LIMITED MOBILITY GROUTING -- PRACTICE IN NORTH AMERICA

Michael Byle, D.GE, F.ASCE,

Overview

- INTRODUCTION
- COMPACTION GROUTING
- LIMITED MOBILITY GROUTING
- LMG MATERIALS AND TECHNOLOGY
- EQUIPMENT
- GROUT INJECTION
- QUALITY CONTROL AND VERIFICATION
- FUTURE DIRECTIONS

Introduction

- Limited Mobility Grouting is a North American Practice
- It began as Compaction Grouting in California in the 1950's
- New Applications of the Technology Broadened its use beyond just compaction to include
  - Void filling
  - Reinforcement
  - Structural Supports

LIMITED MOBILITY GROUTING

"The injection of a stiff grout that does not mix with or penetrate the soil, often displaces the substrate into which it is injected, and does not travel very far from the point of injection"

- Evolved from new applications of Compaction Grouting technology
- Through control of rheology and injection techniques developed for compaction grouting, the ability to create specific shapes and controlled filling of voids became viable.

The Discovery

Photo Courtesy James Warner

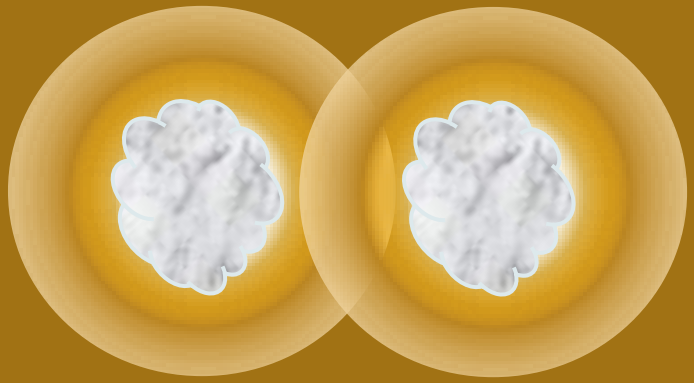
COMPACTION GROUTING

- Grout injected with typically less than 1 in. (25 mm) slump. Normally a soil-cement with sufficient silt sizes for mobility and sufficient sand and gravel sizes to develop internal friction to cause the grout to act as a growing mass as injection continues under pressure.
- The grout generally does not enter soil pores but remains a homogeneous mass
- Controlled displacement to compact loose non-plastic soils

COMPACTION GROUTING

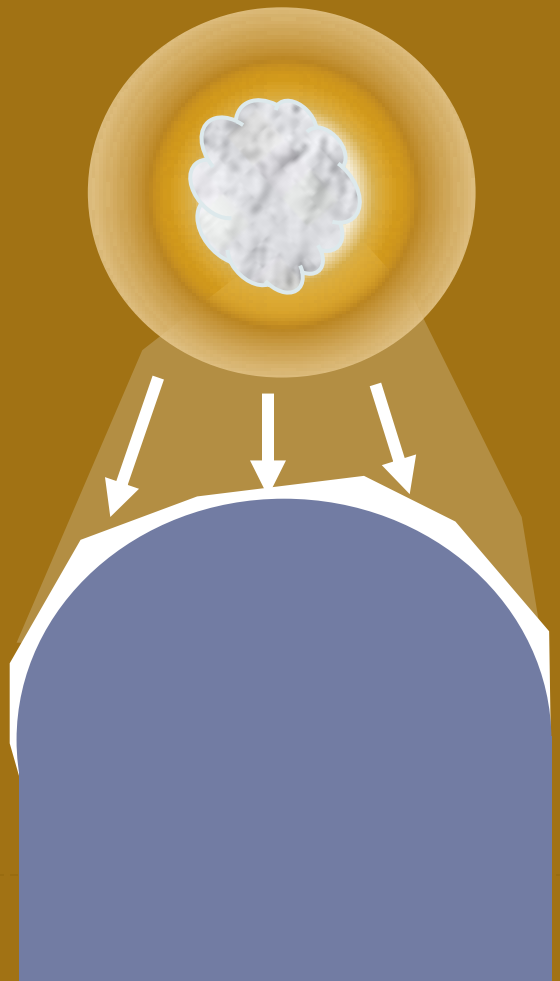
- Arose out of grout jacking where mortar grout is injected under slabs or structures to raise them to proper elevation. Discovered during grouting to jack up a pool
- Mechanism observed as water was displaced from the ground in proportion to the grout injected

COMPACTION GROUTING



Injected Grout displaces soil compacting the surrounding soil

COMPENSATION GROUTING



COMPACTION GROUTING

Note granular breaks as extrusion exits hose. (The number one requirement for acceptable grout)

Compaction Grouting
Injection Rate

- Effect on Volume
  - Slow injection permits greater volume of injection
  - Higher rate reduces volume of injection
  - Rates greater than about 2 CFM (55 L/min) will likely cause hydraulic fracturing and loss of injection control.
- Effect on Pressure
  - Slow injection produces lower pressures
  - Faster injection produces higher pressures
- Slow is required for sensitive applications ~0.5 cf/min (1.5 L/min)

LIMITED MOBILITY GROUTING

Uses:

- *Compaction Grouting*
- *Sealing of Flowing Channels*
- *Pre-grouting of Large Fractures*
- *Abandoned Mine Filling*
- *Structural Supports*
- *Grout Jacking*
- *Soil Reinforcement*
- *Post Grouting of Deep Foundations*

LIMITED MOBILITY GROUTING Applications

- *Grout Jacking:* Injection of grout beneath slabs or structures that have settled, to lift them back into position. The low mobility of the grout constrains it to the intended lift locations.

LIMITED MOBILITY GROUTING Applications

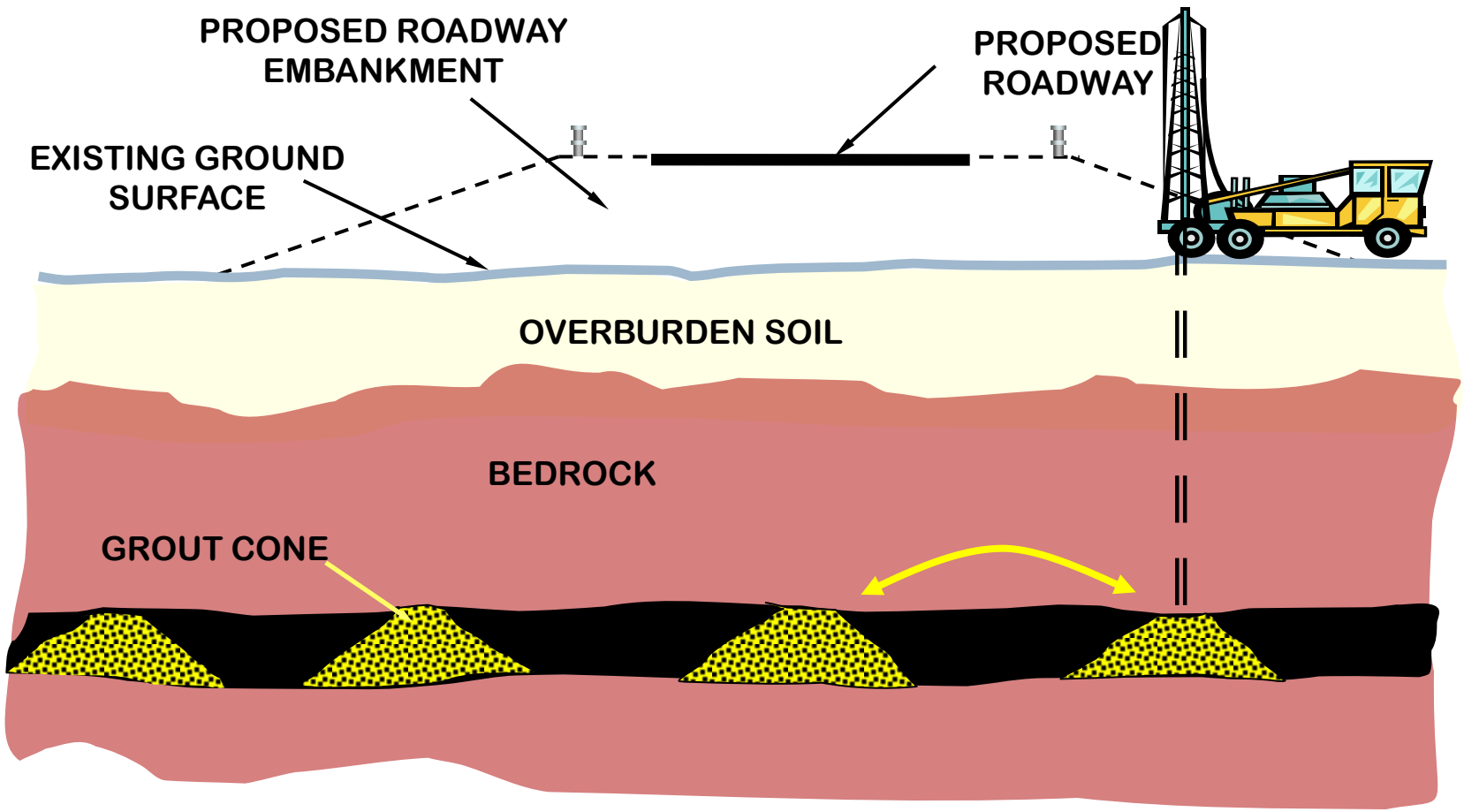
- *Pre-grouting of Large Fractures:*
  - Low mobility grouting is used to pre-grout large fractures to reduce opening sizes, in order to make high mobility rock grouting more effective.
  - A similar practice may also be used in Karst to construct grouted hydraulic barriers.
  - LMG may be used to create barriers to seal off fracture openings without completely filling all fractures.

LIMITED MOBILITY GROUTING Applications

- *Abandoned Mine Filling:* Low mobility grout injected to form high angle of repose conical roof supports that can be used individually or overlapped to form dams within mine drifts so that high mobility grout or flowable fill will be contained to prevent or remediate mine collapse.

Void Filling

Photo Courtesy of Sam Bandimere



SUPPORT WITH GROUT CONES

LIMITED MOBILITY GROUTING Applications

- *Sealing of Flowing Channels:* The injection of low mobility grouts that include water reducing and viscosity modifying admixtures to provide cohesiveness and prevent washout, can effectively seal off active flow in subsurface conduits when pumped at rates sufficient to overwhelm the flow.

