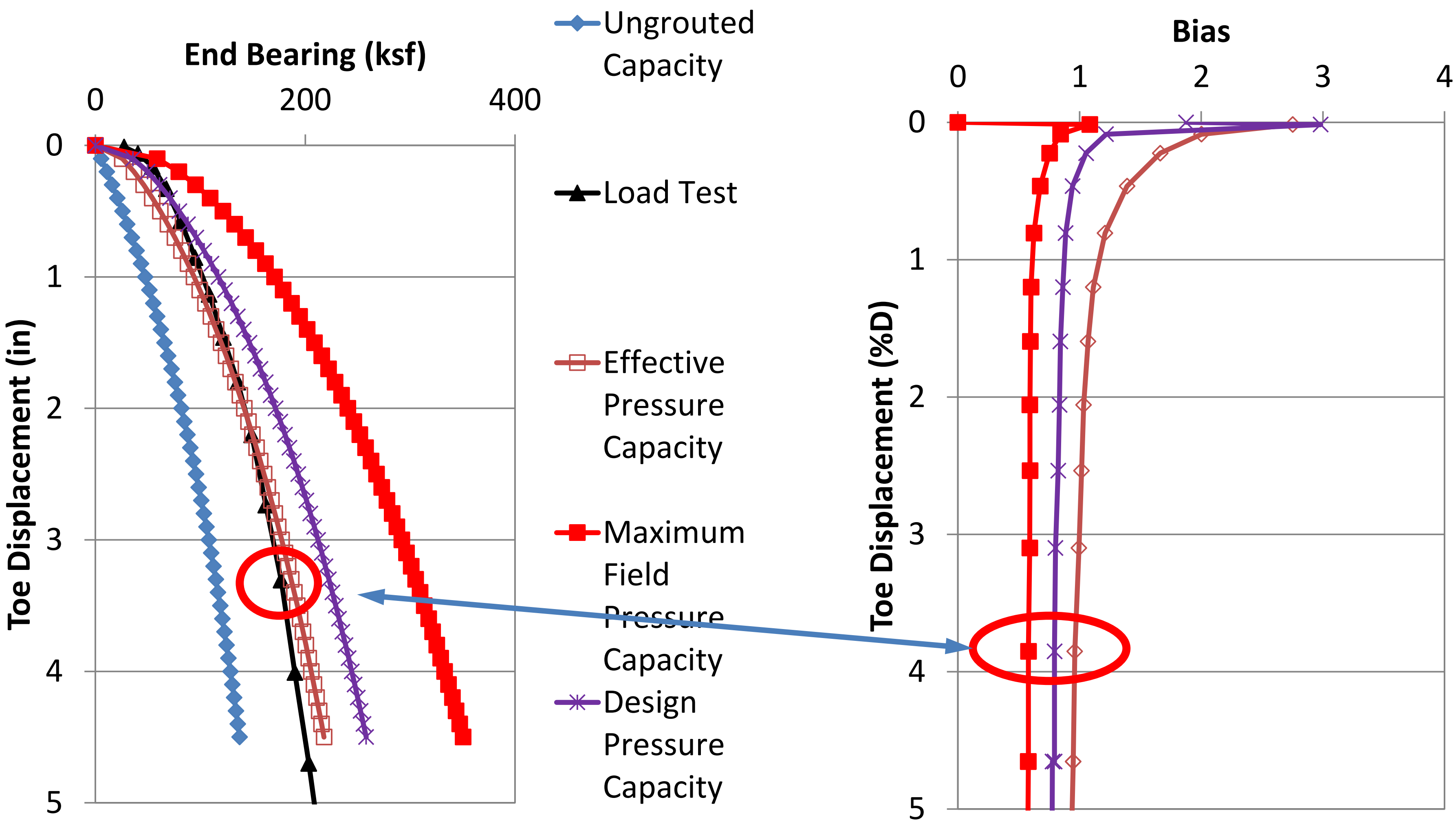
Grout pressure determination



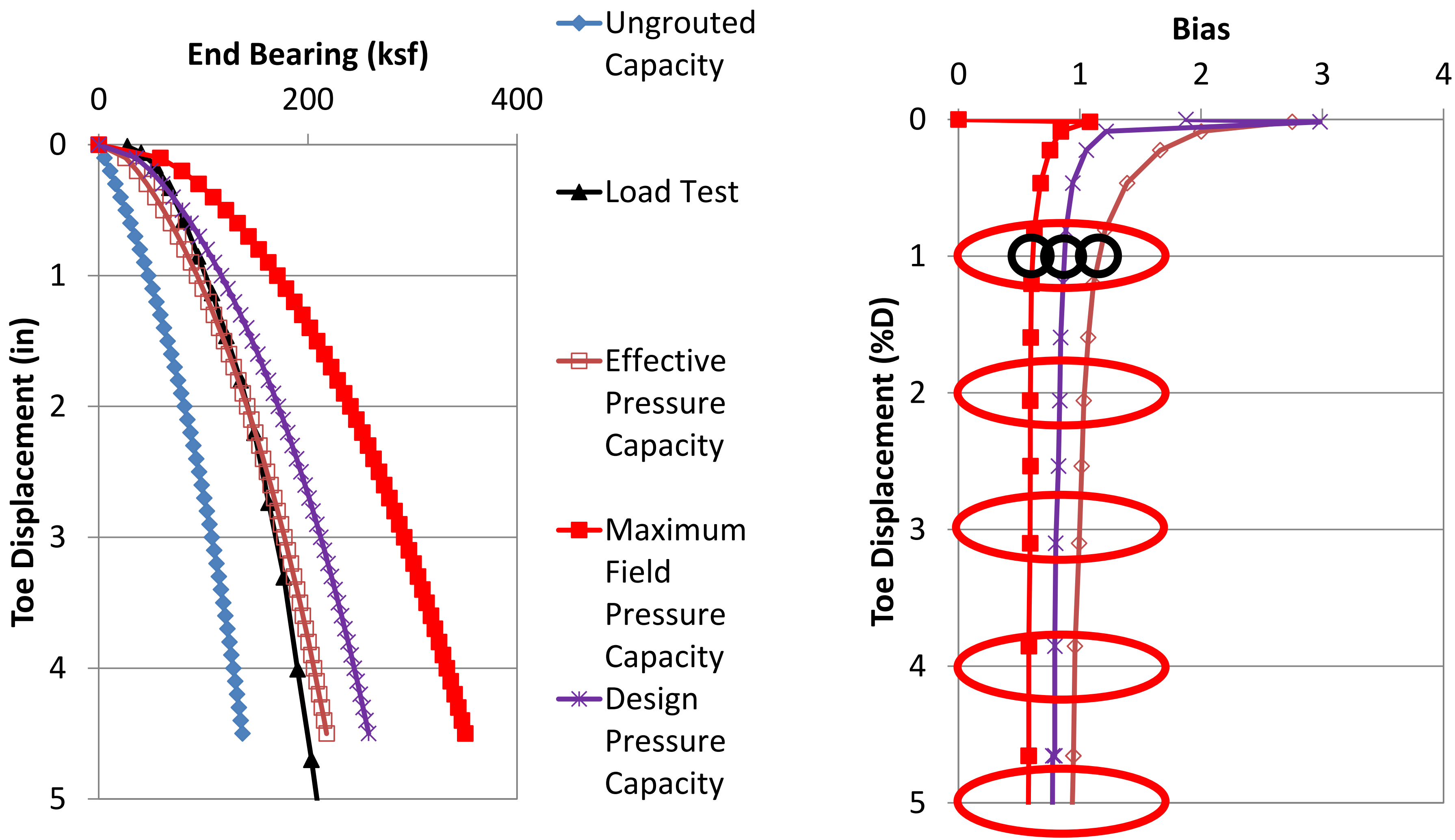
- Grouted normally up to 4MPa
- Exceeded net volume criterion
- Exhibited end bearing failure
- Followed by system blockage
- Met both pressure and volume criterion, but not actually
- Effectively ended at 3MPa



