Developments in Rock Drilling and Grouting Practices in North America

Dr. Donald A. Bruce

GEOSYSTEMS, L.P.
724-942-0570
A Member of:
Geo-Trust

Contents of Presentation

1. Introduction
2. Historical Concepts ("The Old")
3. Current Principles ("The New")
4. Final Thought

1. Introduction

- U.S. rock grouting practice dates from at least 1893 and made “a good start” (Verfel, 1989)
- Thereafter until mid-1990’s:
  - “objectives not fully achieved”
  - “innovative procedures and insightful ideas inconsistently implemented”
  - in general, practices can be kindly described as “traditional” especially with respect to European engineering
- From 1990’s onwards, rolling revolution fed by project-specific demands (especially on USACE and TVA structures) and input of European and Canadian specialists.
- Last few years: tendency in some quarters to return to “traditional” ways and/or recycled 1980’s concepts.

2. Historical Concepts (“The Old”)

- Low bid contracting, highly prescriptive and unchanged specifications:
  - “By the way of illustration, in 1974, Polatty was invited to give an overview of U.S. Dam Grouting Practices: ‘In preparing this paper, I requested copies of current specifications for foundation grouting from several Corps of Engineers districts, the TVA and the Bureau of Reclamation. In comparing these current specifications with copies of specifications that I had in my file that are 30 years old, plus my observations and experience, I concluded that we in the United States have not, in general, changed any of our approaches on grouting. AND THIS IS GOOD’ (emphasis added). Interestingly, he then went on to list ‘difficulty in having sufficient flexibility in the field to make necessary changes to ensure a good grouting job’ as a problem. What a surprise!”

- Poor technically and unresponsive concepts and practices, such as:
  - Vertical holes regardless of rock mass structure, to constant depth and not impermeable toe.
  - Only rotary drilling permitted (air flush synonymous with percussion).
  - "One-row curtain" paradigm.
  - Low grout pressures (equipment limited).
  - Use of "thin" grouts, i.e., of excessive WCR.
  - Termination of work often based on grout takes (not residual permeability) but usually based on budget. (Particularly so in karstic limestone foundations.)

3. Current Principles ("The New")

1. Use of grout caps.
2. Multirow inclined curtains standard.
3. **Broad spectrum of drilling methods, exclusively water flushed for rock grouting.**
4. **Sophisticated grout mix designs and especially the vital importance of Pressure Filtration Coefficient.**
5. High performance grouts and new equipment permit higher pressures to be used where safe.
6. **Injections governed by computer monitoring, control and analysis, use of Optical Televiewer.**
7. Grouting continued until a target residual Lugeon value is reached.
8. Performance specifications and "Best Value" procurement.

3.3 Drilling Technology

- Focus on protecting the embankment (USACE, 1997), e.g., use of sonic, dry duplex.
- Use of water flush in rock (rotary and down-the-hole).
- Use of MWD instrumentation.
- Use of borehole imaging.

Evolution of Rock Drilling Methods

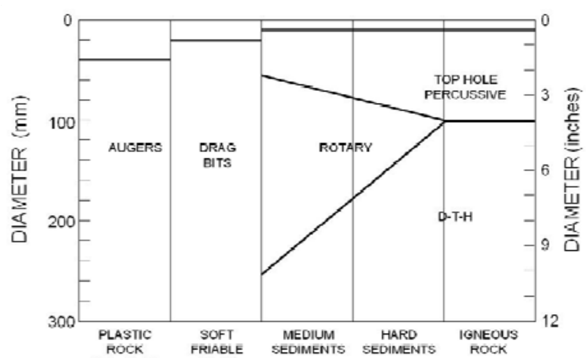


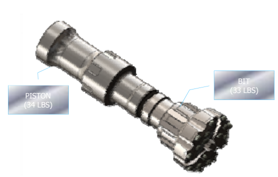
Figure 1. Basic drilling method selection guide for rock using noncoring methods, Littlejohn and Bruce, 1977 (adapted from McGregor 1967).

Rock Drilling Methods (Disco Era)

- Rotary
  - High rpm, low torque, low thrust (blind or core)
  - Low rpm, high torque, high thrust
- Rotary Percussive
  - Top Hammer
  - Down-the-Hole Hammer
    - Direct circulation
    - Reverse circulation
    - Dual fluid drilling
    - Water hammers
- Rotary Vibratory (Sonic)

Some Evolutionary Notes

- DTH usually superior to Top Drive or Rotary
  - penetration rates
  - per foot costs
  - deviation control
  - large diameter (< 40 inches) to greater depths (> 300 feet)
- Very sophisticated computer programs/simulations optimize design for speed, durability, reliability and for special applications (e.g. “short” hammers and high frequency hammers).



New Piston-Bit Combination (Equal Mass)


New Simple, High Frequency RX Hammer

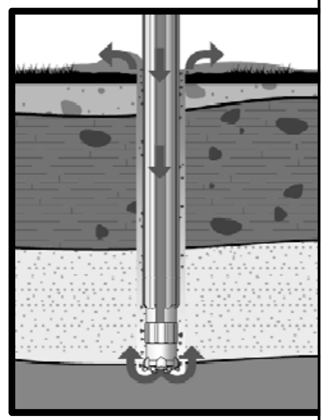
- Air pressures have increased from 1-2 MPa in 1970's, to up to 3.5 MPa today.
- Better understanding of metallurgy of components and bits.
- More widespread use of reverse circulation.
- More widespread use of water powered DTH's — efficiency, lower flushing velocities, straighter holes.
- Use of rotary vibratory methods (Sonic) but mainly for overburden, "the only true innovation to come to the drilling industry since the Chinese invented cable tool drilling some 3,000 years ago" (Roussy, 2002).

