Quantitatively Engineered Grout Curtains

Case: 3-Line Grout Curtain with Drains
Headwater: EL 1000
Tailwater: EL 886
Bottom of Grout Curtain: EL 742
Grout Curtain Permeability: 8e-05 ft/min
Rock Conductivity Functions: As shown

q (curtain) = 2.39e-02 cfm/ft
q (under) = 3.68e-04 cfm/ft
q (total) = 2.42e-02 cfm/ft = 0.18 gpm/ft

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Gannett Fleming
Introduction
Grouting – It Seems So Simple!
Interesting Grouting Comments

- “The foundation wasn’t groutable”
- “Grouting isn’t reliable as a long-term solution”
- “There’s no way to know how the grouting will perform until we fill it up.”
- “The only person that can understand the grouting work is the guy onsite that’s in charge of the program”
- “We spent $2,000,000 and didn’t accomplish anything. I don’t think we’ll ever be authorized to try grouting again.”
- “We grouted until we ran out of budget and then we quit.”
Grouting Program Failures

- Inability to reliably predict performance in advance
- Unsatisfactory initial performance
- Unsatisfactory long-term performance
- Cost overruns, project delays, & claims
- Inability to effectively communicate need for grouting, amount of grouting required, and results of grouting
The Central Question

Is There Something Fundamentally Wrong with Grouting, or Does the Grouting Precisely Reflect How We Approach & Execute the Work?
Grouting results can be predicted

Grouting can be designed, modeled, specified, and verifiably constructed to achieve quantitative results

Grouting results can be clearly understood and communicated

Contracting alternatives exist that will provide incentives for quality equipment and workmanship and which will prevent cost growth and claims

Grouting is a reliable & cost effective method for seepage control
Tools Enabling Successful Quantitative Design and Construction

- Quantitative site characterization, quantitative modeling, and quantitative design of grouting
- Balanced stable grouts
- Electronic monitoring and control of operations
- Computer analysis & presentation of results
- Best Value Contracting and Partnering
Quantitative Design & Construction of Grouting
What Do We Need for Quantitative Design & Construction?

- Thorough understanding of site geology
- Pre-grouting permeabilities
- Workable model for pre- and post-grouting conditions
- Performance requirements
- Design parameters for grouting (width & permeability)
- Real-Time Analysis & Verification to Evaluate Results and Provide Basis for Required Program Modifications in Field
- Ability to Communicate Results to All Project Participants
Site Geology
Site Geology Information Required

- Regional & Site Specific Geologic Information

- Fracture Information for each geologic unit or sub-unit
  - Fracture orientations
  - Fracture widths
  - Fracture spacings
  - Fracture continuity
  - Fracture filling

- Special Conditions
  - Conditions at interface at which grouting is to start
  - Special geologic conditions (i.e. karst features; non-lithified zones; concentrated fracture zones; water loss zones; artesian zones; etc)
Geologic Data Collection
Outcrop Mapping and Conventional Coring
Video Logging & Geophysical Techniques
Pre-Grouting Permeabilities & Flow Regimes
Data Sources
Permeability & Flow Regime Data Sources

- Geologic Information
- Piezometer Data
- Boundary Conditions (HW, TW, Seepage Exit Points)
- Short Stage Pressure Tests in Holes with Appropriate Orientations
Data Validation & Integration

- Validate the available data
- All valid data must be integrated
- Study it until it truly makes qualitative and quantitative sense. In most cases, sufficient valid data exists to do a model that and produces a reasonable representation of current conditions.
- Don’t ignore anomalies. Something is going on.
Grouting Models
Discrete Fracture Flow Models vs. Porous Media Flow Models
Flow through Rock is Discrete Fracture Flow
Discrete Fracture Models

• Based on flow through parallel plates

• \[ Q = Wgb^3i / 12m \]
  – \( b = \text{fracture width} \)
  – \( W = \text{fracture access length} \)
  – \( i = \text{gradient from entry to exit boundary points} \)
  – \( g = \text{unit weight of water} \)
  – \( m = \text{dynamic viscosity of water} \)
For 20 ungrouted 2mm fractures 20 ft long each and under $I = 5$, $Q = 20 \times 20 \times 5 = 2000$ gpm
Q = 700 gpm per ft of length
(Under i = 1)
So Why Not Use Discrete Fracture Models?

