Composite Cut-Off Walls for Existing Dams: Theory and Practice

Dr. Donald A. Bruce[1], Trent L. Dreese[2], Mark C. Harris[3], and Douglas M. Heenan[4]

[1] President, Geosystems, L.P., P.O. Box 237, Venetia, PA 15367, U.S.A., Phone: 724-942-0570, Fax: 724-942-1911, dabruce@geosystemsbruce.com
[2] Vice President, Gannett Fleming Inc., 207 Senate Avenue, Camp Hill, PA 17011, U.S.A., Phone: 717-763-7211 x2686, Fax: (717) 303-0346, tdreese@gfnet.com
[3] Engineering Geologist, U.S. Army Corps of Engineers, P.O. Box 867 - CESWL-EC-DG, Little Rock, AR 72203, U.S.A., Phone: 501-324-5604 x1418, Fax: 501-324-5265, mark.c.harris@usace.army.mil
[4] Vice President, Advanced Construction Techniques Ltd., 3935 Lloydtown Aurora Road, Kettleby ON L0G 1J0, Canada, Phone: 905-939-7755, Fax: 905-939-9305, dheenan@agtgroup.com

ABSTRACT: During the last 10 years, the theory and practice of composite cut-off walls has been developed in the United States. The theory is that, prior to the construction of a remedial concrete diaphragm wall through a dam and into its foundation rock, the whole alignment is systematically grouted to a verified residual permeability. The grouting is conducted in two rows, and the wall is then built between them. This approach has the following advantages:

1. The drilling and grouting constitutes an extremely intense site investigation, as well as being a ground treatment in "clean" fissure conditions. Thus, the depth and extent of the diaphragm wall can be logically determined, i.e., it will be installed only where potentially erodible material has been found in the rock mass. Since the cost of drilling and grouting is a fraction of the cost of a diaphragm wall, the overall project costs are minimized.
2. The alignment of the diaphragm wall is pretreated, so that potentially catastrophic, sudden slurry losses are prevented from occurring.
3. By conducting the drilling and grouting into the clean fissured rock mass below and beyond the concrete diaphragm to an engineered target, the effective extent of the concrete cut-off is significantly and cost-effectively increased.

Guidance is provided on the design and construction of the grouted element of the composite wall structure.

INTRODUCTION

Grout curtains have been used in the U.S. to control seepage in rock masses under and around dams of all types since the 1890's. For a variety of understandable, if not always laudable reasons, the long-term performance of many of these curtains has not been satisfactory, especially in lithologies containing soluble and/or erodible materials. Foundation remediation in such instances traditionally involved regrouting, often of course, using the same means, methods and materials whose defects contributed to the inadequacy in the first place.

Disillusionment on the part of owners and engineers with the apparent inability of these traditional grouting practices to provide a product of acceptable efficiency and durability led to the chorus of "grouting doesn't work" voices in the industry from the mid-1970's onwards. The fact that effective and durable grout curtains were being installed successfully elsewhere in the world, using different perspectives on design, construction and contractor procurement processes, largely escaped the attention of the doubters who, for all their other and obvious qualities, exhibited technological xenophobia.

Partly as a result of the anti-grouting lobby, partly in response to indisputable geological realities and challenges, and building on technical advances in "slurry wall" techniques, the concept and reality of "positive cutoffs" became the mantra for major embankment dam foundation rehabilitation in North America from 1975 onwards. Such walls, built through and under existing dams by either the panel wall technique, or secant large diameter piles, comprise some type of concrete, ranging from high strength to plastic. In contrast to grout curtains, where well over 90% of the cutoff is, in fact, the virgin, in situ rock, these "positive" cutoffs are, conceptually, built of 100% pre-engineered material of well-defined properties. The necessity for such "positive" cutoff walls remains today in certain geological conditions, and the list of successful projects is extremely impressive (Bruce et al., 2006).

From the mid-1980's – albeit in Europe (Lombardi 2003) – a new wave of dam grouting concepts began to emerge. Given that most of the leading North American practitioners had close corporate and/or professional and personal links with this insurgency, it is not surprising that their heretofore moribund industry began to change. By the time of the seminal 2003 ASCE grouting conference in New Orleans, the revolution in North American practice for dam foundation grouting had been clearly demonstrated (e.g., Wilson and Dreese, 2003; Walz et al., 2003). The concept of a Qualitatively Engineered Grout Curtain was affirmed.