Measured vs Predicted (3 pressures)



Measured vs Predicted (3 pressures) and for 31 Shafts



Resistance Factor Computation

$$\phi_R = \frac{\lambda_R[\gamma_D Q_D + \gamma_L Q_L]\sqrt{\dfrac{(1+COV_{QD}^2+COV_{QL}^2)}{(1+COV_R^2)}}}{Q_m \exp\{\beta_T\sqrt{\ln[(1+COV_{QD}^2+COV_{QL}^2)(1+COV_R^2)]}\}}$$

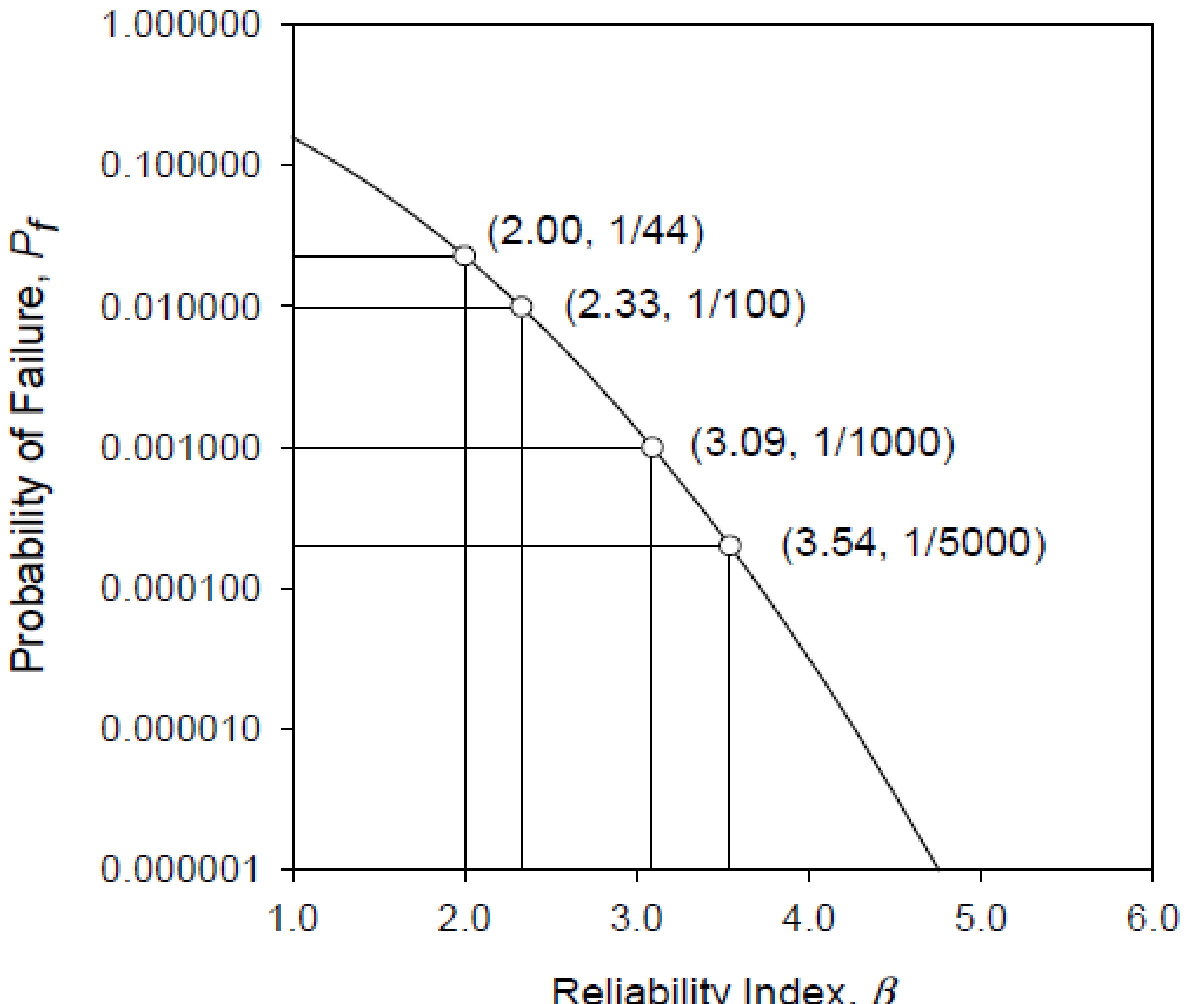
Average Bias @ different %D displacements