Historical Perspective on Percussion Drilling Methods

- Air flush top hammers: Sweden 1873
- Air-powered DTH hammers: 1950
- Water–flushed top hammers: 1973
- Water-Powered DTH: 1988 original patent transfer.
  : 1995 LKAB conduct first full-scale WDTH drilling
  : 25 million linear meters of drilling since (surface and underground)
  : Many applications 2002 to present on U.S. Dams (including Wolf Creek, Clearwater, Center Hill, McCook, Thornton, Logan Martin)

General Background to Water-Powered, Down-the-Hole Hammer Drilling (WDTH)

- Powered by high pressure water (180 bar).
- Generates high frequency and high impact energy.
- Exiting water transports cuttings with sufficient velocity to hole opening.
- Minimum influence on the formation.
- Water column enables hole stability.
- Low up-hole velocity of the water minimises erosion of boreholes (100-500 ft/min).
- Stabilized hammer system results in accurate and straight boreholes
- Less wear on the hammer system

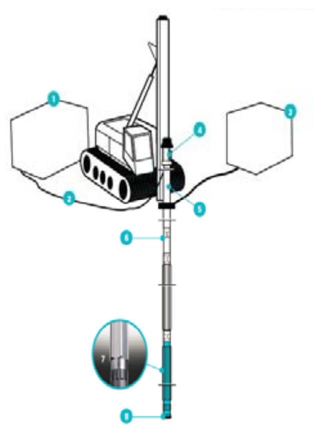


Note: The WDTH has only 2 moving parts.

WDTH Equipment Details

Product Overview

1. High-pressure pump
2. High-pressure hose
3. Water Handling unit
4. Swivel
5. Drill tubes
6. Check valve
7. WDTH hammer
8. Drill bit



Hammer	Ø Drill bit	Water consumption	Max op. pressure
W50 (2")	60mm, 64mm (2 ⅜", 2 ½")	80-130 l/min (20-35 USgpm)	170 bar (2500 psi)
W70 (3")	82mm, 89mm (3 ¼", 3 ½")	130-260 l/min (35-70 USgpm)	180 bar (2600 psi)
W80 (3.5")	95mm , 102mm (3 ¾", 4")	130-260 l/min (35-70 USgpm)	180 bar (2600 psi)
W100 (4")	115mm, 120mm , 127mm (4 ½", 4 ¾", 5")	225-350 l/min (60-95 USgpm)	180 bar (2600 psi)
W120 (5")	130mm, 140mm, 152mm (5 ⅛", 5 ½", 6")	300-450 l/min (80-120 USgpm)	180 bar (2600 psi)
W150 (6")	165mm , 178mm, 190mm, 203mm (6 ½", 7", 7 ½", 8")	350-500 l/min (95-130 USgpm)	150 bar (2200 psi)
W200 (8")	216mm, 254mm (8 ½", 10")	470-670 l/min (125-180 USgpm)	150 bar (2200 psi)

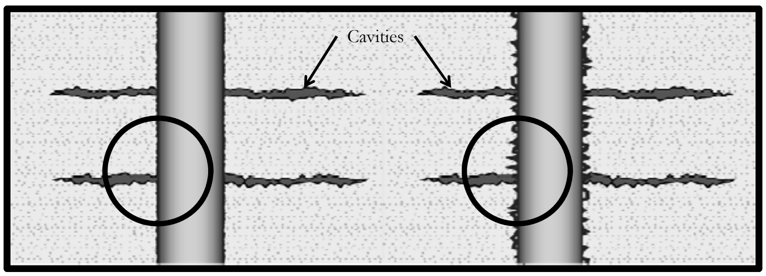
Borehole Quality

Water-powered drilling gives:

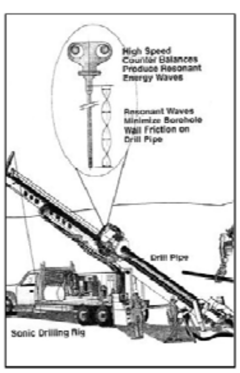
- Cleaner boreholes
  - Allow the cement grout to reach longer into the cavities without dust or oil traces
- Better borehole surface
  - Optimal for use of packers

Air-powered drilling gives:

- Injection of dust and oil in the borehole
  - May cover surface and hinder grout to efficiently connect to the bore hole wall and out to cavities
- Rough surface
  - May be too coarse for packers



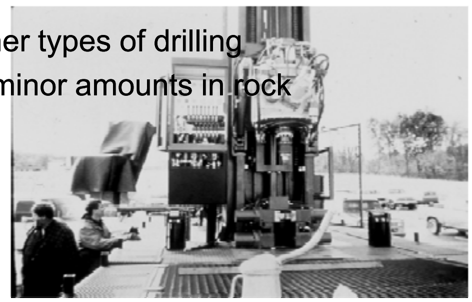
Basic Principles of Sonic Drilling



- Sonic uses high frequency (50-150 Hertz) mechanical vibration combined with rotation and down-pressure.
- Vibrations generated by eccentric counter-rotating rollers in drill head.
- Vibrations coincide with the natural resonate frequency of drill pipe.
- Drill string produces spring-action and delivers energy to bit face.
- Sonic advancement occurs by shearing and minor displacement.