In the U.S. there is now unprecedented levels of expertise and experience in both grout curtains and concrete cutoff walls. This is particularly serendipitous given that the dollar requirement for the application of both technologies – in Federal dams alone in the period 2007-2012 – is of an order equivalent to the aggregate of the preceding 40 years (Halpin, 2007). It is therefore surprising that it is only in recent years that the concept of "composite" walls has been formalized (Bruce et al., 2008). In essence, the cutoff features both techniques, with the grouting facilitating the diaphragm wall construction and providing a cost-effective barrier in rock masses without clay infilling, while the concrete wall assures durability in such potentially erodible horizons and features. This formalization was in fact precipitated by events at Mississinewa Dam, IN in the early 2000's, but is now being employed systematically for the construction of huge remedial cutoffs in carbonate terrains in Missouri (Clearwater Dam), Tennessee (Center Hill Dam), Kentucky (Wolf Creek Dam) in addition to the completed project at Bear Creek Dam, Alabama. Prior to this time, grouting conducted on large concrete cutoff wall projects was typically of a very minor scale and conducted primarily as a scouting or investigatory tool, as was the case at W.F. George Dam, Alabama (Ressi, 2003).

In this paper, critical aspects of grouting and concrete cutoff walls are reviewed — as related to the *composite cutoff philosophy*. Additional background may be found in Bruce et al., 2010, and Weaver and Bruce 2007.

GROUT CURTAINS

Design

Design of grout curtains based on rules of thumb without consideration of the site geology is not an acceptable practice or standard of care. Contemporary approaches are based on the concept of a Quantitatively Engineered Grout Curtain (QEGC), which provides criteria for the maximum acceptable residual permeability and minimum acceptable dimensions of the cutoff (Wilson and Dreese, 1998, 2003). Prerequisite geological investigations and other work required to perform this quantitative design include:

- thorough geologic investigations identifying structure, stratigraphy, weathering, solutioning, and permeability of the foundation rock;
- establishment of project performance requirements in terms of seepage quantities and seepage pressures (design requirements should consider dam safety, cost, and political acceptability or public perception as they relate to residual seepage);
- seepage analyses to determine the need for grouting, the horizontal and vertical limits of the cutoff, the width of the curtain, and the location of the curtain;
- specifications written to assure best practice for field execution of every element of the work; and
- where relevant, the value of the lost water should be compared to the cost of more intensive grouting in a cost-benefit analysis

Quantitative design of grouting requires that the curtain be treated in seepage analyses as an engineered element. The specific geometry of the curtain in terms of depth and width must be included in the model, and the achievable hydraulic conductivity of the curtain must also be assumed. Guidance on assigning grout curtain design parameters and performing seepage analyses for grout curtains is covered in detail by Wilson and Dreese (2003). More substantial and complete guidance on flow modeling of grouted cutoffs is included in the pending update to USACE EM 1110-2-3506.

Construction

Many aspects of the construction of QEGCs have also changed greatly in the last 10 years or so, driven by the goals of achieving improved operational speed and efficiency, satisfying lower residual permeability targets, enhancing QA/QC, verification, and real-time control, and assuring long-term durability and effectiveness. Particularly important advances are as follows:

- The traditional concepts of stage grouting (i.e., up — or down — depending on the stability and permeability of the rock mass) and closure (i.e., Primary-Secondary-Tertiary phases) still apply. However, construction in two initial rows, with the holes in each inclined in opposite directions, has become standard practice.

- Multi-component, balanced, cement-based grouts are used to provide high performance mixes, which provide superior stability and rheological and durability properties. The use of "neat" cement grouts with high water:cement ratios and perhaps nominal amounts of super-plasticizer or bentonite is simply not acceptable (Chuaqui and Bruce, 2003).

- The current state of the art in grouting monitoring and evaluation is a fully integrated system where all field instruments are monitored in real time through a computer interface, all necessary calculations are performed automatically, grouting quantity information is tabulated and summarized electronically, program analyses are conducted automatically by the system using numerous variables, and multiple, custom as-built grouting profiles are automatically generated and maintained. This level of technology provides the most reliable and highest quality project records with minimal operator effort. In fact, the advent of such technology has been found to substantially decrease grouting program costs while providing unprecedented levels of assurance that the design goal is being met (Dreese et al., 2003).
- Modern drilling recording instruments and borehole imaging technology allow for better investigation and understanding of subsurface conditions than was previously possible. Measurement While Drilling (MWD) instrumentation provides additional geological information during the drilling of every hole on a grouting project (Bruce and Davis, 2005) and not only from the limited number of cored investigatory holes. Specific energy and other recorded data can be evaluated and compared to the subsequent grouting data to extract as much information as possible from every hole drilled. Each hole on a grouting project is thereby treated as an exploration hole, and the data gathered are utilized to increase the understanding of subsurface conditions. After a hole has been drilled, borehole imaging can be performed to obtain a "virtual core." This equipment is especially useful for destructively drilled production holes where recovered core is not available for viewing and logging, and it provides invaluable data such as in situ measurements of fracture apertures and bedrock discontinuity geometry. These are then utilized in designing or modifying the grout methods and materials. Borehole images are mapped by qualified personnel, and the data may be further analyzed using stereonet analyses.

