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REMEDIAL GROUTING OF EXISTING EMBANKMENT DAM *FOUNDATIONS: LESSONS LEARNED (AND IGNORED)

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1. BACKGROUND

Since the late 1990's in the U.S.A. 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 [1] [2], at the Honolulu Grouting Conference [3], in USSD publications and conferences, and in more recent textbooks [4] [5]. Final confirmation is provided in the USACE's new Grouting Manual [6], which is a radical overhaul of the prior version (1984).

An observer of the huge remedial grouting projects at Mississinewa, IN, Clearwater, MO, Center Hill, TN, Boone Dam, TN, East Branch Dam, PA, 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 now producing specifications that consistently reflect modern practices, instead of recycling contract documents ("boiler plate") that are inconsistent and awkward amalgam 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

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last few years that certain "lessons learned" during the revolution have not been fully or correctly applied, or have indeed been ignored. 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.

The following topics focus on practical issues associated with the execution of the works, and so exclude reference to design-related issues such as the number and spacing of grout lines; drill hole spacing and orientation; upstage versus downstage; or grouting control principles.

2. LESSONS LEARNED

2.1. DRILLING TECHNIQUES FOR OVERBURDEN AND ROCK

Most remedial grouting projects will involve drilling and casing through overburden and/or embankment fill so that standpipes can be placed to permit safe access to the rock drilling activities therebelow. In essence, neither compressed air nor water is considered acceptable for fear of compromising the integrity or safety of the embankment [7]. This explains the widespread use of the rotary vibratory method ("sonic drilling") and dry, double-head duplex, wherein an inner auger is advanced simultaneously with the outer casing. In both cases, minimal amounts of water are introduced to facilitate progress. Every care should be taken to prevent "cleaning water" used on the working platform from escaping down and around the casing (or standpipe once it has been installed).

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 grouting, 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 the use of air flush. The practice of some contractors to "mist" the air with water is totally misguided, as this actually reduces the chances of drilling a clean hole, not improves them. The best of all worlds arrived in 1995 in the form of the water activated (and flushed) DTH (WDTH) [8]. This tool has been the staple of the better resourced grouting contractors since it was first successfully demonstrated at the McCook Quarry Trial (Chicago, IL) in 2001 and consistently provides high quality holes for grouting.

2.2. DESIGN AND TESTING OF GROUT MIXES

One of the major changes in rock grouting technology in recent years has been the increased level of understanding, and almost universal application of multi-component, balanced, stable grouts. Gone, thankfully, are the days of highly unstable, high water content "neat" mixes wherein the only concession to sophistication would be the (unnecessary) addition of superplasticizer and/or a handful of dry bentonite. The dynamic stability of a particulate grout ("pressure filtration coefficient") is a fundamental control over its ability to penetrate fissures, and is at least equally as important as its grain size and apparent viscosity. Thus, contemporary HMG's ("High Mobility Grouts") can be regarded as "high performance" in that they maximize the injection potential value from every grout hole, instead of simply prematurely clogging up the fissures a very short, and uneconomic distance from the borehole wall.

Acceptable grouts should have minimal bleed ($< 2\%$), and low pressure filtration coefficient (a value of $0.06 \text{ min}^{-1/2}$ is suitable for most cases). Reflecting current "Apparent Lugeon Theory" practice for controlling injection, dominant now in N. America, these grouts can be manufactured in the field to provide mixes with discrete Marsh Cone ranges, e.g., 35; 45; 60 seconds; and infinite. Bear in mind that Marsh Cone readings over about 60 seconds are imprecise measurements, and other measures such as a Flow Cone or Shear Vane might be required, especially for the "closer" mix. The Baroid Mud Balance, for measuring grout specific gravity, and hence checking water:cement ratio, is a particularly simple, cheap and accurate tool, and stands in sharp contrast to the systematic use of grout cubes as a QC/QA tool: practically useless in rock fissure grouting applications. The true goals of a remedial grouting program should be permeability and seepage reduction, and not production of the highest strength grout cubes possible.