Advantages of Sonic Drilling

- Can provide continuous, relatively undisturbed cores in soil (3 to 10-foot diameter) and rock
- Very high penetration rates
- Readily penetrates obstructions
- Depths to 500 feet
- Can easily convert to other types of drilling
- No flush in overburden, minor amounts in rock



Classification of Overburden Drilling Methods as at 2003 (Bruce, 2003)

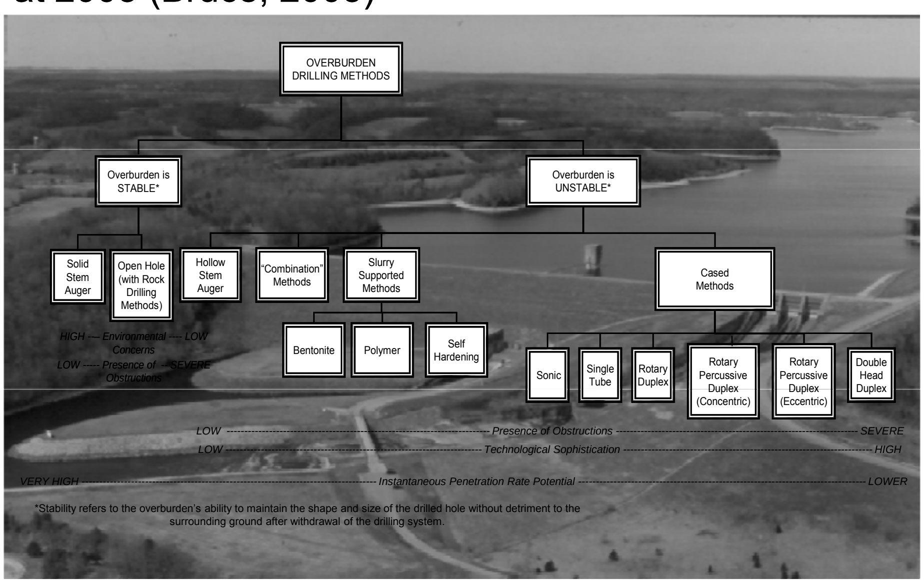


Figure 2. Basic drill method selection guide for overburden (Bruce, 2003).

More Recent Developments

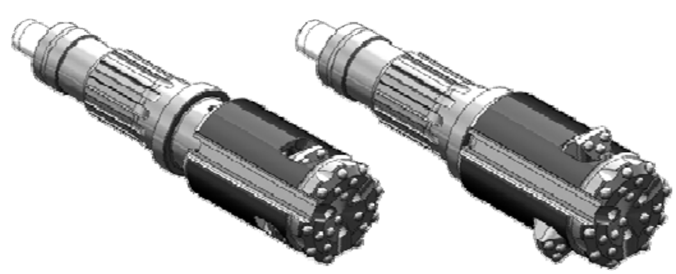
These include:

- Numa “Superjaws” – featuring 2-4 “wings” which open by pressure on the face of the hole. Direct descendent of old Acker Casing Underreamer System.
- Atlas Copco “Elemex” system – a ring on the casing redirects the air flush away from the DTH bit face and so makes it easier to control.
- Center Rock “Rotoloc” system – features a patented method of extending, locking and retracting cutting wings on the central pilot bit, in a very simple and reliable fashion. Does not rely on downwards pressure on the face and leaves nothing behind in the ground.

Roto Loc Description (Center Rock Inc.)

Benefits

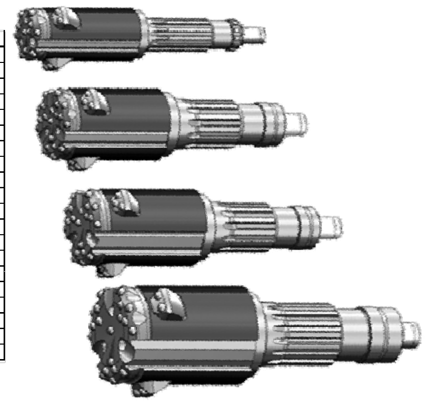
- Faster penetration through difficult overburden,
- Locking wings maintains hole size to clear casing,
- Low casing friction,
- Eliminates need for costly teeth on starter casing,
- Easy to service and maintain,
- Wings can be used to pull casing back,



Roto Loc Systems

System	Shank	Diameter		Applicable Casing		
		Expanded	Retracted	Outside Dia	Inside Dia	Wall
RL-0513-B34	340	5.54	4.07	5.125	4.250	0.438
RL-0513-C40	CR40	5.54	4.07	5.125	4.250	0.438
RL-0550-B34	340	5.87	4.40	5.500	4.670	0.415
RL-0550-C40	CR40	5.87	4.40	5.500	4.670	0.415
RL-0600-C40	CR40	6.40	4.98	6.000	5.118	0.441
RL-0600-Q5	QL50	6.40	4.98	6.000	5.118	0.441
RL-0663-Q5	QL50	7.28	5.58	6.625	5.625	0.500
RL-0663S-B35W	350W	7.28	5.58	6.625	5.625	0.500
RL-0700-Q6	QL60	7.75	5.90	7.000	6.000	0.500
RL-0700-B35W	350W	7.75	5.90	7.000	6.000	0.500
RL-0763-Q6	QL60	8.35	6.50	7.625	6.625	0.500
RL-0763-B35W	350W	8.35	6.50	7.625	6.625	0.500
RL-0863-Q6	QL60	9.33	7.54	8.625	7.625	0.500
RL-0963-Q8	QL80	10.38	8.39	9.625	8.565	0.530
RL-1075-Q8	QL80	11.42	9.45	10.750	9.560	0.595
RL-1188-N10	N10	12.40	10.43	11.875	10.715	0.580
RL-1600S-Q12	Q12	16.93	14.37	16.000	15.250	0.375
RL-2000S-Q12	Q12	20.87	17.93	20.000	19.000	0.500
RL-2400S-Q20	Q20	24.882	21.89	24.000	23.000	0.500

Center Rock Inc.



Recording of Drilling Progress and Parameters (MWD)

- Fundamental Concept
- Manual Monitoring
- Automated Monitoring
- Benefits to Owner and Contractor

Basic Principles of Monitoring While Drilling (MWD)

1. Fundamental Concept

Every hole that is drilled in the ground is a potential source of information on the properties and response of the ground. This obviously applies to designated site investigation holes, but is equally true of every production hole, such as drilled for anchors, micropiles, nails or grout holes. Such information can be collected by two basic methods: manual and automatic. The data must be studied in real time to be useful.