Coef of Variation for Avg Bias

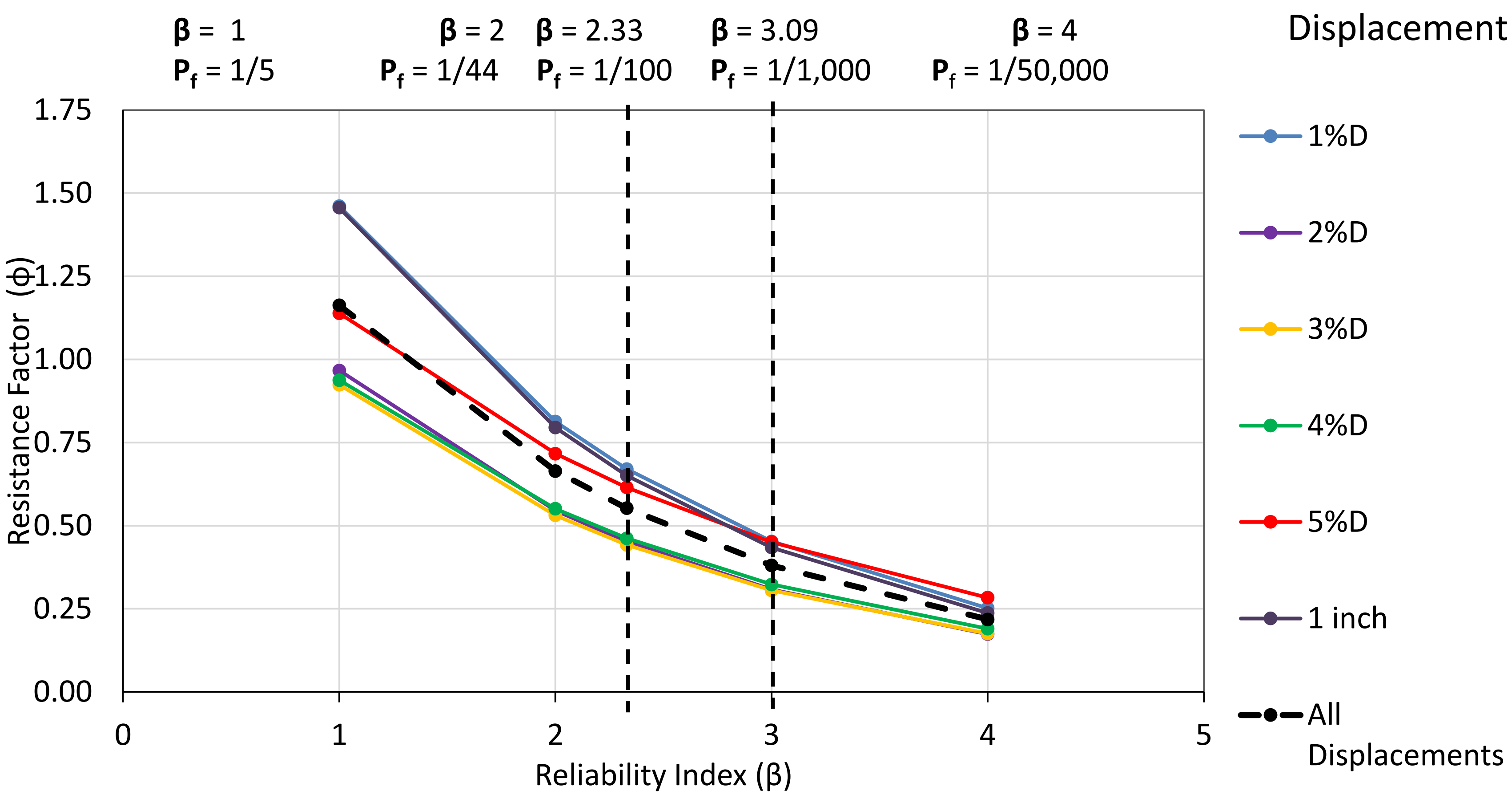
Reliability Index

- Computed for 3 pressures, 5 disp, and 5 reliability values

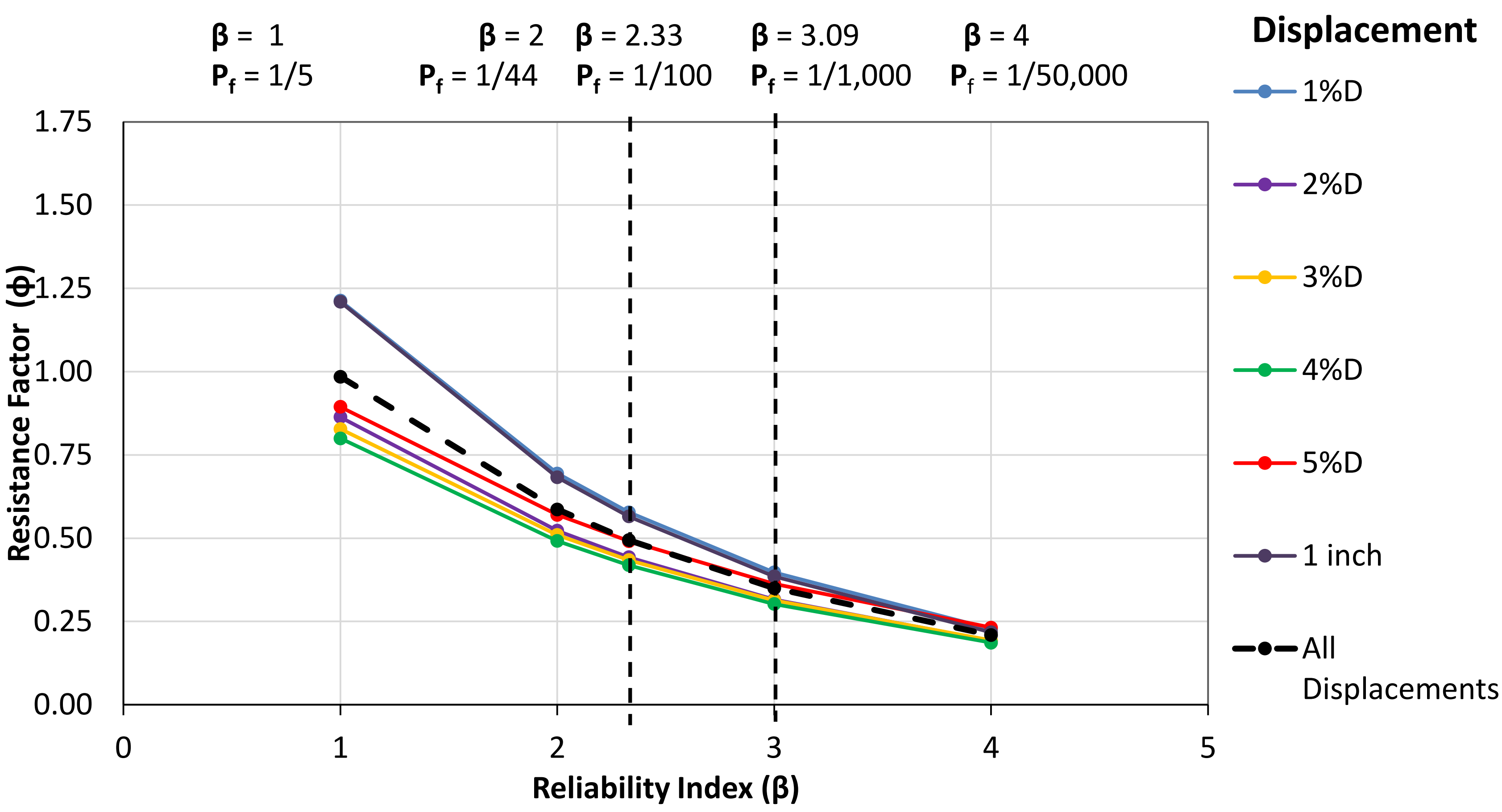
Reliability Index



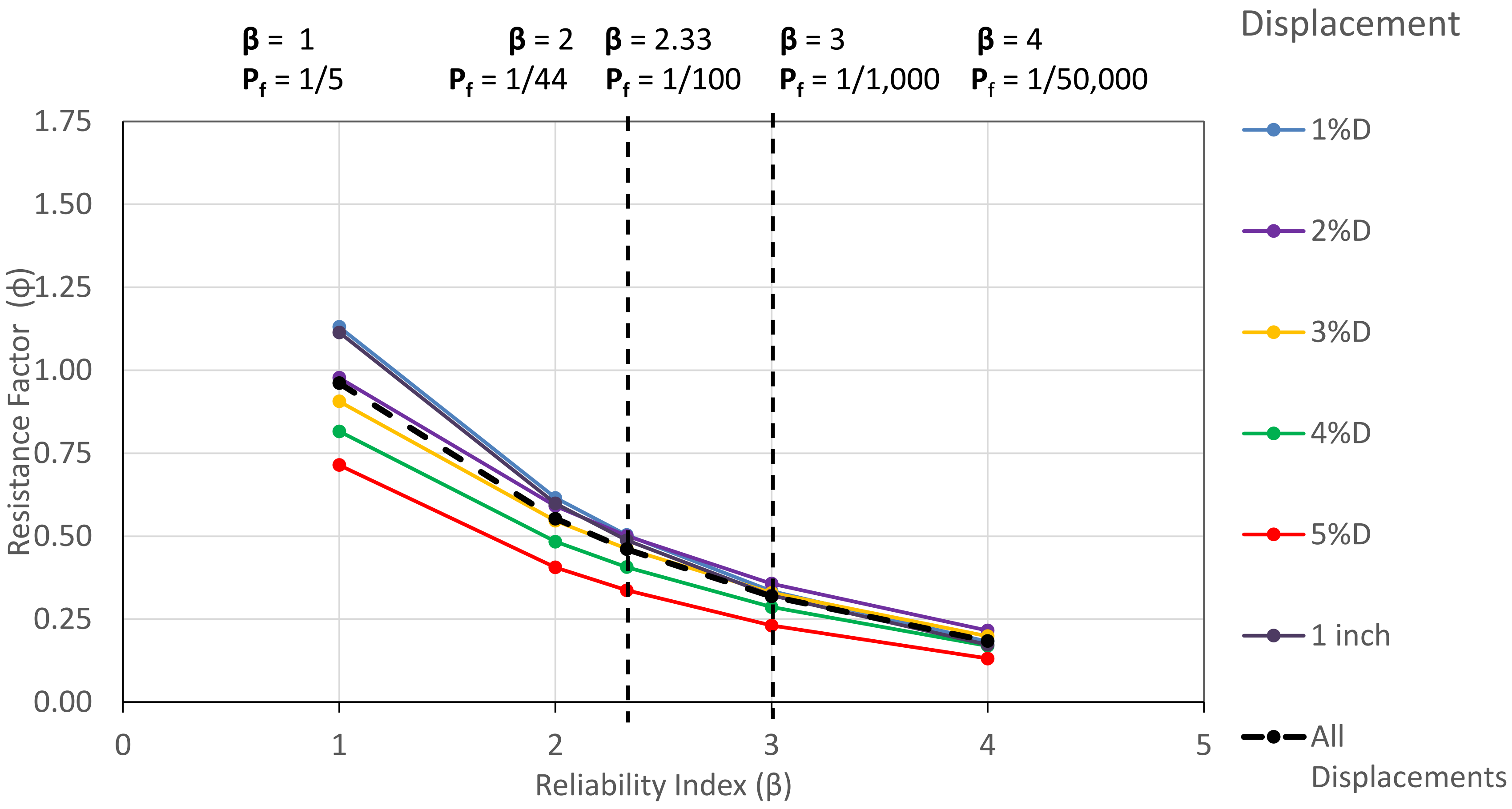
Effective Pressure



Maximum Field Pressure



