

ROCK GROUTING AND THE REMAINING VESTIGES OF DARK ARTS

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ABSTRACT

Platforms such as the six successive international conferences on grouting have allowed tremendous advances in the industry to be chronicled and promoted. As a result, the state of practice and the standard of care are unrecognizable from where they stood 40 years ago. This revolution has been a classic example of the power of supply and demand: the supply side of the equation has been provided by a small group of specialty contractors and consultants responding to the demands placed by owners of major dams whose foundations have been proved dangerously susceptible to deterioration at alarming rates, so posing intolerable risks to dam safety. However, the authors continue to find cases where either the revolutionary innovations have been ignored – either through ignorance or inertia – or where the new approaches are being subverted, usually for commercial gain. This recidivistic tendency threatens to undermine the transition to the quantitatively engineered approaches of the past four decades which have dragged the reputation of grouting out of the trope of being “Smoke and Mirrors”, or a “Dark Art”.

In this paper the authors provide examples of practices and concepts which should be recognized as being wrong, to the point that project efficiency and quality will suffer, and the reputation of grouting will be degraded. These examples include aspects of drilling, placing and sealing standpipes, choice of mix designs, definitions of refusal and closure, real time monitoring, and issues dealing with the design and pricing of projects. Although the focus is on rock grouting, many of the points have relevance to other grouting techniques also.

Keywords: Rock Grouting; Rock Drilling; Grouting Procedures; Mix Designs; Grout Curtains

INTRODUCTION

The revolutionary advances in rock grouting practices in North America over the last 40 years or so have been chronicled and nurtured in the proceedings of the six successive ASCE GeoInstitute/DFI International Grouting Conferences, held in 1982, 1992, 2003, 2012, 2017, and now in 2022. In effect, the conferences in 1982 and 1992 were more “end of the beginning” events, presaging the fundamental technology surge of the later years.

During this same period, textbooks such as Weaver and Bruce (2007) and Bruce (2013) have been published, while the US Army Corps of Engineer’s 2014 “Grouting Technology” Manual was a much needed and dramatic enhancement to the prior version (1984). Many excellent technical papers have been published by practitioners at technical conferences dealing with dams, deep foundations and tunnels, and state of the art principles are taught at intensive short courses. Major grouting projects have been successfully completed in the most challenging of geological and logistical circumstances nationwide, and the subsequent diaspora of enlightened and enthusiastic young grouting engineers has helped greatly to raise standards of performance and quality worldwide.

However, as the Good Book says, “there are none so blind as those who will not see” (Jeremiah 5:21) (Underline added for emphasis) while Proverbs 16:18 of the same source reminds us that “Pride goeth before destruction, and a haughty spirit before a fall”. The secular translation is that a) some engineers

and geologists still choose to cling to the traditional principles and processes and b) let's not get too carried away with ourselves: hubris is neither attractive nor acceptable in our industry.

The authors observe that these two issues, alone and together, are threatening the goal of elevating and maintaining grouting practices at the “quantitatively engineered” level and lifting them out of the trope of being a “Dark Art” or run by “Smoke and Mirrors”. As an industry, we have come far, fast, and successfully, and it is therefore so important that we as the progenitors and guardians of the technology don't regress, relax, and compromise, especially in the face of project specific commercial considerations and pressures. This paper highlights various aspects of design, construction, and verification which need to be reaffirmed, so that we can resist the counter-revolutionary elements lurking in our midst.

FUNDAMENTAL DECLARATION

The concept of exactly what a grout curtain is, is still not properly framed in certain minds. To be clear, it is a three-dimensional structure in the ground, engineered and constructed to a targeted residual permeability. It is a composite block whose purposes are to reduce seepage, modify flow paths, manage uplift pressures, and prevent piping. This structure will comprise by volume, at least 90% of the virgin rock, and about 3-5% grout. The balance, by volume, will consist of ungroutable fissures (i.e., those of very small aperture and very low transmissivity), and/or ungroutable weathering residues (such as the clay in fillings found in karstic terrains). If the projected relative volume of such residues is locally very high, such as in epikarstic horizons, then all the ambitions of a grout curtain cannot be met, and the “composite wall” concept (Bruce et al., 2008) must be implemented to assure long term success, particularly with regards to the goal of stopping piping.