Examples:

1. Helps determine or verify appropriate bond zone horizons for anchors and micropiles.
2. Secondary and higher order holes will demonstrate progressive densification of ground in compaction grouting projects.
3. Helps select appropriate jet grouting parameters.
4. Will provide a mechanical and hydraulic “picture” of the rock mass at each phase of a grout curtain project.

Basic Principles of Monitoring While Drilling (MWD)

Manual Monitoring

- The value of routine drillers' logs can be greatly enhanced by periodic recording of:
  - penetration rate
  - thrust
  - torque
  - flush return characteristics (cuttings, volume)
  - drill "action"
  - interconnections between holes
  - hole stability
  - groundwater observations
- These data can easily be recorded by a good driller who has been briefed about the overall purpose of the project and so understands what to look for.
- These data should be recorded at 5 ft maximum intervals.

Automated Recording of Drilling Progress and Parameters

- Value of real time continuous monitoring for design purposes (manual vs. automatic)
- Look for "exceptions and unexpecteds" [Weaver, 1991]
- Indication of progressive improvement (e.g., denser, less permeable conditions)
- Concept of specific energy
- Several generations/evolutions as software and hardware evolve

Automated Monitoring

Calculation of Specific Energy

$$e = \frac{F}{A} + \frac{2 \pi N T}{AR}$$

where

- e = specific energy (kJ/m3)
- F = thrust (kN)
- A = cross sectional area of hole (m2)
- N = rotational speed (revolutions/second)
- T = torque (kN-m)
- R = penetration rate (m/sec)

"Profile of a Driller"

"Drillers are as diverse a group of people as the industry in which they work. Every drilling operation is different and requires a highly skilled person to ensure that the drilling process is successful."

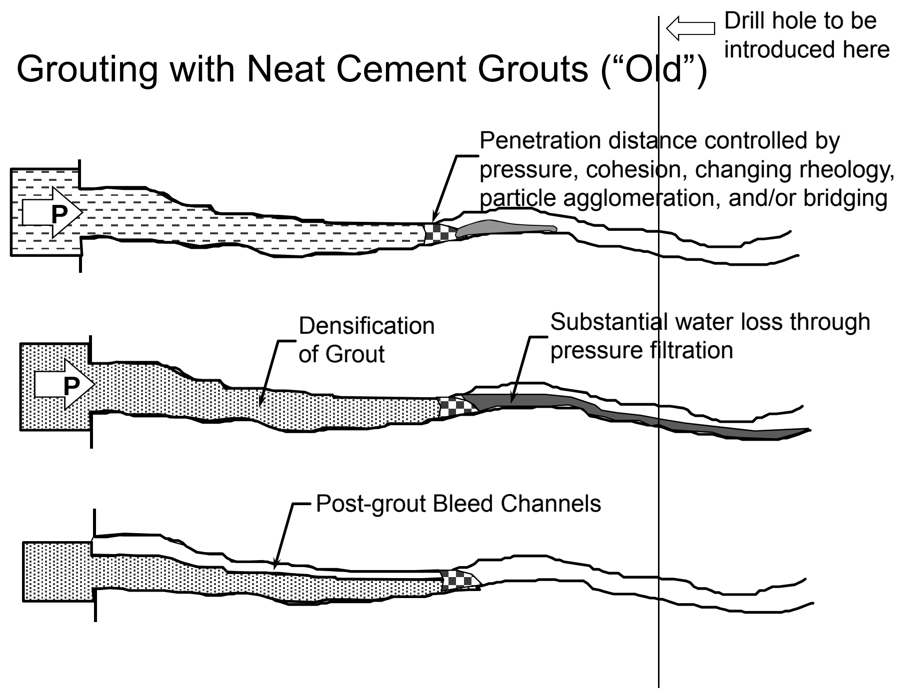
Australian Drilling Industry
Technical Training Committee Ltd. (1997)

3.4 Developments in Cement-Based Grouts

Characteristics of Unstable Water Cement Grouts (“Old”)

- Cement + Water
- Considerable Bleed Potential
- Low Resistance to Pressure Filtration
- Unorganized Particles
- Unpredictable Behavior due to Changing Rheology During Injection
- Marginal Durability

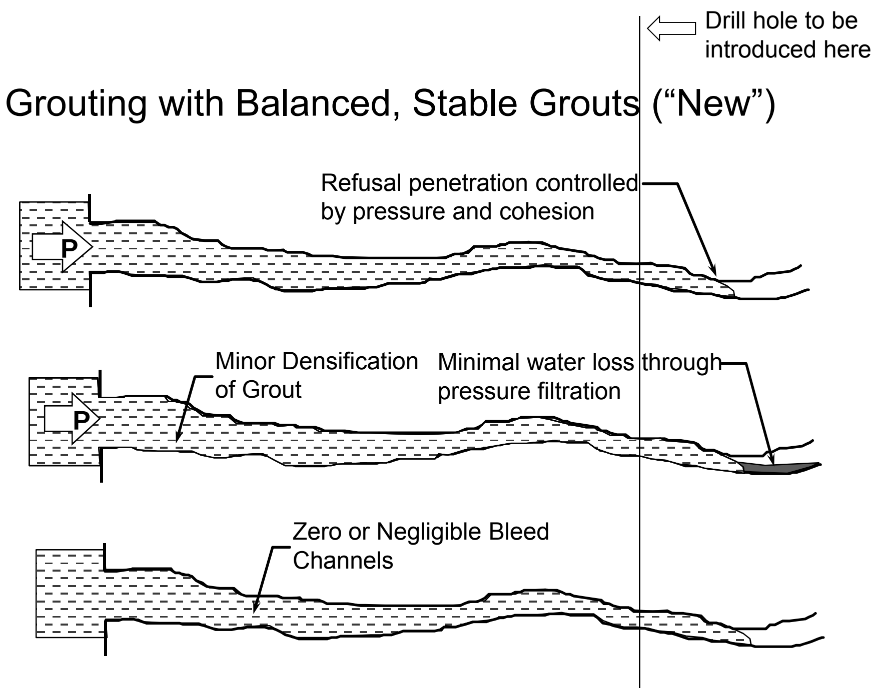
Grouting with Neat Cement Grouts (“Old”)



