Errors, Misunderstandings and Mistakes in Remedial Grouting Projects for Dams

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Abstract. The technical revolution in remedial grouting for dams is well into its second decade of practice in the U.S. Technical papers, textbooks and Government guidelines have been published detailing what is now considered the state of that practice. Many large projects have been undertaken in very challenging technical and dam safety situations, and experiences have been shared. However, the authors still find that not all participants in this field truly appreciate the details and subtleties of our current practice and certain poor practices from earlier decades are beginning to resurface. This paper highlights some of these issues, and offers plain guidance on:

- Design Aspects (such as the number of grout hole rows and maximum safe water testing and grouting pressures.
- Construction Details (such as the true value of an engineered, concrete working platform, the use of Water-Powered Down-the-Hole Hammers, the difference between Refusal and Closure, and the correct placement of standpipes for epikarst treatment).
- Analytical Details (the difference between real and Apparent Lugeon values, and their relation to residual permeability).
- QA/QC Aspects (such as tolerable ranges for fluid grout properties, and the necessity to have a functional DMS system).
- Dam Safety Monitoring (such as the need for Joint Instrumentation Monitoring Programs, and long-term performance monitoring).

The authors trust that this paper will be of interest and value to owners, engineers and contractors alike, since all parties are (or should be) committed to ensuring a project that is successful in the eyes of all.

I. BACKGROUND

It is widely recorded that since the late 1990's in the U.S. there has been a technological revolution in rock fissure grouting practices, primarily as a result of the technical and dam safety challenges which have typified the dam remediation market. This revolution has been well documented in numerous papers at the New Orleans Grouting Conferences (2003 and 2012), in USSD and ASDSO publications and conferences, and in more recent textbooks (Weaver and Bruce, 2007 and Bruce 2012). Final confirmation is provided in the USACE's new Grouting Manual (2014) which is a radical overhaul of the prior version (1984).

An observer of successive huge karst grouting projects for USACE structures at Mississinewa, IN, Clearwater, MO, Center Hill, TN, and Wolf Creek, KY as examples, cannot fail to note the sophistication (and the curious similarities) of the means, methods and materials each contractor has used. It is equally clear that owners and designers are producing specifications that consistently reflect modern practices, instead of recycling contract documents ("boiler plate") that are inconsistent and awkward amalga of the old and the new.

The authors are involved in different contractual and oversight roles in a large number of remedial grouting projects for dams. We have noted over the last few years that certain basic tenets of the revolution have not been correctly applied, or applied at all. If left unchecked, these regressions will have the effect of reducing the quality and reliability of the finished product, and will increase the prospects of contractual disputes.

II. DESIGN-RELATED ISSUES

A. Number and Spacing of Grout Lines

The number of grout lines and the spacing between each grout line are typically concerns for foundation grouting programs that involve the future construction of a positive cutoff wall. Good practice for the construction of a grout curtain only solution (typically used for new dam construction) involves the use of two or more grout lines (or rows). In addition, these lines are spaced such that each line's "zone of influence", based on anticipated grout spread, sufficiently overlaps with the other adjacent lines. This overlap provides several benefits to the overall effectiveness of the grout curtain. Benefits include providing a more intensively grouted rock mass, with each grout hole adding to the overall permeability reduction of not just the grout line itself, but to the entire rock mass.

Recent applications of grout curtains in large dam rehabilitation projects have incorporated the design and construction of a minimum two line curtain with a second phase positive cutoff wall, whereby the two line grout curtain provides upstream and downstream seepage reduction against potential slurry losses in the areas of the bedrock foundation where the future cutoff wall is to be constructed ("composite wall" concept). There has been a general trend to widen the distance between the two main grout lines in an effort to avoid potential obstructions to the cutoff wall equipment with lost or stuck drill steel that may need to be abandoned due to operational issues or difficult geologic conditions encountered.

The decision to widen the spacing between the two main lines of the grout curtain, while performed in the best interests of the safe and efficient operation of the cutoff wall equipment, should be balanced with the knowledge that such widening has an adverse impact on the overall effectiveness of the grout curtain. In extreme cases, the two grout lines are so far apart such that each line effectively behaves as an independent grout curtain with no mutual influence or benefit in permeability reduction from the other line. The result is the need to drill additional holes in each individual line in order to achieve the target residual permeability.

