ROCK GROUTING FOR DAMS AND THE NEED TO FIGHT REGRESSIVE THINKING

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ABSTRACT

It is generally recognized, both nationally and internationally, that rock grouting theory and practice in North America has undergone a most positive revolution during the last decade or so. Key elements of this progress have included the development and use of suites of balanced, stable High Mobility Grouts (HMG); increasing use of Low Mobility Grouts (LMG); new overburden and rock drilling methods; computer monitoring control and analysis; and the use of Apparent Lugeon Theory and Lugeon testing to assure proper stage refusals and low residual permeabilities, respectively. These concepts have been most strongly implemented on major Federal dam remediation projects. Also, certain consultants are using them on smaller, non-Federal projects.

However, the author has noted over the past few years a distinctly retrogressive faction in the grouting industry which, if left unchallenged, will undo much of the advantages gained over the last decade. Examples include a reversion to the use of highly unstable HMG's as engineers confuse "thin" and high water content. Perhaps more concerning is the re-emergence in certain circles of the thirty-year-old GIN Method (Grouting Intensity Number). This method was devised with the laudable goal of trying to assure a certain basic standard of care in grouting projects in countries of a lesser degree of resource and sophistication.

In this paper, the author urges against the regression in U.S. grouting practice, which is in danger of occurring due to a relapse into old, unsatisfactory habits, and a "rediscovery" of outdated and inappropriate methodologies. The U.S. grouting industry today is ranked amongst the most active and effective in the world, and this level of approbation should be guarded and cultivated, not let slide.

INTRODUCTION

Rock grouting for dam foundations has been carried out in the U.S. since at least 1893 when the limestone bedrock of a dam in the New Croton Project, NY, was treated with cement grout (Franklin and Dusseault, 1989). Opinions differ on the method of injections (Glossop, 1961, Littlejohn , 2003), although other reports (Verfel, 1989) strongly suggest that U.S. grouting procedures had made "a good start."

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For the best part of the following hundred years, the intense history of dam grouting in the U.S. is, to some extent, a picture of objectives not fully achieved, innovative procedures and insightful ideas inconsistently implemented, and a number of questionable practices unthinkingly perpetuated. During the last 15 years, however, in many — but not all — parts of our practice, there has been a radical change in our concepts and in our approaches to such work. Partly drawing from knowledge made available in the U.S. by European specialists, for example at the seminal grouting conferences hosted in New Orleans in 1982, 1992 and 2003, and partly by the very challenging problems posed by the need to construct remedial grout curtains in our own dams, especially on karst, there has been a technological revolution in dam grouting practices in the U.S. This revolution has greatly benefited the owners of these dams, and dams themselves, and — by association — the grouting profession at large.

However, the proven advantages and successes of this uniquely tailored advance have not yet everywhere been recognized, and have not always been upheld and consistently defended. We therefore find that in some regions, or in certain organizations — or most sadly in certain sections of certain organizations — rock grouting is still being specified in the terms of 50 years ago. Equally, there are increasing numbers of projects being specified and run according to "new concepts" which, in reality, are new only to the designers and represent a retrogressive step of almost 30 years.

In the following sections, the old, the new and the retrogressive concepts of rock fissure grouting are presented to provide a platform for logically arguing against the old and the retrogressive ways of approaching work of this type. Given the relatively high volume of dam grouting — especially for remedial applications — being conducted today, we have now arrived at a particularly important time to have this debate.

HISTORICAL CONCEPTS ("THE OLD")

There is a trove of published information to be found on this subject, including the Proceedings from the New Orleans Grouting Conference in 1982, the "Foundations for Dams" Conference (1974) and textbooks by Houlsby (1990), and Weaver (1991) in particular. Even more important are the unpublished reports, memoranda and manuals produced on a project-specific basis, or by companies or governmental organizations. These had special gravitas because their authors strongly influenced the next generation of grouting engineers while they, themselves, were elevated to the position of "consultants" on other projects in different governances.

Bearing in mind the unprecedented level of activity in those years in new dam grouting, as well as the national puritanism towards "low bid" contracting, specifications were highly prescriptive and restrictive. Such prescriptions did nothing to stimulate innovation since the contractor was reduced to the status of the cheapest purveyor of labor, equipment and materials, while the goal of the owners' inspectors was to ensure that the specifications were enforced to the letter, via "hole by hole" direction of the grouting activities.