Inherent in this concept is that a curtain is not a two-dimensional membrane which can be provided by a single row of grout holes, no matter how closely the holes have been drilled. (As an aside, we now surmise that the perceived need for very closely spaced holes – say less than 18 inches – in historical grouting projects, was due to the rheological inefficiency of the grout mixes, resulting from an ignorance of the crowning control of their pressure filtration coefficient, discussed further below). The technical and economic failure of some traditional single row curtains is one of the main reasons that potential owners were – and still are, regretfully – somewhat nervous and reticent about using grouting, especially during times of economic challenges.

So, the corollary is that a curtain must ensure its three-dimensional configuration by featuring at least two rows of grout holes, preferably inclined in opposite directions to assure interception of all major discontinuity sets, and to compensate for the natural tendency of drill holes to deviate, potentially causing “windows” in the curtain. However, one should be careful with certain Agency “standards” (and indeed none exist *strictu sensu* in North America) which, for example, *mandate* three or four rows of holes. This in fact is a relic of the “rule of thumb” design approach. An appropriate standard of care is a properly grouted, two row curtain, followed by the installation of Verification Holes between these rows to confirm the residual permeability of the grouted structure which has been achieved to that point. Should that residual permeability not meet specification or design requirements, then further grouting in the inter-row area is warranted, especially in those zones of the foundation found to contain geological “features”, such as major faults or shear zones and especially those comprising potentially erodible residuum.

Three – and four – are just numbers. They are not a design basis. For grout curtains, these numbers are simply an anachronistic paradigm.

OWNERS' SPECIFICATIONS AND CONTRACTORS' SUBMITTALS

The “Dark Arts” – if indeed they are to surface on any given project – are often times the confluence of defective or ambiguous specifications, and clever and calculated exploitation of the same by an opportunistic contractor. The authors have provided guidance previously on the drafting of specifications which provide the bones of a successful project, both technically and contractually (Bruce and Dreese, 2010). Without repeating the details, the following potentially dark areas need to be properly addressed.

When drafting a specification:

- Provide all relevant geotechnical and geological exploration data and reports in a well-organized and easily accessible fashion. An undisciplined “data dump” is an inadequate and lazy form of briefing.
- Provide the Design Basis Memorandum clearly showing the purpose, location, extent, and composition of the curtain, and the measures of its success (e.g., residual permeability, reduction of seepages, piezometric changes).
- Provide technical specifications which are pertinent to the project at hand, and not dusty, recycled documents from decades past. These specifications (and the overarching design) should reflect the best of contemporary practice and developments, and not archaic “rule of thumb” paradigms.
- Clearly state the geological, logistic, environmental, and other restraints which may impact the bidders’ decisions, and which constitute “pressure points” for the Owner.
- Equally clearly state which techniques or methods are not acceptable (e.g., air flush drilling), and which specified requirements are not negotiable (e.g., the use of real time computer monitoring, and stable grout mixes).
- Declare the basis for the various work item quantities to be bid, especially the foreseen percentages of Secondary, Tertiary, and Quaternary holes relative to Primaries, and the estimated average grout consumptions for each order of holes. Better to do this up front as a de facto Geotechnical Baseline (which will have value to both parties) than to provide no basis for defending or prosecuting a later claim based on major changes in quantities or inappropriate assumptions. In this regard, the specifications should be clear as to the amount of downstaging relative to upstaging which is anticipated. This should be a realistic estimate so that the Owner can operate comfortably within a sensible economic umbrella when the works are underway and the (more expensive) downstaging is required, especially in the upper elevations of the curtain.
- Make crystal clear which party in the field will be primarily responsible for key decisions, such as the terminal depth of overburden casing, the progression of mix changes in any one stage – and again – the decision to downstage where necessary. Always, the Owner is responsible for instructing higher order holes, but he must do so in a fashion that respects the Contractor’s continuity and efficiency of work.
- “Unbalancing” certain items of a bid is a common contractor ploy. However, the Owner should make it very clear that any such act on the part of the Contractor is only and solely at the Contractor’s risk and will not be a legitimate basis for a claim should the Contractor’s interpretation or ploy not prove to have been a reasonable risk, when compared to the Design Basis assumptions.