Verification and Performance

Successfully achieving a cutoff closure is a three-step process: achieving closure on individual stages and holes; achieving closure on individual lines; and achieving closure on the entire curtain. Proper closure on individual stages and holes is primarily a function of the following six items: (1) drilling a properly flushed hole, effectively washing the hole, and understanding the geology of the stages being grouted; (2) applying that knowledge, along with the results of water-pressure testing, to determine technically effective and cost-effective stage selection; (3) selecting appropriate starting mixes; (4) real-time monitoring of the grouting and assessment of the characteristics of each grouting operation; (5) making good and informed decisions regarding when to change grout mixes during injection within a stage; and (6) managing the hole to completion (i.e., refusal to further grout injection) within a reasonable amount of time. The key during grouting is to gradually reduce the apparent Lugeon value of the stage to practically zero. The apparent Lugeon value is calculated using a stable grout as the test fluid, and taking into account the apparent viscosity of the grout relative to water.

Pumping large quantities of grout for an extended period of time without any indication of achieving refusal (i.e., a reduction in the apparent Lugeon value) is generally a waste of precious time and good grout. Unless a large cavity has been encountered, the grout being used in this case has a cohesion that is too low and is simply traveling a great distance through a single fracture. Grout mixes need to be designed properly for economy and value, especially in karstified conditions.

Each row of a grout curtain, and the completed curtain, should be analyzed in detail. Each section of the grout curtain should be evaluated, and closure plots of pre-grouting permeability for each series of holes in the section should be plotted. As grouting progresses, the plots should show a continual decrease in pre-grouting permeability for each successive series of holes. For example, the results for the exploratory holes and Primary holes from the first row within a section represent the "natural permeability" of the formation. Secondary holes on each row should show a reduced permeability compared to the Primary holes due to the permeability reduction associated with grouting of the primaries. Similarly, the pre-grouting permeability of Tertiary holes should show a marked decline relative to the Secondary holes, and so on.

In addition to performing the analyses described previously, it is also necessary to review profiles indicating the geology, water testing, and grouting results. Review of the profiles with the water Lugeon values displayed on each zone or stage gives confirmation that the formation behavior is consistent with the grouting data, and permits rapid evaluation of any trends or problem areas requiring additional attention. In addition, this review permits identification of specific holes, or stages within a hole, that behaved abnormally and that could be skewing the results of the closure analysis. For example, the average pre-grouting permeability of Tertiary holes that appear on a closure analysis plot may be 10 Lugeons, but that average may be caused by one Tertiary hole that had an extraordinarily high reading: averages are interesting, but spatial distributions are critical.

Review of the grout row profiles with the grout takes displayed is also necessary along with comparison of the average grout takes compared to the average Lugeon values reported by the closure analysis. Areas of abnormally high or low grout takes in comparison to the Lugeon values should be identified for further analysis. The grouting records for these abnormal zones should be reviewed carefully, along with the pressure testing and grouting records from adjacent holes.

CONCRETE CUTOFF WALLS

Investigations, Design, Specifications and Contractor Procurement

Intensive, focused site investigations are essential as the basis for cutoff design and contractor bidding purposes. In particular, these investigations must not only identify rock mass lithology, structure, abrasivity, and strength ("rippability"), but also the potential for loss of slurry during panel excavation. This has not always been done, and cost and schedule have suffered accordingly on certain major projects. Special considerations have had to be made when designing cutoffs that must abut existing concrete structures, or that must be installed in very steep-sided valley sections, or that must toe in to especially strong rock.

"Test sections" have proven to be extremely valuable, especially for permitting contractors to refine their means, methods, and quality-control systems. Such programs have also given the dam safety officials and owners the opportunity to gain confidence and understanding in the response of their dams to the invasive surgery that constitutes cutoff wall construction. Furthermore, such programs have occasionally shown that the foreseen construction method was practically impossible (e.g., a hydromill at Beaver Dam, AR) or that significant facilitation works were required (e.g., pre-grouting of the wall alignment at Mississinewa Dam, IN).