Characteristics of Balanced Stable Water Cement Grouts ("New")

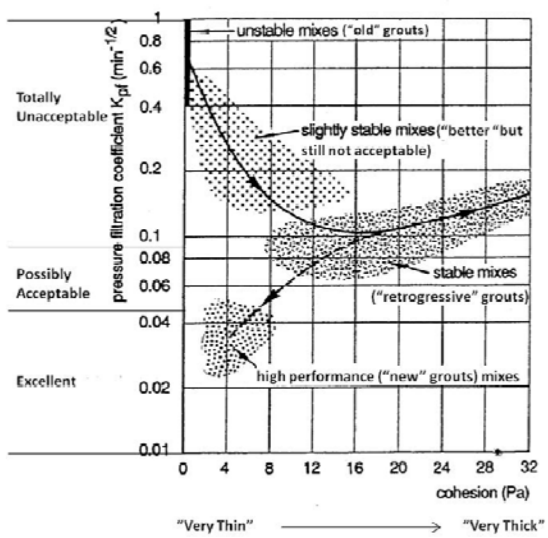
- Cement + Water + Rheology Modifiers
- Zero Bleed
- Resistant to Pressure Filtration
- Organized Particles
- Minimal Change in Rheology During Injection

Grouting with Balanced, Stable Grouts ("New")



Common Additives to Balanced Stable Cement-Based Suspension Grouts

- Water
- Portland Cement (typically Type III)
- Bentonite
- Silica Fume
- Flyash (usually Type F)
- Welan Gum or other Viscosity Modifier
- Dispersant (SuperP)



Historical path of development from unstable mixes to contemporary balanced multicomponent mixes (modified after DePaoli et al., 1992).

3.6 Real-Time Computer Monitoring

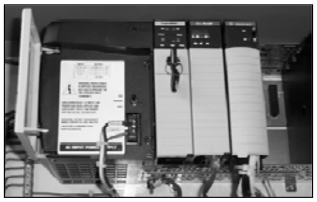
- Description: System that measures, records and displays flow and pressure during pressure testing and/or grouting operations.
- Output
  - *Real-Time Graphs*
  - *Trend Plots*
  - *CADD Drawings*
  - *Work Summaries, Daily Pay Items, Analysis Charts, and Closure Plots*
- Levels of Computer Monitoring*****
  - *Level 1 Technology: Dipstick and Gage*
  - *Level 2 Technology: Real-Time Data Collection & Display System*
  - *Level 3 Technology: Advanced Integrated Analytical Systems (AIA Systems)*
- Benefits to Grouting Program (Levels 2 & 3 Only)
  - *Ability to make sound engineering decisions during grouting operations*
  - *Facilitates generation & retrieval of project records*
  - *Fast, easy display of grouting results (CADD Drawings)*
  - *Analytical tools to assess grouting performance*

* Note: Only Level 2 and 3 Technologies are recommended for future grouting projects

Advantages

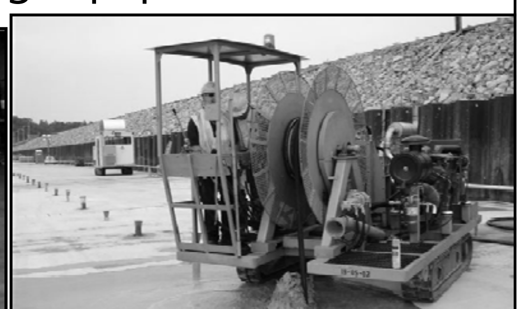
- Measurement Accuracy Significantly Improved
- Real Time Data is obtained (2-10 seconds vs. 5-15 min.)
- Allows one to use higher pressures with confidence; Dilation and Lifting easily picked up on screen
- Formation Response to procedure changes (mix or pressure) are known immediately
- Accelerates the Work
- Reduces Inspection Manpower Requirements (~25% for Level 2 Technology and ~60% for Level 3)
- Permits reallocation of resources to analyze program results and recommend cost effective program modifications.

Components of Computer Grouting System



- Pressure Transducers & Magnetic Flow Meters
- Power and Signal Cables or Telemetry System
- Processor to convert current signal to voltage
- Analog to Digital Converter
- Monitoring Software
- Computer(s)
- Radio Communication System

Monitoring Equipment

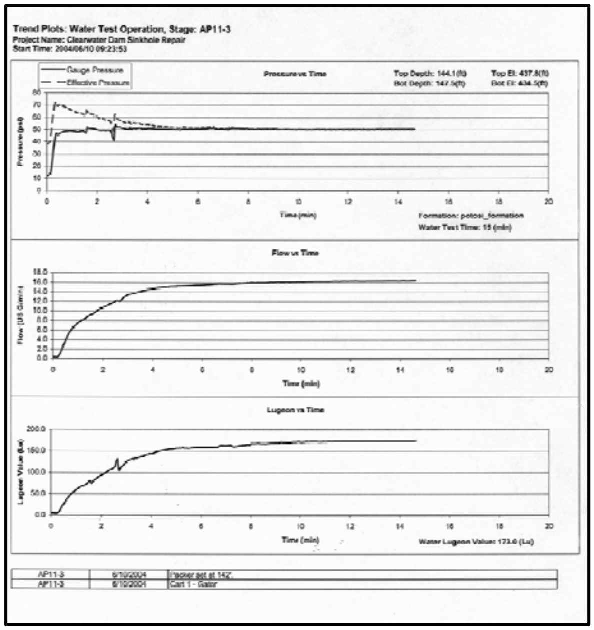


Level 3 Computer Monitoring System

Available Systems

- Numerous hardware and software packages now available
  - *IntelliGrout*
  - CAGES
  - SINNUS
  - I-Grout
  - Grout Monitor
  - GROUT I.T.
- Systems vary in their capabilities, but all provide real-time monitoring of flow rate and pressure

