

Rock Grouting Principles for New and Remedial Dam Projects



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Geosystems LP

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Agenda

1. Applications and Basics (15 mins)
2. Design Considerations for Quantitatively Engineered Grout Curtains (30 mins)
Q & A (5 mins)
3. Grouting in Rock: Standard Operations and Sequences (35 mins)
4. Limited Mobility Grouting (LMG) for Dam and Levee Remediation (25 mins)
5. Closure (5 mins)
Q & A (5 mins)

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1. Applications and Basics of Rock Grouting



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Purpose for Dams and Levees

- Seepage Reduction through Foundations
- Reduction of Uplift Pressures on Gravity Dams
- Minimize flow paths and erosive velocities at soil to rock interface of embankment dams
- Reduce settlement and potential cracking of concrete dams
- Contraction Joint Grouting post shrinkage
- An element of a "Composite Cutoff" wall
- Equally valid for new dam construction and remedial projects

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Grouted Cutoffs for Seepage Reduction

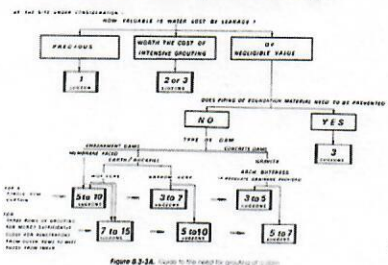
- Grouted Cutoffs are commonly referred to as "Grout Curtains"
- Term Grout Curtain is a misnomer
 - Infers a thin continuous element (e.g. shower curtain or membrane)
 - In reality, grouted zone width is highly variable. Wider grouted zone in open joints, thinner zone in joints of moderate opening, and very limited width in very tight joints or fine fractures.
 - Curtains may contain defects due to missed joints or bleed water accumulation

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When is Grouting Necessary?



From Housby 1990

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Grouting Lingo

- Primary Hole – First Hole Series
- Secondary Hole – Second Hole Series
- Tertiary Hole – Third Hole Series
- Quaternary Hole – Fourth Hole Series
- Quinary Hole – Fifth Hole Series

etc., etc., etc...

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Closure Grouting

Step 1: Drill and grout primary holes.

Step 2: Split space primary holes with secondary holes.

Step 3: Split space primary and secondary holes with tertiary holes.

Step 4: Continue with additional holes series as necessary to achieve desired results.

Note: "Refusal" refers to bringing a stage of a hole to what is in effect "grout tightness".

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Single Row Grouting

- ❖ Applicable only to sites with excellent rock quality and rock durability.
- ❖ Penetration of grout in fine fractures must be considered, i.e. width of curtain.
- ❖ Requires good grouting techniques and thorough analysis of results.
- ❖ Some zones may require additional holes offset from single line.

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Single Row Curtain



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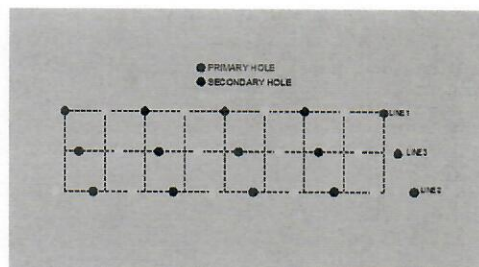
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Multiple Row Curtain

- Provides thicker zone of improved foundation (wider curtain).
- Lesser chance of defect not being intersected and treated.
- Verifiable results with closure line.
- Essential where erodible material exists.

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Grout Hole Spacing

- Typical Primary hole spacing of 20 to 40 feet (6 to 12 meters).
 - Typical spacing selected to minimize connections during grouting of primary holes
- Spacing is highly dependent upon geology and required frequency of grout hole intersections with formation joints.
- Err on the side of caution when determining hole spacing and required number of holes.
- Final hole spacing is typically 5 to 10 feet (2 to 3 meters)

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Grout Hole Inclination

- Grout hole inclinations should be designed to intersect open joints as frequently as possible.
- Designers must have thorough understanding of site geology.
- Equipment limitations also must be considered.
- Standard practice now is to have minimum 2 rows of opposite inclined holes.

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Grout Line Spacing

- Houlsby, "It is important to make the spacing between rows in multiple curtains a distance that is less than about twice the general penetration distance."
- Therefore, fine fractures with short grout penetration distance equals tightly spaced rows. Large fractures with long grout penetration distance equals wider row spacing.
- Standard practice is now to have 6-10 ft spacing.

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Consolidation Grouting a.k.a Blanket Grouting

- When is it necessary?
 - USBR Rule of Thumb – Consolidation grouting performed for gravity dams 100' or higher
- Consequences if not utilized
- Typical layouts
- Typical Hole Spacing

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Reasons for Blanket Grouting

- Whenever structure movements must be minimized
- Minimize potential for erosion at soil rock interface within core contact area
- Treatment of weathered zones at depth (cheaper than excavation and backfill)
- Reduction in foundation permeability

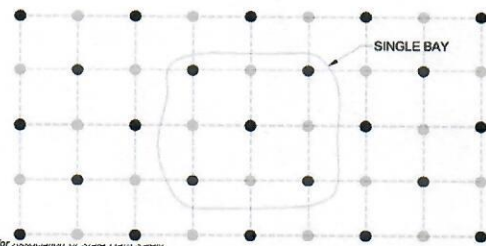
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Hole Layout for Consolidation Grouting

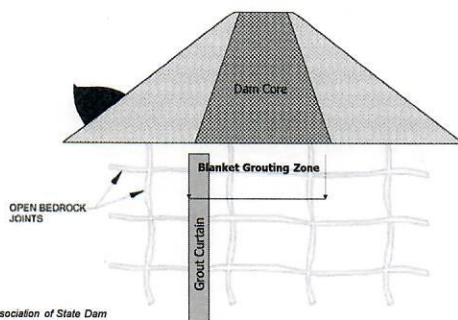
- PRIMARY HOLE
- SECONDARY HOLE
- TERTIARY HOLE



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Blanket Grouting Hole Spacing

- Primary hole spacing typically 40 feet (12 meters), and final hole spacing not more than 5 feet (1.5 meters).
- Poor rock quality and frequent grout connections to adjacent holes may necessitate wide primary hole spacing.