By the way of illustration, in 1974, Polatty was invited to give an overview of U.S. Dam Grouting Practices: "In preparing this paper, I requested copies of current specifications for foundation grouting from several Corps of Engineers districts, the TVA and the Bureau of Reclamation. In comparing these current specifications with copies of specifications that I had in my file 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 list "difficulty in having sufficient flexibility in the field to make necessary changes to ensure a good grouting job" as a problem. What a surprise!

As a consequence, several important historical paradigms became embedded in our national practice as late as the 1980's. These include:

- The drilling of vertical holes, to a target depth (as opposed to stratigraphic horizon). The only common exception (e.g., Albritton, 1982) would be the concept of inclining the curtain upstream, so as to physically distance it from the downstream drains.

- The use of rotary drilling (often just coring) since in the early days of the 20th century since only such drills could use water flush. Percussion drilling was then synonymous with the use of air flush, which many (but not all) did recognize as detrimental to fissure cleanliness and amenability to grout. (The age old debate about rotary versus percussion drilling as being more suitable for grout holes was wrongly focused: it should have been water versus air.)

- The concept of a "one row curtain," except notably under the cores of embankment dams, where even then the shallowest possible excuse was taken to revert to one row.

- The use of relatively low grout pressures, resulting from the recurrent specification to provide "constant" pressures which therefore meant the use of progressive cavity pumps ("Moynos") as opposed to higher pressure piston or ram pumps.

- The use of "thin" grouts (with excessive water:cement ratios often well in excess of 10 by weight – although typically mixes were measured by volume). Such mixes of course were easy to pump due to their low apparent viscosity, but naturally had extremely high bleed values and horrible pressure filtration resistance. These mixes were allied with a fundamental distrust/unawareness of the benefits of additives (except for calcium chloride in "taker" situations) although, latterly, the use of bentonite was entertained and ongoing though somewhat misguided experimentation with superplasticizers was conducted in certain quarters.

- Curtains were grouted until a certain cement refusal was obtained (e.g., 1 bag per foot) as opposed to a measured residual permeability. This is, however, a charitable view: often the grouting was discontinued when the budget was expended and, in the aftermath when the underseepage became of alarming quantities, the cry was made that "the grouting didn't work!" The general result (Weaver and Bruce, 2007) of these deficiencies was either a) a poor travel of grout in the ground, leading to the drilling of families of higher order holes at ridiculously close centers (e.g., 1 foot at Chickamauga Dam, TN), or b) uncontrollable flow of "thin" grouts into karstic voids or similar major features.

It is somewhat of a testament to the enlightened, the lucky, and the meticulous that so many of the curtains constructed in the period from the 1920's to the early 1980's in particular appear to have actually functioned adequately given the restrictions, the misconceptions and the prescriptions. Uncharitable views would have it that such curtains may not have been needed at all, from a dam performance or safety viewpoint, and that the curtain was inserted by rote and by paradigm. On the other hand, the fact that so many of our dams have now been remediated, or are facing remediation as a result of an ineffective, incomplete and/or deteriorating grout curtain, does lead us back to the inescapable fact that the "old ways" in retrospect contained major flaws in their workings. One definition of the word "insanity" is to continue to do the same thing even when it has been repeatedly proved to fail or to be wrong. To persist with, or revert to, the "old" ways of grouting dam foundations is an example of this definition.

CURRENT PRINCIPLES ("THE NEW")

There had arrived in the North American scene by the mid-1990's a potent mixture of knowledge and opportunity. As arguably first articulated at a Grouting Seminar in Toronto, ON in 1989, but certainly emphasized to the cogniscenti in New Orleans in 1992, the world of dam grouting in North America had begun to change dramatically. This statement is made with all due recognition of Dr. Wally Baker who, some years before, had instigated an advance into new technical fields, but an advance which proved economically unsustainable in the face of prevalent contracting and procurement vehicles of the time.