LIMITED MOBILITY GROUTING Applications

- *Structural Supports:* Injection of low mobility grout to create columns to act as structural support for buildings and other structures.
  - underpinning
  - earth support
  - creation of structural arches to support rubble foundations on grout piles.

LMG Grout Columns for Underpinning and Excavation Support

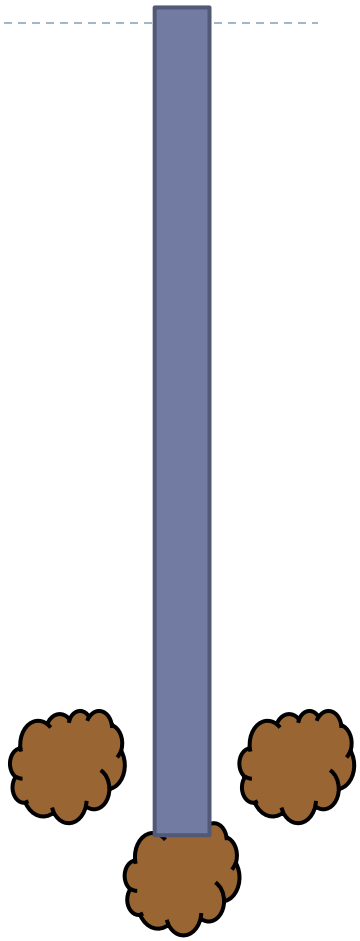
Photo Courtesy of Rembco Geotechnical Constructors

LIMITED MOBILITY GROUTING Applications

- *Controlled Void filling:*
  - Injections of grout used to fill openings in the ground such as Karst cavities, mine openings, subsurface erosion, cavities left from piping failure, settlement beneath structures, etc.
  - Control of grout rheology permits limited filling without loss of grout to areas outside the area of concern
  - Limited permeation of open graded materials

LIMITED MOBILITY GROUTING Applications

- *Post Grouting of Deep Foundations:*
  - Injection of limited mobility grout is used to increase the horizontal stress and densify soils surrounding piles shaft in the ground to increase the capacity of the foundation element in friction.
  - Controlled injection of structural grout can be used to increase the bearing area of the pile tip.
  - Compaction grouting below the base of drilled shafts can be used to increase end bearing capacity.



LIMITED MOBILITY GROUTING

Applications

- *Reinforcement:* Low mobility grout columns used to add stiffness and strength to soil masses for slope stabilization and embankment support.

(Video)

TYPICAL LMG MATERIALS

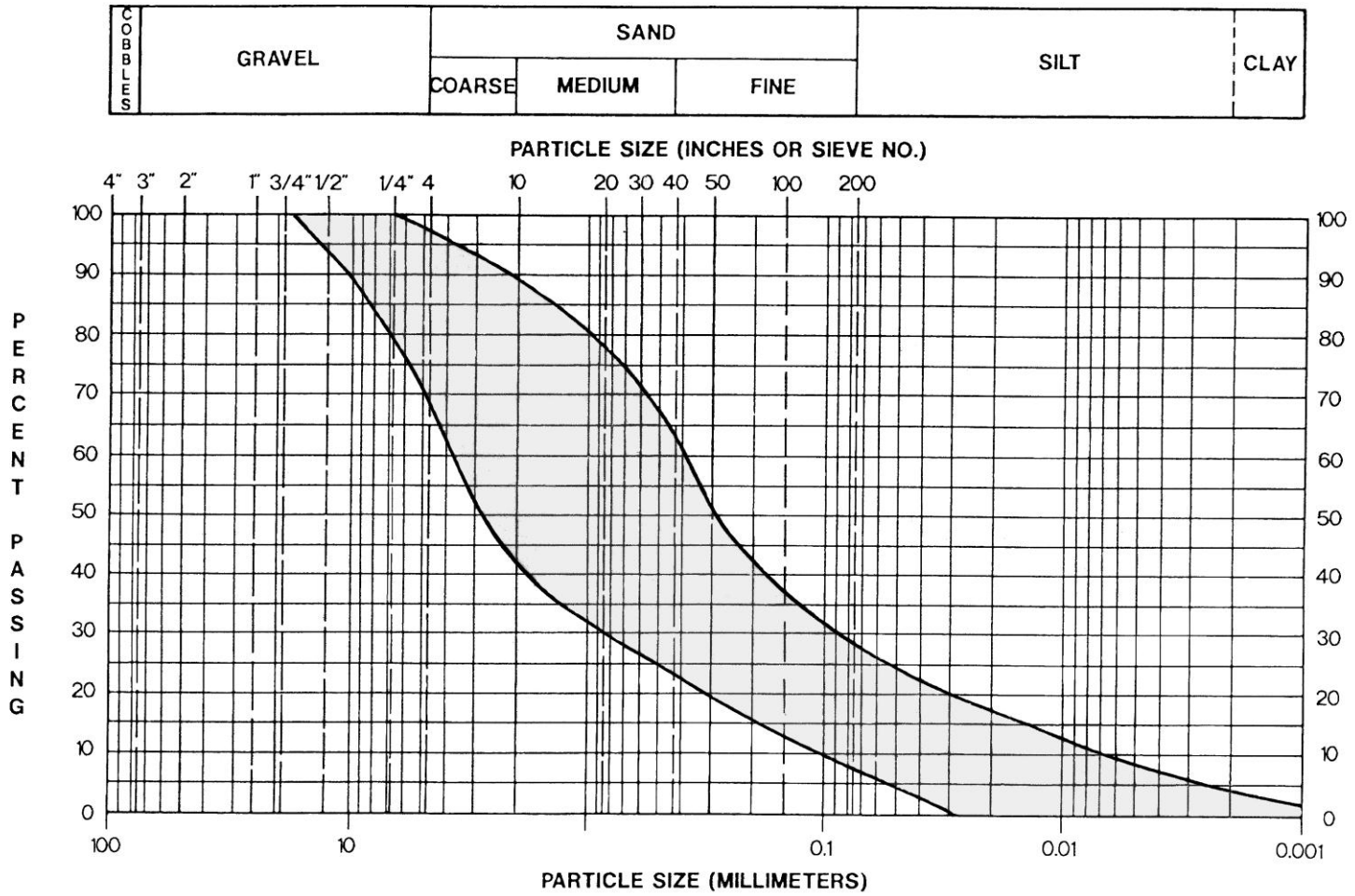
Primary ingredients include:

- Aggregate (Soil)
  - Sand
  - Gravel
  - Silt
- Portland Cement
- Water
- Additives and Admixtures (optional)

LMG Materials – Aggregate

- Aggregate most often includes broadly graded sand
- Silt is necessary for pumping and to retain cement and water in the mix, though admixtures may be suitable for this purpose in less critical applications such as void filling.
- Fine gravel is frequently added to improve control of the mix and reduce mobility
- Natural rounded grain aggregates are best

LMG Materials – Aggregate



LMG MATERIALS – Portland Cement

- Cement is added to provide structural capacity to injected grout masses
- Cement is not required where structural strength of the grout is not important (e.g. compaction grouting)
- Cement is often used as a pumping aid and to increase the 'comfort level' of engineers

TYPICAL LMG MATERIALS

New Options:

- Additives and admixtures
  - fly ash, bottom ash, hydrated lime diatomaceous earth, fire clay, and bentonite
  - plasticizers, high range water reducers, anti-washout agents, viscosity modifiers, and air-entrainment
  - Not typically used for compaction grouting

LMG Materials – Additives

- Clays may be added in very small quantities but will increase mobility and may result in hydraulic fracturing and loss of control
- Fly ash, diatomaceous earth, or hydrated lime may be added to replace or supplement silt size material where sufficient natural silt is not available
  - Particle size and shape can affect pumpability and internal friction of grout
  - Test mixes and test injections are required where silt substitutes are used.
- Chemical admixtures may be used for specific conditions to improve performance , though care should be taken to assure internal friction and grout control is not compromised

Grout Mobility

- Controlled by:
  - Grout rheology
    - Grout formulation
    - Water content
    - Plasticity vs internal friction
  - Soil-Grout interaction
  - Injection rate
    - High rate – high resistance
    - Pore pressure dissipation

Photo Courtesy James Warner

Effect of Plasticity

non plastic fines

plastic fines

Photos Courtesy James Warner

Exception that proves the rule

LMG EQUIPMENT

- **Mixing**
  - *Horizontal Paddle Mixers*
  - *Auger Mixers*
- **Pumping**
  - **Duplex Piston Pumps**
    - **S-tube preferable**
    - **1,500 psi (10 Mpa) [application dependent, 2000 psi (14 Mpa) common and easy to acquire.]**
    - **Low pumping rate < 2 CFM (55 L/min) for most applications**
    - **High pumping rate needed to stanch conduit flows**