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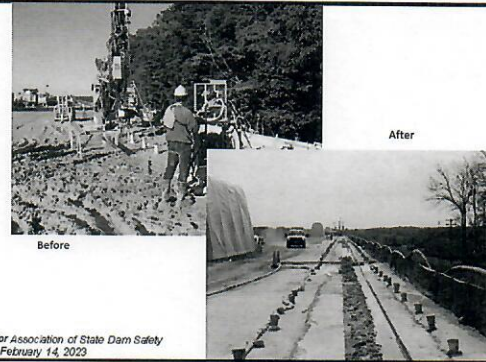
Grout Caps

- Why should they be considered or used?
 - Higher pressures can be used on top stage
 - Eliminates the need for grout nipples (packer can be set within the grout cap)
- Regularizes the foundation surface
 - Aids accessing hole locations
 - Reduces potential for hole contamination
- Increases worker safety and productivity
 - Cleaner working environment – reduces tripping or slipping hazards
 - Can be constructed to drain to facilitate site cleanup

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2. Design Considerations for Quantitatively Engineered Grout Curtains



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Historical Context

- Traditional Practices
- Highly prescriptive specifications.
 - Almost complete absence of rational design and acceptance processes and widespread use of "rules of thumb" for design and execution.
 - Use of:
 - vertical holes to a predetermined depth
 - single row grout curtains
 - long downstages of predetermined length
 - rotary drilling (percussion = air flush)
 - low and conservative grout pressures
 - "thin" grouts
 - "dipstick, gage and stopwatch" methods for injection control
 - termination of work based on grout takes (and/or cost)



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To further illustrate this "traditional" mentality, one may consider the opinion of James Polatty, formerly of the USACE, and a prominent grouting engineer of the period. In an invited lecture on U.S. dam grouting practices in 1974, he gave the following synopsis:

"In preparing this paper, I requested copies of current specifications for foundation grouting from several Corps of Engineers districts, the TVA and Bureau of Reclamation. In comparing these current specifications with copies of specifications that I had in my files 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 cite "difficulty in having sufficient flexibility in the field to make necessary changes to ensure a good grouting job" as a problem on certain of his projects, while "communications and training" was also listed as a challenge.

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Grouting Program Failures

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

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These archaic practices were totally unsuited to the post-1990 remedial grouting demands with respect to logistics, geology, performance and dam safety.



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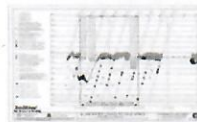
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However,

Since late 1990's, there has been a "technological revolution" in rock mass grouting in North America due to:

- a) Demand/challenges of market (especially remedial curtains in karst).
- b) Advances in technology, driven by a limited number of contractors and consultants.
- c) More appropriate, project-specific specifications ("performance based"), not recycled "boiler plate."



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Contemporary Practices

- Market conditions/industry inertia up until mid-1990's were generally against new technologies. Notable exceptions were USACE/ Reclamation at Ridgway Dam, CO, and Upper Stillwater Dam, UT, and the initial promotion of GIN Theory.
- Technology was totally changed after the association of Advanced Construction Techniques, Toronto, ON (Contractor) and Gannett Fleming, Inc., Harrisburg, PA (Consultant).
- They simultaneously introduced numerous technical developments – as an integrated package – and design concepts (e.g., Quantitatively Engineered Grout Curtains) at a time when the USACE was moving towards "Best Value," as opposed to "Low Bid," and more Performance-based Specifications.

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- The associated design improvements have included:

- o multirow curtains
- o inclined holes in each row
- o depth of curtain determined by geology and/or by rigorous seepage analyses
- o stage lengths commensurate with the structural geology
- o use of the highest safe grouting pressures
- o verification of proper stage refusals
- o verification of residual in-situ permeability upon closure

- Fundamental developments have been made in the construction techniques

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Grouting 2023

- Grouting results can be predicted.
- Grouting can be designed, modeled, specified, and verifiably constructed to achieve targeted, quantified 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 and cost effective method for seepage control.

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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 and presentation of results
- Best Value Contracting and Partnering

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What Do We Need for Quantitative Design and Construction ?

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

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Site Geology Information Required

- Regional and 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)

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Developments in QA/QC and Monitoring



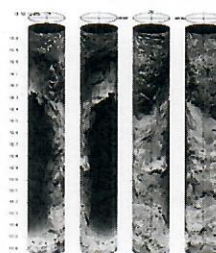
Robertson Geo-Digger System

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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.

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Permeability and Flow Regime Data Sources

- Geologic Information
- Piezometer Data
- Boundary Conditions (HW, TW, Seepage Exit Points)
- Short Stage Pressure Tests in Holes with Appropriate Orientations
- Note: flow through rock masses is discrete fracture/conduit flow, not a porous media flow model

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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.*

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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*

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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*

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Generally Available Design Guidelines

- Readily groutable materials
 - $k > 1 \times 10^{-3}$ cm/sec (> 100 Lugeons)
 - Reductions of 1-3 orders of magnitude (depending on a number of factors)
- Marginally groutable materials
 - $k = 1 \times 10^{-4}$ cm/sec (10 Lugeons)
 - Reductions of 1-2 orders of magnitude (depending on a number of factors)
- Barely groutable materials
 - $k < 1 \times 10^{-5}$ cm/sec (1 Lugeon)
 - Require special measures

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Factors Affecting Grouting

- | | |
|--|--|
| <ul style="list-style-type: none"> • Geology • Drilling technique • Grout Materials • Grout Mixes • Mixing Equipment • Hole Washing • Grout Pumping Equipment • System Setup • Valves and fittings • Bleed • Grouting technique | <ul style="list-style-type: none"> • Hole spacing • Hole depth • Hole sequencing • Hole staging • Pressures • Contractor experience • Refusal criteria • Contract incentives and disincentives • Inspection and control • Testing and analysis |
|--|--|

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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*

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Injection Pressures

- U.S. rule of thumb is 0.5 psi/ft for overburden and 1 psi/ft in rock
- European rule of thumbs range from 2 to 4 psi/ft
- Weaver provides guidelines based on rock quality in Dam Foundation Grouting
- Drilling is the most costly grouting activity
 - Maximizing grout injection pressure maximizes radius of grout spread. Increased grout penetration may result in fewer holes
- Real-time monitoring allows safe pressures to be determined, which often exceed the US rule of thumb

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Weaver and Bruce – Injection Pressures

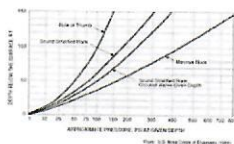


Figure 7. Injection pressures used in all 16 grouting practices.



Figure 8. Injection pressures used in Swedish grouting practice.