This is not a comprehensive list, merely a start. Expert, experienced input to the development of Contract Documents is an essential ingredient of a proper specification.

When drafting a Contractor’s submittal:

- It is not uncommon that the successful (and most typically, the low) bidder realizes issues with his bid only when he begins to write his post-award submittals. Nowadays, most specialty companies have integrated estimating and construction departments so that neither group can

blame the other for “errors and omissions” between bidding and building. Nevertheless, even experienced personnel, typically under time pressure from other projects, will make innocent errors in their bidding processes. For example, the specification adjectives “minimum” and “maximum” may have been overlooked in favor of an absolute value, such as the length of embedment of a standpipe into appropriate quality rock. Or the impacts of spatial and temporal restrictions on drilling and grouting, between and within rows, and on staging, may not have been fully appreciated. In such cases, there can be a tendency for the Dark Arts to appear in the form of statements which on their innocent face, cover these weaknesses, with the hope that they can be slid by the reviewer. This is not right. Honesty and transparency at the submittal stage are integral to establishing a mutually trusting working platform.

- In similar vein, submittals should clearly list and address alternatives which are strictly not in compliance with the specifications, but which may enhance the progress and quality of the works, in the specialty contractor’s opinion. This is mutually productive food for thought.
- In (the most common) cases where the grouting contractor is a subcontractor, the grouting contractor should have verified in advance of his submittal that his foreseen work sequence reflects the reality of the general contractor’s schedule. This is for example, the case where the grouting contractor anticipates a full and unrestricted access to the whole working platform to most efficiently deploy his resources, whereas the reality may be that the general contractor can only provide the access in discrete sections, given his other priorities, such as river diversion and fill placement schedules.
- Submittals should be reviewed in a timely and comprehensive manner, so that any areas of disagreement or misunderstanding can be discussed and resolved in meetings before work commences.

SOME TECHNICAL VESTIGES TO BE EXHUMED

- Grout 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.
- Upstage vs. Downstage: the pros and cons of these methods are discussed at length in textbooks and technical papers, and it is assumed that the reader is already well versed. Suffice it to remind that on any one project they are not mutually exclusive, and in fact, for remedial curtains under existing embankments it is strongly recommended to downstage at least the top 20 feet or so in order to form an in-situ umbrella of treated ground to protect the base of the embankment from deeper activities. Even for curtains for new dams, where there is a possibility of grout readily breaking out at the surface, then the same process can be followed. Certainly upstaging is cheaper and faster, but don’t shoehorn it into a project for non-technical reasons.
- Work Platforms: in similar vein, the temptation to not provide a proper, concrete working platform must be strongly resisted. In fact, the cost of providing such a platform is miniscule relative to its benefits, which include enhanced personnel safety, ease of spoils handling, accurate hole setting out and identification, easier tracking of equipment, prevention of near-surface connections and leakages, and all-round improvement of efficiency and productivity.
- Rock Drilling: there is a convincing body of experimental and practical evidence which points towards water flush being required in drilling for rock fissure grouting, and not compressed air