Grout Mixing

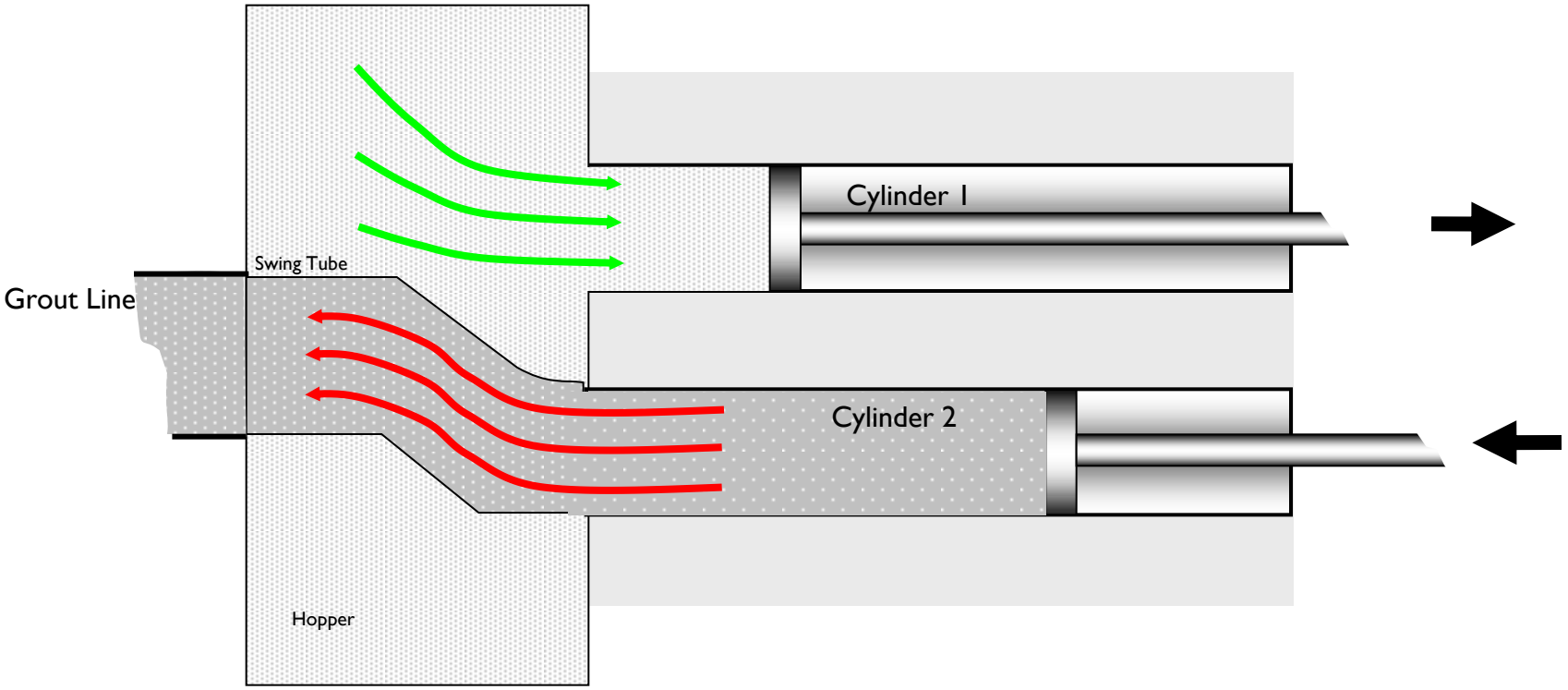
Grout Pumps

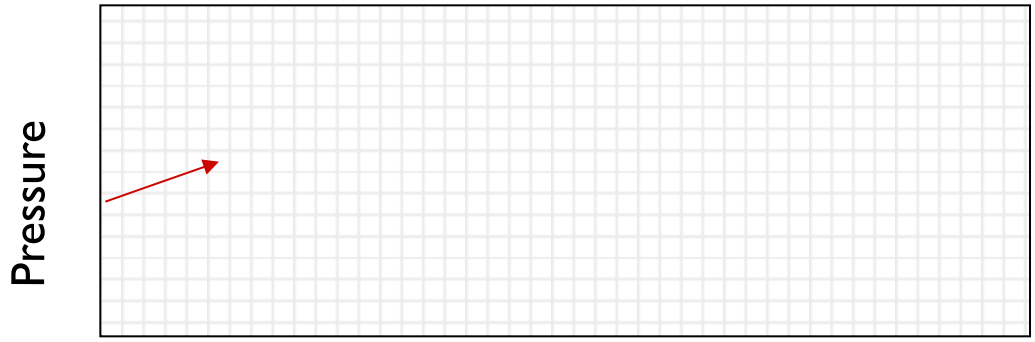
LMG EQUIPMENT

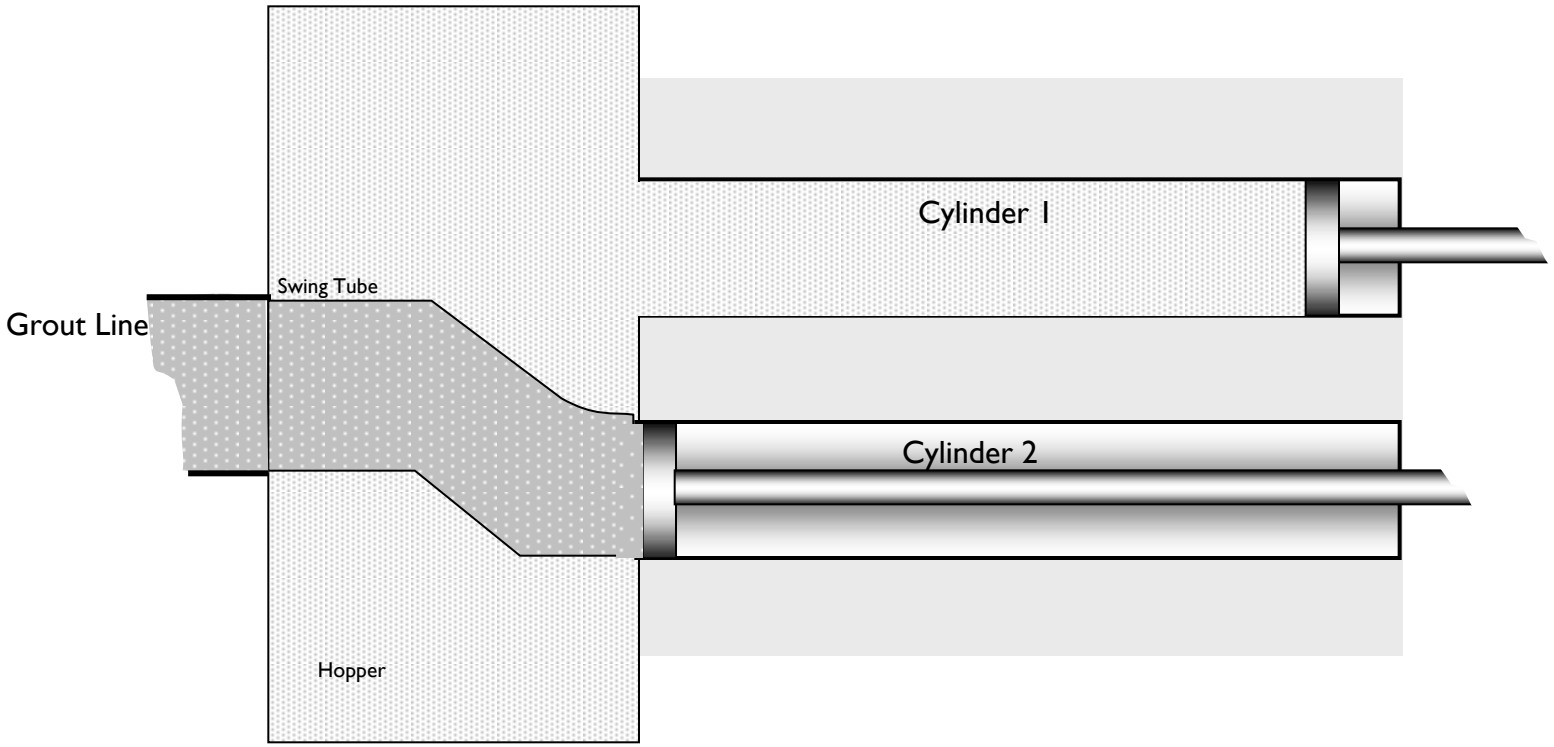
- **Casing and Hose**
  - No abrupt sectional changes
  - High strength joints sufficient for repeated extraction
  - Flush walled
  - Joint length suitable for installation/extraction methods
- **Fittings**
  - Gage Saver
  - Jacks for extraction
  - Long radius sweep fittings