B. Angled Hole vs. Vertical Hole Orientation

The orientation of the production grout holes should always be set to maximize the intercept of the principal joint sets within the rock mass, while giving appropriate consideration to drilling method limitations. Designers are often tempted to specify vertical holes for a combination of convenience, hole stability, hole alignment (avoiding excessive deviation), and perceived cost savings. However, this approach has the potential to leave ungrouted or poorly grouted zones within the bedrock foundation due to missed or inadequately grouted fractures. Geologic formations that are horizontally bedded generally have a primary joint set that is perpendicular to the plane of the bedding, i.e., vertical or near vertical. Therefore, grout hole orientations that are also vertical reduce both the probability and frequency that an individual vertical fracture is intersected by a production hole and treated with grout.

The near vertical joints in the rock are typically the most open (permeable), and therefore should be intersected and grouted as frequently as possible. Bedrock formations with horizontal bedding and near vertical joint sets should have production grout holes oriented at minimum of 10° from vertical and are usually between 15°-30° from vertical based on analysis of the bedding and fracture joint sets. Vertical production grout holes are only recommended for bedrock formations in which the bedding and primary joint sets are both oriented to near 45° or flatter from horizontal.

C. Upstage vs. Downstage

The decision to exclusively utilize upstage over downstage grouting procedures in many recent dam rehabilitation projects is fraught with the misunderstanding of the importance of employing downstage methods immediately below the soil/rock interface to protect the embankment, as well as the misconception and bias toward the perception that upstage is the cheaper method of grouting. However, the assumption that upstage grouting is or will be cheaper is often based on the fact that drilling is the most expensive activity on a grouting project. In reality, it is the effectiveness of the grouting operation that will affect hole stability (collapse) and permeability reduction of the rock mass during future hole series which in turn determines the need for additional holes. It is therefore imperative that all portions of the hole be grouted effectively. Unstable, collapsed holes limit access to fractures and reduce the effectiveness of grouting a production hole (or requires multiple redrills), and thus affects the overall quality and cost of the grouting.

The common misconception is to view the multiple drilling and grouting steps of the standard downstage program, which may include some additional set ups and redrill payment quantities, and conclude that upstage is more cost effective, because downstage is more expensive per hole. However, the rock formation to be treated will not likely behave according to perceptions of cost saving or the wishes of the designer to execute an upstage program. Houlsby (1990) offers the following prophetic observation on upstage grouting:

> *"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 cost and are keeping their finger crossed that all will go well and holes won't collapse too often."*

When hole stability cannot be achieved through upstage methods, downstage methods must be implemented. Grouting projects in karst should automatically be viewed as a downstage program first, and should only switch to upstage once it is demonstrated that hole stability can be maintained full depth.

For remedial grouting through an existing embankment, the top stage or stages should always be downstaged and brought to closure to protect the embankment from attack by the water used in drilling of deeper stages. The depth of the initial downstage treatment is dependent upon both the angle of the holes and the spacing between holes. Figures 1 and 2 illustrate the relationship between hole angle, hole spacing, and the depth of treatment required to intersect all potential vertical fractures that have the ability to convey water to the soil rock interface.