flush. This is all to do with cleaning – not blocking – to fissures intercepted by the boreholes, and thereby elevating the amenability of said fissures to subsequent grout placements. The old argument of percussion vs rotary drilling was in effect one of air flush vs water flush, reflecting the equipment characteristics of the time. Of course, some contractors and agencies will always favor rotary drilling and may even allow top hammer rotary percussion drilling for holes less than say 100 feet. However, it would be regressive of them to disallow or ignore the substantial benefits of water-powered down-the-hole-hammers. These have been widely used in North America since the turn of the century with consistent success and widespread appreciation. Deniers point to the use of activating water pressures of over 2,000 psi – which is true – but tend to ignore that water is an incompressible medium, unlike air. Thus, having activated the hammer and escaping from the hammer, the now (low pressure) water gurgles happily to the surface. In doing so, its relatively low up hole velocity (36-120 m/min), i.e., about 20 times less than compressed air, minimizes damage to the borehole wall while still effectively removing rock debris. Hence, packers can be set more easily and securely and the amenability of the fissures to subsequent grout injections is assured. While air flush for rock fissure grouting holes is being eradicated, one unfortunate vestige is to support the use of “misting” i.e., the introduction of water into the compressed air stream of a percussion drilled hole. This is thoroughly bad practice and will result in greatly reducing the amenability of the fissures. “Misting” is not water flushing. Even the following technique of “flushing” the grout hole with (low pressure) water prior to grouting, may not be effective in dislodging drill debris blown into fissures by the high velocities of air flush.

- Overburden Drilling: quite simply, the advice of the USACE ER 1110-1-1807 reissued in December 2014 should be followed, as detailed by Stare et al., (2012). There should be no debate: compressed air should never be allowed in any embankment, and water flush only under the strictest set of operational controls.
- Placement of Standpipes Through Existing Embankments: this is a process the proper implementation of which is essential to dam safety during the subsequent water testing and grouting in the rock below. However, some contractors are reverting to traditional simplistic methods of trying to fill the annulus between (temporary) drill casing and (permanent) standpipe. You know who you are and what you’re doing! Guidance on the proper way to install standpipes is provided in Bruce et al., (2017), building on earlier publications on the subject. Among the key conclusions of these authors were the following:
 - staged grouting of the standpipe annulus is not required or justified in the vast majority of cases, being over conservative.
 - the annulus must be fully grouted, with the volume not limited to a theoretical amount.
 - the most effective results are obtained by the use of a proper MPSP (Multiple Packer Sleeved Pipe, which is not the same as Tube à Manchette), which will feature a barrier bag inflated at the embankment/foundation interface. This will hydraulically separate the embankment from the foundation, and allow separate treatment of the foundation and the annulus.

We reiterate, this is a most important topic, and the consequences of regression can be severe in terms of causing harm to the existing embankment.

- Refusal and Closure: “refusal” is reached when the stage in question accepts only a minimal rate of grout flow over say a five-minute period at the maximum targeted effective pressure. That rate will be dictated by the project’s goals and geology but is typically 0.25-0.75 gpm. It is a process designed to maximize the effectiveness of the injection and the role of the drill hole. On the contrary, “closure” is declared when a section of a curtain is judged to have been completed to satisfy the design residual permeability target. This involves attentive study of stage water and grout injection records, with final acceptance based on the results from specially installed Verification Borings (VB’s). This study should also incorporate the images from Optical and/or

- Acoustic Televiewers to rationalize water and grout injection characteristics with respect to fissure geometry and aperture. Stages have refusal, curtains have closure.
- **Mix Designs:** to our dismay, we still find cases where there is neither inclination nor requirement to use stable grout mixes. Stability does not only refer to “static” stability (i.e., the Bleed Test) but equally importantly to stability under pressure (i.e., the pressure filtration coefficient). The background was first published by DePaoli et al., (1992) but is still unappreciated by many. In short, stable, high performance, penetrative grout mixes must comprise a blend of materials which enhance the good qualities while compensating for the adverse qualities. This is where the term “balanced”, modified cement-based grouts originates. Hence, over the past 25 years or so, it has become standard practice to require suites of mixes using water, cement, bentonite, pozzolan, stabilizer, and superplasticizers to attain satisfactory grouts. These lessons should not be overlooked, forgotten, or dismissed: neat cement grouts with “a touch” of superplasticizer simply do not cut it. The door should be kept open to the advances of the additive/admixture manufacturers, who may well be able to provide products which simplify the mixes, provided these mixes will still display satisfactory static and pressure stability, rheology, and stiffening/setting times. This logic of the development of such stable grouts is illustrated in Figure 1. The ultimate goal is the creation of a grout mix with the lowest practical pressure filtration coefficient and the lowest practical apparent viscosity.