Of particular significance was a paper by DePaoli et al. (1992) which, in a deceptively understated way, explained quite clearly the critical control and importance of pressure filtration coefficient over the effective travel of grouts into fissures, and hence their efficiency in generating low and durable residual rock mass permeability. As described in Weaver and Bruce (2007), pressure filtration can be conceived as follows:

"The injection of particulate grouts into small apertures is similar to pressing the grout against a filter material: depending on the formulation of the grout, water can be expelled from the grout in motion, leading to the development of cementitious filter cake at the borehole wall. With more time, the cake blocks off the entrance to the aperture and so renders the aperture inaccessible to further injection via that avenue. This tendency of the grout to lose water during injection is quantified by the term *pressure filtration coefficient* (K_{pf})…"

"To enhance the penetrability of a grout, a low-pressure filtration coefficient that minimizes the increase in apparent viscosity (Figure 1) is required. The general relationship between the two vital parameters of cohesion and pressure filtration coefficient is shown in Figure 2. Whereas cohesion was traditionally minimized in simple cement–water grouts by using extremely high w:c ratios (Albritton 1982), such mixes

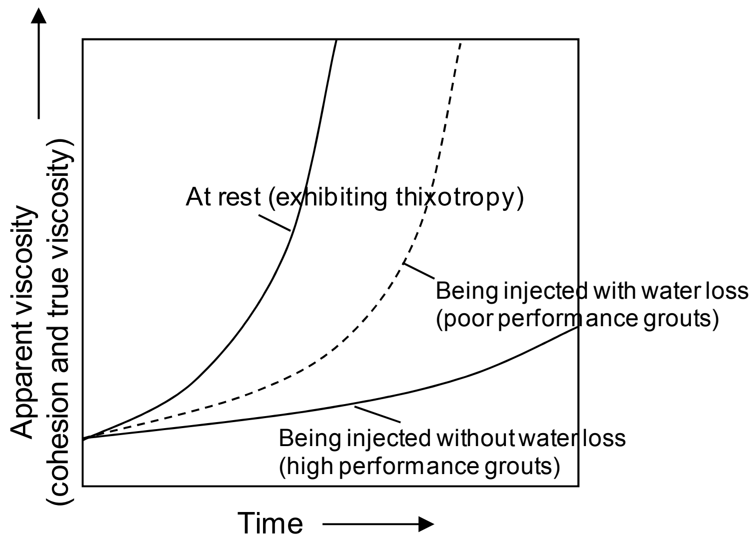


Figure 1. Rheological behavior of typical Binghamian fluids (modified after Mongilardi and Tornaghi, 1986).

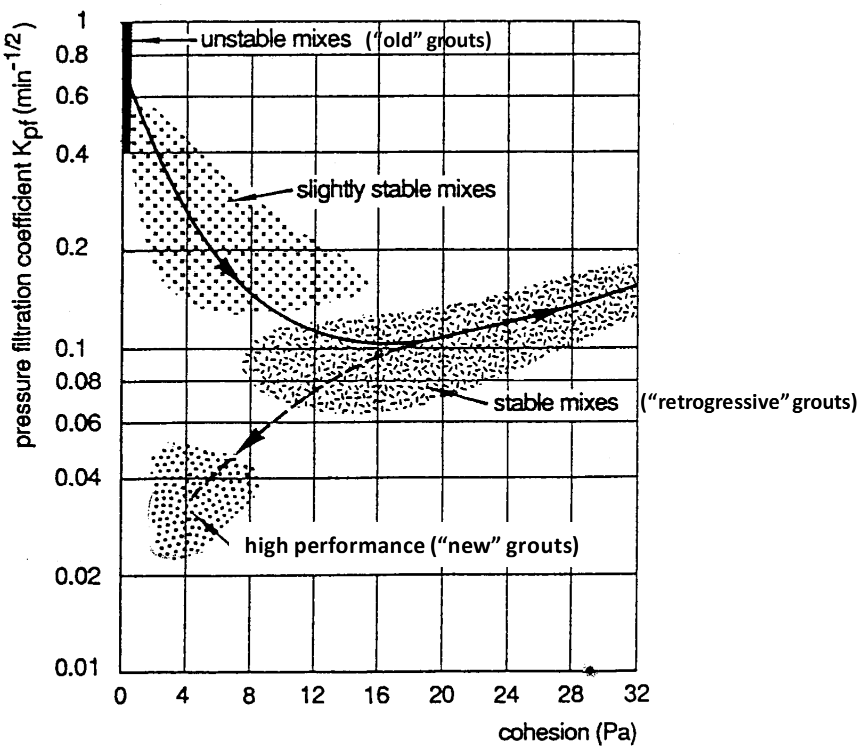


Figure 2. Historical path of development from unstable mixes to contemporary balanced multi-component mixes (modified after De Paoli et al., 1992).