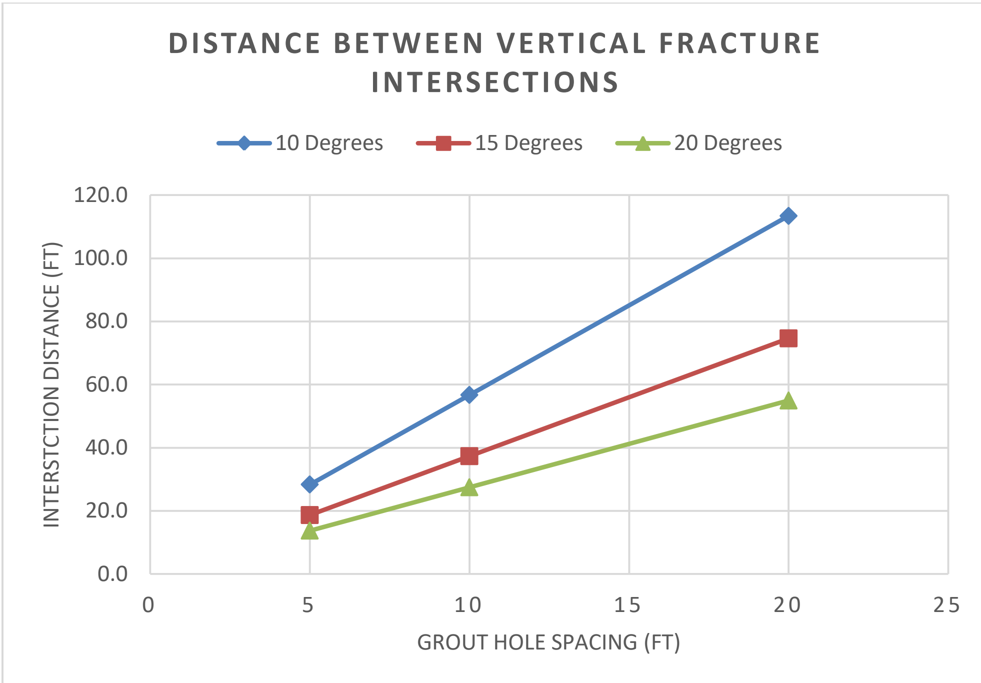

Figure 1. Relationship between hole spacing, hole orientation, and intersection distance to vertical fractures.

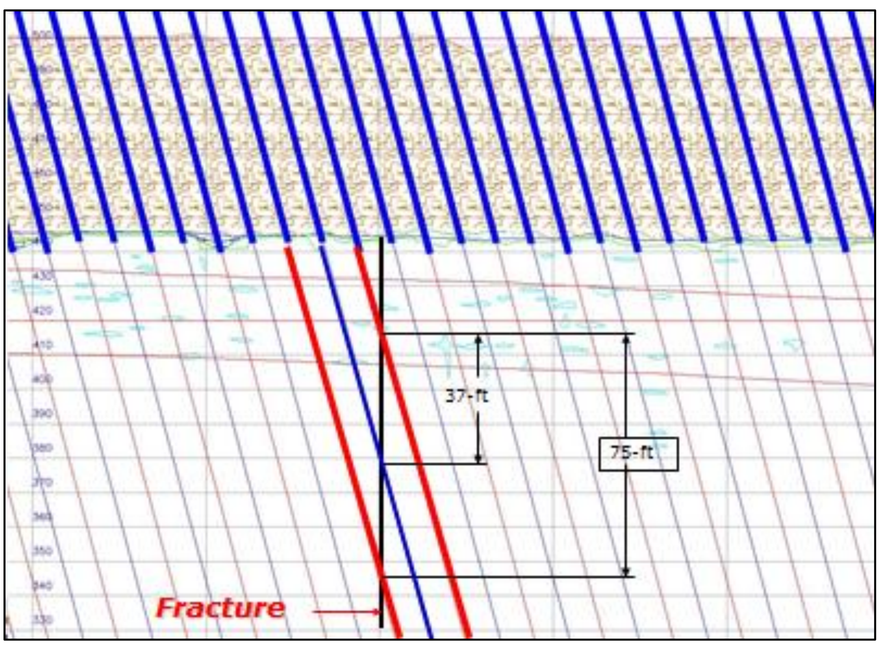

Figure 2. Visual representation of distance required for intersection of vertical fractures (15° Holes, 20 ft vs. 10 ft hole spacing).

From a budgetary standpoint, all foundation grouting rehabilitation projects in known karst formations should anticipate full downstage and estimate quantities and prices accordingly. If a grouting program is able to switch certain hole series or portions of the program to upstage the project will recognize a cost savings, but is covered should upstage methods not be achievable.

III. CONSTRUCTION-RELATED ISSUES

A. Working Platforms

There are still rare instances when the owner (and/or the engineer) does not recognize the value of an engineered, concrete working platform from which to conduct all drilling, water pressure testing and grouting operations. Sure, it is an expense, with no direct benefit to the in-situ rock mass treatment and, of course, the platform typically has to be removed after the grouting is complete. However, there are several strong benefits that collectively overcome the "cost factor" of a platform, including:

- It is a boon to the safety of personnel.
- It allows all spoils to be collected and led away so protecting the dam's surfaces.
- It facilitates hole location and identification.
- It allows the safe passage of all the drilling and ancillary equipment.
- It provides a firm anchorage for standpipes.
- It can assist in preventing near-surface connections between holes.
- It enables very efficient work processes that add up to cost and schedule savings.

Grouting is ultimately a series of multiple individual operations, each with highly repetitive tasks, linked together into an assembly line process (one in which the individual construction equipment pieces move and the widgets (i.e. grout holes) being produced remain stationary). The execution of drilling and grouting needs to be viewed as an assembly line process whereby the improvement in the efficiency of the means and methods benefits both the overall quality and consistency of the final product as well as the cost and schedule. A concrete work platform is the means by which a smooth and effective drilling and grout assembly line process is achieved.