Trend Plots – Water Pressure Testing

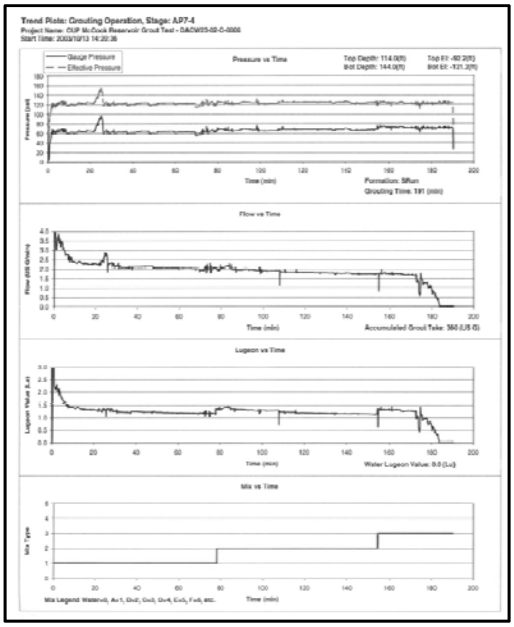


Apparent Lugeon Value

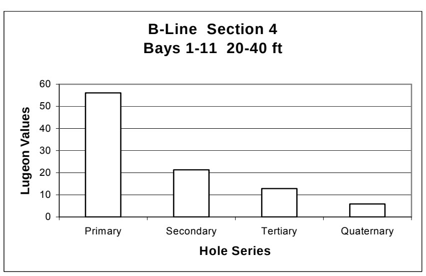
Standard equation for determining lugeon value with water times a correction factor equal to the ratio of the apparent viscosity of grout (a Bingham Fluid) to the apparent viscosity of water (a Newtonian Fluid) used to bring stages to a proper refusal.

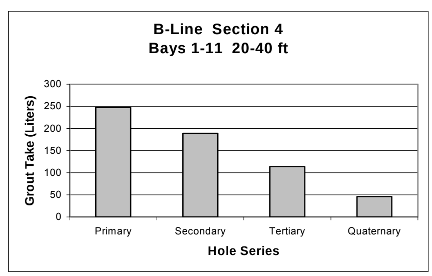
$$Lu_{app} = \frac{Q(L/min)}{Stage\ Length(m)} \times \frac{143psi}{P_{eff}} \times \frac{V_{Marsh\ of\ Grout}}{28sec}$$

