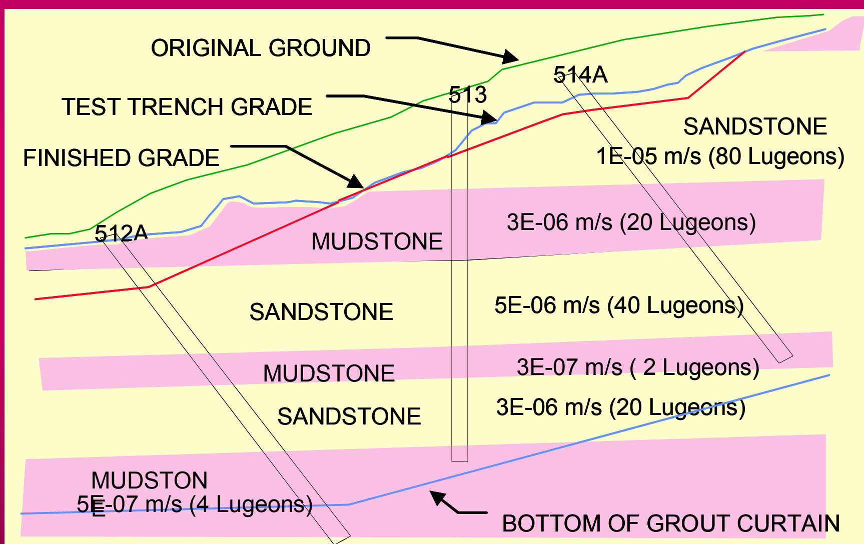
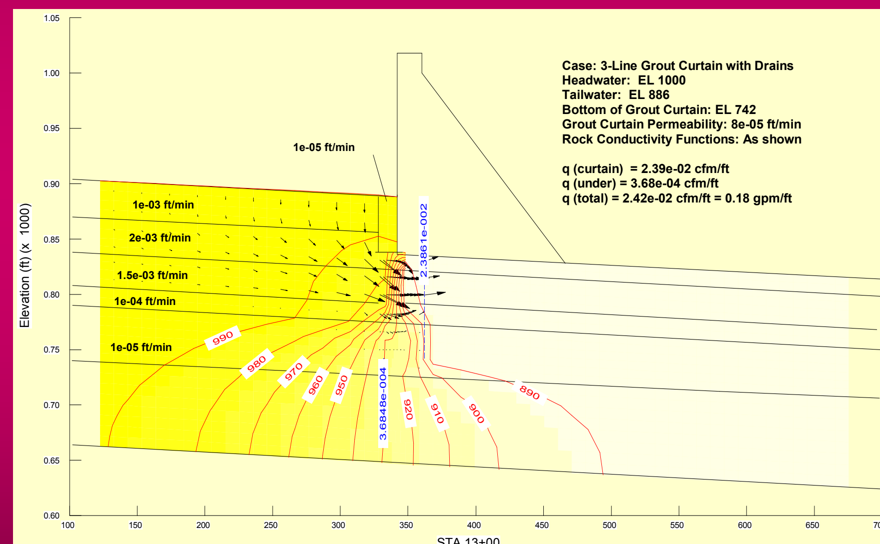
2005 Tri-Service Infrastructure Conference

“Re-Energizing Engineering Excellence”

Quantitatively Engineered Grout Curtains





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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 2005

- *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 <u>each</u> 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