have high K_{pf} values, which severely curtail their penetrability. However, by using much lower water contents (typically less than 1.5 weight by volume) and combinations of stabilizing and plasticizing admixtures and additives (including bentonite, silica fume, and Welan Gum), grouts of low viscosity (less than 60 seconds Marsh), low cohesion, minimal bleed, and excellent K_{pf} values (less than 0.02 $min^{-1/2}$) can be produced. DePaoli et al. (1992) found that even under moderate injection pressures, such balanced, stabilized grouts provided enhanced penetrability and performance via the following:

- an increased radius of travel;
- a more efficient sealing ability as a result of the improved penetrability and the lower permeability of the mix;
- a high volumetric yield, with uniformly filled voids; and
- a higher erosion resistance because of improved mechanical strength for a given cement content."

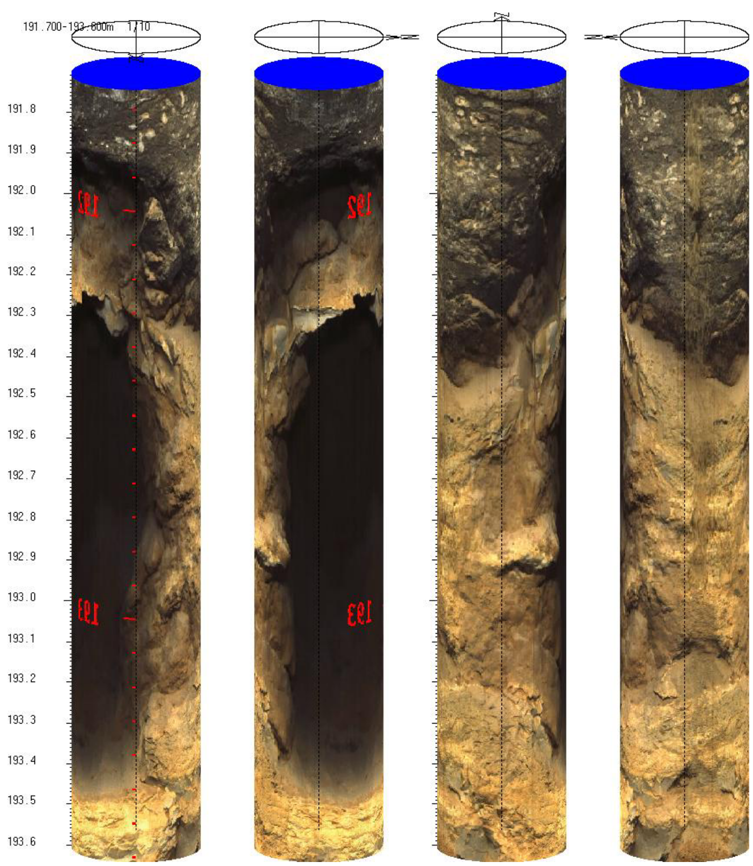
Of course, it must be acknowledged that other factors will impact curtain effectiveness, but never in the U.S. literature before 1992 was the significance (or even concept) of "pressure filtration" mentioned in conjunction with rock grouting.

It is only fair to separate from the comparison between "old" and "new" those elements which are, by invention and technology, the exclusive privilege of the "new." Much has been written and rightly so, about the tremendously beneficial effect that the use of computer-based systems have had on the collection, processing, interpretation and display of data from the field (Dreese et al., 2003). No reputable grouting project of any significant scale or importance does now not have such a capability, feeding news back into a central "mission control" (Photograph 1), and back into the Project Executive's desk in head office, as well. The best of these systems can now integrate all the drilling and water testing data, as well as the grouting data, to compliment and compare with the historical site investigation data (and original grouting information) which may be available on any particular project. Given the power of this knowledge, curtains can be constructed to engineered standards with a degree of reliability and confidence which was unthinkable under old regimes.