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Recommendations

- Use maximum safe grouting pressure. Conventional rules of thumb can be used as a guide but should not be considered the "bible".
 - U.S. rules of thumb are too conservative
- Use grout with small enough grain size
- Use grout that is amenable to formation
- Use either permeability reduction method or GIN Principle
 - Either method can be used successfully if results are evaluated and necessary changes to procedures or materials are implemented
- Must evaluate results with sufficient number of actual in-situ water testing

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Remedial Grouting

- Becoming more and more common as structures from the dam building era of the 1940's to 1960's age.
 - Many grouted with low durability grouts
 - Only vertical holes used
 - Never achieved closure
 - No grout curtain installed during original construction
- Requires very controlled drilling methods above rock (USACE and FERC Guidelines)

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Benefits of MPSP at Interface

- Positive isolation of interface before casing removal
- High confidence level for fully grouting casing annulus
- Allows for treatment of interface and top several feet of rock with suitable grout mix

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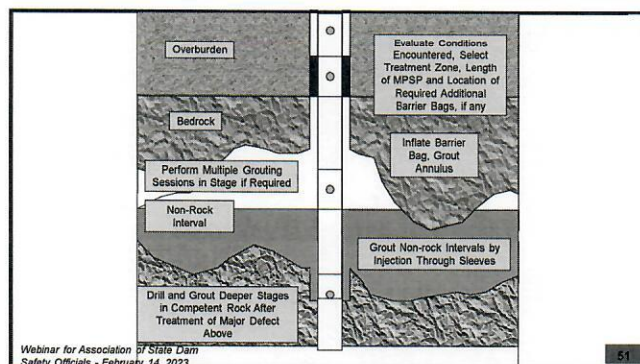
Benefits of MPSP for Large Non-Rock Intervals

- System allows for isolation of major defects with barrier bag system and treatment as required with various HMG materials
- Accommodates multiple injection sessions
- Poor rock conditions near surface can be isolated and treated, while also permitting upstage grouting in stages below where more competent rock is present
- Could be considered as an alternative to downstage grouting in particularly poor ground conditions
- Known areas of major non-rock intervals can be targeted for treatment using MPSP methods by intentionally advancing overburden methods to the known bottom of solutioning

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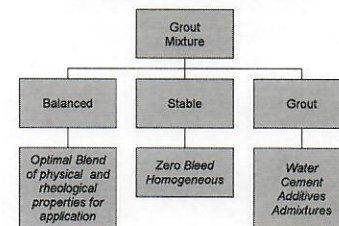


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Balanced Stable Grout



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What are the Desired Properties of a Cement-Based Suspension Grout?

- Low cohesion
- Viscosity consistent with acceptable penetration rate
- Zero bleed
- Constant rheology during application
- Dispersed particles
- High durability
- Resistance to washout

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Characteristics of Unstable Water Cement Grouts

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

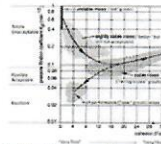
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Grout Mixes and Equipment

- Penetrability controlled by cement grain size, and grout apparent cohesion, but especially by pressure filtration coefficient.



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

- The required properties can only be achieved by multi-component grouts ("stable, balanced") incorporating water, cement, bentonite, superplasticizer and stabilizer et al.
- Stable grouts allow "Apparent Lugeon Theory" for automated injection control to be used.

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Typical Fluid for HMG Properties ("High Performance" Grouts)

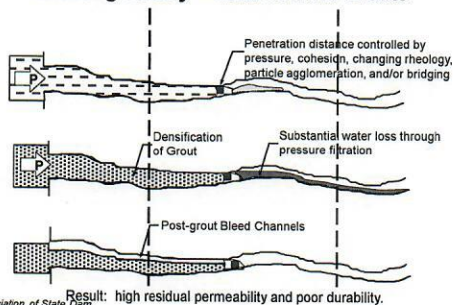
CATEGORY	TEST	REALISED LIMITS
Routine Field QA/QC	• Marsh Funnel (Fluidity)	Mix A 30-35 s Mix B 40-45 s Mix C 55-60 s Mix D > 60 s
	• Hydroid Mud Balance (s.g. and so WCR)	+ 0.02
	• Bleed (static stability)	≤ 2%
Classification/Design Requirement	• Pressure Filtration (stability during injection)	0.04 to 0.08 min ^{1/2}
	• Initial and Final Set Times	4-12 hours
	• Cube Strengths	Practically useless

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Grouting Theory - Neat Cement Grouts

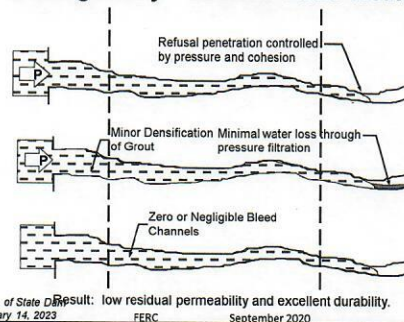


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Grouting Theory - Balanced Stable Grouts



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FERC

September 2020

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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 (Superplasticizer)

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Field Testing of Grout Mixtures

- Typical tests
 - Marsh Funnel for Apparent Viscosity
 - Penetrometer or Vane Shear for Cohesion and Time to Initial / Final Gelation
 - API Filter Press for Mix Stability under pressure
 - Graduated Cylinder for Bleed Characteristics
 - Baroid Mud Balance for Mix Control
 - Vicat Needle for Initial and Final Set Times
- Typical QC Equipment
 - Mixing Equipment Itself
 - Onsite Fully Equipped Laboratory

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Field Quality Control of Grout Mixtures

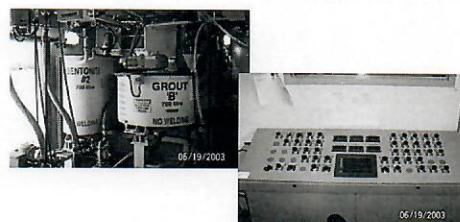


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Field Quality Control of Grout Mixtures



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Advantages of Balanced Stable Grouts

- Dispersed structure, stable rheology and lower cohesion result in increased penetrability and greater radius of grout spread.
- Zero bleed – The fractures that are filled remain 100% filled.
- Increased penetration and zero bleed result in lower residual permeability.
- Lower residual curtain and grout matrix permeability and the addition of a pozzolan, which reacts with lime that is freed during hydration process, results in increased durability.
- Washout resistance

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Overview

- Grout curtains are being systematically engineered to satisfy the in-situ residual permeabilities required by the design (1-5 Lugeons).
- Every major project has provided compliant results using "new technologies"
- Curtains are being used as integral part of the "Composite Wall" concept to explore and improve the rock before construction of a concrete diaphragm wall between the outer rows.
- Every such project has been successfully and safely completed.
- Several contractors are now skilled in the use of the "new technologies".
- USACE's Engineering Manual on Grouting Technology (July 2014).