McCook Reservoir Test Grouting – Chicago District USACE

Pre-Grouting Permeabilities
&
Flow Regimes

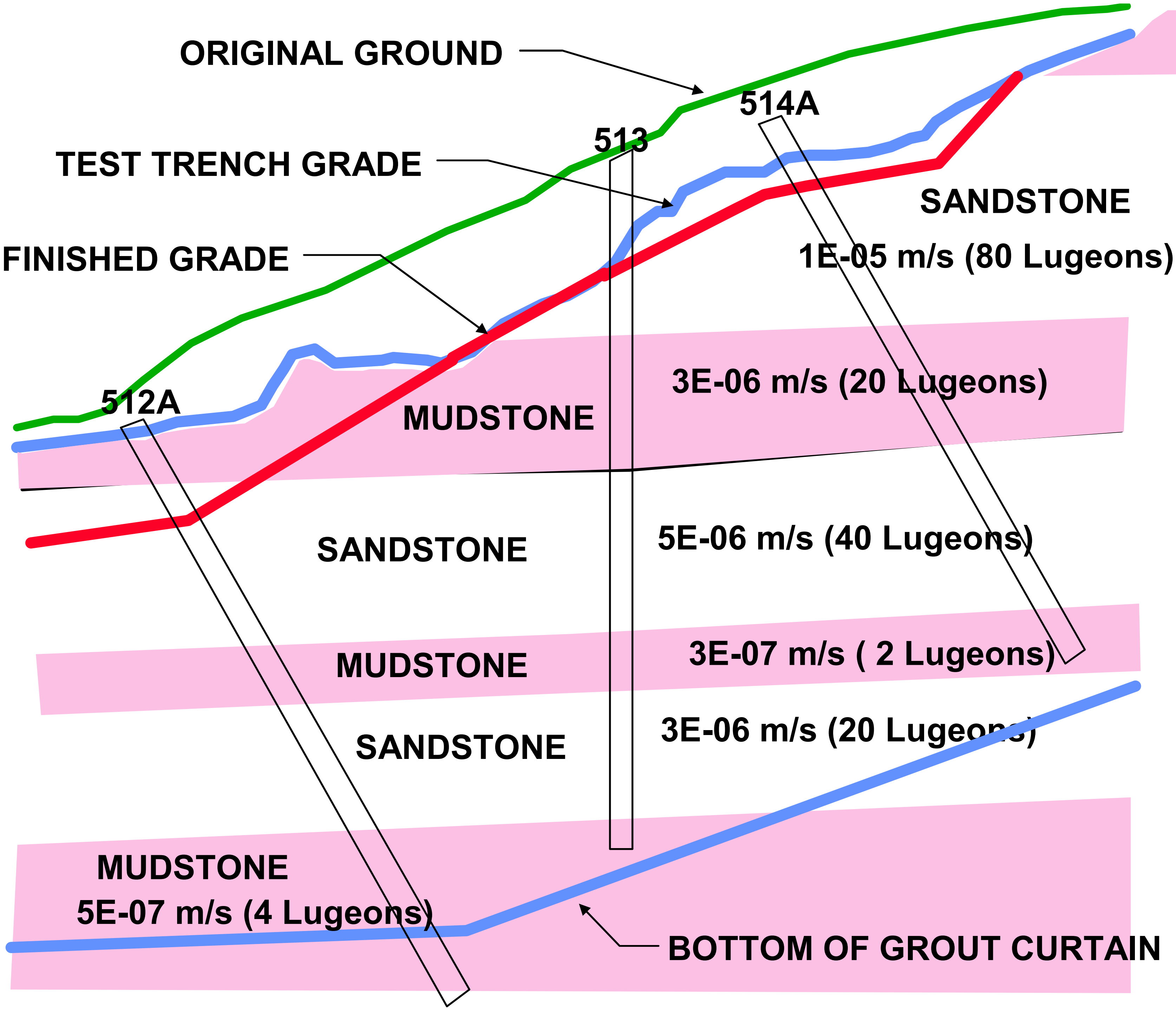
Data Sources

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 anomolies. Something is going on.*



ORIGINAL GROUND
TEST TRENCH GRADE
FINISHED GRADE
513
514A
512A
SANDSTONE
1E-05 m/s (80 Lugeons)
MUDSTONE
3E-06 m/s (20 Lugeons)
SANDSTONE
5E-06 m/s (40 Lugeons)
MUDSTONE
3E-07 m/s (2 Lugeons)
SANDSTONE
3E-06 m/s (20 Lugeons)
MUDSTONE
5E-07 m/s (4 Lugeons)
BOTTOM OF GROUT CURTAIN

Grouting Models

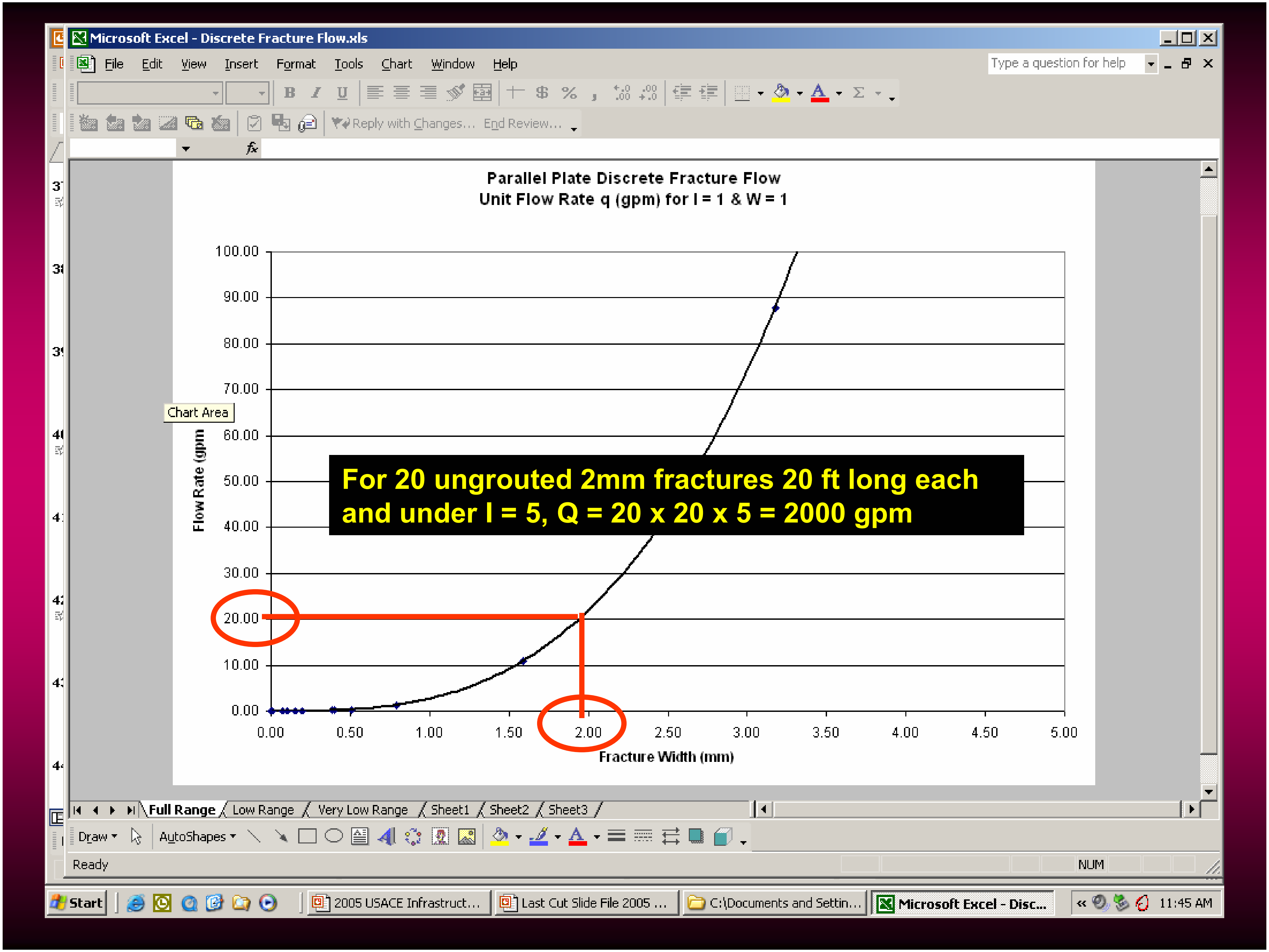
Discrete Fracture Flow Models
vs.
Porous Media Flow Models