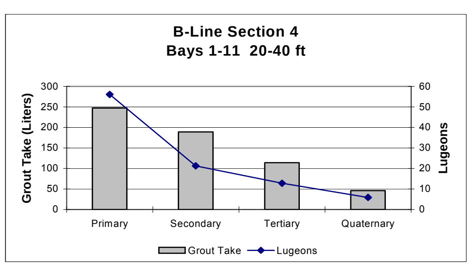
Trend Plots – Grouting



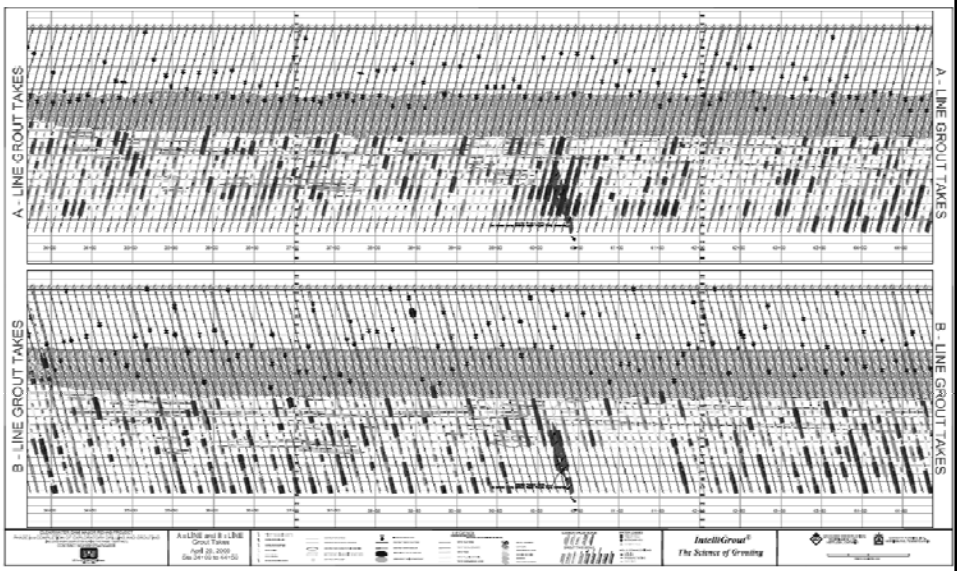
Closure Analysis – by Hole Series



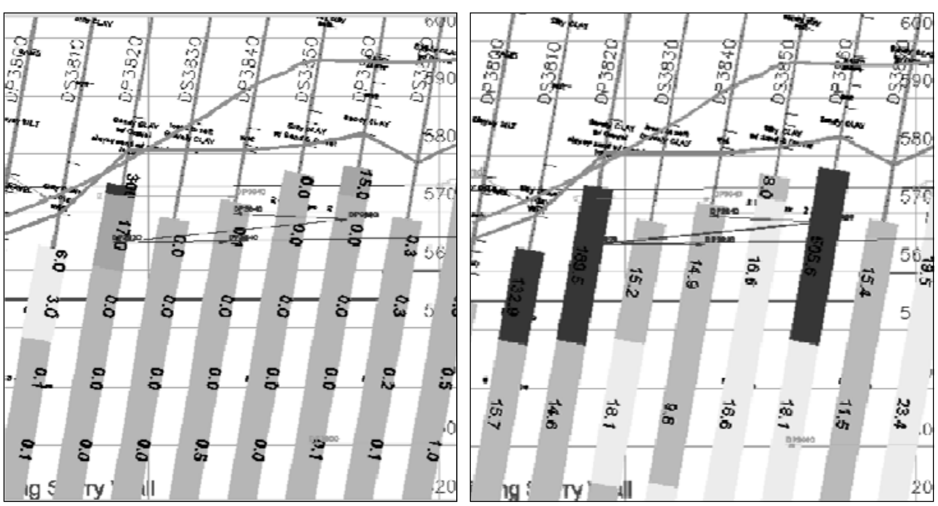




CADD Drawings

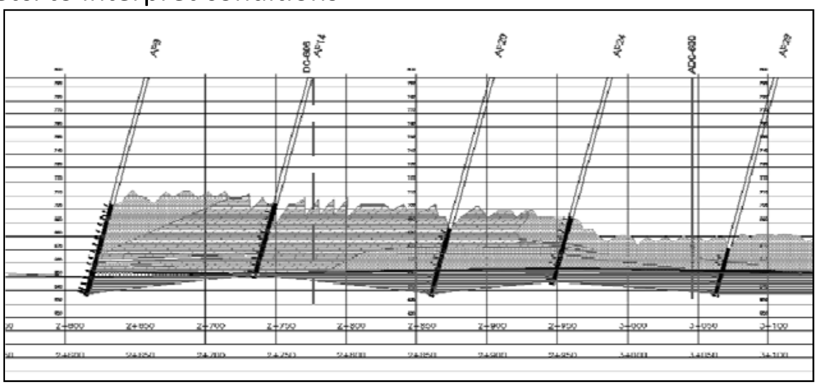


Comparison of Pressure Testing and Grouting Results



Interactive Geology

- Logical organization of Geotechnical and Geological Data
- Electronic link between data
- Eliminates sorting through paper logs, photographs, lab test results, etc. to interpret conditions



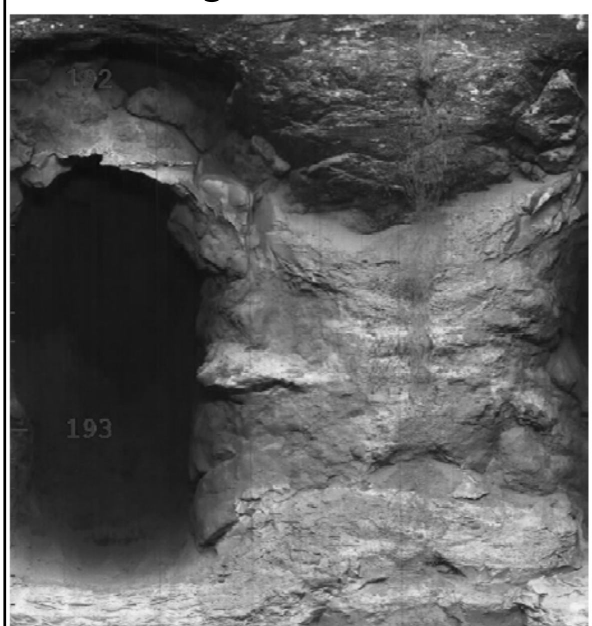
High Resolution Borehole Imaging

- Description: A high resolution down-the-hole camera that is able to create detailed images of the borehole walls as it traverses the length of the hole.
- Output
  - *Inclination and Azimuth*
  - *X,Y,Z Coordinates (Deviation Survey)*
  - *Image Log (wrapped, unwrapped, multiple orientations)*
  - *Strike and Dip of fracture sets*
  - *Aperture Thickness*
  - *Stereonet Plots of discontinuity data*
- Benefits to Grouting Program
  - *Every hole can be treated as an "Exploration" hole*
  - *Accurate observation of in-situ rock conditions*
  - *Ability to "see" fractures, infilling, cavities and solution features*
  - *Demystifies broken zones and core losses (observed in core holes samples)*
  - *Ability to determine appropriate grouting method*
  - *Verification of grouting effectiveness*

High Resolution Borehole Imaging

- Technology continues to improve
- Destructive drilling and imaging to acquire virtual core is cost effective alternative to core drilling
- Allows user to see rock mass in undisturbed state
- Images from before and after washing can differ so timing must be considered
- Comparison of images to water testing very useful in understanding what is going on during grouting

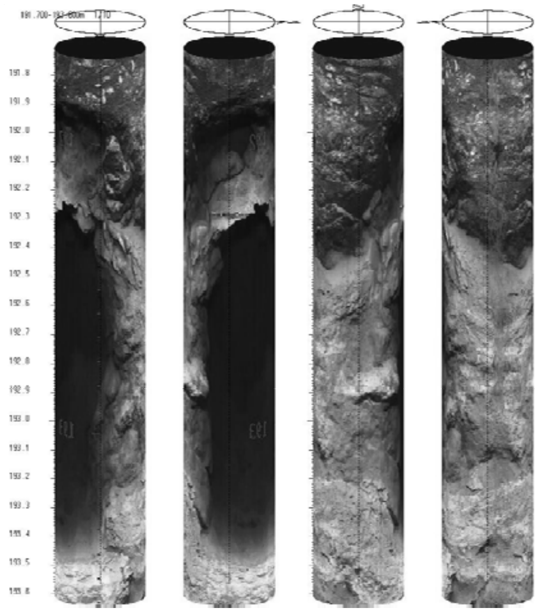
High Resolution Borehole Imaging



S36.70U
192.3' - 193.4:
Solution feature in Leipers Fm.