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Q & A

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3. Grouting in Rock: Standard Operations and Sequence



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Upstage Technique

- ☐ Drill to final depth in one continuous operation
- ☐ Wash to final depth in one continuous operation
- ☐ Water Test from final depth to top of hole in one continuous operation
- ☐ Grout from final depth to top of hole in one continuous operation

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Downstage Technique

- ☐ Drill to predetermined depth
- ☐ Wash to predetermined depth
- ☐ Water Test from predetermined depth to top of hole or previous drilled depth
- ☐ Grout from predetermined depth to top of hole or previous drilled depth
- ☐ Repeat operations sequentially until final depth is achieved

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Selecting Grouting Method

- Upstage Drilling and Grouting
 - Cheapest and most common method
- Downstage Drilling and Grouting
 - Technically superior to upstage methods in all cases
 - Provides the highest quality data
 - Generally accepted by most notable Authors as the "best" grouting method
 - Safest method for embankment dams on fractured rock foundations
 - Traditionally reserved for difficult or problematic ground conditions due to perceived economics

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Quotes from Authors on Upstage

- (Houlsby, *Construction and Design of Cement Grouting*, 1990) "This is the cheapest method on sites where all goes well but not where they don't. Its apparent lower cost is often an attraction to specification writers who are trying to minimize costs and are keeping their fingers crossed that all will go well and holes won't collapse too often."
- (Warner, *Practical Handbook of Grouting*, 2004) "With the substantial limitations this method should probably be reserved for grouting in very competent rock."
- "In sufficiently massive rock with defects generally uniform in width, this is unquestionably the fastest and most efficient method. However, this ideal condition seldom exists in the real work of grouting, so the method is often problem prone, especially where fractured rock zones are encountered. The initially perceived savings can therefore rapidly decrease."
- "There are also substantial technical shortcomings to this progression... Obviously, a greater amount of drill cuttings will find their way into higher joints and defects. Significantly, this is usually the zone containing the largest number of defects and where the highest quality of work is needed because of contact with the dam body."
- (Weaver and Bruce, *Dam Foundation Grouting*, 2006) "It is generally applicable where minimal problems are encountered with seating packers, where the bore holes are mechanically stable, or with grout bypassing the packer through rock."
- "A hole may collapse before or after the packer is introduced, leading to incomplete treatment."

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Upstage vs. Downstage

- Practical Downstage Grouting
 - Use downstage grouting until you prove you can use upstage rather than attempting upstage and finding out downstage is required
 - Perform downstage grouting as a general practice on hole series, grout lines or entire curtain segments in poor ground conditions
 - Best Practice is to plan ahead and proactively use downstage to benefit the schedule and technically benefit the project

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Special Conditions

- Water Loss During Drilling
 - Always stop drilling and grout as a separate stage when water losses are experienced
 - The hole has encountered a major feature that will dominate the grout injection
 - Continued drilling will result in cuttings being injected into and contaminating the fracture that resulted in the water loss
 - Drilling difficulties and lost tooling may result from continued drilling
- Artesian Conditions
 - Some specifications require stopping and grouting as a special stage because major feature has been encountered
 - Hole contamination and drilling difficulties not an issue as the hole is making water

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Special Conditions

- Connections to Adjacent Holes
 - Record connection during drilling, washing, water testing, or grouting so that connection is anticipated when performing future operations
 - Connections during water testing – set packer in adjacent hole to acquire truer water test result
 - Connections during grouting – recommend that connected hole be actively injected simultaneously with original hole.
 - Placing blind packer results in connected hole being grouted at reduced effective pressure from originating hole.
 - Connections during upstage result in entire hole being grouted.

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Hole Washing

- Purpose is to evacuate remaining drill cuttings, clean hole side walls and clean entrance into fractures.
 - Cuttings or soil grains can be carried into the fracture and lead to clogging and premature refusal
- Washing should continue until the return water is clear.
- Where water is lost or a connection develops to an adjacent hole, washing should be performed for a prescribed duration of approximately 5 to 10 minute

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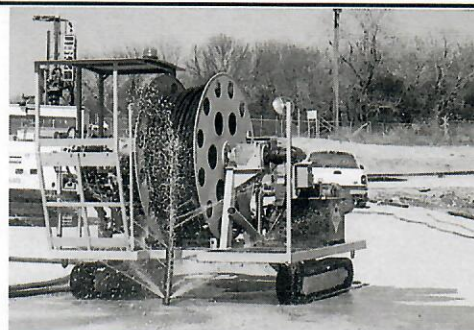
Hole Washing

- Soil Filled Fractures
 - Cannot inject enough water to wash out infilled fractures of any size
 - At best, a channel is eroded to accommodate the volume of the water flush
 - Do not assume that infilling has been removed to a significant degree
 - Co-injection of air with water to "irritate" the flow in the fracture might increase the amount of removed material

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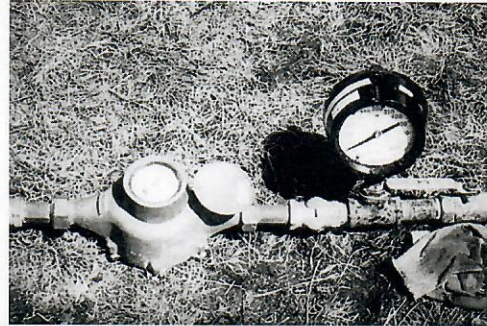
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Pressure Testing

- Header
- Single or Double Packer System
- Interpreting Results
- "Instrumented Packer"

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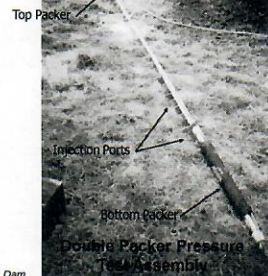
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Lugeon Value

Measure of Permeability is commonly used in grouting project

- 1 Lugeon is approximately equal to 1.3×10^{-3} cm/sec.
- Definition: Equal to 1 liter of take per meter of hole at 10 bars pressure

Calculation of Value

$$L_{\text{rock}} = \frac{Q}{I} \frac{1800.6}{P_{\text{eff}}} \frac{T_{\text{marsh}}}{28}$$

- Metric Units:

$$L_{\text{rock}} = \frac{Q}{I} \frac{145}{P_{\text{eff}}} \frac{T_{\text{maria}}}{28}$$

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SAMPLE - PRESSURE TESTING & PRESSURE WASHING RECORD

Gannett Fleming
 1000 Walnut Street, Suite 2000, Philadelphia, PA 19106
 Tel: 215.382.2000 Fax: 215.382.2001
 www.gannett-fleming.com

ROCK PRESSURE TESTING & WASHING

Page 1 of 2

Project Wash State Comm

Disc of ES + ES 57

MOB NO 544371

CLEVELAND Engineering Co.
 DATE ORDER 6/5/67

Elevation Top of Hole 158.8
Diameter of Hole 8.000

Name of Inspector: James
 Sub-Area: 100

總發行 尹乃德尹德昌 電話 02-2201-0000

Inclination: 52 degrees

Gauge Elevation: +0.91

Segn	Feet	Seg
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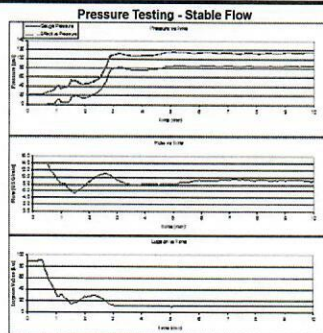
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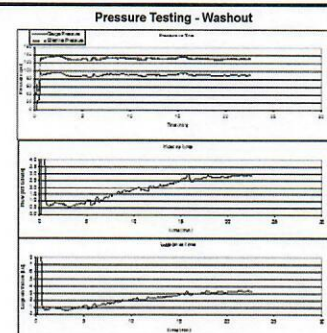
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Step Pressure Testing