Flow through Rock is Discrete Fracture Flow

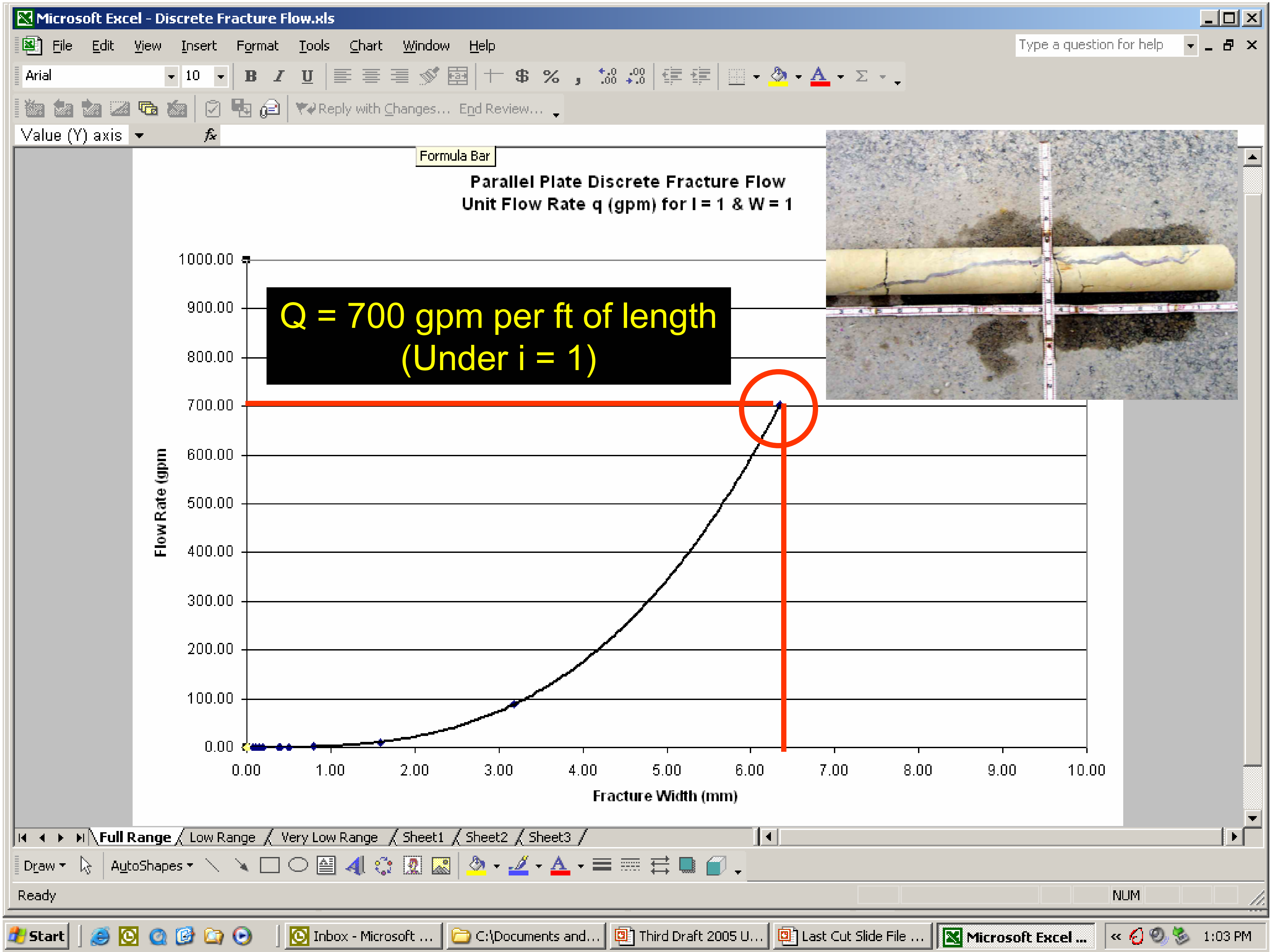
Discrete Fracture Models

- *Based on flow through parallel plates*

- $Q = W\mathbf{g}b^3i / 12\mathbf{m}$
  - ***b = fracture width***
  - ***W = fracture access length***
  - ***i = gradient from entry to exit boundary points***
  - ***g = unit weight of water***
  - ***m = dynamic visosity of water***