Design Pressure

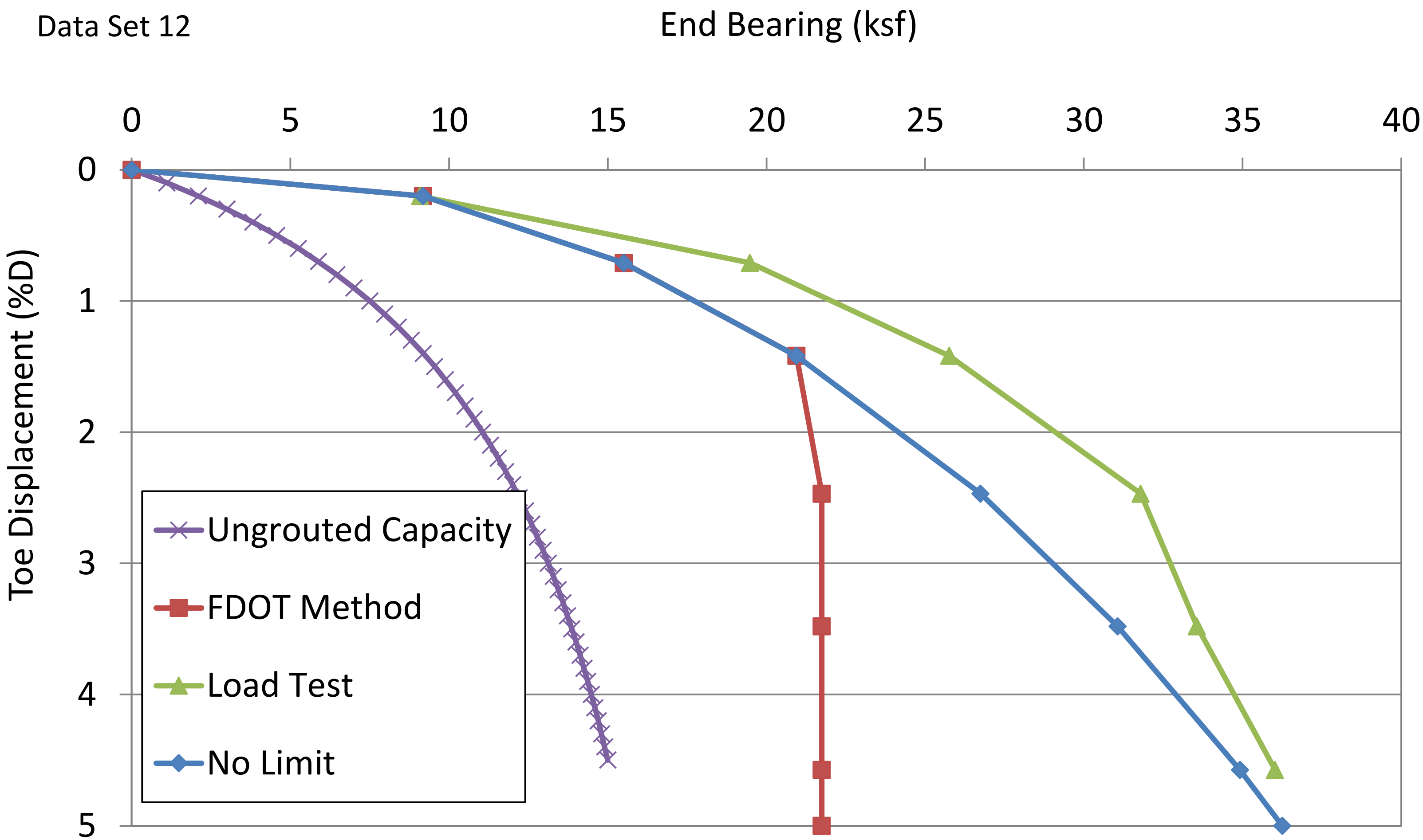


Summary for $\beta = 2.33$

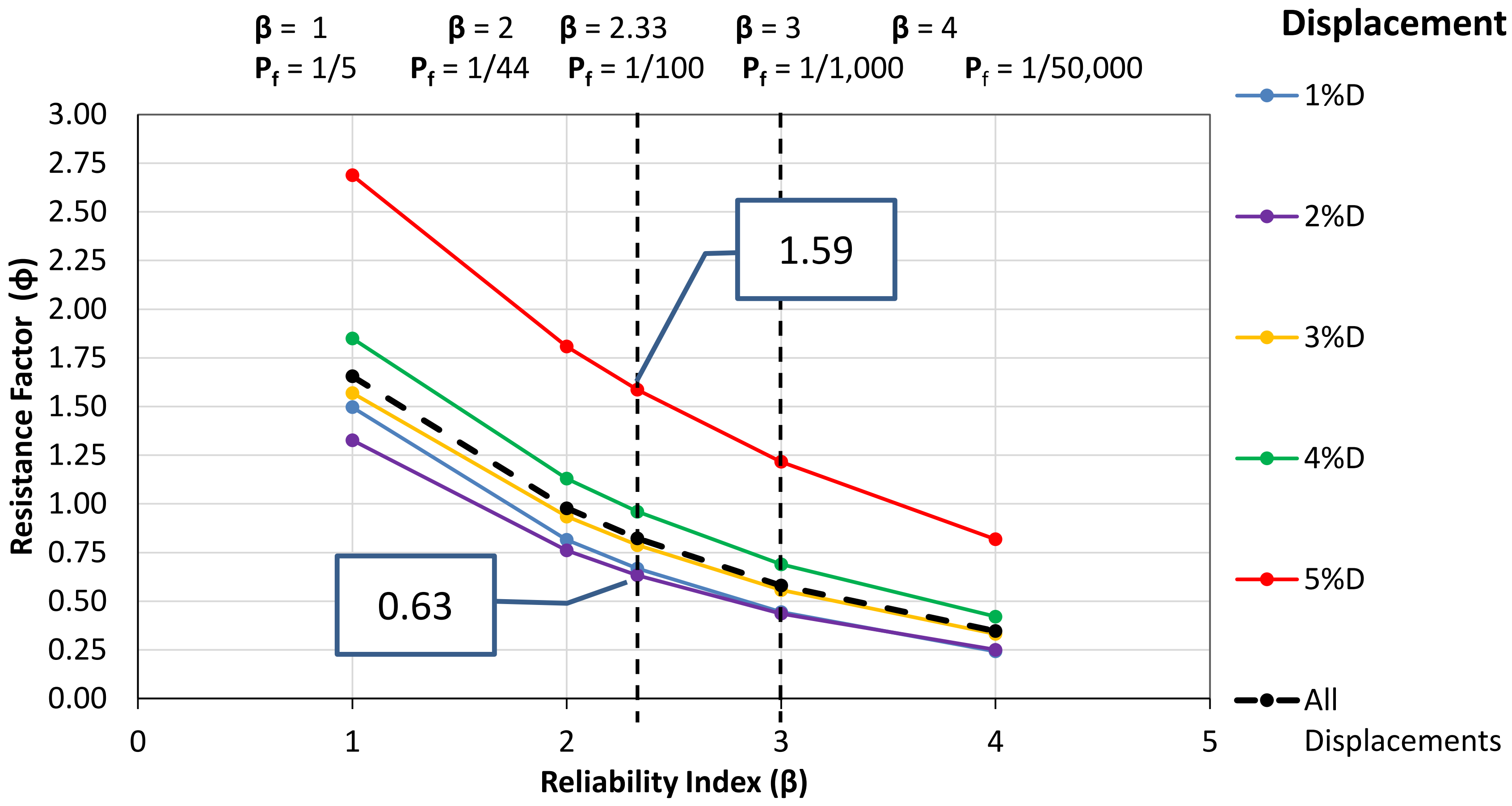
Bias Criteria	Resistance Factor (ϕ)						
	1in	1%D	2%D	3%D	4%D	5%D	All
Effective pressure (field verified / inspection plots)	0.65	0.67	0.45	0.44	0.46	0.61	0.55