Drilling and grouting is also a water intensive program. Water, drilling cuttings, and grout wastes are constantly emitted from production holes and require a safe and efficient means for proper collection and removal. The collection and treatment of these large volumes of fouled water must be clearly identified in the specification and incorporated into the site infrastructure and layout. Anything less than a uniform concrete surface will quickly degrade with the introduction of the large amounts of water and solid wastes generated by the accumulated drilling and grouting of each hole. Individual tasks then become bogged down having to traverse and work on a platform that is constantly filled with mud, muck, and waste products generated by the various operations. The overall time to perform each task is significantly increased when operating from a platform that requires constant maintenance and repair. Safety hazards are increased and efficiency goes down. Project shutdown due to safety or environmental concerns is inevitable.

A hypothetical example illustrating the cumulative savings of an efficient work platform shows that by reducing the amount of time it takes to perform a single critical path operation, say just 5 minutes required to setup and grout a stage, saves nearly 14 days of schedule and cost for each 1000 foot-long section of a 2 Line curtain, with 5 foot c-c hole spacing, and average of 10 stages per hole (1000ft/5ft/hole *2 Lines*10 stages/hole * 5 mins/stage = 20,000 min = 13.9 days). With multiple activities on the critical path, months can be saved by the construction of a safe and reliable work platform.

B. The Use of Water-Powered Down-the-Hole Hammers

It is one of the oldest debates in the drilling and grouting industry: percussion versus rotary methods and air flush versus water flush. Past practice has been dictated by the capabilities of the drilling industry: given that air flush is not permissible for rock fissure grout holes, or when drilling in karstic limestone formations under existing embankments, much traditional work was done by rotary drilling, either coring or "blind," using water flush.

Rotary percussion drilling, especially of the Down-the-Hole (DTH) variety, has distinct advantages over rotary drilling in terms of speed and deviation control, but was always synonymous with air flush. The practice of some contractors to "mist" the air with water is totally misguided, as this reduces the chances of drilling a clean hole, not improves it. The best of all worlds arrived in 1995 in the form of the water activated (and flushed) DTH (WDTH) (Bruce et al., 2013) (Figure 3).

This tool has been the staple of grouting contractors since it was first successfully demonstrated at the McCook Quarry Trial (Chicago, IL) in 2001.The true advantages of the WDTH greatly outweigh the perceived disadvantages: piezometric "spikes" on nearby piezometers do occasionally occur, but are transient, dissipating very quickly. We know of no recorded Dam Safety Incident caused by the use of WDTH.

Figure 3. Photo of rotary percussion drill with water activated Down-the-Hole Hammer (Upper Left).

C. Refusal and Closure

Each and every stage of every grout hole must be brought to a true and proper "refusal." This means that the maximum specified pressure has been held over a certain period (say 5 minutes) at a certain maximum flow rate (typically 1-3 liters per minute, depending on the project's residual permeability goals and the nature of the rock mass). "Closure," on the other hand, is when a section of the curtain has been judged to have been completed with a degree of certainty that the subsequent verification test holes will indeed confirm that the target residual permeability has been achieved. A proper judgment of closure depends on a holistic analysis of all available and relevant information, such as drilling logs, water tests, grout take analyses and dam instrument response.

Lax refusal criteria will result in incompletely and inefficiently grouted stages. Given that the cost of drilling a new hole is likely the most expensive operation in typical foundation grouting programs, each and every hole should be viewed as an opportunity to reduce the bedrock permeability and should be grouted to the fullest extent possible. This includes grouting as close to absolute refusal (zero flow) as possible. How close to absolute refusal should the designer set the criterion? According to Houlsby (1990), "My practice is to go as close as the order of accuracy of the measuring methods allows." In Houlsby's day, the method of measurement was typically performed with dip sticks and stop watches to measure differences in volume in the agitator tank verse time, which is why refusal criteria from that era were typically set at 1 cubic foot or less measured over 10 minutes (0.75 gpm or 3 Liters per minute). With the current use of electronic flowmeters and real-time monitoring computer systems, the higher accuracy and complete time-history plot allows the project team to grout to as low 0.2 gpm (or 1 liter per minute) or less depending on the application and target permeability. Many current specifications, however, have not taken advantage of the increased accuracy of these new systems and have kept refusal flow criteria closer to 0.75 gpm.