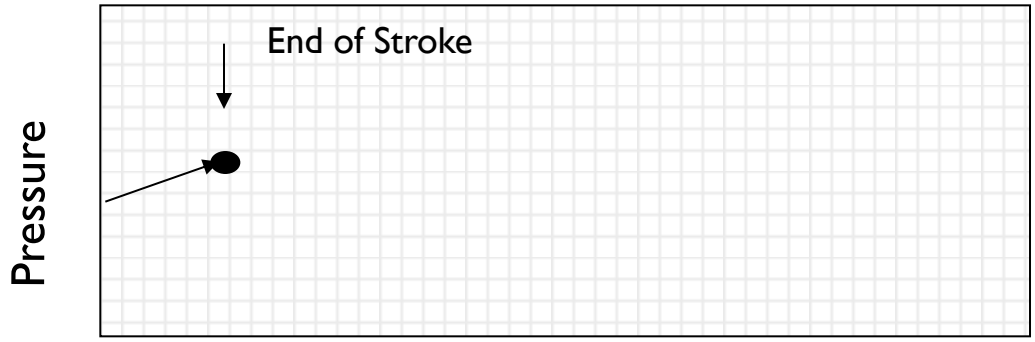
LMG GROUT INJECTION

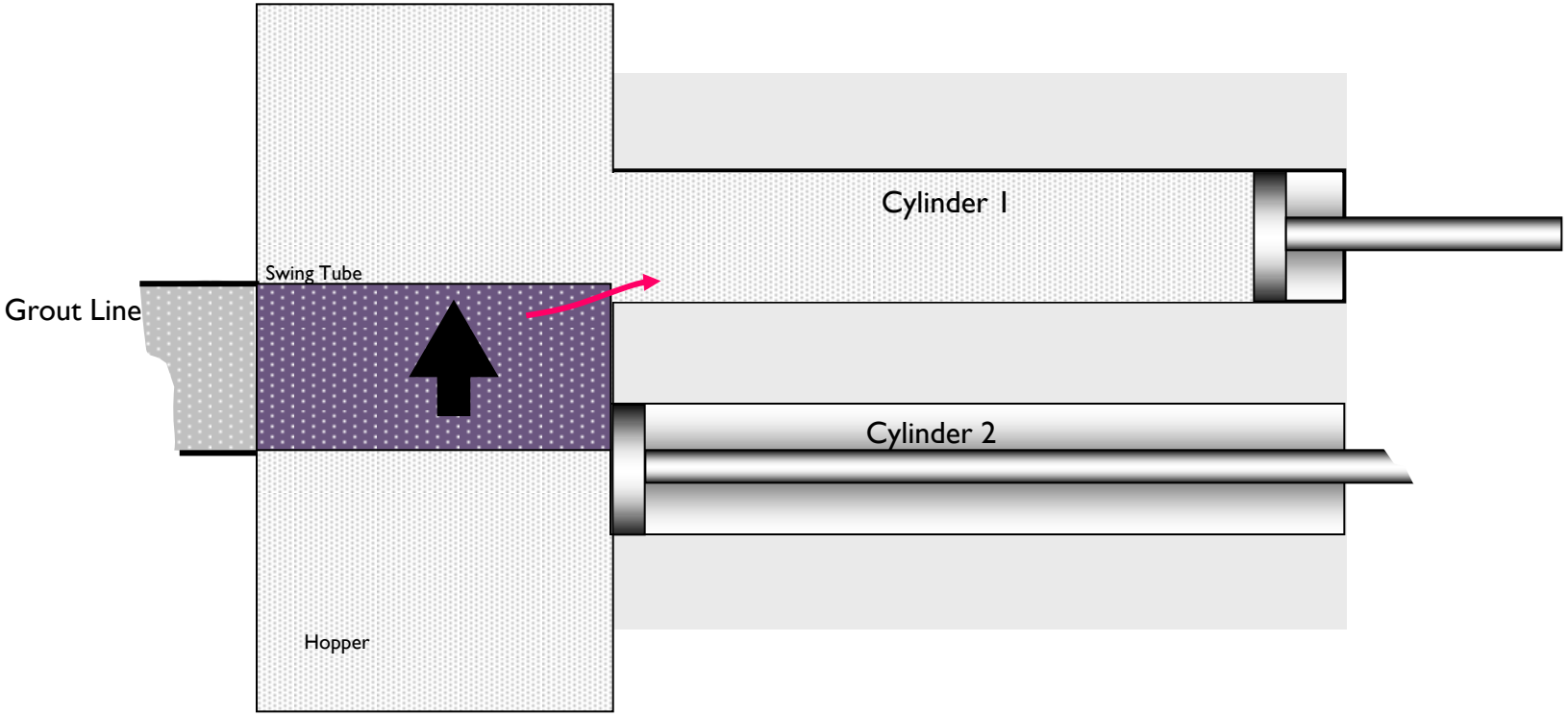
- Rate Dependent
  - Quality and control depend on the rate
  - Soil properties affect optimal rates
  - Typical compaction grouting at 1-2 cf/min (25-55 L/min)
  - Slower rates in sensitive areas
  - Faster rates may be acceptable for some filling and for sealing off high volume water flow
- There Are a Few Simple Controls
  - Rate
  - Mix
  - Location
  - Confinement