Another child of the new age is the Optical or Accoustic Televiewer, an extremely acute and reliable instrument which basically provides a "flat core" of a preexisting hole (Photograph 2). With this capability, the borehole wall conditions of drill holes — formed "destructively" without the expense of core drilling — can be closely scrutinized, and compared with results from permeability tests and grout injections. This is an extremely important diagnostic tool, and represents a compatibility far beyond the grainy, boring images hitherto provided by down-the-hole video cameras.

Returning to a comparison of "old" and "new" concepts, the fundamental change in attitudes towards mix designs and mix properties has already been discussed: it is one absolutely vital component in the revolution. However, even today, the author finds specifications — or worse, projects — where the grout mix design comprises three

Photograph 1



Photograph 2

components at best, and mixes are changed from “thin” to “thick” by changing from water:cement ratios of 3:1 to 0.8:1, or 0.6:1 in the case of “gulpers.” This is simply inexcusable and not acceptable given the state of knowledge which currently exists and is freely available on this subject.

Other areas of important distinction in contemporary grout curtain design and construction may be summarized as follows:

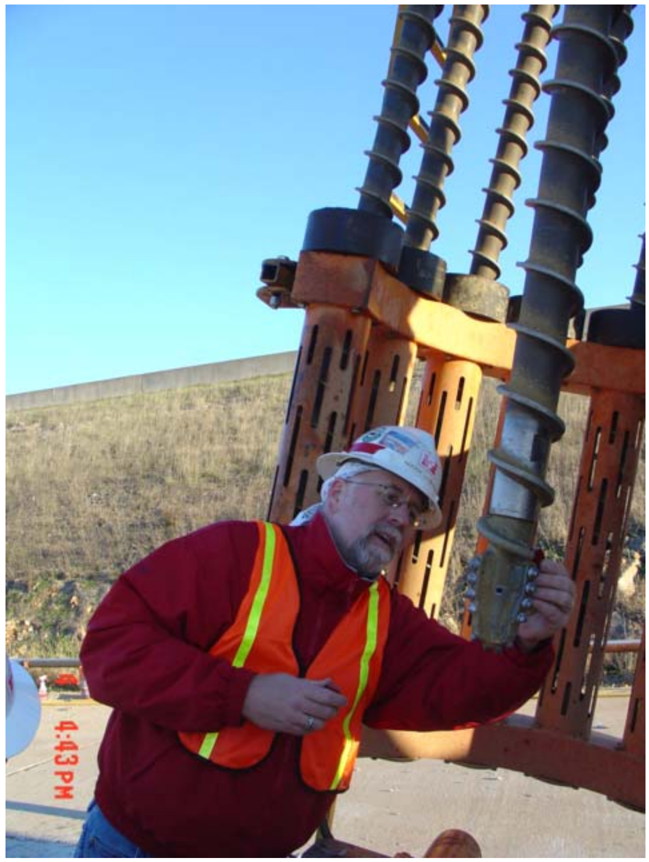
- Curtain Geometry: Curtains must have, as a minimum, 2 rows of holes, which extend, wherever feasible technically, into a confining layer. They are not simply installed to a target depth below ground surface. Also, the holes in each row are inclined say 15º off vertical. The inclination of each row of holes is in the opposite direction, thereby producing a “criss cross” effect, assured to intercept all fissure sets, especially those vertically oriented. The zone between these “outer rows,” typically about 10 feet wide, is then available for additional “tightening” holes, perhaps using special or different grouting materials, and for drilling and testing Verification Borings which are installed to demonstrate the residual permeability achieved by the curtain.

- Residual Permeability: The purpose of a grout curtain is to stop water flowing through the rock mass. Therefore, its acceptability as an engineered structure must be verified by measuring its residual permeability — to water, not some arbitrary limiting grout take. (As described above, an inappropriate grout will have premature refusal in certain fissures, while not reducing the permeability of the ground further away.) This test is best done in cored (or Optilogged) holes, using multipressure Lugeon Tests as first described by Houlsby (1976).

- Declaring the Target Residual Permeability: Residual permeability is the goal which must be declared as part of the design by the Engineer and which therefore must be satisfied by the Contractor. A grout curtain truly now is a “Quantitatively Engineered” structure (Wilson and Dreese, 2003), created by real-time control of subsurface construction processes. This “measure of success” will vary from project to project, as articulated by, for example, Houlsby (1990), but is vital to declare and essential to satisfy.