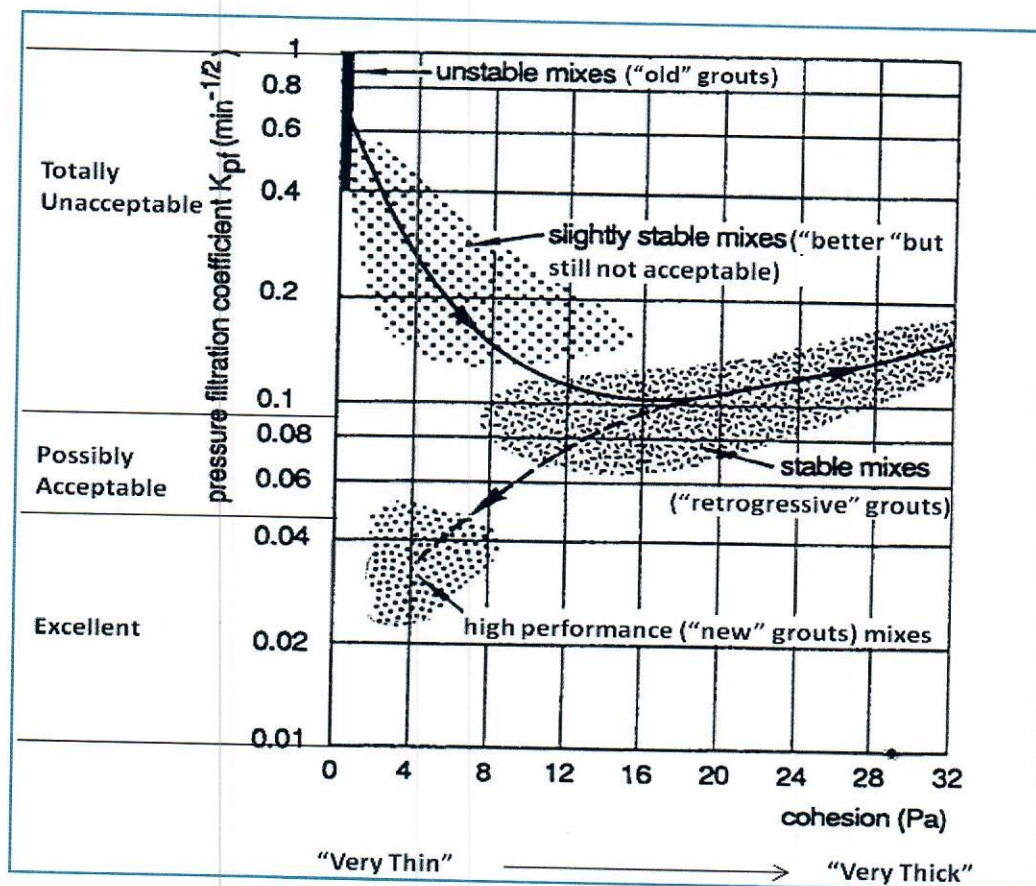


Figure 1: Historical path of development from unstable mixes to contemporary balanced multicomponent mixes (modified after DePaoli et al., 1992).