Every project has involved a high degree of risk and complexity and has demanded superior levels of collaboration between designer and contractor. This situation has been best satisfied by procuring a contractor on the basis of "best value," not "low bid." This involves the use of RFP's (Requests for Proposals) with a heavy emphasis on the technical submittal and, in particular, on corporate experience, expertise, and resources, and the project-specific Method Statement. These projects are essentially based on performance, as opposed to prescriptive specifications. Partnering arrangements (which are post-contract) have proven to be very useful to both parties when entered into with confidence, enthusiasm, and trust.

Construction and QA/QC

The specialty contractors have developed an impressive and responsive variety of equipment and techniques to ensure cost-effective penetration and appropriate wall continuity in a wide range of ground conditions. More than one technique, e.g., clamshell followed by hydromill, has frequently been used on the same project and especially where boulders or obstructed conditions have been encountered (Bruce et al., 2006).

Cutoffs can be safely constructed with high lake levels, provided that the slurry level in the trench can be maintained a minimum of 3 feet above these levels. In particularly challenging geological conditions, this may demand pre-treatment of the embankment (e.g., Mud Mountain Dam, WA) or the rock mass (Mississinewa Dam, IN, Clearwater Dam, MO) to guard against massive, sudden slurry loss. For less severe geological conditions, contractors have developed a variety of defenses against slurry losses of smaller volume and rate by assuring large slurry reserves, using flocculating agents and fillers in the slurry, or by limiting the open-panel width.

Very tight verticality tolerances are necessary to ensure continuity, especially in deeper cutoffs. Such tolerances have been not only difficult to satisfy, but also difficult to measure accurately (to within 0.5 percent of wall depth) and verify.

The deepest panel walls have been installed at Wells Dam, WA (223 feet, clamshell) and at Mud Mountain Dam, WA (402 feet, hydromill). The hydromill has proved to be the method of choice for large cutoffs in fill, alluvial soils, and in rock masses of unconfined compressive strengths less than 10,000 psi (massive) to 20,000 psi (fissile or highly fractured and therefore rippable).

Secant pile cutoffs are, by comparison, expensive and intricate to build. However, they are the only option in certain conditions (e.g., heavily karstified, but otherwise hard limestone rock masses) that would otherwise defeat the hydromill. The deepest such wall (albeit a composite pile/panel wall) was the first — at Wolf Creek, KY, in 1975. It reached a maximum of 280 feet. The most recent pure secant pile wall in carbonate terrain was constructed at Beaver Dam, AR, 1992-1994, up to 185 feet deep while a secant/panel combination is currently being installed at Wolf Creek Dam, KY to considerably greater depths.

A wide range of backfill materials has been used, ranging from low strength plastic concrete to conventional high strength concrete. This is a critical design decision.

The preparation and maintenance of a stable and durable working platform has proven always to be a beneficial investment, and its value should not be underestimated.

The highest standards of real-time quality assurance/ quality control (QA/QC) and verification are essential to specify and implement. This applies to every phase of the excavation process, and to each of the materials employed.

Enhancements have progressively been made in cutoff excavation technology, especially to raise productivity (particularly in difficult geological conditions), to increase the mechanical reliability of the equipment, and to improve the practicality and accuracy of deviation control and measurement.

Potential Construction Issues with Cutoffs

Satisfactory construction of positive cutoff walls requires experience, skill, and dedication to quality in every aspect of the construction processes, including site preparation, element excavation, trench or hole cleaning, concrete mixing, and concrete placement. A positive cutoff requires the elements of the wall to be continuous and interconnected.

The following issues are possible concerns that must be taken into account in wall construction to prevent defects:

- Element deviation — Misalignment of the equipment or inability to control the excavation equipment can cause significant deviation of elements and can therefore result in a gap in the completed wall. Inclinometers installed on the excavation equipment will give real time alignment and the use of an ultrasonic monitor (Koden) intermittently during panel excavation and upon completion of the panel excavation will ensure verticality required by the construction specifications.