- Stage Refusal: Each and every stage should now be brought to a virtually total refusal. When viewing the grouting process on the computer monitor, this means an Apparent Lugeon Value of practically zero for each stage (i.e., the (stable) grout is used as a test fluid in the same way as water is). In reality, this means that the stage in question is consuming grout at less than 0.1 gpm over a period of, say, 5 minutes, at target pressure. More lax refusal criteria will result in incompletely and inefficiently grouted stages, and so higher than desirable residual permeabilities in the rock mass.

- Drilling Methods and Concepts: Water is the drilling and flushing medium of choice in rock masses. Whether the drilling is done by percussive methods (top hole, or water-powered down-the-hole hammer) or rotary methods (which tend now to be less competitive and have greater deviations) is technically immaterial. Also, the development of commercially viable rotary-sonic systems (Bruce and Davis, 2005) has provided a method which has entirely satisfied federal regulations (USACE, 1997) for drilling through existing embankment dams without fear of hydro or pneumatic fracture. In this regard, it is also the case that innovative contractors can devise other conforming overburden drilling systems which are equally protective of embankment fills (<u>Photograph 3</u>).



Photograph 3

In all drilling operations, the recording of drilling parameters (e.g., rate of penetration, flush characteristics, torque and so on) has been regularized by developing automatic recorders as opposed to relying on drillers or junior field engineers: the overall rise in the quality and usefulness of these data has been predictably spectacular.

- <u>Specifications and Contractor Procurement Processes</u>: Specifications are no longer so prescriptive ("yes: we do need the head of the contractor as well as his arms") and so all contracts are not let on the low bid basis, although to do otherwise is still not permissible for many organizations, especially in the public sector. Grouting contractors are being hired, correctly, based on their skills and experience and not just their capability of calculating a low price. There is absolutely no doubt that this "Best Value" approach has raised technical standards across the board and has, interestingly, honed the competitive instincts of all competent contractors: all this is to the inestimable benefit of the projects themselves. Further insight on specifications is provided in Bruce and Dreese (2010).

RETROGRESSIVE PRINCIPLES (I.E., “THE RETROGRESSIVE”)

The fact is that certain engineers in North America have become involved in projects where a certain expertise in curtain grouting is needed and where, for commercial reasons, they have chosen to go their own way, and/or to “reinvent the wheel.” The uncomfortable truth is that they are either not aware of the “new” approach, or do not have the technical background to be able to differentiate its value in comparison with older principles advocated by “old friends” in the industry who are in fact typically not grouting engineers by practice. A classic example of this is the sporadic emergence of the use of GIN Theory as the guiding principle for curtain grouting on certain U.S. projects.

Dr. Giovanni Lombardi is a Swiss dam engineering expert who is an extremely influential figure, especially in developing countries. His long association with Dr. Don Deere, particularly in projects involving curtain grouting on South American dams, included the development in the 1980’s of “GIN Theory” (the GIN component referring to “Grouting Intensity Number”). This was laudably developed to assure for the client a certain standard of care and quality would be achieved on projects which were in remote areas and/or were to be built by contractors with (somewhat) limited experience and expertise.

Together by 1993 they had articulated an approach to grouting that takes into account the specific energy expended in the injection process. Their approach assumes that, for any given interval, the energy expended is approximately equal to the product of the final pressure (p) and the volume (V) of grout that is injected. The numerical value of this product is called the grouting intensity number, or GIN. Depending on the units used, this number may be expressed in bar-liters per meter. They recommended taking into account site-specific factors, including the ultimate reservoir head, the characteristics of the bedrock discontinuities, stratification, weak zones, weathering, and in situ state of stress in selecting a GIN number that — in conjunction with limiting values of volume and pressure — is to be used for easily grouted fissures as well as for finer fissures. They reasoned that because the pressure decreases quite rapidly as the grout moves away from the borehole in tight fissures, the total uplift pressure even at high injection pressures will as a rule be much lower than the overburden weight, except in the uppermost 5 to 10 m of the foundation. On that basis, they indicated that a limiting pressure as high as 50 bars might be appropriate if high-intensity grouting were desired. However, for most conditions, they recommended using a limiting pressure of 30 bars and a limiting volume of 200 L/m.