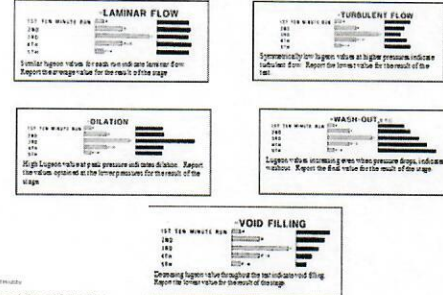
- Perform at 5 pressures (low, moderate, peak, moderate, low)
 - Example 50%, 75%, 100%, 75%, and 50% of the maximum test pressure
 - Can be used to aid in establishing safe injection pressures for grouting
- Reasons for Performing
 - Can assess if flow is laminar or turbulent (fracture size)
 - Indicates dilation or lifting if threshold pressures are exceeded
 - Can determine if void filling or washout of infilling is occurring

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Interpreting Pressure Testing Trends



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Grouting

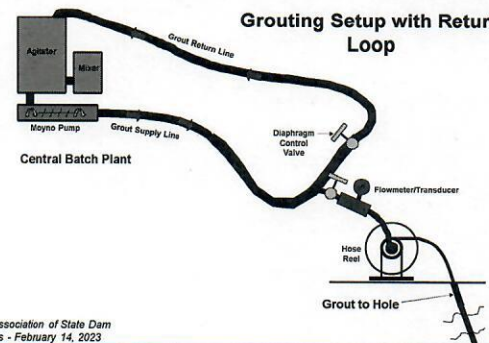
- Batch Plant
 - Mixers, Agitators, Pumps
- Circulation Loop
- Special Site Conditions

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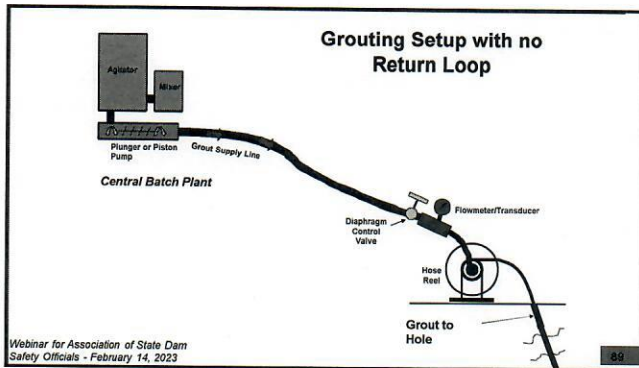
Grouting Setup with Return Loop



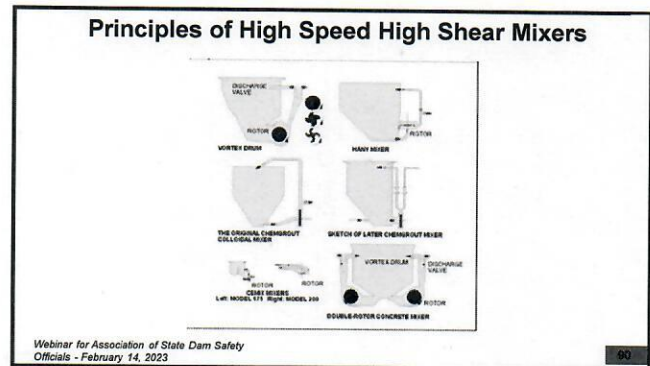
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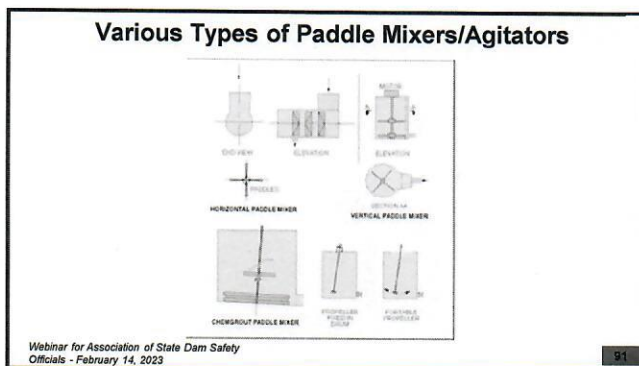
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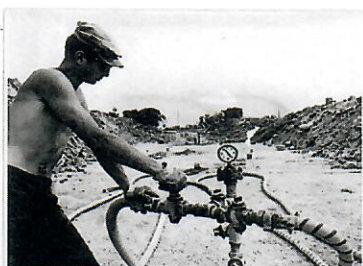


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Traditional Injection Control



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"Dipstick and Gage" Monitoring (early 1970's)



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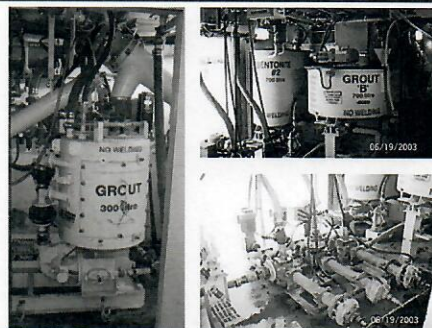
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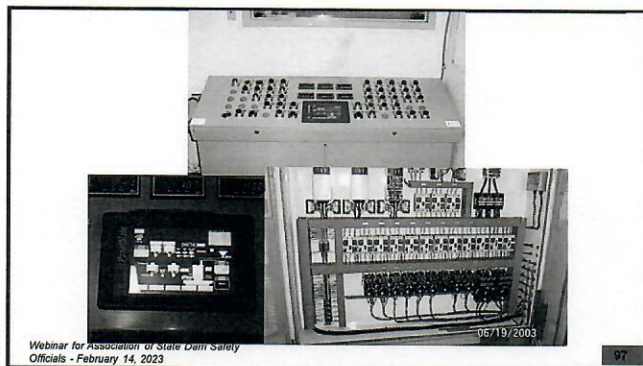
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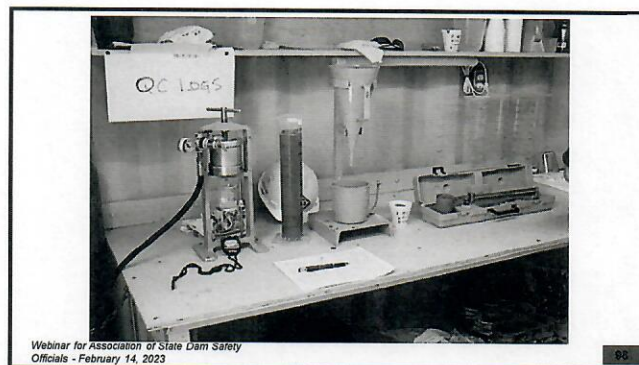
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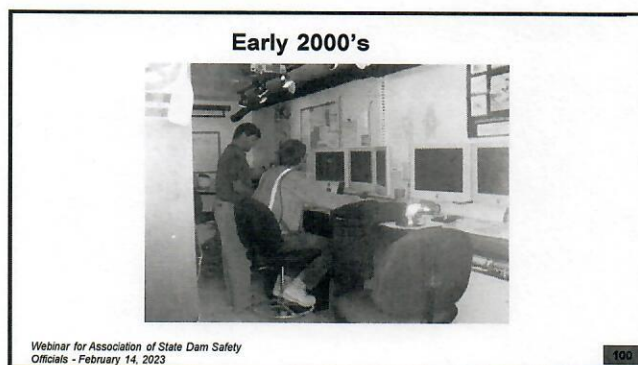
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Current State of Best Practice