Microsoft Excel - Discrete Fracture Flow.xls
Parallel Plate Discrete Fracture Flow
Unit Flow Rate q (gpm) for I = 1 & W = 1
Flow Rate (gpm)
Fracture Width (mm)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
For 20 ungrouted 2mm fractures 20 ft long each and under I = 5, Q = 20 x 20 x 5 = 2000 gpm
Chart Area
Full Range
Low Range
Very Low Range
Sheet1
Sheet2
Sheet3



Microsoft Excel - Discrete Fracture Flow.xls
File Edit View Insert Format Tools Chart Window Help
Type a question for help
Arial
10
Reply with Changes... End Review...
Value (Y) axis
Formula Bar
Parallel Plate Discrete Fracture Flow
Unit Flow Rate q (gpm) for I = 1 & W = 1
Q = 700 gpm per ft of length
(Under i = 1)
Flow Rate (gpm)
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Fracture Width (mm)
Full Range
Low Range
Very Low Range
Sheet1
Sheet2
Sheet3
Draw
AutoShapes
Ready
NUM
Start
Inbox - Microsoft ...
C:\Documents and...
Third Draft 2005 U...
Last Cut Slide File ...
Microsoft Excel ...
1:03 PM

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

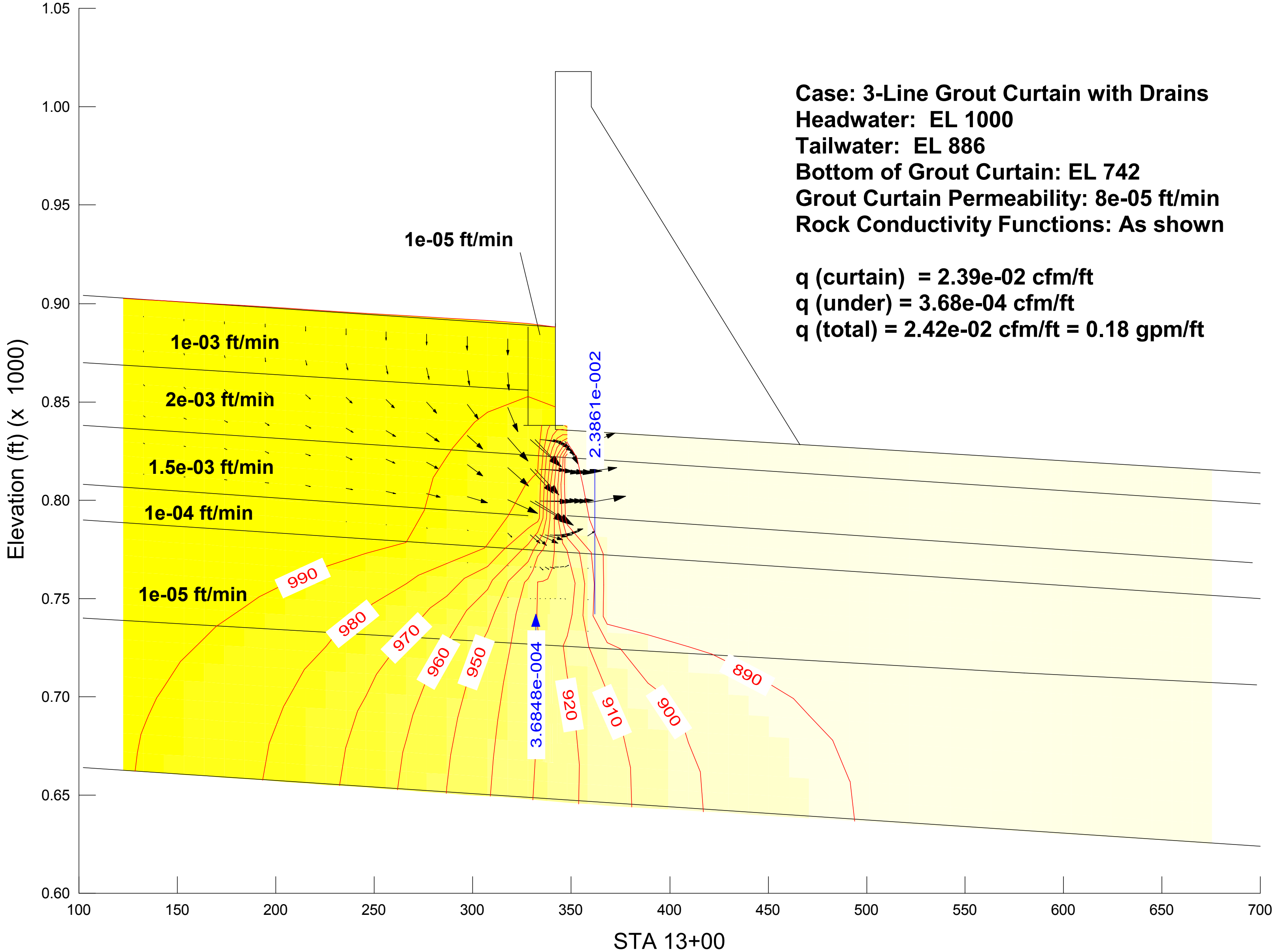
Why Porous Media Models Work

- *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