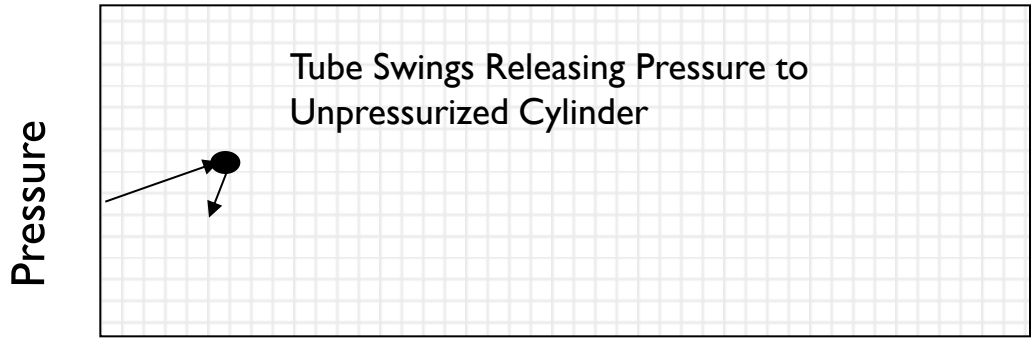

Cylinder 1
Swing Tube
Grout Line
Cylinder 2
Hopper

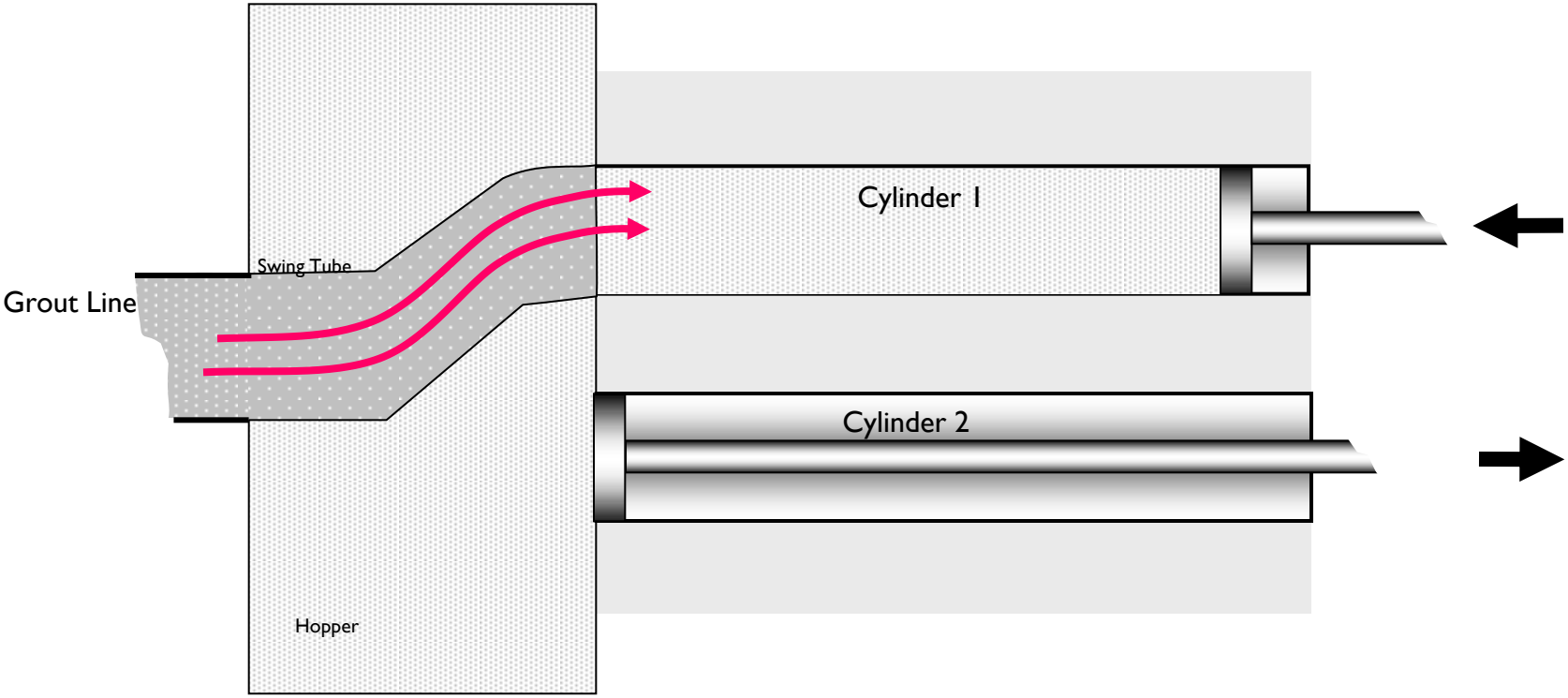

Pressure
Volume of Grout

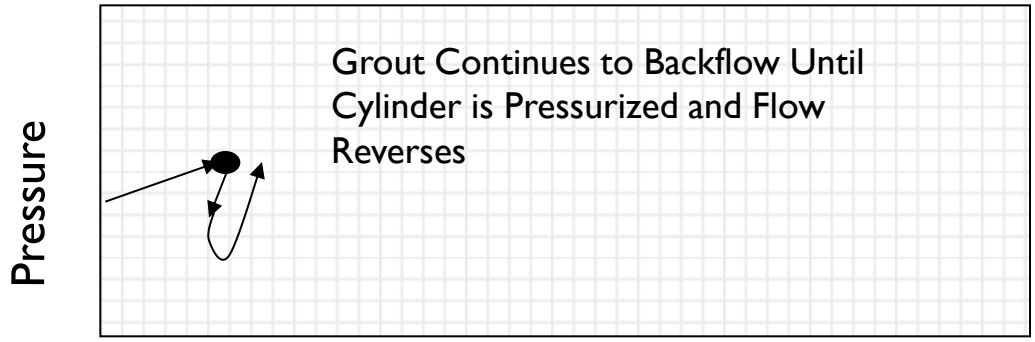

Cylinder 1
Swing Tube
Grout Line
Cylinder 2
Hopper

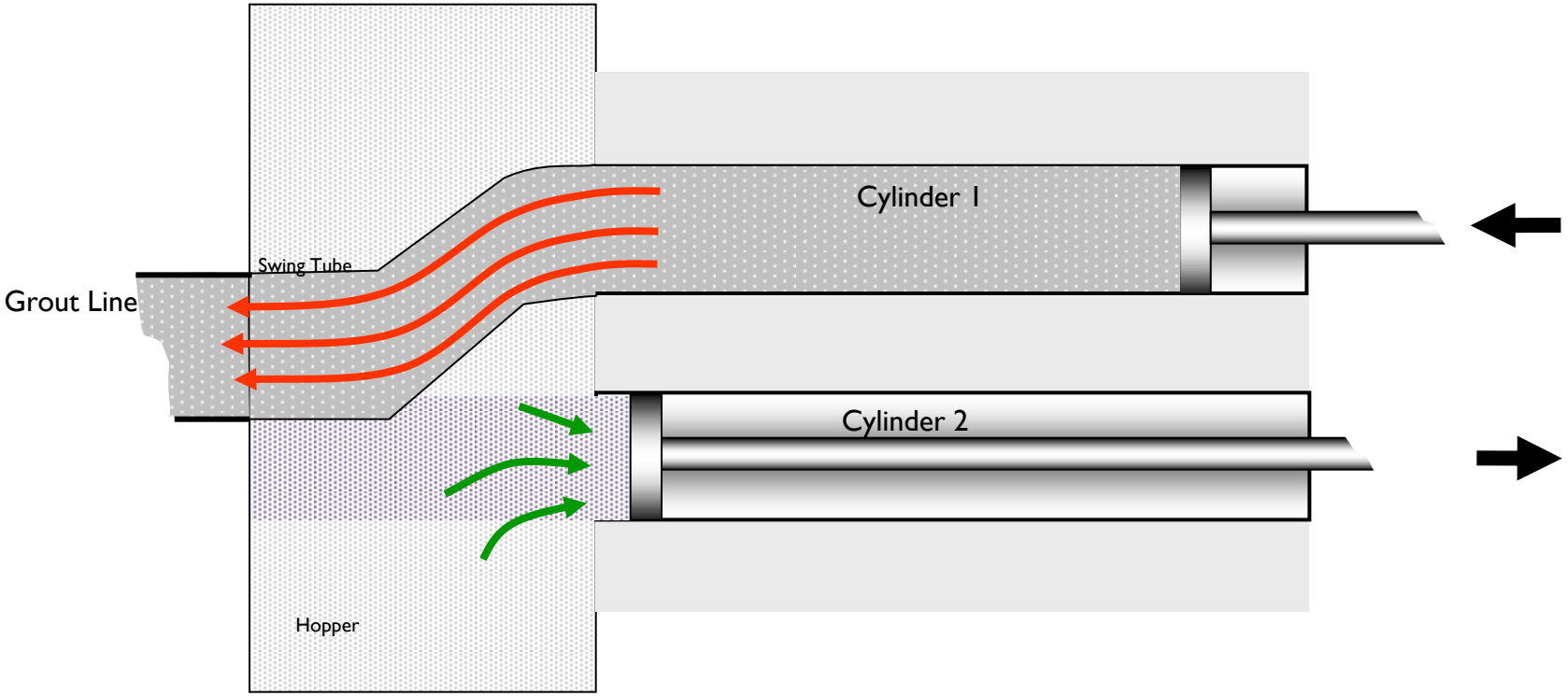

End of Stroke
Pressure
Volume of Grout

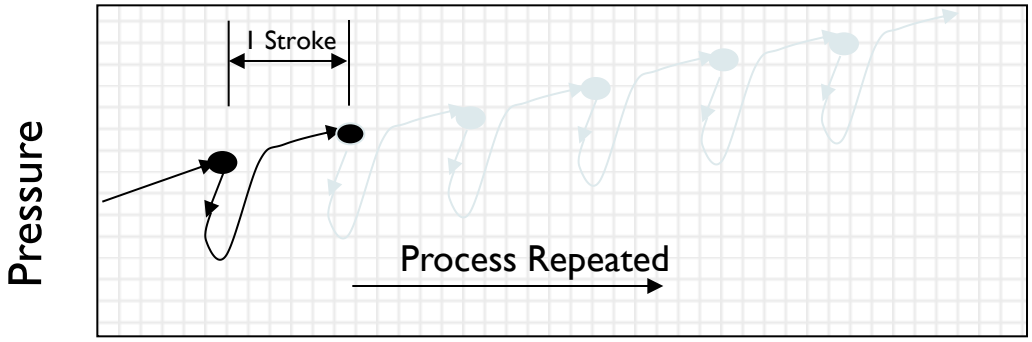

Cylinder 1
Swing Tube
Grout Line
Cylinder 2
Hopper

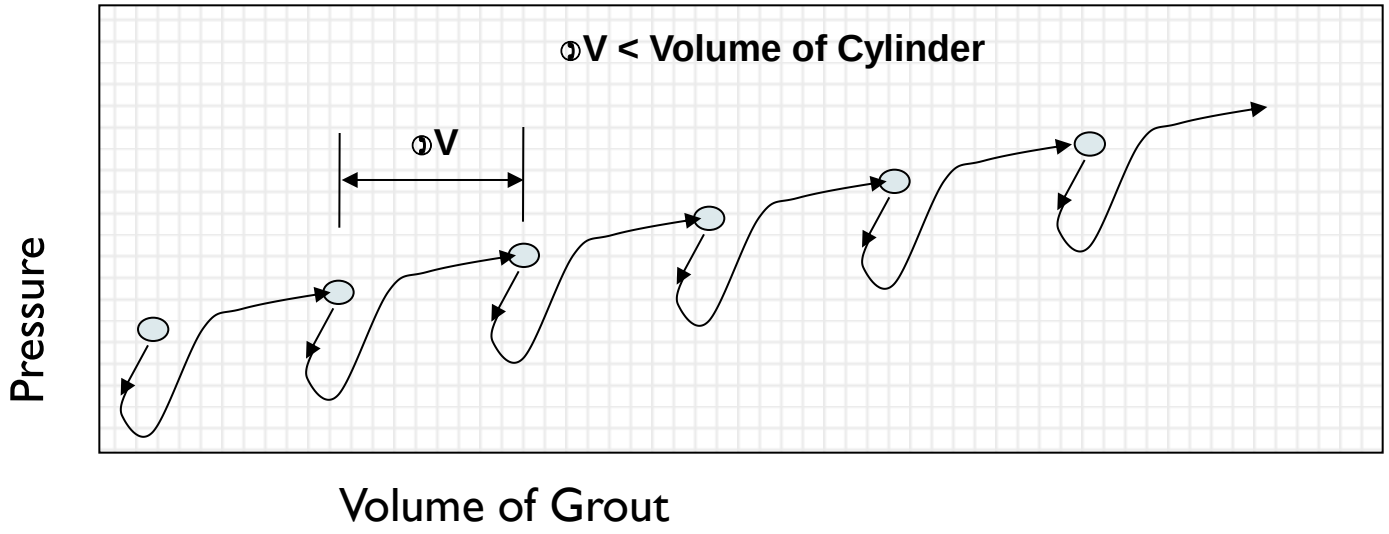

Tube Swings Releasing Pressure to
Unpressurized Cylinder
Pressure
Volume of Grout

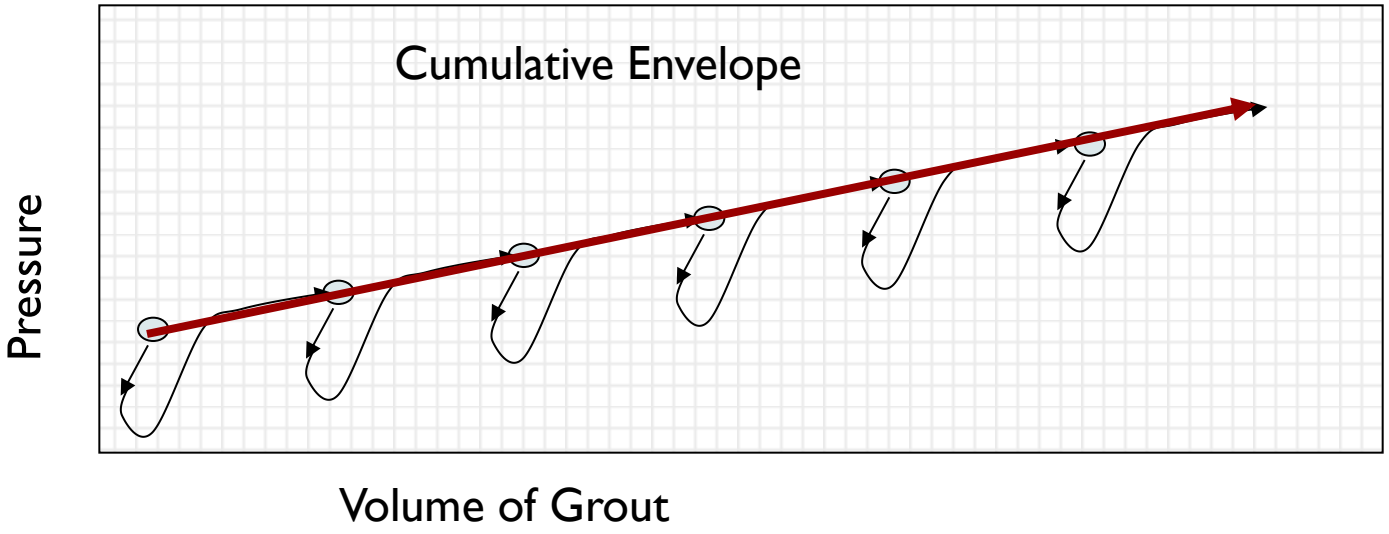

Cylinder 1
Swing Tube
Grout Line
Cylinder 2
Hopper

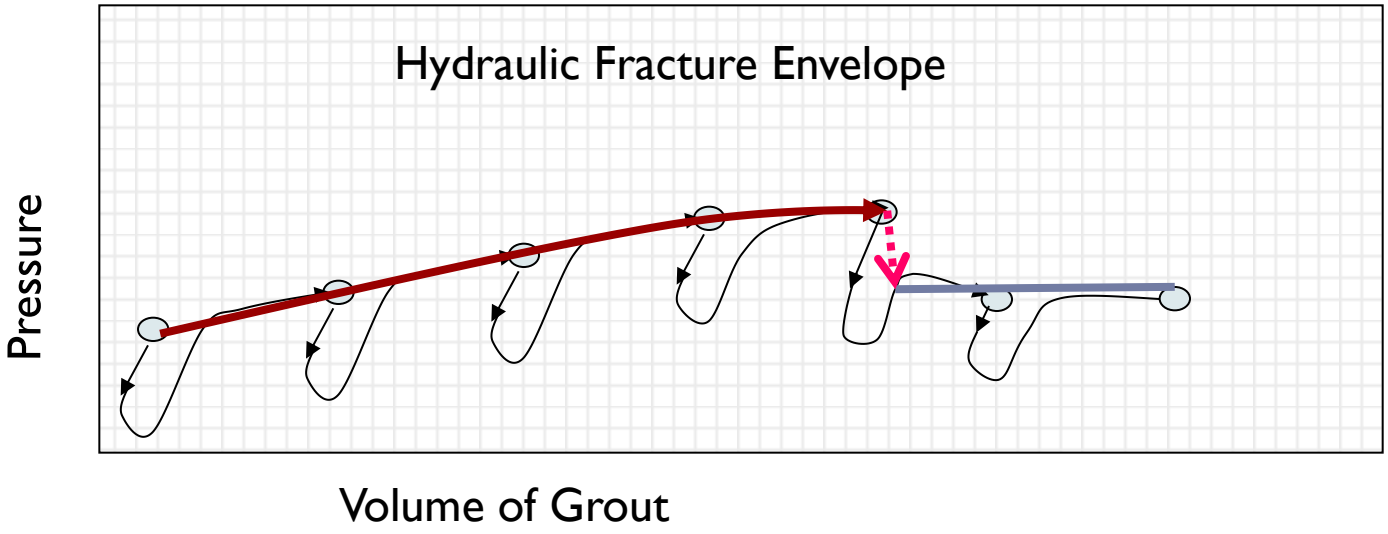

Grout Continues to Backflow Until Cylinder is Pressurized and Flow Reverses
Pressure
Volume of Grout