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Refusal vs. Closure Resolution

- Refusal
 - Every Grout Stage should be brought to proper Refusal: otherwise the (expensive) drill hole has not been efficiently exploited
 - Example: 0.25 gpm (~1 lpm) held for 5 minutes: some specs are now relaxing to 0.75 or 1.0 gpm
 - Achieved on an Individual Stage Basis
 - "Refusal" Does Not Mean "Closure"
- Closure
 - Permeability of the Rock Mass Attained to a Degree of Certainty
 - Compared to Target Permeability
 - Holistic Analysis of Achieved Results at Each Hole Series and Each Line
 - Statistical Methods
- Apparent Lugeon Theory
 - For rheologically stable grouts, then the grouting operation can be analyzed and controlled as if water were being injected.

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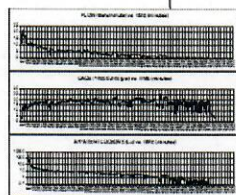
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- Apparent Lugeon value (Lu_a) is calculated (and displayed in real time) as for water Lugeon value, i.e.,

$$Lu_a = \frac{\text{water flow rate}}{\text{pressure} \times \text{stage length}}$$

$$Lu_a = \frac{\text{grout flow rate}}{\text{pressure} \times \text{stage length}} \times \frac{\text{marsh grout}}{\text{marsh water}}$$



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4. LIMITED MOBILITY GROUTING (LMG) FOR DAM AND LEVEE REMEDIATION

4.1 General Principles

4.2 Case Histories

(Note: LMG also used at Clearwater, Wolf Creek, and Boone Dams as part of the "composite cutoff" construction).

These are discussed in Section 7.2.



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4.1 GENERAL PRINCIPLES

LMG is the broad term now used for the methods and materials used for:

- Soil densification ("compaction grouting")
- Lifting and levelling of structures
- Soil displacement (e.g., soft residual clays in epikarst)
- Void filling (karst, mine workings)

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Compaction Grouting – Overview / reminders

- Mechanical process used to densify loose soils
- Grout displaces soil in shear
- Forces soil grains into tighter packing
- Air and water expelled=> pore volume reduced
- Treated ground contains stiff grout masses and densified soil.
- Arguably one of the most sustainable ground improvement technologies!
- Drilling typically does not dictate a schedule on a CG grouting job. Appropriate injection rate controls.
- Void filling in dynamic flow conditions.

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COMPACTION GROUT

"Grout injected with less than 1 in. (25 mm) slump. Normally a soil -cement with sufficient silt sizes to provide plasticity together with *sufficient sand sizes to develop internal friction*. The grout generally does not enter soil pores but remains in a homogeneous mass that gives controlled displacement to compact loose soils, gives controlled placement for lifting of structures or both."

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Compaction Grouting – Materials Fundamentals

Compaction grouts typically are:

- Low-Slump (1/2" to 1 1/2").
- Low-Mobility – does not travel far from the point of injection. Tunnels and Mine grouting may need 1/4" slump for plug grouting
- Low compressive strengths (300 to 1,500 psi). Rigid Inclusions may be on the order of 2500 psi
- Well graded blend of gravel to silt and clay sized particles, usually classifying as a silty Sand (SM) (Unified Classification System). Mine tailings and recycled concrete have been utilized as well.

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Compaction Grouting – Short History

- Began in mid-20th Century.
- Only major grouting technology to originate in United States.
- Today, CG technology is used worldwide.
- CG development progressed through the efforts and innovations of many small, independent contractors.
- Fundamentals don't (shouldn't) change internationally
- Basic fundamentals don't change from decade to decade.

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San Diego - 1991



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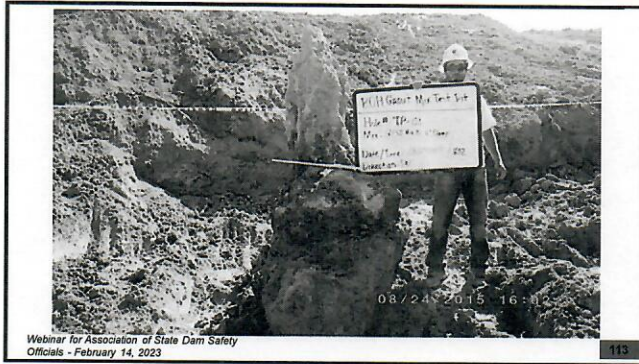
San Diego - 1994



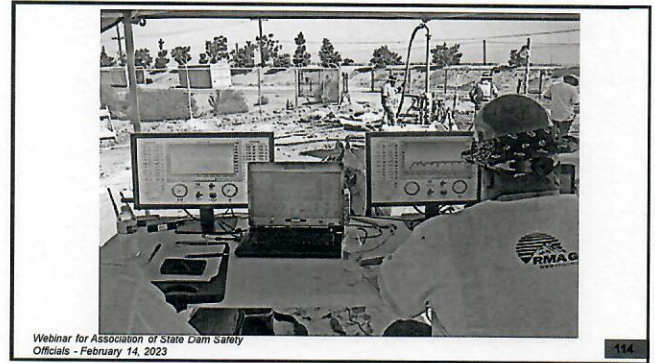
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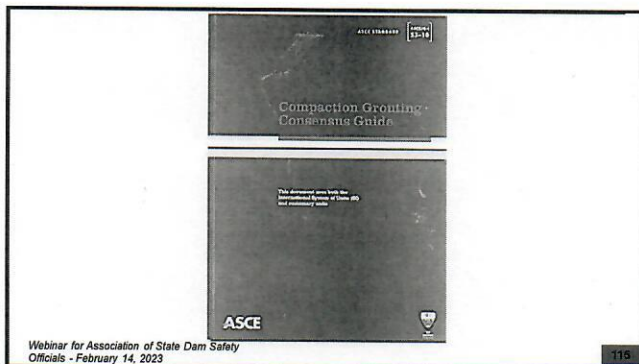
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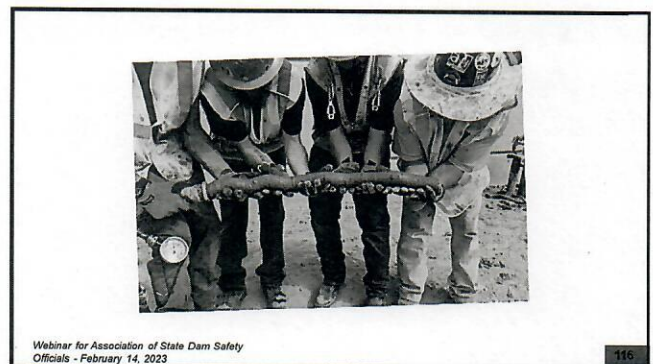
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Refusal Criteria