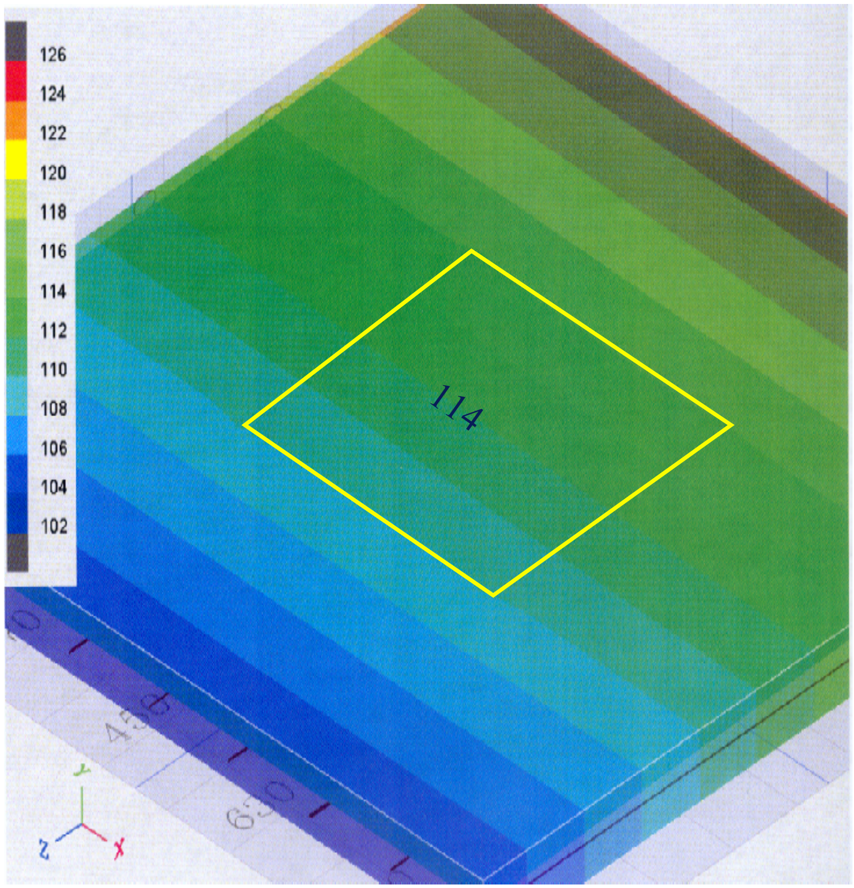
PENN FOREST DAM REPLACEMENT PROJECT

FINAL GROUT CURTAIN - VALLEY SECTION

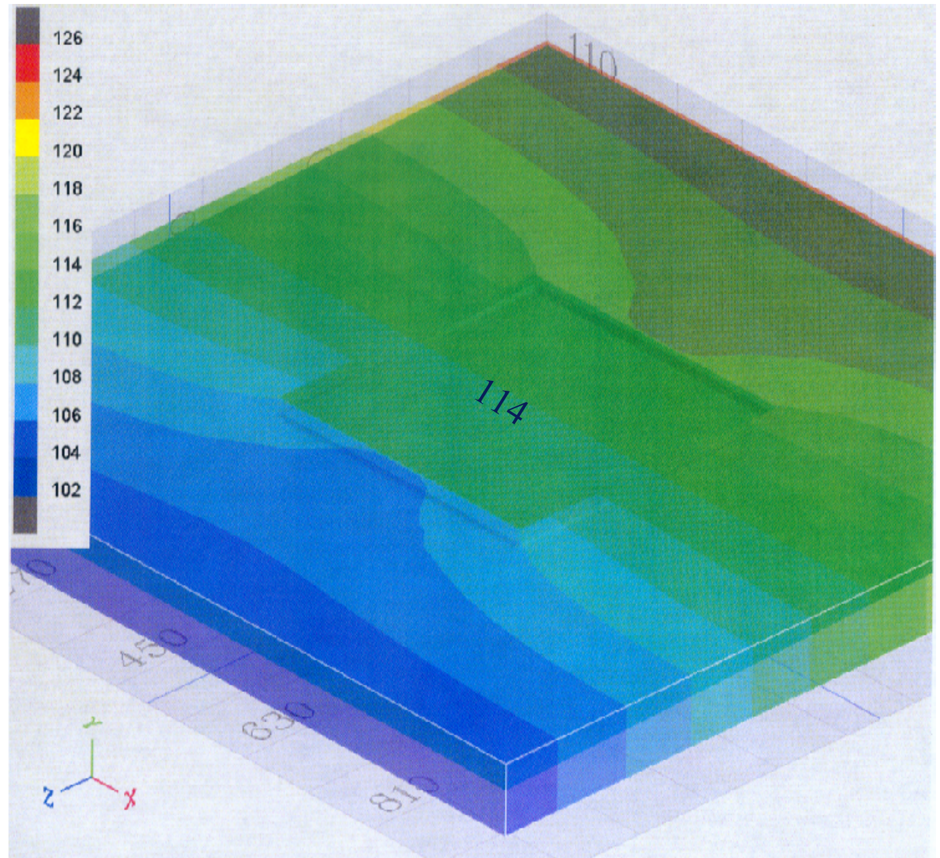


Sophisticated 3D Flow Model

No Containment System

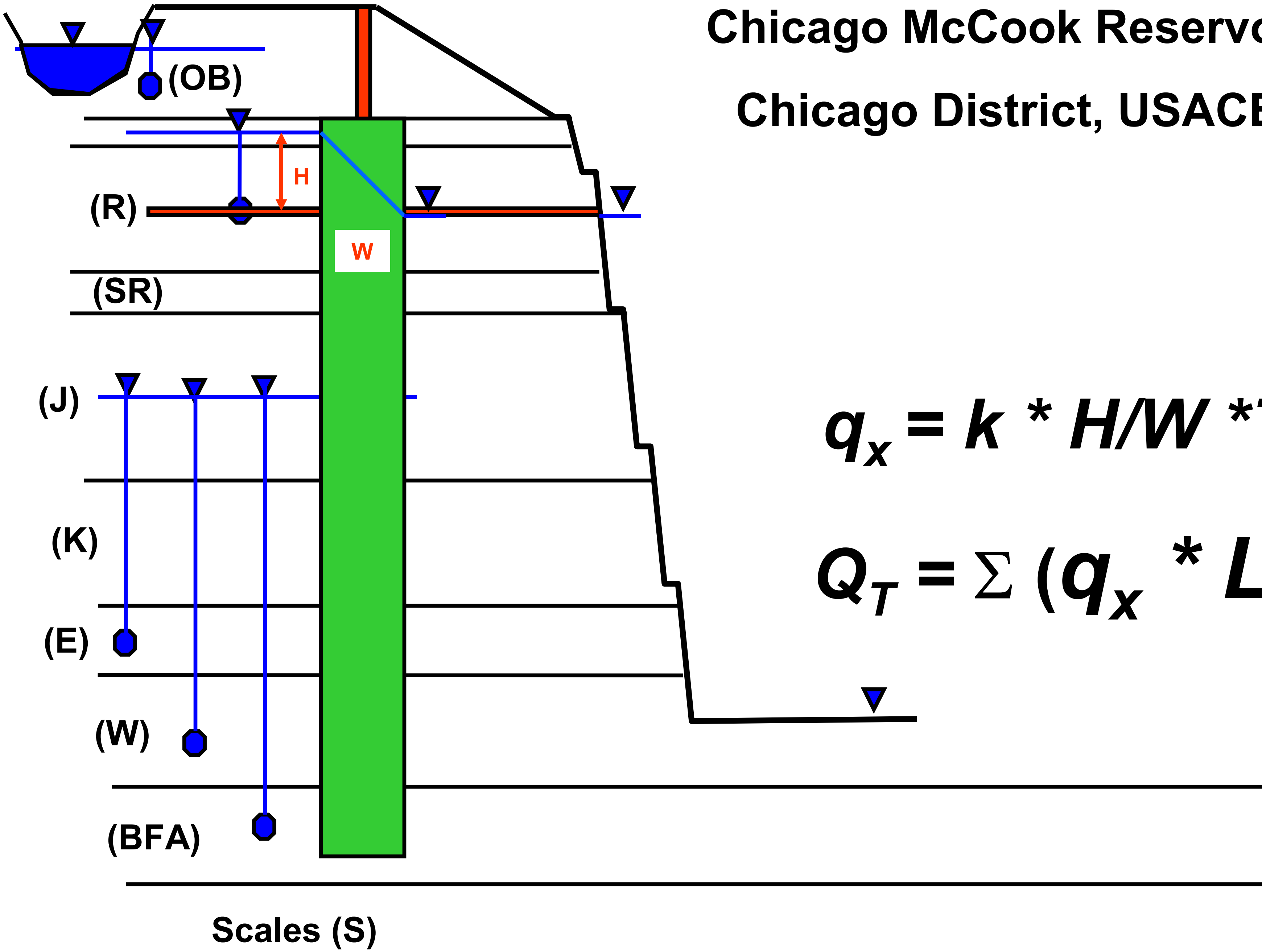


1-Lu Grout Curtain



Chicago McCook Reservoir

Chicago District, USACE



$$q_x = k * H/W * T$$

$$Q_T = \Sigma\,(q_x * L)$$

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

Hunting Run Dam
Pump Storage Drought Supply
Incremental Cost Benefit Analysis – Grouting Cost vs. Water Value
5 Lu Criteria Selected