Many designers may also view the additional time to grout to a lower refusal flow criterion as unnecessary and expensive. To the contrary, the last amounts of grout injected during the final refusal of a grout stage can be some of the most important time and effort spent to achieve closure, especially if the time spent reduces the number of additional holes to be drilled to complete what the prior holes and stages were not able to compete. Designers should consider the costs of drilling additional holes as well as the implications in regards to dam safety (especially for holes that need to be drilled and installed through embankments) when setting refusal flow criteria. Additional time grouting to lower (stricter) refusal criteria will likely help to reduce the number of additional holes to be added, drilled, water pressure tested, and grouted. All of these operations come with some measured amount of risk involving dam safety, so a reduction in the number of instances that these operations are performed should be viewed as an improvement.

Refusal criteria should also consider the frequency of joint intersections and or the likelihood of not connecting directly to a solution feature or solutioned widened joint (Figure 4).

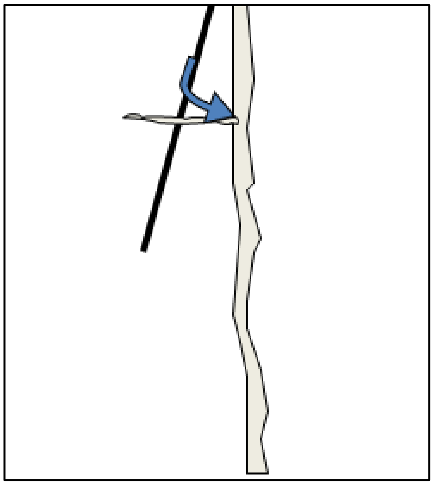

Figure 4. Illustration of indirect grouting connection of large fracture from a tight fracture.

Grouting these higher permeability features through a tighter bedding plane can result in the refusal criteria being "achieved" prior to complete filling of the solution feature. The result is a high residual permeability that will likely go unnoticed until tested by reservoir filling or a slurry loss during cutoff wall construction.

D. Standpipes and MPSP

USACE ER 1110-1-1807 (1997) is commonly acknowledged when installing standpipes or Multiple Port Sleeve Port pipes through embankment dams during remedial grouting. This Engineering Regulation has a significant amount of discussion on the potential for hydraulic fracturing while drilling and backfilling drill holes through embankments. This has led to the development of specification provisions that require or potentially require that grouting of standpipes installed through an embankment be performed in stages. The concern over hydraulic fracturing has also led to specifications that require water testing and grouting be performed under very low pressures or under gravity head. The following is a quote from the current version of the ER.

"For borings that penetrate zones with low confining stress it is possible to induce hydraulic fracturing from the gravity pressure. When grouting borings in these locations or if significant grout losses are observed, the grout backfilling should be done in stages allowing the grout to set between stages."

This statement in the ER and concerns regarding embankment hydraulic fracturing have resulted in grouting specifications that limit backfilling of the annular space outside of a standpipe to heights of only 25 or 50 feet above the water table. Such requirements are extremely expensive as they require that a drill rig and crew be kept on standby for a day or days for each standpipe installed. A typical large remedial embankment grouting project will have hundreds of standpipes. Stage grouting of the standpipe annular space also results in the risk of grouting the drill casing into the embankment if the casing is not pulled far enough, or for the embankment to collapse around the standpipe when the casing is pulled above the grout level.

Such staged requirements may well be appropriate when drilling investigation borings or installing instrumentation. However, in the case where grouting is being performed as a pretreatment for future cutoff wall construction, these requirements are considered to be nonsensical by the authors. The grouting program in these cases is an investigation and treatment program in advance of performing much larger and riskier excavations through the embankment. In the case where a slurry-supported trench is being considered or is specified for the cutoff wall construction, this large excavation will be uncased. It seems logical that if a zone of the embankment was prone to hydraulic fracturing under gravity head that the dam safety engineer would want to determine this during the grouting program where only very small diameter holes are being drilled, the fluid being used is self-hardening and the fluid quantity is limited and can be controlled. If these zones of low confining pressure are not discovered and treated by the grouting program in advance of the cutoff wall construction, the continuous slurry filled panel or trench will most certainly "discover" this zone of weakness. The surface area and volume of non-hardening bentonite slurry in a typical panel excavation is orders of magnitude greater than the surface area and annular space volume around a typical drill hole. Furthermore, if a hydraulic fracturing event does occur during panel wall excavation resulting in slurry loss, the specified procedure is to add slurry to maintain the trench full (i.e. maintain the pressure the caused the fracture to propagate). It seems obvious that the more cautious and prudent approach is to identify any weak zones during the course of the drilling and grouting program and to systematically treat the identified weak zones by compaction grouting or other means prior to excavating uncased higher risk elements through the dam embankment.