Cylinder 1
Swing Tube
Grout Line
Cylinder 2
Hopper


1 Stroke
Pressure
Process Repeated
Volume of Grout

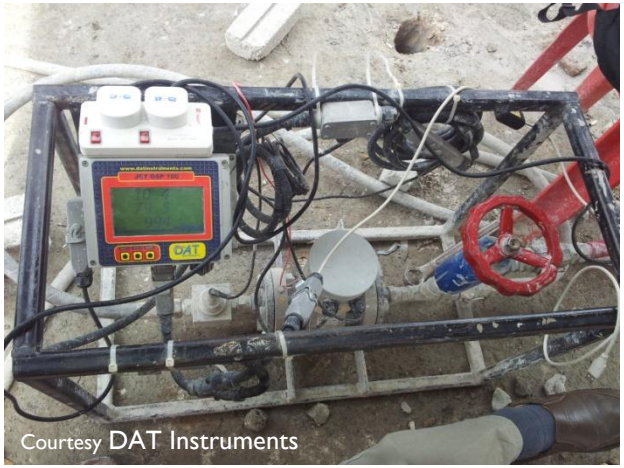

∂V < Volume of Cylinder
∂V
Pressure
Volume of Grout


Cumulative Envelope
Pressure
Volume of Grout

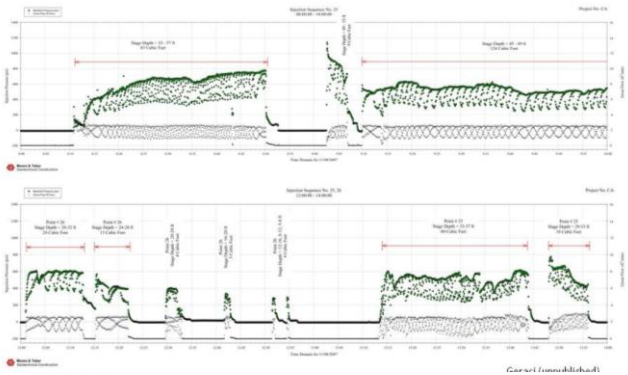

Hydraulic Fracture Envelope
Pressure
Volume of Grout

LMG QUALITY CONTROL

- Monitoring
  - Grout consistency, grainy surface at breaks
  - Flow rate
  - Pressure
  - Location
- Real-time Pressure and Flow Measurement – computer aided



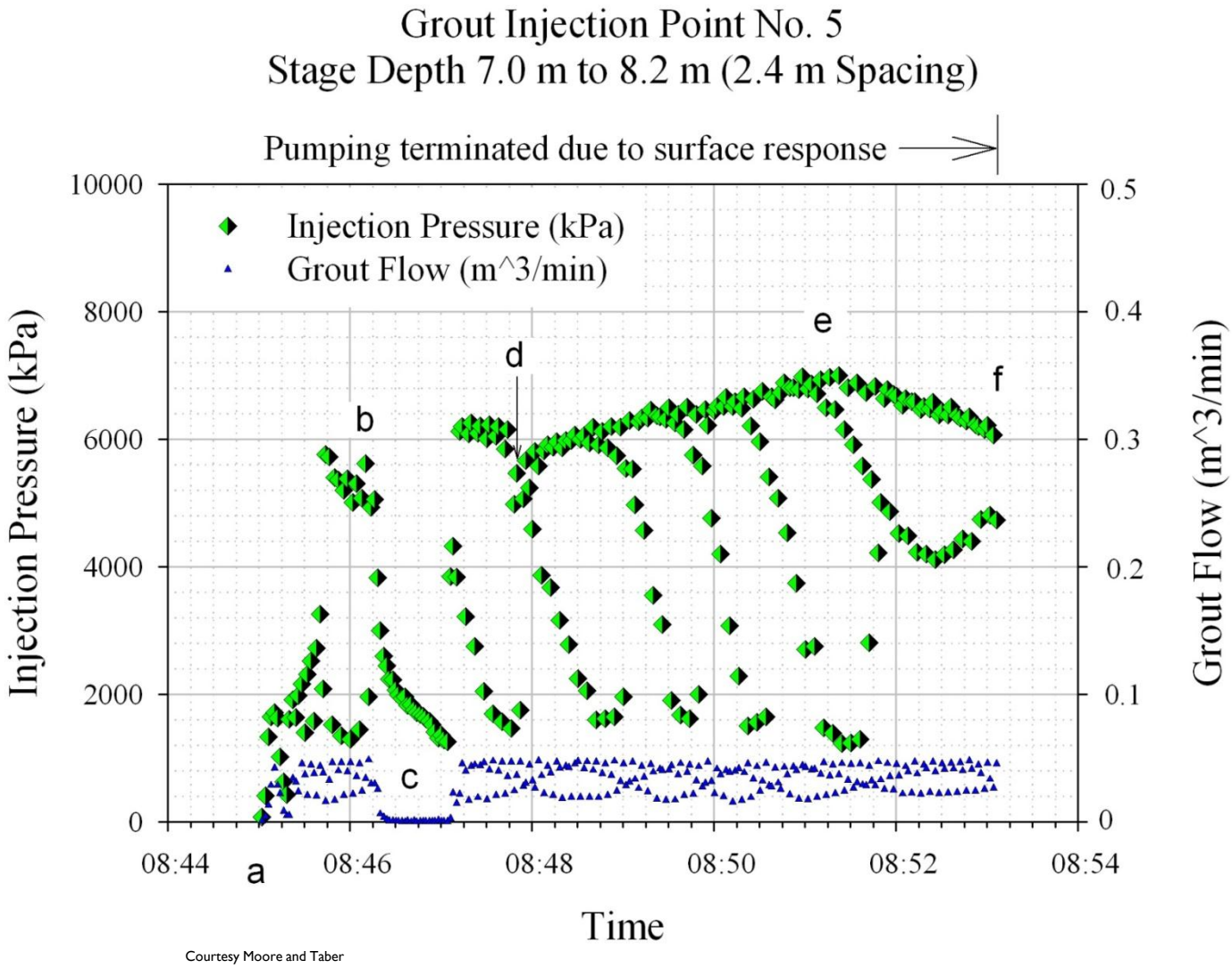
Courtesy DAT Instruments


Courtesy Moore and Taber

Quality Control for LMG

- Advances in equipment technology will improve the ability to inject very stiff grouts at controlled rates

Real-Time Compaction Grouting Data

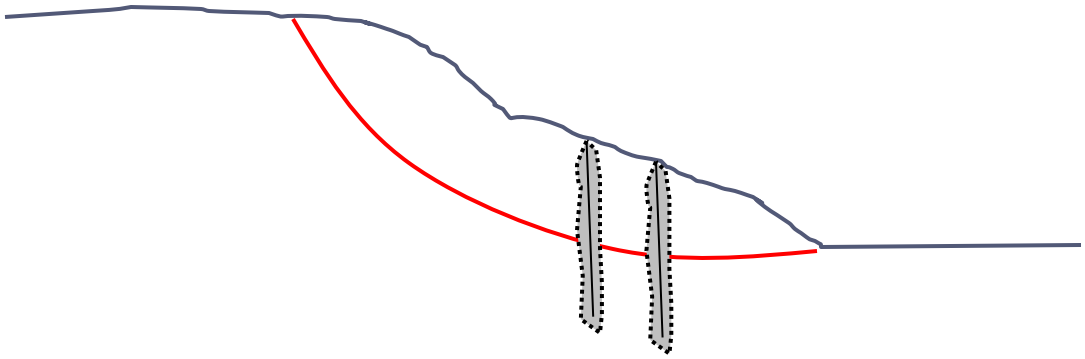


Courtesy Moore and Taber

- Jeff Geraci (2007)

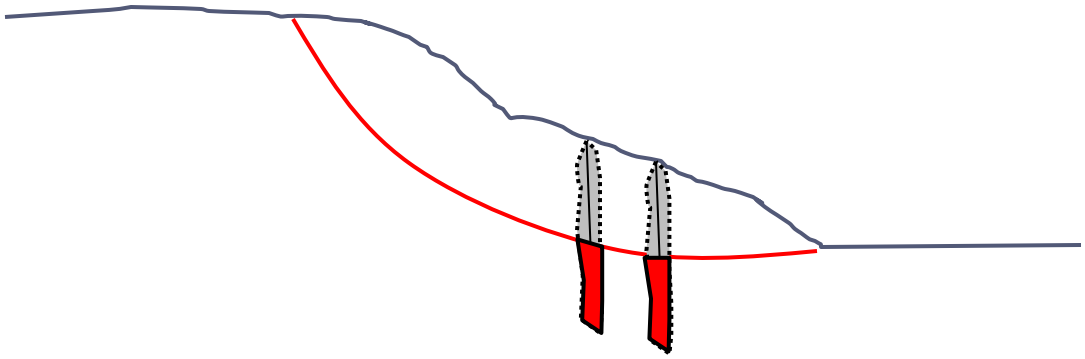
Shear Reinforcement

- Shear strength of grouted pile may be used to resist unbalanced earth pressures to the extent that it can be mobilized and transmitted into the unstable mass
- Steel reinforcement generally appropriate for shear loadings to ensure continuity of stress transfer within the grout pile