- Fractures aren’t parallel plates
- Fracture width “b” is extremely difficult to ascertain.
- Generally don’t know fracture continuity, which is essential for “W” term
- Requires knowing number fractures in each fracture set as well as size distribution
Porous Media Flow Models
Why Porous Media Models Work

• Scale of problem is generally ok (i.e. fracture density relative to volume being modeled is such that it approximates a porous media).

• Data easy to get – packer tests determine equivalent rock mass permeability

• For well-grouted rock, the residual permeability is comprised of very small flow paths that very closely approximates a porous media

• After grouting, assuming we achieve about a two-order magnitude of permeability reduction, the ungrouted rock on either side does not control behavior.
Examples of Porous Media Models
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\[ q \text{ (total)} = 2.42e^{-02} \text{ cfm/ft} = 0.18 \text{ gpm/ft} \]
Sophisticated 3D Flow Model

No Containment System

1-Lu Grout Curtain
Chicago McCook Reservoir
Chicago District, USACE

\[ q_x = k \times \frac{H}{W} \times T \]

\[ Q_T = \sum (q_x \times L) \]
Things to Remember

• The sophistication of the model is far less important than the quality of the data and the fundamental correctness of the model.

• Defective grouting (i.e. missed fractures) may leak very badly due to discrete fracture flow rules and is further aggravated by increased gradients. Essential to directly access all fractures at appropriate interval while grouting.

• Poor grouting (i.e. partially unfilled fractures) will leak proportionally to the residual fracture thickness cubed. Essential to go to very tight refusal criteria and use non-bleed grouts.
Establishing Project Performance Requirements
Methods for Setting Performance Requirements

- Permissible total seepage rates or unit seepage rates
- Desired pressure distributions
- Gradient limitations
- Residual fracture widths
- Cost-benefit analyses
- Compatibility with other elements in combined cutoff systems
- Environmental considerations
Examples of Project Performance Requirements
Penn Forest Replacement Dam
- Length = 2500 ft
- Head = 180 ft

- Design Total Residual Seepage < 200 gpm
- Required Residual Permeability = 3 Lugeon
**Table 6.3**

**Benefit of Seepage Reduction vs. Cost of Grouting - $25 Million Project**

<table>
<thead>
<tr>
<th>Curtain Configuration and Performance Characteristics</th>
<th>Estimated Seepage Quantity (MGD)</th>
<th>Total Value of Residual Seepage</th>
<th>Cost Benefit Achieved by Alternative</th>
<th>Construction Cost for Alternative</th>
<th>Benefit Cost Ratio</th>
<th>Incremental Benefits for Increased Intensity</th>
<th>Incremental Costs for Increased Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ungrouted w/ Drains</td>
<td>1.27</td>
<td>$3,969,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-Line Curtain (5 Lu)</td>
<td>0.46</td>
<td>$1,438,000</td>
<td>$2,531,000</td>
<td>$1,335,000</td>
<td>1.90</td>
<td>$2,531,000</td>
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<tr>
<td>3-Line Curtain (3 Lu)</td>
<td>0.23</td>
<td>$719,000</td>
<td>$3,250,000</td>
<td>$2,410,000</td>
<td>1.35</td>
<td>$719,000</td>
<td>$1,075,000</td>
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<tr>
<td>3-Line Curtain (1 Lu)</td>
<td>0.08</td>
<td>$250,000</td>
<td>$3,769,000</td>
<td>$2,870,000</td>
<td>1.31</td>
<td>$519,000</td>
<td>$460,000</td>
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</tbody>
</table>