- Lugeons and Apparent Lugeons: remarkably, there is still confusion and misuse regarding these terms in certain quarters. The Lugeon value indicates the permeability of the formation to water. The Apparent Lugeon value is a measure of the formation's amenability to grout: for the Apparent Lugeon value to have relevance, the grout must be stable, ensuring constant rheology during injection i.e., have a low-pressure filtration coefficient. Observing the development of the Apparent Lugeon value during injection is a vital aid to ensuring proper refusal since the top line of the equation used to calculate it is a rate of flow unit (liters/minute). The Apparent Lugeon value is not a target for refusal, nor is it a measure of the residual permeability of the formation. Water pressure testing of the final order of grout holes, and of Verification Borings will yield the true residual permeability of the curtain, as noted above.
- Grout Testing: routine daily QC tests should include measurements of specific gravity (by Baroid Mud Balance, to confirm the correct proportions of the mix have been batched), rheology (by Marsh Cone), and observations of stiffening and hardening times (which are temperature sensitive). "Classification" tests, carried out when developing suitable mixes, or at weekly/monthly intervals for recalibration, include bleed and pressure filtration. Sampling for strength is practically useless, but may be conducted at the beginning of projects, for information only. The Marsh Cone is only accurate and meaningful for mixes of up to 60 seconds flow, and results above that should be evaluated for broad trends and consistency only, and not measured or recorded to a decimal of a second.
- Computer Aided Monitoring: there are basically three different levels of sophistication, as detailed by Hockenberry et al., (2012). While manual spot checks should always be made, there is no debate that some form of computer monitoring and control is the standard of care in most grouting projects. Proper computer monitoring equipment is like a camera – it doesn't lie.
- Data Management Systems (DMS): it is now common practice for an Owner to insist that the Contractor collect, presents and stores all his construction data in some form of an automated DMS (Data Management System). We have found that 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-trained, dedicated, and experienced engineer on the Owner's side.

CLOSURE

The revolutionary advances made in rock grouting since the mid-1990's have been hard won and expensively funded. It is our collective responsibility to continue to promote these advances to upcoming generations of grouters, and to be on guard against any regressions, whether innocent or intentional. The quality of the works conducted in the last 25 years or so has been outstanding, especially for remedial projects in karstified terrains. For that reason alone, the lure of the "Dark Arts" must be resisted.

REFERENCES

Bruce, D.A. (2013). "Specialty Construction Techniques for Dam and Levee Remediation", Spon Press, an imprint of Taylor and Francis, Editor, 304 pp.

Bruce, D.A., T.L. Dreese, and D.M. Heenan (2008). "Concrete Walls and Grout Curtains in the Twenty-First Century: The Concept of Composite Cut-Offs for Seepage Control", USSD Annual Conference, Portland, OR, April 28-May 2, 35 pp.

- Bruce, D.A. and T.L. Dreese. (2010). "Specifications for Rock Mass Grouting", ASDSO Dam Safety Conference, September 19-23, Seattle, WA, 12 pp.
- Bruce, D.A., T.L. Dreese, and C. Hallahan (2017). "Errors, Misunderstandings and Mistakes in Remedial Grouting Projects for Dams", 5th International Grouting, Deep Mixing, and Diaphragm Walls Conference, International Conference Organization for Grouting (ICOG), Honolulu, Hawaii, July 9-12, 14 pp.
- DePaoli, B., B. Bosco, R. Granata, and D.A. Bruce. (1992). "Fundamental Observations on Cement Based Grouts (1) : Traditional Materials." Proc. ASCE Conference, "Grouting, Soil Improvement and Geosynthetics," New Orleans, LA, February 25-28, 2 Volumes, pp. 474-485.
- Hockenberry, A.N., D.P. Stare, C.M. Hallahan, and T.L. Dreese (2012) "Ten Years of Computer Monitoring and Beyond", Deep Foundation Institute, 4th International Conference on Grouting and Deep Mixing, New Orleans, LA, February 15-18, pp 1516-1530.
- Stare, D.P., A.N. Hockenberry, T.L. Dreese, D.B. Wilson, and D.A. Bruce. (2012). "Protection of Embankments during Drilling and Grouting", Deep Foundation Institute, 4th International Conference on Grouting and Deep Mixing, New Orleans, LA, February 15-18, pp 1304-1313.
- U.S. Army Corps of Engineers (1984). Grouting Technology: Engineers Manual EM 1110-2-3506.
- U.S. Army Corps of Engineers (1997). "Engineering and Design Procedures for Drilling in Earth Embankments", CECW-E.G., Report no. 1110-1-1807, September 30. Reissued December 31, 2014.
- U.S. Army Corps of Engineers (2014). "Grouting Technology", Engineering Manual 1110-2-3506, July 3.
- Weaver, K.D. and D.A. Bruce (2007). "Dam Foundation Grouting, Revised and Expanded Edition", American Society of Civil Engineers, ASCE Press, New York, 504 pp.