2.3. PLACEMENT AND SEALING OF STANDPIPES AND MPSP'S

This is a process the quality of which is frequently overlooked, even though it is absolutely fundamental to the safe grouting of existing embankment dam foundations.

The USACE Engineering Regulation [7] provides significant discussion on the potential for hydraulic fracturing while backfilling drill holes through embankments. This has led, in some quarters, to the development of specification provisions that require that grouting of standpipes installed through an embankment be performed in stages. A 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 Regulation.

"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 Regulation, together with concerns regarding embankment hydraulic fracturing, have resulted in grouting specifications that limit backfilling of the annular space outside of a standpipe (“casing grout”) to heights of only 10-15 m above the water table. Such requirements are extremely expensive to implement as they require that a drill rig and crew be kept on standby for days for each standpipe installed. 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 might be an affordable conservative approach when drilling a limited number of borings for investigation 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 for the cutoff wall construction, this large excavation will be uncased. It seems logical that if a zone of the embankment were prone to hydraulic fracturing under gravity head, the Engineer would want to determine this during the grouting program where only small diameter holes are being drilled, the fluid being used is self-hardening and the fluid quantity is limited and can be easily 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 that 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.

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 in which the designer wishes to avoid potential hydrofracture. This option involves the use of Multi-Port Sleeve Pipe (MPSP) with a barrier bag that is inflated with grout at the embankment/foundation interface. The barrier bag hydraulically separates the embankment from the bedrock foundation with the use of a barrier bag. (Figure 1).

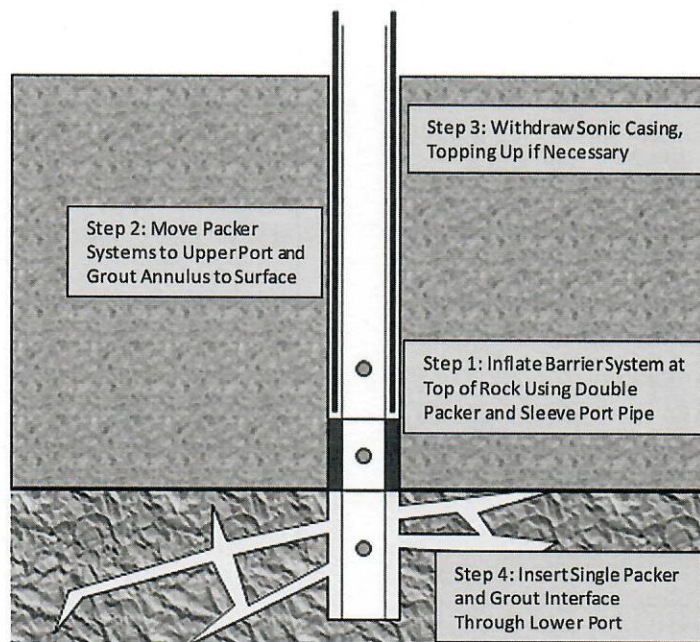


Fig. 1
Separation of embankment and foundation

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 that hydrofracturing of the embankment is not occurring. Grout coming to the surface around the outside of a standpipe that was incompletely filled during installation is not evidence of hydrofracturing: it is evidence that the installation method is inappropriate and has created a dam safety concern.

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.

2.4. DATA MANAGEMENT SYSTEM (DMS)

It is now common practice for an Owner to insist that the contractor collects, presents and stores all his construction data in real time 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, scale and seriousness 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 controlling and analyzing the treatment in real time, and informing all interested parties on the progress and effectiveness of the work (e.g., via Trend Analyses). It 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. All parties must have simultaneous access to all the information generated during the works.

2.5. REFUSAL AND CLOSURE

Each and every stage of every grout hole must be brought to a true and proper "refusal" in accordance with Apparent Lugeon Theory. 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, optical televiewer logs, grout take analyses and dam instrument response.