Somewhat counter to grouting standpipes in stages, some recent grouting programs have elected to limit the amount of annulus standpipe grout used during installation, as a predetermined multiple of theoretical annulus volumes. In these cases, the standpipe annulus was being grouted through the bottom of the standpipe under gravity head. This approach poses several concerns in regards to the effectiveness of grout treatment and more importantly in regards to dam safety. First, the act of prematurely halting the addition of grout into a formation that is readily accepting the grout is counter to the very goals of the grouting program. Second, not continuing to provide grout during the standpipe installation allows for potential incomplete filling of the hole annulus, as the annulus grout is lost to the formation. This situation lends to defects or incomplete filling of the annulus. These defects can permit direct connection of embankment materials to the foundation and/or connection of grouting fluids up into the embankment during the drilling and grouting operations at lower depths. Both situations are serious dam safety issues.

Arguments for the cessation of annulus grout include avoiding potential hydrofracture of soft embankment or foundation soils above the bedrock. However, it should be noted that most standpipes are drilled and installed into the top of rock immediately below the embankment. This zone of rock is often the most permeable and the zone of rock that most likely led to the need for the remediation being conducted. It is much more likely that any grout take during standpipe installation is flowing into the bedrock or weathered features of the rock (or an alluvium layer remnant immediately above rock) rather than into embankment materials. Bedrock that is being treated during standpipe installation should be viewed as part of the treatment program and should be grouted to refusal just as any other standard grout stage.

In order to adequately backfill and install standpipes, the designer has two options. The first option is to backfill the entire annulus in one complete operation, adding grout as needed and maintaining a continuous head of grout in the annulus at all times until the grout comes to surface and remains at the surface. The second option is recommended for areas of suspected weak embankment soils or zones that the designer wishes to avoid potential hydrofacture. This option involves the use of Multi-Port Sleeve Pipe (MPSP) with a barrier bag (Figure 5) that is inflated at the embankment/foundation interface. The barrier bag hydraulically separates the embankment from the bedrock foundation (Figure 6).

Figure 5. MPSP standpipe with barrier bag.

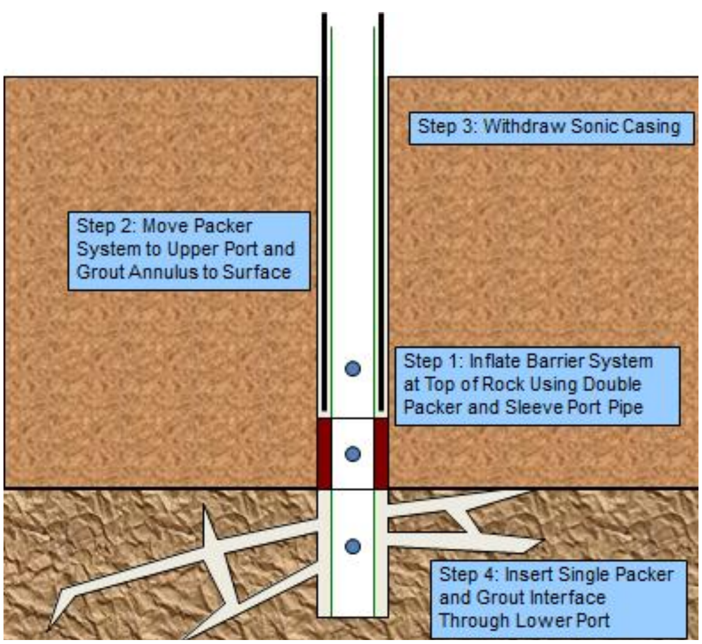

Figure 6. Separation of embankment and foundation with the use of a barrier bag.

The annulus can then be filled through a port in the standpipe above the barrier bag, while the critical interface and bedrock immediately below the bag can be treated and evaluated as a separate grouting stage. Either option involves the continuous and uninterrupted backfilling of the hole annulus within the embankment to the top of the hole. Use of the barrier bag to separate and isolate the embankment from the foundation is the only method that verifies if hydrofracturing of the embankment has or is occurring. Grout coming to the surface around outside of a standpipe that was incompletely filled during installation is not evidence of hydrofracturing. It is evidence, however, that the installation method being used is inappropriate and has created a dam safety concern.