- Pre-established cutoff criteria for the grouting program at a given increment or stage
 - **Pressure** – when a certain maximum predetermined pressure is recorded at the injection header
 - **Quantity** – when a predetermined amount is injected at a given stage
 - **Movement** – when undesirable movement is detected
- Can be modified in the field based on actual in-situ conditions
 - If one tweaks the program too frequently and prematurely, one loses the ability to compare valuable data

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Injection Rate

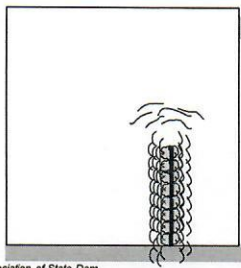
- Typical injection rate is on the order of 2ft³/min.
- Slower rates may be needed for sensitive applications.
- Higher rates may be used under certain conditions depending on soil and depth (but likely needs advanced monitoring and/or analysis).

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Compaction Grouting Mechanics Summary



- Grouting performed in "Stages", usually from the bottom-up.
- Each stage is pumped until terminal criterion is met.
- Casing is withdrawn in regular intervals as successive stages are pumped.
- Result is a relatively uniform column of treated soil.

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4.2 TWO CASE HISTORIES

- Tims Ford Dam, TN
- Logan Martin Dam, AL



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CASE HISTORY

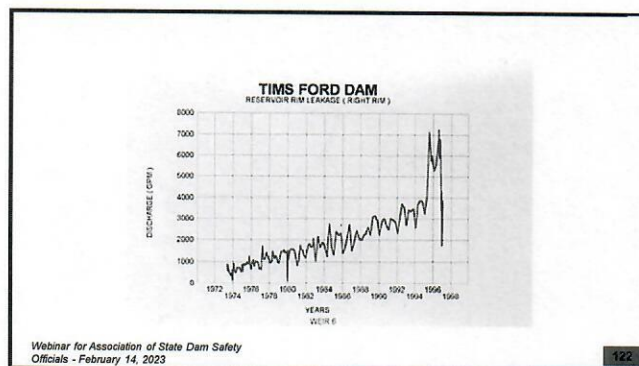
TIMS FORD RIGHT RIM LEAKAGE

- Weirs utilized to monitor leakage through right rim
- Recorded flow vs. time
- Landslide on hillside observed
- Implemented grouting program to reduce leakage
- Monitoring leakage after grouting

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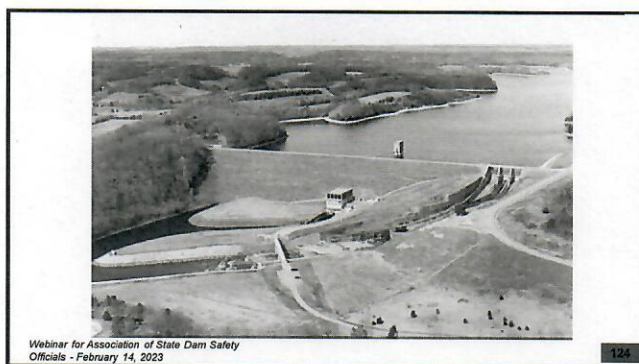
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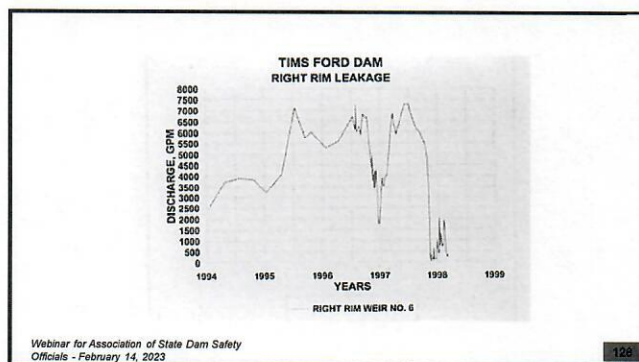
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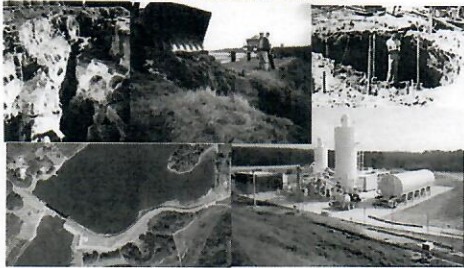


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Long-Term Grouting of a Karst Foundation at Logan Martin Dam, Alabama



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Brief Introduction to Logan Martin Dam



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Geology:

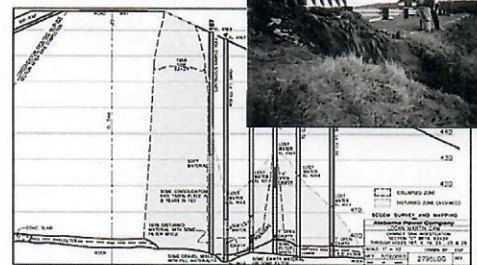
- Paleozoic carbonate bedrock, mainly siliceous dolomites.
- Extensive, complex folding and faulting facilitating massive, deep karstic solution features.
- Multiple seepage paths along stratigraphic zones, faults, joints and fold axes, to depths of over 120 m below the dam.
- Project has had (is having) ongoing phases of intensive geological mapping, culminating in current geological model development

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1968 Sinkhole



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Phases of Grouting since Construction

- Phase 1 - Original Construction Grouting (1960, 1964)
- Phase 2 - Emergency Chimney Sink Grouting (1968)
- Phase 3 - Grouting Programs (1972-1990)
- Phase 4 - Deep Grouting Program (1991-2006)
- Phase 5 - Compaction Grouting Program (2005-2008)
- Phase 6 - West Side Grouting (2008-2011)
- Phase 7 - Deep Curtain Regrout (2011-Present)
- Phase 8 - Downstream Shallow LMG Grouting (2013-Present)
- Phase 9 - Deep Rock Zone and Areas to the East (2016-Present)

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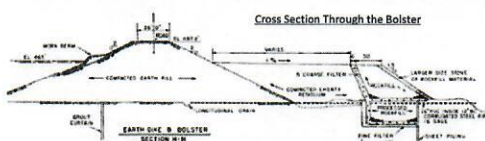
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Additional deep into-rock piezometers on Bolster drilled as future grout monitoring instrumentation led to unsettling findings:

- Difficulties in setting casing, communications of pressure and drilling fluid between drill holes and instrumentation.
- Review of historic drill log data, framed in reference to the recent drilling data and the communication anomalies, led APC/SCS to conclude additional protection prudent to mitigate sinkholes.
- **Problem:** Untreated upper bedrock zone: 50 feet thick, consist of about 30% voids (filled and unfilled), underlying a relatively thin "roof" of competent rock.