Lax refusal criteria will result in incompletely and inefficiently grouted stages. These can also lead to partially grouted fractures resulting in a high residual permeability. Given the limited number of fracture intersections by grout holes and given that the cost of drilling a new hole or holes 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.

Many designers may view the additional time to grout to a low refusal flow criterion as unnecessary and expensive. To the contrary, the last volumes 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 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 low refusal criteria will 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.

One of the gifts we accept from the use of stable grouts (i.e., those grouts with minimal bleed and 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 an Apparent Lugeon Value during the initial grouting of any stage, 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. Grout curtains should not be brought to closure based solely on

Apparent Lugeon Values, however, 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.

2.6. ALLOWABLE SAFE INJECTION PRESSURES

A prime rule in any remediation is “First – Do No Harm,” and this is a logical and proper dictum to which the authors fully subscribe. However, the whole issue of safe rock grouting pressures under existing dams has reached levels of hysteria, especially in uninformed and inexperienced circles. Bearing in mind that a) a dam foundation is a 3D structure, b) contemporary computer-aided grouting control and recording systems provide essentially continuous real-time pressure/rate of injection data for each stage, and c) QA/QC programs are generally now quite sophisticated, then the authors believe that the highest safe injection pressures should be used, for both economic and technical reasons. “Rules of Thumb” (e.g., 1 psi/foot) can be discarded provided proper and progressive testing is conducted, and all processes are carefully controlled and monitored during injection.

2.7. JOINT INSTRUMENTATION MONITORING PLANS AND LONG-TERM PERFORMANCE MONITORING

It is normally the case that the dam to be remediated will already have some amount of instrumentation in its body and in its foundation. (It is usually the case that the results of this instrumentation will have highlighted the actual need for remediation, in concert with visual observations.) Further instrumentation should be 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 to do so. 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.

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.

3. CLOSURE

It has become very easy to become an “instant” expert, or an “internet” expert, whereupon a great deal of information on any given subject matter can be quickly accessed. However, experience is not so quickly or so easily gained, and its value in a specialty engineering process such as grouting cannot be overstated. The authors’ opinions expressed in this paper reflect their respective experiences, and they have done so in the hope that the opinions will leaven the bread of the internet expert thrown into the midst of a major dam remediation project involving drilling and grouting, both processes previously inexperienced.

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SUMMARY

There has been a technological revolution in rock grouting for dam remediation projects in the U.S. stretching back almost 20 years. This has been extensively described in many conferences and publications, and has resulted in a very high level of technical competence and project performance. However, the authors have observed that many "lessons learned" in that period have not been universally applied or, in some cases, have been ignored. This paper reaffirms many of the practical lessons learned in many grouting processes, including:

- Drilling techniques for overburden and rock,
- Design and testing of grout mixes,
- Placement and sealing of standpipes and MPSP's,
- Data management systems,
- Refusal and closure,
- Allowable safe injection pressures,
- Joint instrumentation monitoring plans, and long-term performance monitoring.

Depuis près de 20 ans se déroule une révolution technologique en ce qui concerne l'injection du rocher pour les projets de réhabilitation des barrages aux États-Unis. Ce sujet a été largement traité à plusieurs conférences et dans maintes publications, et en est résulté une amélioration considérable des compétences techniques et de la performance des projets. Cependant, les auteurs considèrent que les « leçons apprises » n'ont pas toutes été considérées, et dans certains cas, ont été ignorées. Cet article réitère plusieurs des meilleures pratiques dans les processus d'injection, incluant :

- Techniques de forage pour le mort-terrain et le roc,
- Conception et essais de mélanges de coulis,
- Emplacement et étanchéité des conduits,
- Système de gestion des données
- Refus et fermeture
- Pressions d'injection admissibles et sécuritaires
- Programme de suivi de l'injection et suivi à long terme du comportement

KEYWORDS

Automated monitoring, boring, construction, cutoff, embankment dam, foundation treatment, grout curtain, grouting, karst, quality control.

Auscultation automatique, forage, construction, barrage en remblai, traitement des fondations, écran d'injection, injection, karst, control de qualité.