Other smaller issues involved with the installation of standpipes and MPSP include not allowing the addition of water in the MPSP to counterweight against the buoyant forces within the borehole, and not allowing for the flushing of grout wastes inside newly installed MPSP generated during installation. The reasoning for not allowing these measures are similar to those previously stated for not allowing a static head of grout within the annulus. For the same reasons previously stated, water should be allowed to counterweight the MPSP. Other methods used to hold down or counterweight the MPSP involve restraint or force applied at the top of the MPSP. Typically MPSP casing is made of PVC that, while sturdy, is brittle and susceptible to the compressive and buckling forces on the long slender length if applied from the top. Flushing grout wastes inside the MPSP should also be allowed once an initial gel of the annulus grout has occurred and there is no danger of water escaping into the embankment.

On a similar note, use of very low excess pressures or even gravity head during water testing and grouting due to fears of hydraulic fracturing in advance of cutoff wall construction is misguided. Again, if a zone of the embankment or gouge within rock defects is susceptible to fracture or erosion under low pressures, then one needs to know this prior to excavating the cutoff wall. On one recent project, the allowable water pressures during testing were so low that the headloss through the delivery pipe was not exceeded when flow started and zones with zero water take subsequently consumed very large quantities of grout during pressure grouting. If these zones had not been grouted under pressure due to the low or zero water take and had been backfilled in stages in accordance with the requirements above, then a future large slurry loss during cutoff wall excavation would have been the inevitable result.

IV. ANALYTICAL ISSUES

The meaning and value of water pressure testing as a routine and integral part of a proper grouting program has long been recognized (Houlsby, 1976, 1990, and Bruce and Millmore, 1983), and indeed is the subject of a paper in this Conference (Paisley et al. 2017). In our practice, the unit of measurement is the Lugeon, named after Maurice of that ilk. He defined it as a flow of 1 l/m/min at an excess of pressure of 10 bars (that being equivalent to the head exerted by a typical dam in the French Alps in 1933). The water pressure test projects a true Lugeon value, although its accuracy may be in question given all the various head flow corrections which have to be made, or are simply ignored in the Modified Lugeon Test of Houlsby 1976.

One of the gifts we accept from the use of stable grouts (i.e., those grouts with minimal pressure filtration) is that they maintain a relatively constant rheology during their period of injection: they do not allow water to be squeezed out of the mix, into fissures, when under pressure. Thus, a grout with constant rheology (i.e., like water has) can thus be regarded as not only a fissure filler, but also a test fluid. This allows us to calculate, at any given time, an Apparent Lugeon Value, calculated in the same way as a Water (True) Lugeon Value, but corrected by a factor being Marsh time (grout) / Marsh time (water).

Grout curtains should always be grouted to a target True Lugeon Value (residual permeability). Individual stages should be brought towards refusal by observing and controlling the Apparent Lugeon value, subject to the final “refusal” flow rate discussed in Section 3.3, above. Grout curtains should not be brought to closure based solely on Apparent Lugeon Values, as the authors have observed on a major recent project in the Pacific North West. Water testing of the final hole series and verification holes should always be performed to prove the residual permeability of the treated rock mass.

V. QA/QC ISSUES

A. HMG and LMG Mixes

Just as a grout for fissure treatment is different than a concrete for above-ground construction, so the testing and QA/QC of these two different materials must be separated. For example, the testing of cubes for strength is irrelevant and unnecessary for grouts, as a routine QA/QC test. For grouts, we divide the tests into 2 basic categories: (i) classification, and (ii) QA/QC.

Table 1 summarizes these tests.

Table 1. Routine and classification tests.

TEST GROUP	HMG	LMG
Routine [Field Tests]	• Marsh funnel (flow) • Baroid mud balance (s.g.) • Bleed (stability)	• Slump • Homogeneity (visual)
Classification [For R.P.O.]	• Pressure filtration (stability under pressure) • Initial and final setting times • Cube strengths	• Initial and final setting times • Cube strengths

The routine tests are conducted regularly each day on a specified frequency. The classification tests are conducted before the work commences, for Record Purposes Only, and would also include the results from the routine tests. Given the critical importance of the pressure filtration value for a HMG, it is often found that this test is conducted as a routine QA/QC test but say on a weekly as opposed to daily basis.