Maximum field pressure	0.57	0.58	0.44	0.43	0.42	0.49	0.49
Design Side shear predicted pressure	0.49	0.50	0.50	0.46	0.41	0.34	0.46

Displacement at 100% Side Shear

Effect of FDOT End Bearing Limit



Effect of End Bearing Limit



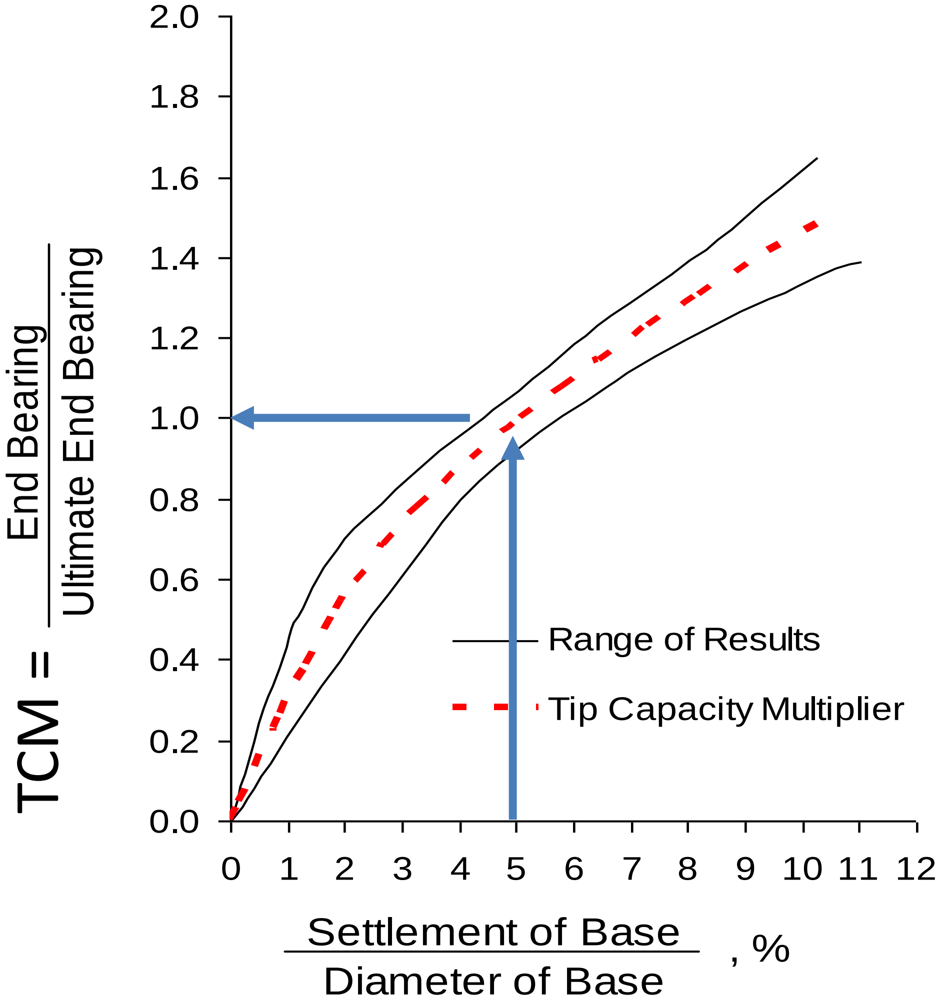
2006 Design Method (No Limit)