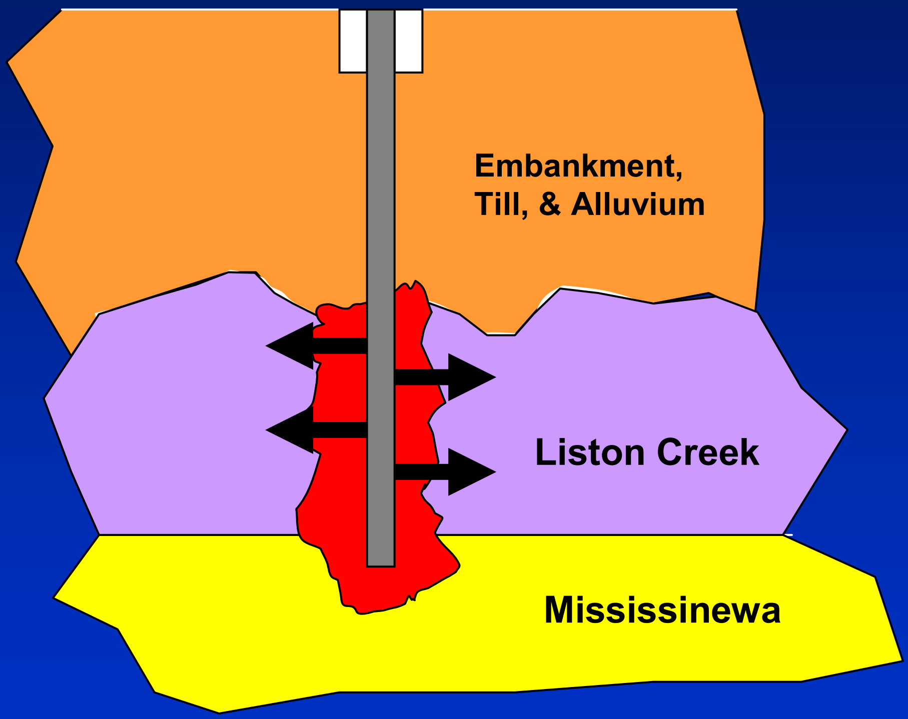
Table 6.3
Benefit of Seepage Reduction vs. Cost of Grouting - $25 Million Project
Cost of Seepage per MGD = $3,125,000

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

Table 6.4
Benefit of Seepage Reduction vs Cost of Grouting - $30 Million Project
Cost of Seepage per MGD = $3,750,000

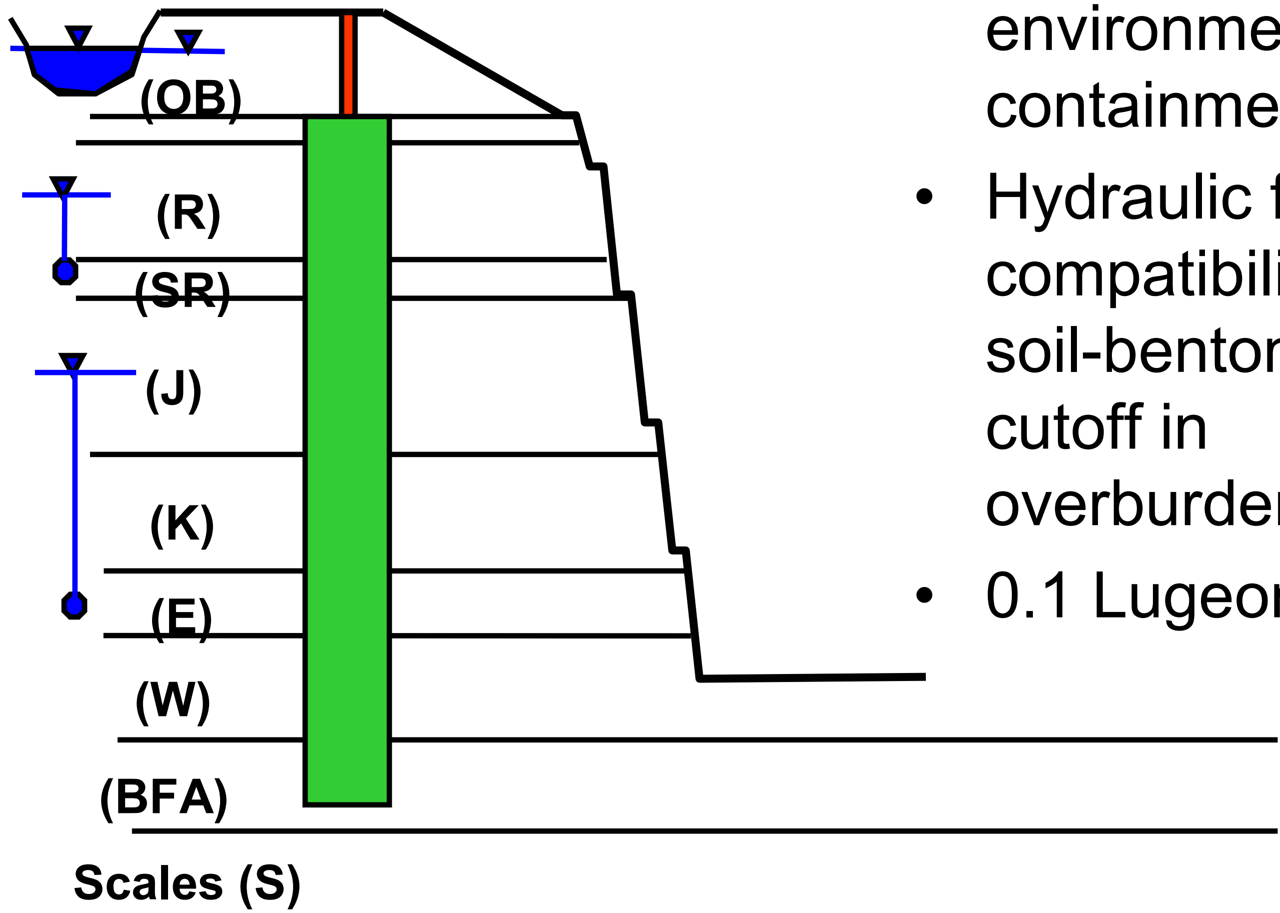
Curtain Configuration and Performance Characteristics	Estimated Seepage Quantity (MGD)	Total Value of Residual Seepage	Cost Benefit Achieved by Alternative	Construction Cost for Alternative	Benefit Cost Ratio	Incremental Benefits for Increased Intensity	Incremental Costs for Increased Intensity
Ungrouted w/ Drains	1.27	$4,763,000					
1-Line Curtain (5 Lu)	0.46	$1,725,000	$3.038,000	$1,335,000	2.28	$3,038,000	$1,335,000
3-Line Curtain (3 Lu)	0.23	$862,500	$3,900,500	$2,410,000	1.62	$862,500	$1,075,000
3-Line Curtain (1 Lu)	0.08	$300,000	$4,463,000	$2,870,000	1.56	$562,500	$460,000