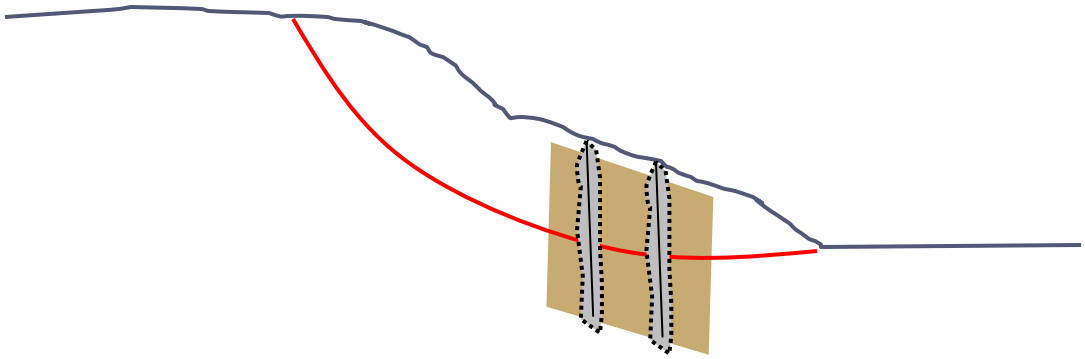
Shear Reinforcement

- Embedment and anchorage of the base of the grout pile must be sufficient to mobilize the required shear capacity at potential shear planes.
- Verification testing and construction controls are required to assure required reinforcement is attained



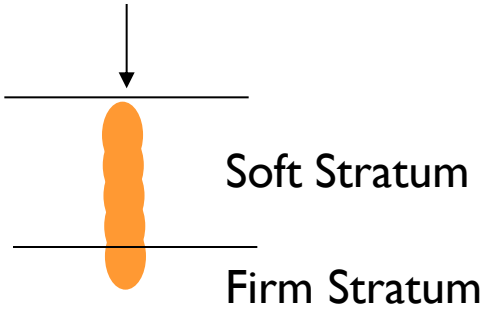
Shear Reinforcement

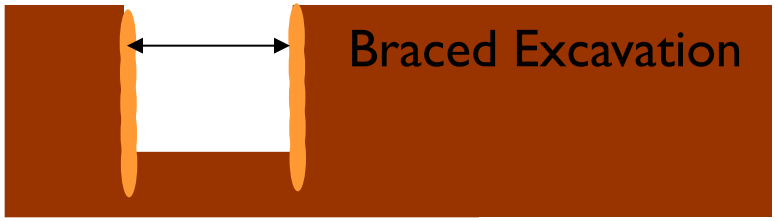
- Even where the intent is shear reinforcement, the displacement during injection will produce compaction that may be considered in the design.

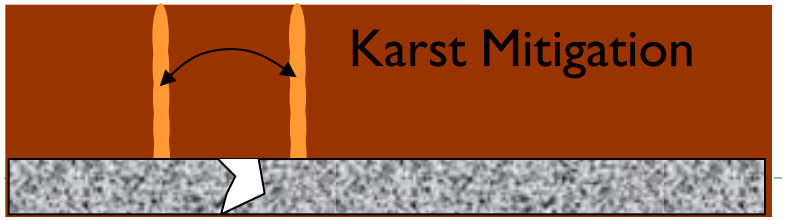


Grout Piles

- Function
  - Load carrying member
  - Lateral confinement
  - Shear transfer







LMG Grout Columns for Underpinning and Excavation Support

Enhanced Soil Arching eliminates need for lagging for short term protected excavations

Here vertical grout piles are anchored by slab and act primarily in shear and bending

Photo Courtesy of Rembco Geotechnical Constructors

Grout Pile Capacity

- Is a function of Grout Strength
- Requires grout continuity
- Column Dimensions
- Reinforcement (insert bar)
- Skin Friction
- End Bearing (not typical)
- Rock Penetration (not typical)

Grout Pile Design

- Structural Design as for normal plain concrete
- Skin friction equal to soil friction for granular soils
  - Allowance may be made for densification
  - Be cautious about use of residual stress
- End bearing can be enhanced by enlarging base
- Verify sound rock below base

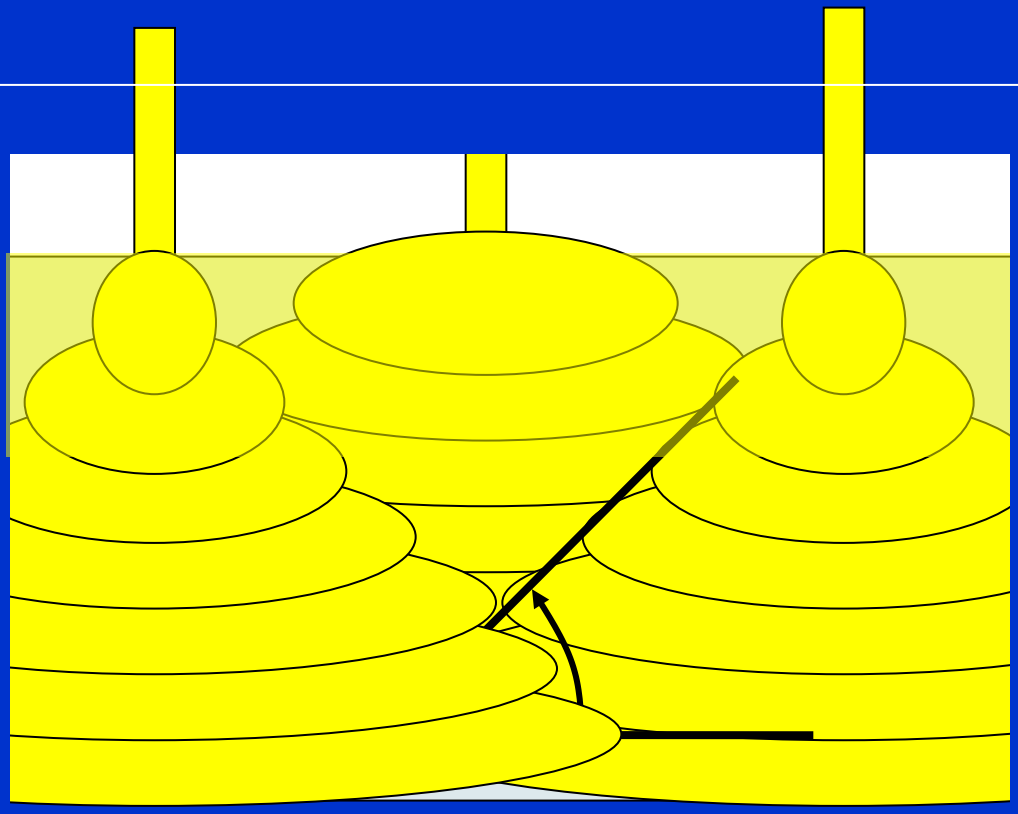
Construction of Grout Piles

1) Drill in riser casing
2) Insert Reinforcing bar into riser (if required)
3) Pump Grout through riser
4) Withdraw riser in small controlled increments with continuous injection to construct column

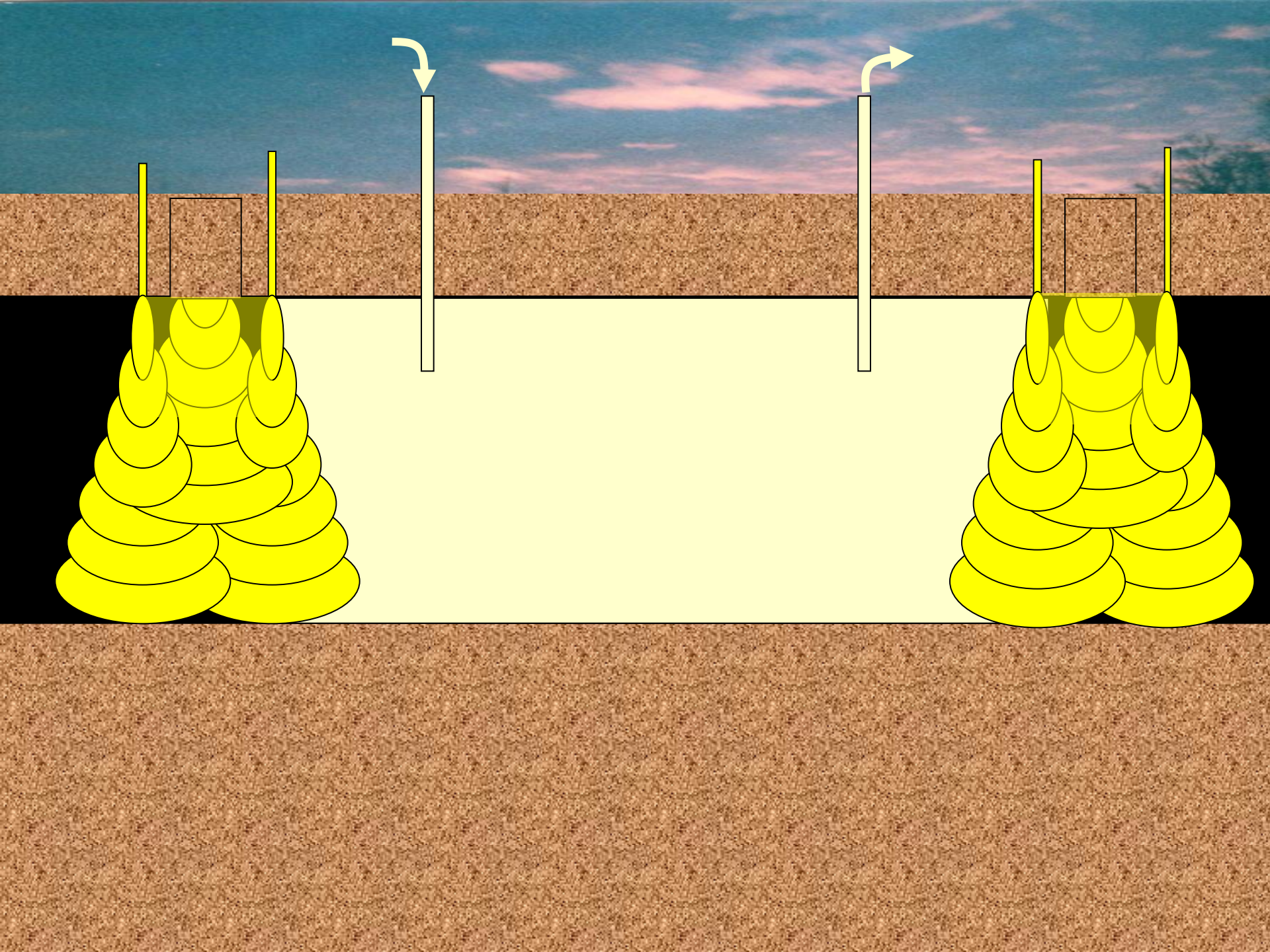
Grout Fill Applications

- Filling Mine Voids
- Filling Karst Openings
- Where volume of fill required is less than the limits of the interconnected openings
- May add setting agent