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BOC, APC, FERC Convened a Brainstorming Meeting February, 2013

Concluded: Although not judged to be an immediate dam safety issue, the APC/SCS project team felt that this was a concern which should be addressed forthwith.

How should this problem be treated to reduce risk?

Two methods debated:

- Discrete grout columns with Low Mobility Grout (LMG) to reinforce the zone of concern; and
- "Block" infilling approach, using Medium and/or High Mobility Grout (MMG and/or HMG)

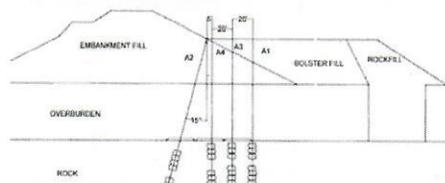
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Plan A- Discrete LMG Grout Columns

- Test Area: Two rows with four grout holes per row.
- 20 feet general grid spacing based on fracture patterns; Discrete columns ~5 foot diameter
- Hole closest to the slope of the dam was drilled at a 15 degree angle upstream.
- Drilling techniques discussed in paper.



Plan A- LMG Grout Columns (not to scale)

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Plan A- LMG Grout Columns (Continued)

Stage grouted hole using following mix (per cubic yard):

- 350 lbs. of cement
- 2000 lbs. of concrete sand
- 1200 lbs. of fly-ash
- Enough water to yield a 3 to 4-inch slump (in the range of 40 gallons)

- Grouted from bottom up, five foot stages
- Initial Termination criterion: grout until effective pressure between 150 and 200 psi or about 3.5 cubic feet of grout injected, whichever came first.
- Objective was to form approximately 5 foot diameter columns (based on a 30 percent void ratio).
- Grout mix was adjusted to a higher slump and injected to form a cap along the top of rock (mushroom corbel).
- Downstream hole grouted first followed by the upstream hole. No more than two holes were open at a time. Following the first two holes, the middle grout holes were drilled.

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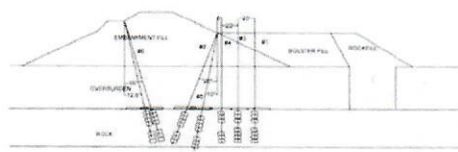
Field Test Program Results

- Upon completion of the test sections, the discrete column approach was found to be more appropriate due to large grout takes found to be needed for infilling due to the large void ratio.
- Proposed to core discrete column locations to see results
- Instrumentation response: a couple piezometers experienced slight rises during drilling that quickly dissipated; no pH hits or drain flow changes were noted. No grouting of instruments or grout shows in drains
- Overall rock mass "voidage" encountered in discrete columns had been found to be around 26-30% in the 50 foot thick treatment zone.
- Typically, the grout take at each discrete column was 14 to 16 cubic yards.

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Final Configuration of LMG Column Layout at Each Station (not to scale)

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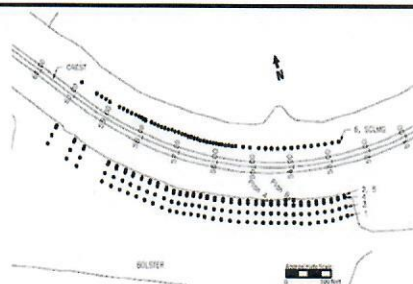
Production Grouting

- The production work proceeded without significant incident (most of the bugs were worked out during the test section phase of work).
- 263 column locations were grouted.
- Prior to grouting, each hole was evaluated based upon available data such as the location and number of cavities (whether or not the cavities were open or mud filled) void ratio, and number of stages.
- A total of 2,156 cubic yards of low mobility grout has been injected into the formation.
- The average grout take at each column location was 8.2 cubic yards.
- A total of 36 stations (20 feet on center) were treated along the downstream bolster.

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Final Plan of LMG Column Locations at Ground Surface as Constructed (Black Dots)

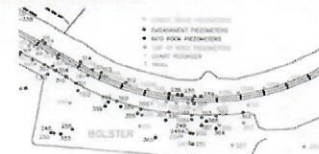
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Instrumentation During Production Grouting

- 10 deformation monuments, located along the downstream crest of the dike at the even 100-foot stations.
- 7 lateral toe drains monitored for flow, clarity and pH.
- Laser survey equipment is arranged on the slope of the embankment or on the bolster immediately upstream of active grouting locations to monitor for heave.
- 65 open-stand-pipe piezometers and wells.



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Piezometer Response

- Water elevations were influenced by drilling and grouting in all top-of-rock and into-rock piezometers relatively close to the grout holes.
- In many cases there was a rapid rise in water levels recorded by nearby piezometers, which returned to normal following cessation of drilling or pumping grout.
- Interestingly, 7 piezometers were lowered by 1 to 3 feet. 3 Piezometers appear to have been permanently raised slightly, but continue to show tailrace pressure influences and therefore the ability to drain.
- Two piezometers were inadvertently grouted up during the grouting process .

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Final Project Findings

- Final average void ratio being about 26 percent
- Grout unconfined strength values found from test cylinders measured over 4,000 psi (27.6 MPa) at 28 days. More than adequate strength to carry the design column loads.
- Following the completion of the LMG grouting, 4 additional test core holes drilled. Grout was found in cavities that would have been open or filled with loose material. Very little grout was found outside the theoretical diameter of a column.
- Construction of the individual columns did not cause any adverse change in flow or pore pressures (based on instrument monitoring).

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5. Closure

- Rock fissure grouting practices have developed greatly in the US since the late 1990's, partly due to the challenges posed by the need for remedial grouting of karstic foundations.
- There are many examples of successful applications for Federal and non-Federal projects.
- There is a relatively small pool of very experienced, well resourced specialty contractors. Such qualifications are essential for remedial work in particular.
- A prime requirement in every project is to prevent damage to the embankment and the foundation.
- HMG and LMG can be used alone, or together, or as components of a "Composite Wall" (i.e., grouting followed by a "positive" cutoff e.g., a diaphragm wall).
- There is a very rich technical literature, based on Conferences and Textbooks, offering guidance to non-specialist engineers and geologists.

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THANK YOU

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Q & A

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