**Table 6.4**

**Benefit of Seepage Reduction vs Cost of Grouting - $30 Million Project**

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<th>Curtain Configuration and Performance Characteristics</th>
<th>Estimated Seepage Quantity (MGD)</th>
<th>Total Value of Residual Seepage</th>
<th>Cost Benefit Achieved by Alternative</th>
<th>Construction Cost for Alternative</th>
<th>Benefit Cost Ratio</th>
<th>Incremental Benefits for Increased Intensity</th>
<th>Incremental Costs for Increased Intensity</th>
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</thead>
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<td>Ungrouted w/ Drains</td>
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<td>$4,763,000</td>
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<td>2.28</td>
<td>$3,038,000</td>
<td>$1,335,000</td>
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<tr>
<td>3-Line Curtain (3 Lu)</td>
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<td>$1,075,000</td>
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<tr>
<td>3-Line Curtain (1 Lu)</td>
<td>0.08</td>
<td>$300,000</td>
<td>$4,463,000</td>
<td>$2,870,000</td>
<td>1.56</td>
<td>$562,500</td>
<td>$460,000</td>
</tr>
</tbody>
</table>
Mississinewa Dam
Slurry Wall Pre-Grouting

- Prevent catastrophic loss of slurry during panel excavation
- Minimum grouting necessary
- Entire 12-ft width grouted to 10 Lu to limit routine slurry loss to manageable rates
Chicago McCook CSO Storage Reservoir Perimeter Grouting

- Grout as tightly as possible for environmental containment
- Hydraulic flux compatibility with soil-bentonite cutoff in overburden
- 0.1 Lugeon Goal
Grouting Design Parameters
Parameters Required for Grouting Design

- **Width of grouted zone for single and multiple line configurations**
  - Radius of spread varies with fracture size, pressure, duration, mix
  - Reasonable to assume 5 ft effective radius of spread

- **Realistically achievable residual permeability for single and multiple line configurations**

“This is where it gets a bit dicey”
Generally Available Design Guidelines

• **Readily groutable materials**
  – \( k > 1 \times 10^{-3} \text{ cm/sec} (> 100 \text{ Lugeons}) \)
  – Reductions of 1-3 orders of magnitude (depending on a number of factors)

• **Marginally groutable materials**
  – \( k = 1 \times 10^{-4} \text{ cm/sec} (10 \text{ Lugeons}) \)
  – Reductions of 1-2 orders of magnitude (depending on a number of factors)

• **Barely groutable materials**
  – \( k < 1 \times 10^{-5} \text{ cm/sec} (1 \text{ Lugeon}) \)
  – Require special measures
Given the potential range of residual permeabilities, is expected \( Q = 10 \text{ gpm} \) or \( 100 \text{ gpm} \) or \( 1,000 \text{ gpm} \) or \( 10,000 \text{ gpm} \), and what are the “factors” that determine the results we should reasonably expect?
Factors Affecting Grouting

- Geology
- Drilling technique
- Grout Materials
- Grout Mixes
- Mixing Equipment
- Hole Washing
- Grout Pumping Equipment
- System Setup
- Valves and fittings
- Bleed
- Grouting technique

- Hole spacing
- Hole depth
- Hole sequencing
- Hole staging
- Pressures
- Contractor experience
- Refusal criteria
- Contract incentives & disincentives
- Inspection & control
- Testing & analysis
Realities of Grouting

• Grouting results are absolutely affected by all of the factors

• Some variables have been essentially eliminated in current industry practice

• Remaining variables can be grouped into various design / construction performance levels
QEGC Predicted Results vs. Project Results

Grouting M & T Level

Residual Permeability (m/s)

1.0E-08
1.0E-07
1.0E-06
1.0E-05
1.0E-04

(800 Lu)

(80 Lu)

(8 Lu)

(1 Lu)
Real-Time Analysis & Verification and Communication of Results
Contracting Issues
Contracting for Performance

- Must structure and prepare contract documents to ensure that you get the end products and services desired

- Quality of equipment and personnel is critical

- Contracts must not contain disincentives to achieving quality results

- Low bid contracting doesn’t work – operating at this level is not a commodity

- Best Value Selection is being used by USACE and is best option
Special Recognition

Mike Klosterman, Geologist, HQ USACE
Steve Hornbeck, Geologist, Louisville District
Tim Flaherty, Geologist, Louisville District
Kevin Jefferson, Contracting Officer, Louisville District
Bill Rochford, Engineer, Chicago District
Joe Kissane, Geologist, Chicago District
Larry Green, Contracting Officer, Chicago District
Mark Harris, Geologist, Little Rock District
Pat Jordan, Geologist, Little Rock District
Jon Wedgeworth, COR, Little Rock District
R. Leroy Arnold, Engineer, Little Rock District
Thank You

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