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 x 10-3 cm/sec (> 100 Lugeons)*
  - *Reductions of 1-3 orders of magnitude (depending on a number of factors)*
- *Marginally groutable materials*
  - *k = 1 x 10-4 cm/sec (10 Lugeons)*
  - *Reductions of 1-2 orders of magnitude (depending on a number of factors)*
- *Barely groutable materials*
  - *k < 1 x 10-5 cm/sec (1 Lugeon)*
  - *Require special measures*

Given the potential range of residual permeabilities, is expected Q = 10 gpm or 100 gpm or 1,000 gpm or 10,000 gpm, and what are the "factors" that determine the results we should reasonably expect?

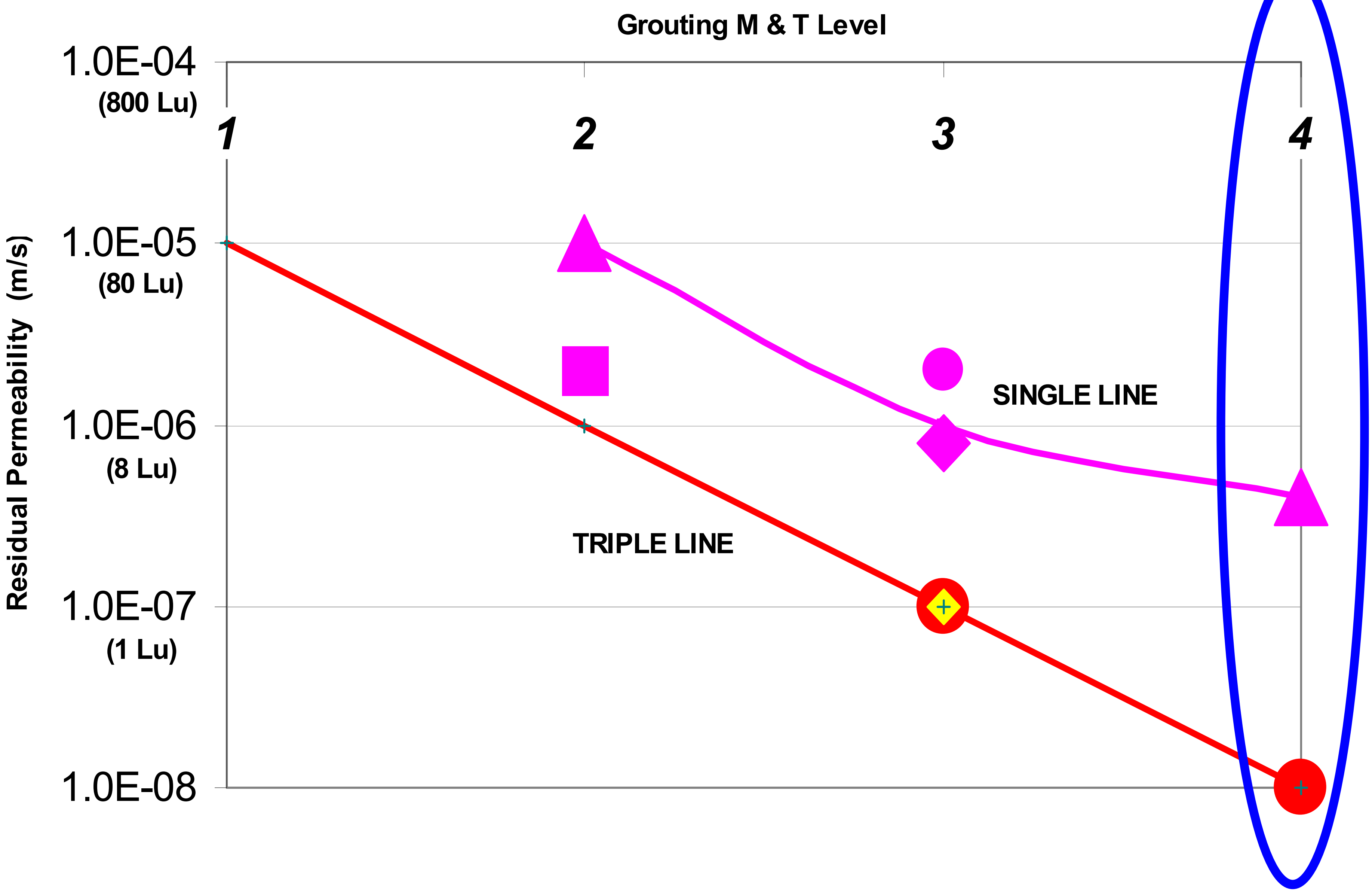
Factors Affecting Grouting

- *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



Real-Time Analysis & Verification and Communication of Results

IntelliGrout Control & Analysis Center

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

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Thank You

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