Perhaps anticipating objections to the grout volume limitation imposed by the GIN rule, Lombardi (2003) stated that the nominal limitation could actually be treated as a decision point rather than as an absolute, rigid stopping point. He suggested that the decision might be one of the following:

- Continue injection of grout.
- Terminate injection of grout.
- Temporarily stop grouting and resume injection after a period of time.
- Abandon the hole and drill another nearby.
- Add a product, for example, an antiwashout agent, to the grout mix, or take some other appropriate measure

It would appear that application of the GIN principle entails use of a single "moderately thick" superplasticized stable grout, defined in this case as a grout with less than 5% bleed after 2 hours, throughout the injection process. This grout is injected at a steady low to moderate rate, allowing the pressure to build up gradually as the grout penetrates farther into the foundation rock mass. Real-time monitoring of a series of relationships or parameters by computer graphics is required. These relationships and parameters include curves of pressure versus time, grout flow rate versus time, total injected volume versus time, and the derivative curve of flow rate divided by pressure versus time.

Lombardi and Deere (1993) stated that the GIN principle had been used in construction of grout curtains for dams in Turkey, Mexico, Argentina, Austria, Switzerland, and Ecuador. However, Ewert (2003) vociferously pointed out that application of the GIN principle in certain geologic conditions and in some rock types may be inappropriate, especially if the grouting program is in the hands of inexperienced personnel. His adverse opinions regarding the GIN principle included the following:

- The maximum pressures proposed by the principle are too high for most rock types, causing hydrofracturing and unnecessarily large grout takes.

- The maximum volumes allowed by the principle when grouting at low pressures are inadequate to ensure complete filling of wider open joints.

That particular, and memorable, technical session in New Orleans in 2003 continued at a rapid pace for much longer than the organizers had intended, reflecting much credit in both protagonists. The opinion of the author is as follows:

- Hydraulic fracturing (and, for that matter, fracture dilation or surface displacement) can readily and quickly be recognized by competent, experienced personnel using modern real-time monitoring equipment and procedures. Injection pressures can then be reduced, and injection can be slowed or stopped as appropriate before excessive volumes of grout are injected.

- On the second point, although adjusting the rheology of the grout rather than halting injection to limit grout travel after some prescribed maximum volume has been injected, is favorable application of conservative curtain closure criteria and procedures would, in most if not all cases, provide additional opportunities to complete the filling of wider open joints.

In retrospect, had the esteemed Dr. Lombardi strongly and widely promoted his Theory in the U.S. during the time of the U.S. grouting industry “fin de ciecle” (i.e., the late 1980’s), then it is highly probable that the entire North American continent, in addition to South America, would have had a different grouting direction. Instead, this flare from Europe has fallen between the two stools of the U.S. grouting practice, one anchored in the early 1920’s, the other springing from the revolution of the mid-1990’s. In summary, GIN Theory most probably has worked well and was an excellent option in the grouting interregnum in developing countries during the latter decades of the 20th Century. However, the approaches developed in North America over the last 15 years have been verified to give truly exceptional, compliant and consistent results, using means and methods which are site-specific.

CONCLUSION

Current U.S. dam curtain grouting practice for seepage control has evolved during the last 15 years or so to a level that it can assure a responsive and effective solution to any project-specific challenge, be it a remedial application, or a new dam curtain. For the benefit of the industry, it is essential that two tasks are implemented. The first is to eradicate the “old ways”: this in itself is a matter of technical education, although the quality, intensity and consistency of the education need to be pursued with constancy and vigor. The second is to be on guard against regression, which is typified by adoption of concepts which were popular decades ago in other countries, but for different reasons, did not arrive in the U.S.

For the first time in our dam grouting history, North America has a current approach and a track record which is without equal in the world. This is partly due to the severity of the challenges we face, but also is a result of a typically uniquely North American melanage of concepts and resources. The recent record speaks for itself with excellent results having been achieved on remedial grouting projects at many USACE DSAC-1 projects in particular. While we should and will remain receptive to new developments, we must not allow the industry to give up the successes of the last decade.

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