Grout Fill



Opening



Grout Fill

- Angle of Repose
- Grout Strength
- Placement Rate
- Stage size
- Supplemental Injections

LMG VERIFICATION

- Monitoring, recording and continual evaluation of injection parameters (at a minimum: flow rate and pressure for each injection).
- Real time digital monitoring strongly recommended
- Test Grouting
- Post Grouting Excavation
- Measurement of in situ Soil Properties
- Performance criteria

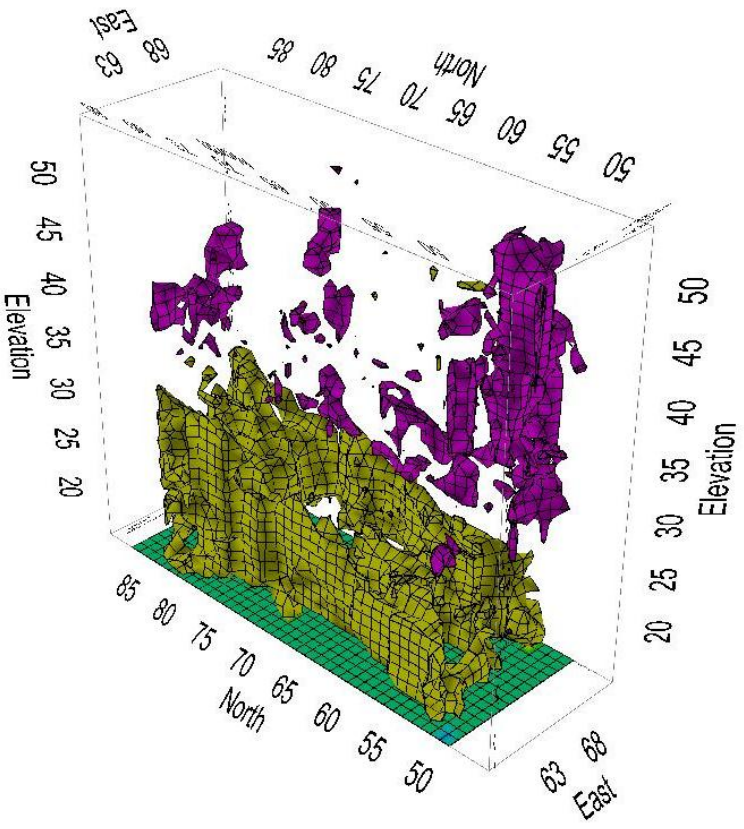
FUTURE DIRECTIONS FOR LMG

- Advances in material science will enable greater control and improved performance of limited mobility grouts, and reduce difficulty in finding appropriate aggregates

- Research together with digital data acquisition will lead to improved understanding of mechanisms and better quality

FUTURE DIRECTIONS FOR LMG

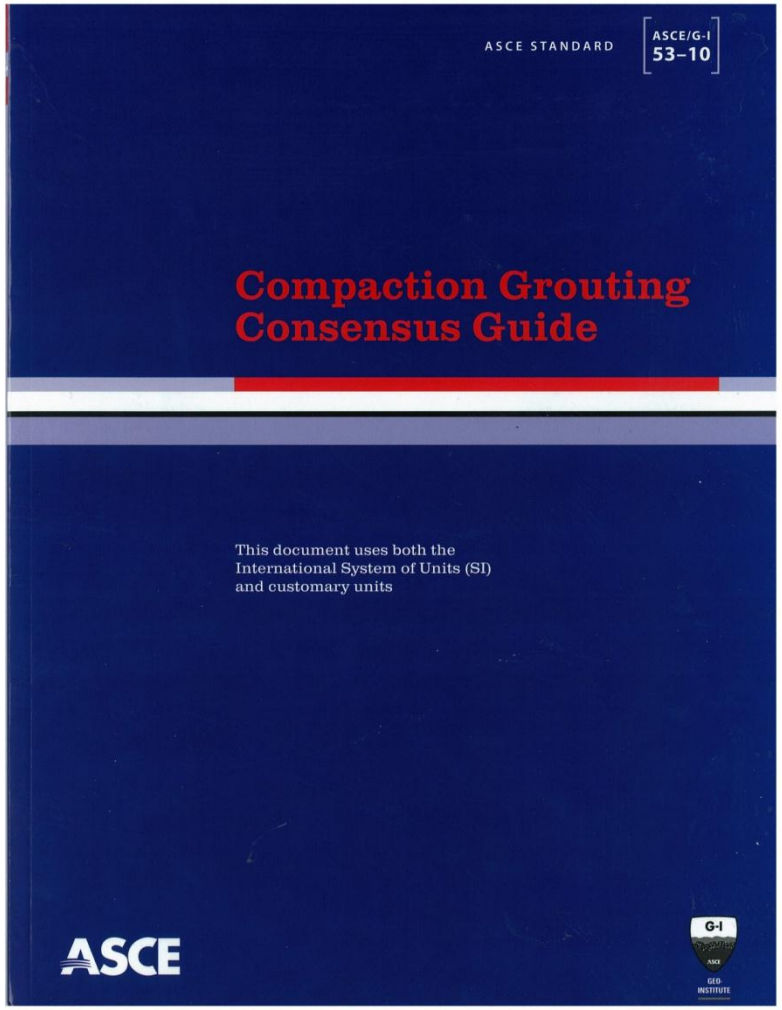
- Advances in geophysical methods and imaging technology will enable better understanding and verification of grouting performance

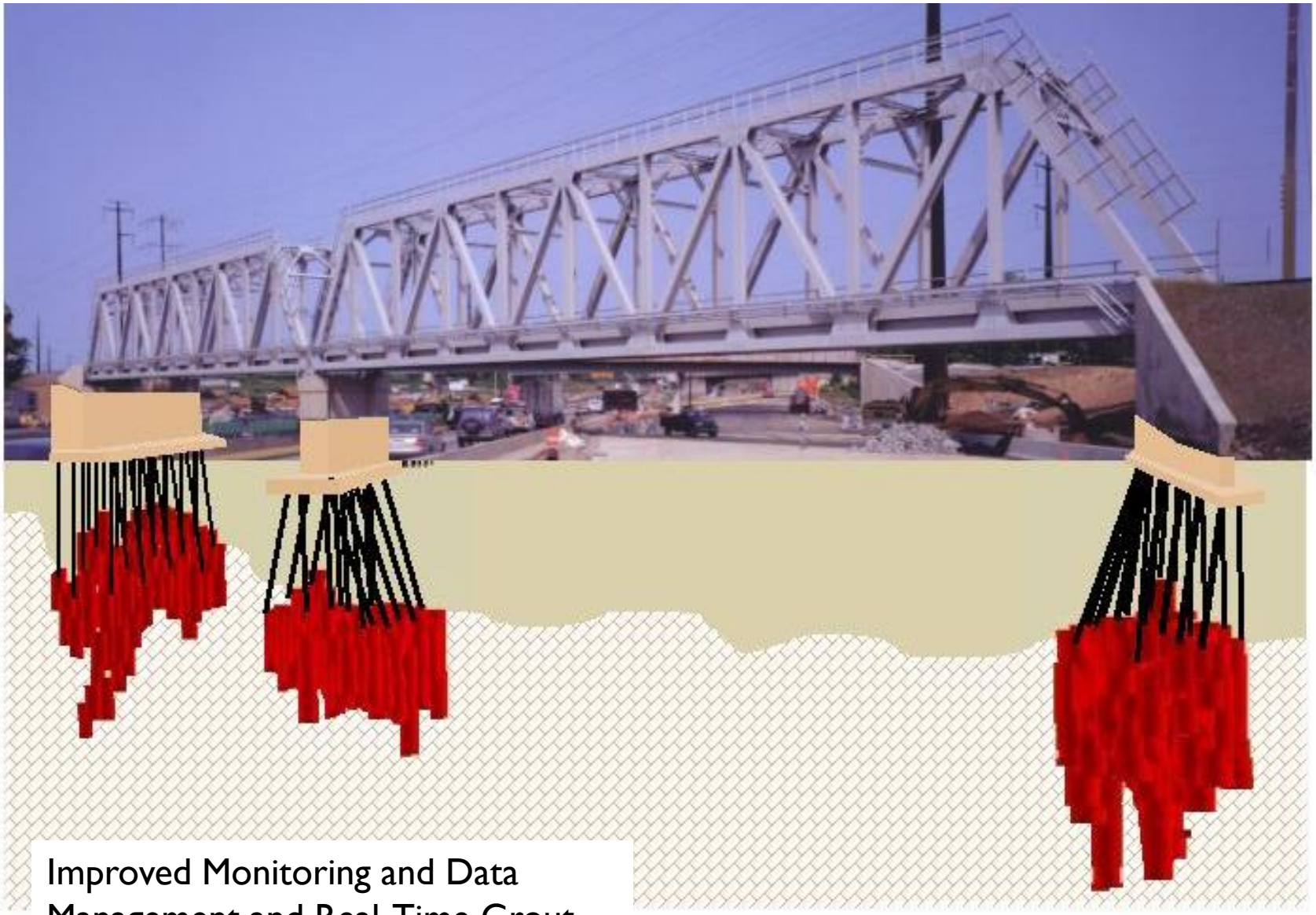


FUTURE DIRECTIONS FOR LMG

Development of Standards such as the Compaction Grouting Consensus Guide will help gain broader acceptance of the method

Appropriate standards that do not limit innovation





Improved Monitoring and Data Management and Real-Time Grout Control


Research on soil Grout Interaction
Improved models of Behavior for Better Design

LIMITED MOBILITY GROUTING -- PAST, PRESENT, AND FUTURE

James Warner, P.E., F.ASCE and Michael Boyle, P.E., D.GE, F.ASCE

Thank you!