Bias Criteria	Resistance Factor, ϕ		Resistance Factor, ϕ	
	1%D Displacement		All Displacements	
	β = 2.33	β = 3.00	**β = 2.33**	β = 3.00
Effective pressure (tri-axis plots)	**0.67**	0.45	**0.55**	0.38

FDOT Method (Limits end bearing to grout pressure)

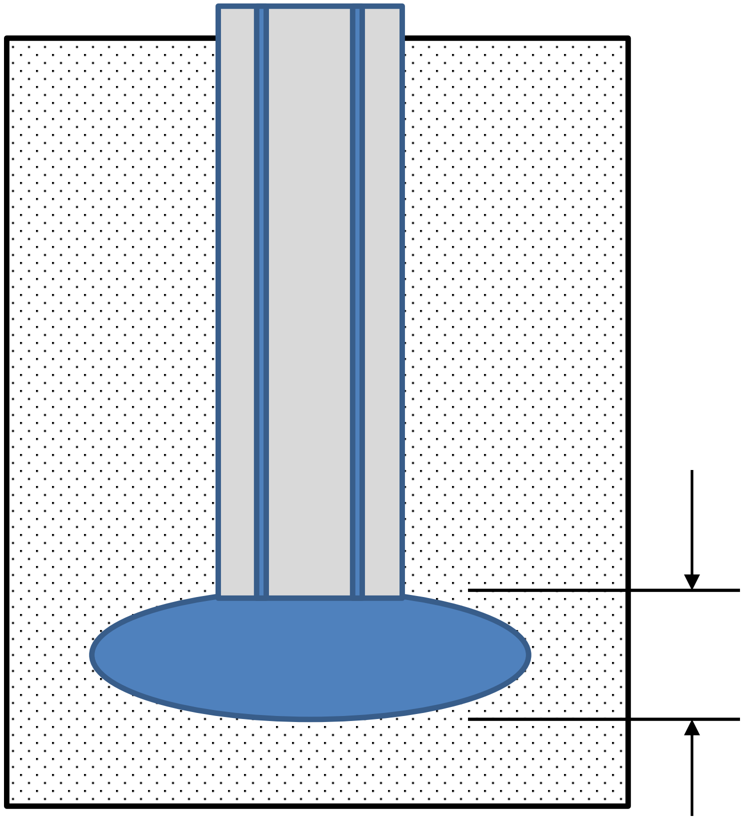
Bias Criteria	Resistance Factor, ϕ		Resistance Factor, ϕ	
	1%D Displacement		All Displacements	
	β = 2.33	β = 3.00	**β = 2.33**	β = 3.00
Effective pressure (tri-axis plots)	**0.67**	0.44	**0.82**	0.58