Regarding the individual tests, much has been written about the details (e.g., Chuaqui and Bruce, 2003, Naudts et al., 2003). However, as commonsense suggestions, we would offer the following:

- Marsh Cone: the test is accurate and meaningful only for mixes of ≤ 60 seconds flow time. The apparatus was designed for testing drilling muds, not particulate grouts of high apparent cohesion. QC test values should generally fall to within ± 2 sec. However, due to using an apparatus not designed for grouts, test values that fall out of the stated acceptable range do not necessarily indicate inferior grout and should not automatically constitute non-compliance. For more accurate and consistent readings, a viscosity meter can be considered.
- Bleed: the goal is usually zero, but in reality < 2% is acceptable provided the other criteria are met.
- Pressure Filtration: a target of 0.04 $min^{-1/2}$ if often set. This is an extremely onerous target, especially for the "starting mix" (i.e., ≤ 35 seconds Marsh). Such low targets are only really necessary when treating fine fissures at high excess pressures. A relaxation to a higher value (say 0.08 $min^{-1/2}$) is warranted when filling voids or masses with wider aperture fissures.
- Slump: this is the common field test for an LMG other than the "hand squeeze" test favored (and understood) only by certain experienced engineers. Attaining a slump < 1″ regularly may be practically impossible given the natural variability of the mix and its components. It is much more relevant to set a higher target, say 1½ or 2″, and permit a ± ½″ variation.
- Cube Strength: Should be used for general reference only. Prior emphasis on strength and requirements for frequent testing can be traced back to the perceived need for grout durability and resistance to erosion. It should be noted that even the weakest balanced stable grouts (in the range of 100-200 psi compressive strength) are significantly more durable than infill soils or open fractures the grouts are used to replace. According to Houlsby (1990), "Poor grouting can be leached away by seepage or attacked by chemically and biologically or weakened by erosion of soft materials around it." Houlsby adds, "The aim is to fill the cracks completely." So the true goal of a grouting program should be permeability and seepage reduction, not producing the highest strength grout possible.

B. Data Management Systems (DMS)

It is now common practice for an Owner to insist that the contractor collects, presents and stores all his construction data in some form of an automated DMS (Data Management System). We have found that the contractors are often overwhelmed (initially at least) by the needs and scale of such a system. This must not be permitted by the Owner to occur: a fully compliant DMS must be up and running before production work commences. From the technical viewpoint alone, it is integral to informing all interested parties on the progress and effectiveness of the work (e.g., via Trend Analyses), and is therefore the only true basis for determining when the work is actually complete or if further work (e.g., higher order holes) is required, and where.

The Contractor's DMS must be controlled by a suitably qualified grouting engineer (not just an IT specialist). There must be a similarly-equipped, dedicated and experienced engineer on the Owner's side.

VI. DAM SAFETY MONITORING AND INSTRUMENTATION

A. Joint Instrumentation Monitoring Plan

It is normally the case that the dam to be remediated will already have some amount of instrumentation. (It is usually the case that the results of this instrumentation have highlighted the actual need for remediation, in concert with visual observations.) Further instrumentation is invariably added just before or during the grouting, to target specific "problem areas," or simply to ensure a broad coverage without data gaps. The result is a plethora of instruments, typically now configured to provide data in real time.

It is essential for Dam Safety Assurance during construction that the Owner and the Contractor partner to collect, study and act upon these data in real time, regardless of whose contractual responsibility or liability it may be. The most efficient strategy is to create, prior to construction having commenced, a Joint Instrumentation Monitoring Plan (JIMP). This will identify which instruments are to be read, by whom, and at what frequency. The JIMP will also provide Threshold and Action Level guidance for each instrument, and identify courses of action when these levels are reached.

We also note that a JIMP is implemented most effectively when the Owner and the Contractor can view the data while being physically in a joint "Mission Control" facility. In this way, the impact of the Contractor's work on the dam and its foundation can be seen in real time, and acted upon accordingly when necessary.

B. Long-Term Monitoring

We consistently observe that after the curtain or cutoff has been built, little attention is paid to continuing to use the in-situ instrumentation to monitor the long-term efficiency of the cutoff. Even less attention is devoted to publishing such data so that the dam remediation community can have the benefit of a successful (or unsuccessful) case history. Such long-term monitoring is the responsibility of the Owner, and this should be regarded by them as an essential cost outlay – perhaps as part of the routine O&M budget.

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Donald Bruce received his BS (Geology and Mineralogy) and Ph.D (Geotechnical Engineering) from Aberdeen University, Scotland. He thereafter worked in specialty geotechnical construction in projects worldwide. As President of Geosystems LP, Donald specializes in the application of ground treatment, improvement and retention techniques, principally associated with dams, levees, deep foundations, tunnels and mines. Dr. Bruce is a Chartered Civil Engineer and Fellow of the Institute of Civil Engineers (UK), and a Licensed Geologist/Engineering Geologist (US). He has authored over 300 technical papers and three textbooks, most recently "Dam Foundation Grouting" (with Weaver); and Specialty Construction Techniques for Dam and Levee Remediation."