191' to 194' described in drill log as "very soft rock; clay also present; cuttings are dull white."

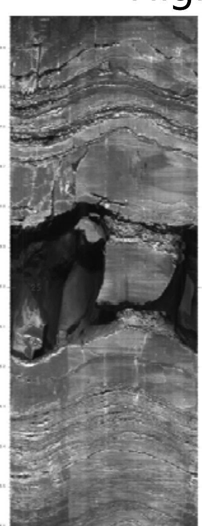
High Resolution Borehole Imaging



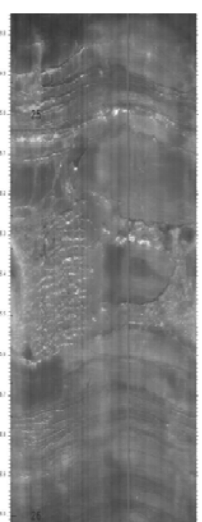
S36.70U
192.3' - 193.4:
Solution feature in
Leipers Fm.

Wrapped image
suggests feature trends
NW-SE, normal to dam.

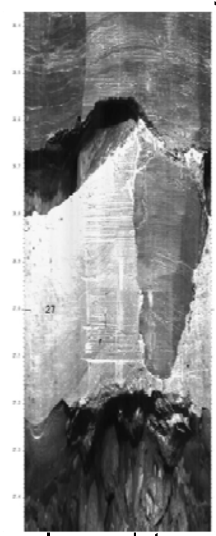
High Resolution Borehole Imaging



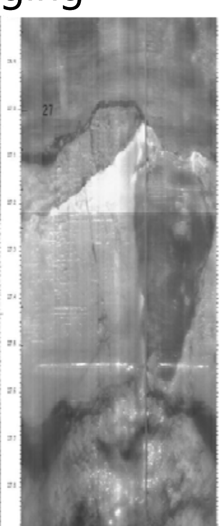
Before Grouting



After Grouting



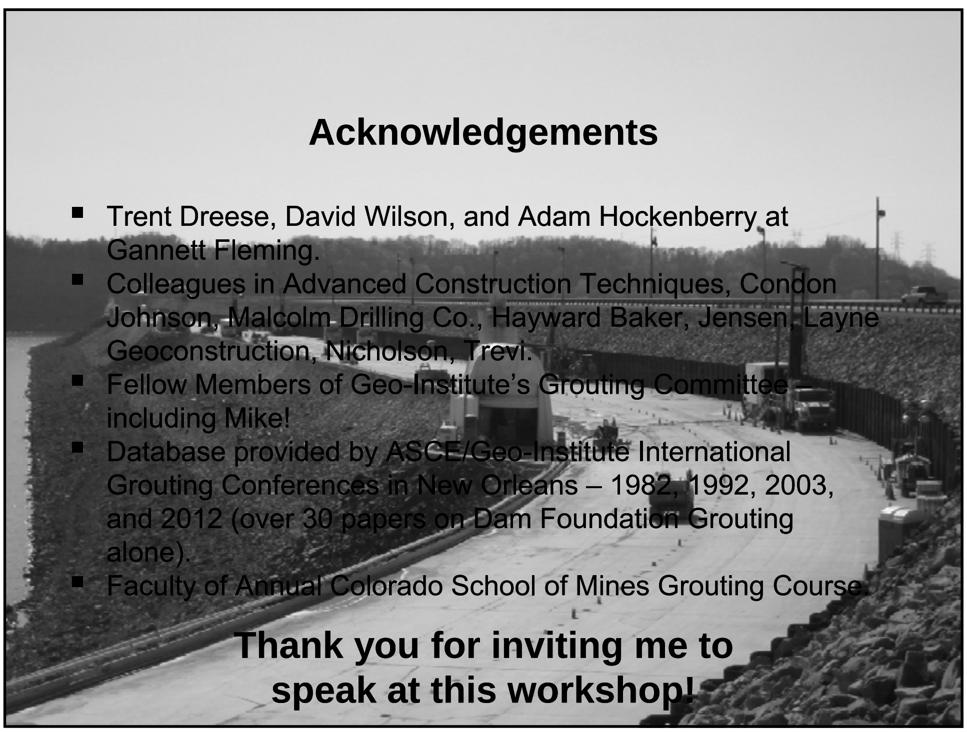
Incomplete Grouting



Additional Grouting

4. Final Thought

Each of the individual technologies discussed adds value to the quality of a grouting program. Each piece of added technology adds to the overall “picture” of a grouting program, by increasing the understanding of the in-situ subsurface conditions and/or the response of the subsurface to grouting operations. A grouting program with these technologies integrated together can better evaluate the effectiveness of the grouting operations which will, in turn, help to achieve project goals and objectives.



Acknowledgements

- Trent Dreese, David Wilson, and Adam Hockenberry at Gannett Fleming.
- Colleagues in Advanced Construction Techniques, Condon Johnson, Malcolm Drilling Co., Hayward Baker, Jensen, Layne Geoconstruction, Nicholson, Trevi.
- Fellow Members of Geo-Institute’s Grouting Committee – including Mike!
- Database provided by ASCE/Geo-Institute International Grouting Conferences in New Orleans – 1982, 1992, 2003, and 2012 (over 30 papers on Dam Foundation Grouting alone).
- Faculty of Annual Colorado School of Mines Grouting Course.

Thank you for inviting me to speak at this workshop!