End Bearing Displacement Limit

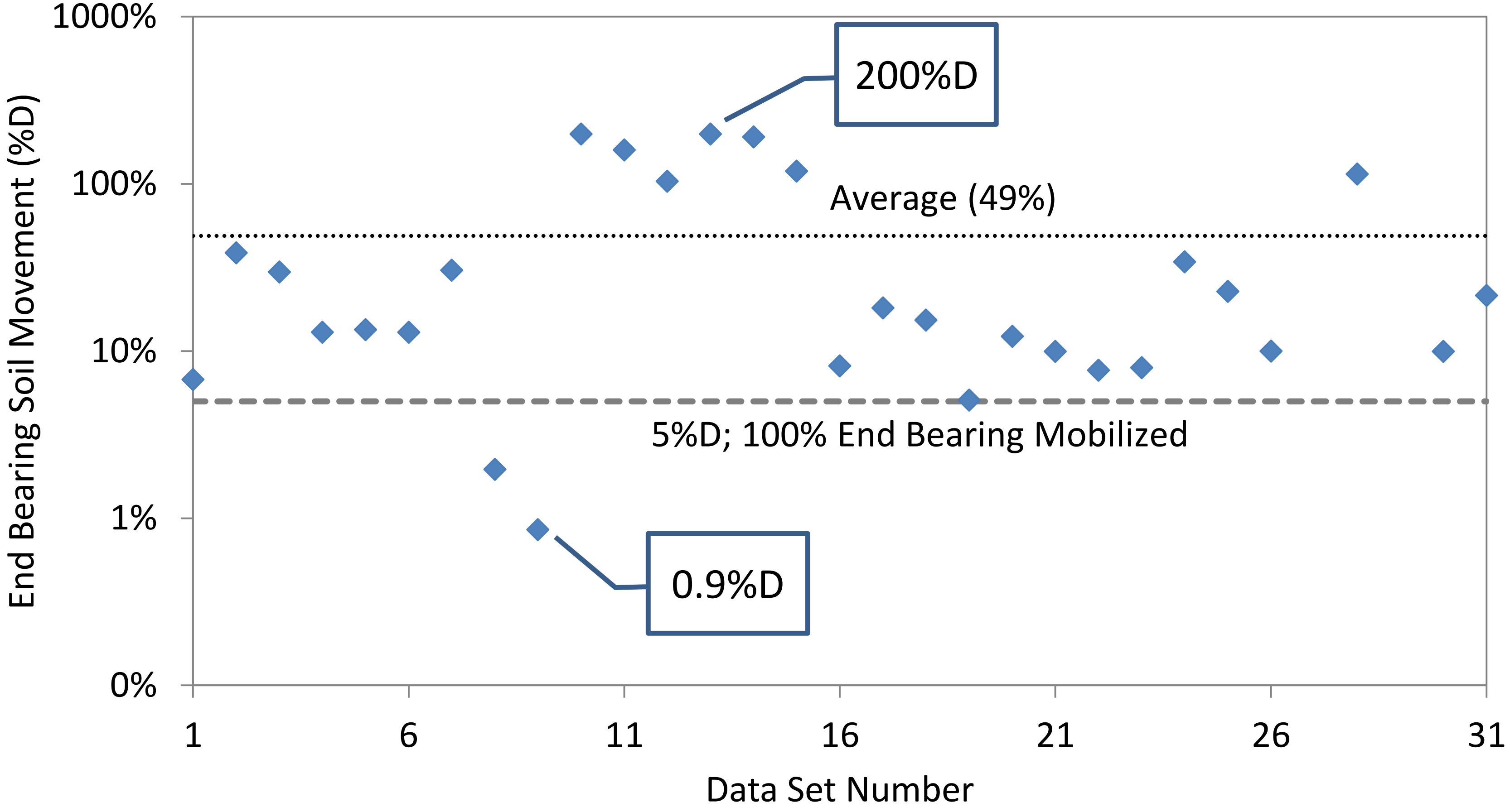


O'Neill (1988) estimated capacity would increase with displacement up to 12%D

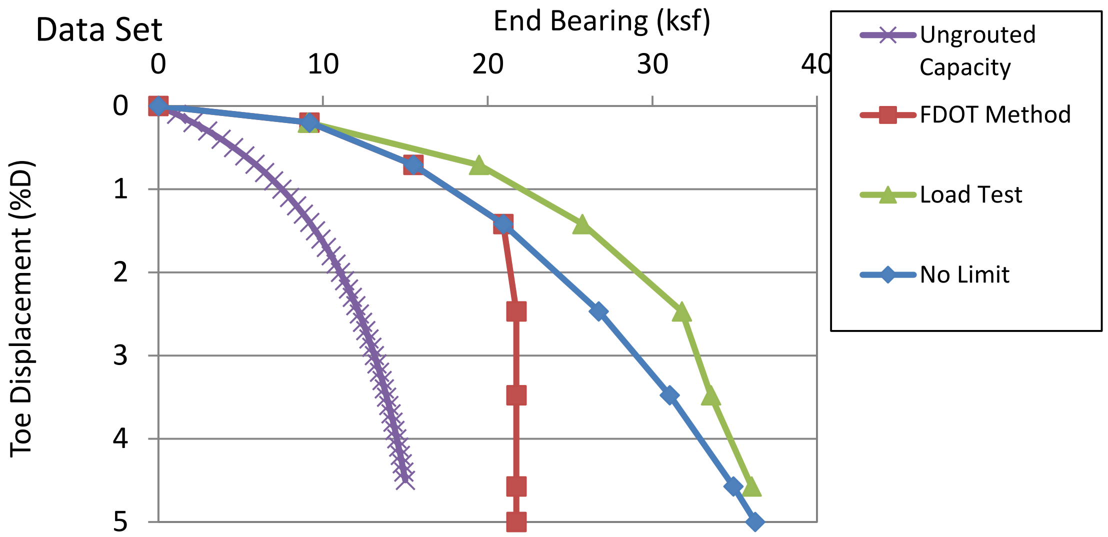
Bruce (1985) up to 15%D



Estimated End Bearing Displacement



Replace End Bearing Limit with Displacement Limit



Bias Criteria	2006 Method (No Limit)		FDOT Method (w/limit)	
	1%D Displacement		1%D Displacement	
	β = 2.33	β = 3.00	**β = 2.33**	β = 3.00
Effective pressure (tri-axis plots)	**0.67**	0.45	**0.67**	0.44

Current Resistance Factors

AASHTO

Method/Soil/Condition			Resistance Factor
Nominal Axial Compressive Resistance of Single-Drilled Shafts	Side resistance in Clay	alpha method (O'Neill and Reese, 1999)	0.45
	Tip resistance in clay	Total Stress (O'Neill and Reese, 1999)	0.40
	Side resistance in sand	beta method (O'Neill and Reese, 1999)	**0.55**
	Tip resistance in sand	O'Neill and Reese (1999)	**0.50**
	Side resistance in IGMs	O'Neill and Reese (1999)	0.60
	Tip resistance in IGMs	O'Neill and Reese (1999)	0.55
	Side resistance in rock	Horvath and Kenney (1979) O'Neill and Reese (1999)	0.55
	Side resistance in rock	Carter and Kulhawy (1988)	0.50
	Tip resistance in rock	Canadian Geotechnical Society (1985) Pressuremeter Method (CGS, 1985) O'Neill and Reese (1999)	0.50

FDOT

Loading	Design Method	Construction QC Method	Resistance Factor	
			Redundant	Non-redundant
Compression	For soil: FHWA alpha or beta method	Specifications	**0.6**	0.5
	For rock socket: McVay's method neglecting end bearing	Specifications	0.6	0.5
	For rock socket: McVay's method including 1/3 end bearing	Specifications	0.55	0.45
	For rock socket: McVay's method	Statnamic Load Testing	0.7	0.6
	For rock socket: McVay's method	Static Load Testing	0.75	0.65

Recommended Resistance Factors

FDOT

Loading	Design Method	Construction QC Method	Resistance Factor	
			Redundant	Non-redundant
Compression	For soil: FHWA alpha or beta method	Specifications	**0.6**	**0.5**
	For rock socket: McVay's method neglecting end bearing	Specifications	0.6	0.5
	For rock socket: McVay's method including 1/3 end bearing	Specifications	0.55	0.45
	Post grouted tip resistance in sand	***Tri-axis grouting verification***	***0.65****	***0.45****
	For rock socket: McVay's method	Statnamic Load Testing	0.7	0.6
	For rock socket: McVay's method	Static Load Testing	0.75	0.65

*with 1%D end bearing displacement limit

1.0

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

Recommended Resistance Factors

FDOT

Loading	Design Method	Construction QC Method	Resistance Factor	
			Redundant	Non-redundant
Compression	For soil: FHWA alpha or beta method	Specifications	**0.6**	**0.5**
	For rock socket: McVay's method neglecting end bearing	Specifications	0.6	0.5
	For rock socket: McVay's method including 1/3 end bearing	Specifications	0.55	0.45
	Post grouted tip resistance in sand	***Tri-axis grouting verification***	***0.65****	***0.45****
	For rock socket: McVay's method	Statnamic Load Testing	0.7	0.6
	For rock socket: McVay's method	Static Load Testing	0.75	0.65

*with 1%D end bearing displacement limit

Revised FDOT Method

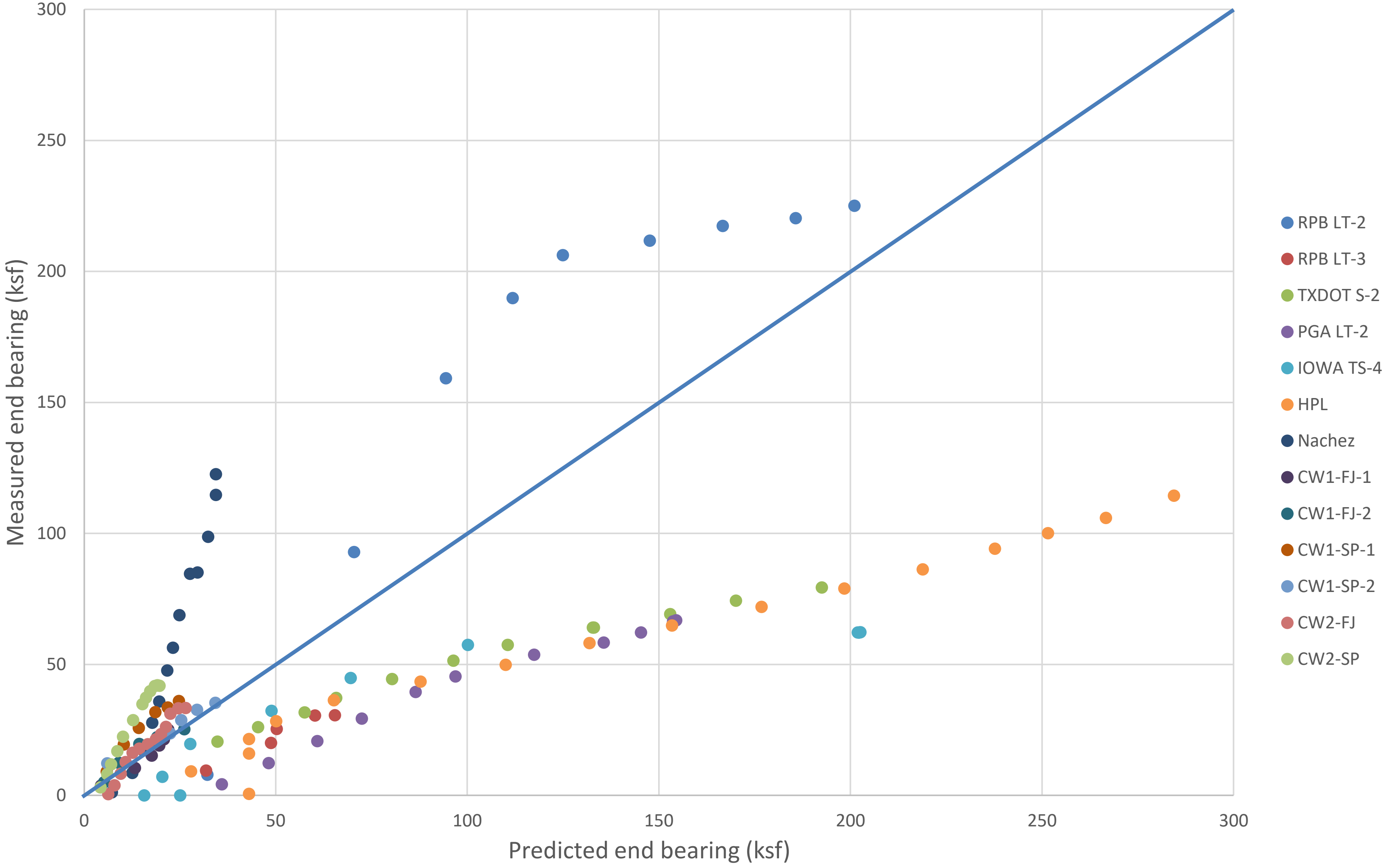
$$q = \left(0.713(GPI) + \frac{\%D}{0.4(\%D)+3.0}\right) 0.6N$$

Summary

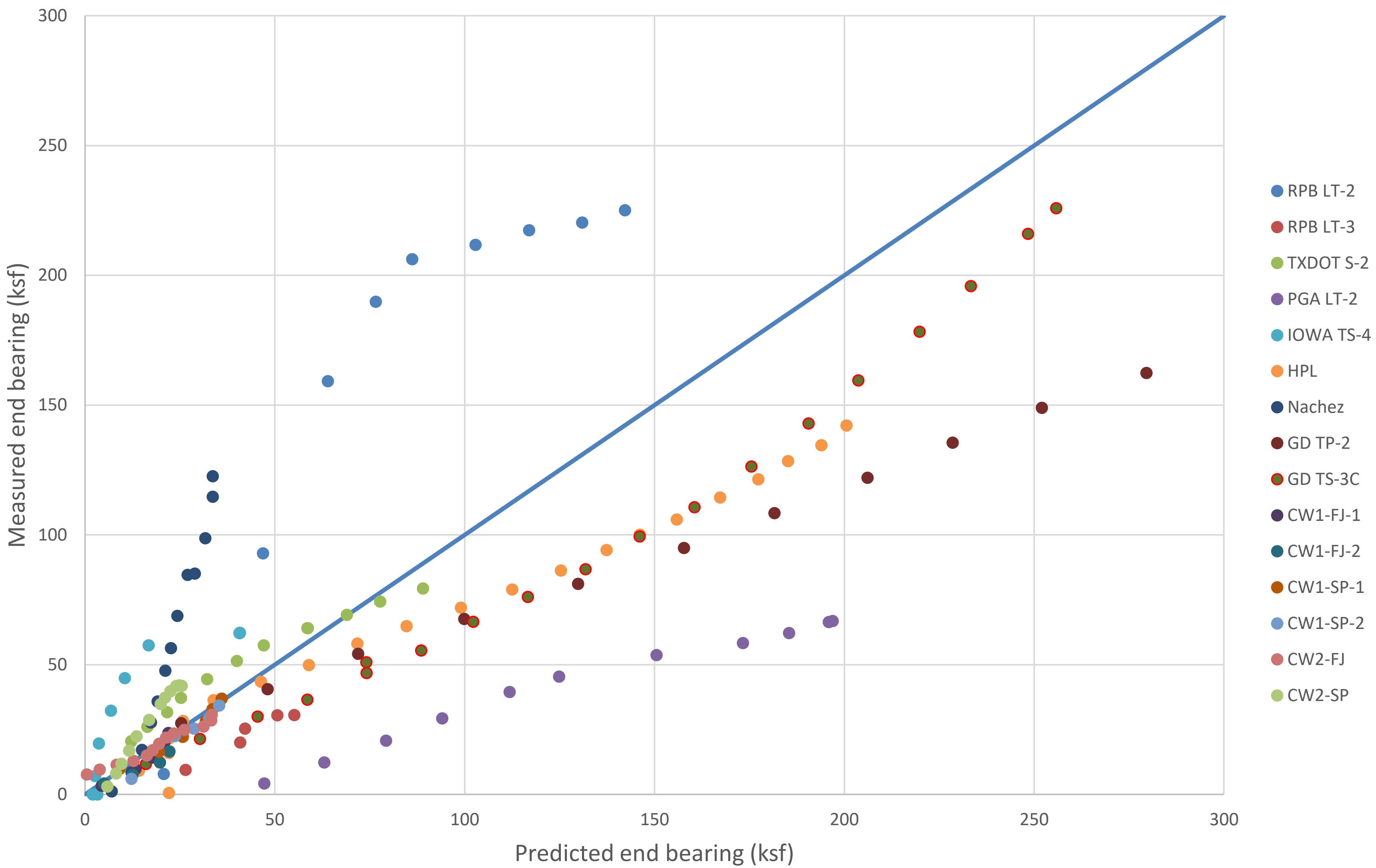
- Resistance factors for post grouted end bearing of shafts in sand were determined from 31 test shaft case studies.
- The design grout pressure can be estimated from boring logs but must be verified in the field via tri-axis plots to qualify for the recommended resistance factors.
- FDOT grouted end bearing capacity limit would be best imposed as an end bearing displacement limit with little change to the net effect.

Questions

Measured vs Predicted
(side shear predicted pressure)



Measured vs Predicted (max field recorded pressure)



Measured vs Predicted (effective grout pressure)