- Uncontrolled slurry loss — Although bentonite slurries are proven in creating a filter cake in soils, their ability to form a filter cake in rock fractures is limited. As a general rule of thumb, if water is lost during exploration drilling, one should assume that slurry losses in rock will occur during element excavation. If the rock mass is sufficiently permeable, uncontrollable and complete slurry loss can occur. Slurry losses in embankments have also occurred on past projects due to hydrofracturing of susceptible zones. This is a particularly sensitive issue when excavating through epikarstic horizons, and major karstic features lower in the formation. In this regard, epikarst is defined as the transition/interface zone between soil and the underlying, more competent, if still karstified, rock. Epikarst typically contains very fractured and solutioned conditions, and much residual material and voided areas. Epikarst usually plays an extremely important role in the hydrogeological regime of karst aquifers.
- Trench stability – The factors of safety of slurry-supported excavations in soil are not high. Movement of wedges into the trench or "squeeze in" of soft zones can occur.
- Concrete segregation – Mix design and construction practices (tremie process) during backfill must be optimized so as to prevent segregation or honeycombing within the completed wall.
- Soil or slurry inclusions – The occurrence of soil- or slurry-filled defects or inclusions in completed walls has been recognized. These defects are not critical if small or discontinuous, but they become significant if they fully penetrate fully across the width of the wall.
- Panel joint cleanliness – Imperfections or pervious zones along the joints between elements are sources of leakage through completed walls. Cleaning of adjacent completed elements by circulating fresh slurry is necessary to minimize the contamination of joints. In extreme cases, mechanical cleaning with "brushes" has to be conducted. It is imperative that the joints be cored to demonstrate a proper bond between adjacent elements.

"COMPOSITE" CUTOFFS

The Basic Premise

In recent years, there have been a number of projects, both completed and in planning, that have featured the construction of a concrete cutoff wall installed through the dam and into karstified carbonate bedrock. The basic premise of such a "positive" cutoff is clear and logical: the presence of large clay-filled solution features in the bedrock will defeat the ability of a grout curtain — even when designed and built using best contemporary practices — to provide a cutoff of acceptable efficiency and durability. This is particularly important when permanent "walk-away" solutions are required that must be robust, reliable, and durable. There is no question that rock fissure grouting techniques are incompatible with satisfying that long-term goal in the presence of substantial clayey infill materials. However, the benefits of a concrete cutoff come at a substantial financial premium over those provided by a grout curtain. A typical industry average cost for a grouted cutoff is of the order of \$20–\$50 per square foot. The cost of a concrete cutoff is anywhere from 5 to 10 times this figure, depending on the technique (i.e., panel or secant), the ground conditions, the depth of the cutoff, and the challenges of the site logistics. Furthermore, the construction of a concrete cutoff wall through the typical karstified limestone or dolomite rock mass will involve the excavation of the rock (which in the main part will be in fact very hard, impermeable, and competent with unconfined compressive strength values in excess of 20,000 psi) and backfilling that relatively thin diaphragm with a material of strength 5,000 psi or less. In effect, great effort and expense are expended to provide a membrane through the greater part of the project which is of lower strength than the rock mass excavated to construct it.

Another practical factor that has often been overlooked historically is that construction of a concrete cutoff wall may simply not be feasible in ground conditions that permit the panel trench-stabilizing medium (i.e., bentonite or polymer slurry) or the drill flush medium (air or water) to be lost into the formation: in extremis, either of these phenomena could create a dam safety threat, let alone the loss of very expensive excavation or drilling equipment at depth. The solution, not surprisingly, in such situations has been to suspend the wall construction and to systematically and intensively pre-treat the formation by grouting.

In doing so, however, it has not been always the case that the designer of the wall has appreciated that, in addition to this campaign of drilling, water-pressure testing, and grouting (constituting a facilitating improvement to the rock mass), such work also constitutes a most detailed site investigation — at very close centers — of the whole extent of the originally foreseen concrete cutoff area. It is reasonable, therefore, to deduce that the data from these pretreatment programs can be used to review the true required extent of the subsequent concrete wall, and thereby reduce overall project costs with sound justification.

The concept may then be taken a stage further. Instead of drilling and grouting being conducted only as a remedial/facilitating operation under emergency conditions, it can be specified as a rigorous design concept to:

- precisely identify the location and extent of the major karstic features that are actually required to be cutoff with a concrete wall;
- pre-treat the ground, and especially the epikarst, to an intensity that bentonite slurry or drill flush will not be suddenly lost during the concrete wall construction (a typical acceptance criterion is 10 Lugeons); and
- grout, to a verified engineered standard, the rock mass that does not contain erodible material in its fissures around and under the karstic features (a typical acceptance criterion is in the range of 1–3 Lugeons).

By embracing these precepts, it is therefore logical to define the concept of a "composite cutoff": an expensive concrete wall, where actually required for long-term performance certitude, plus a contiguous and enveloping grout curtain to provide acceptable levels of impermeability and durability in those portions of the rock mass with minimal erodible fissure infill material.

Conceptual Illustrations

With one eye on the immediate future requirements of seepage remediation involving cutoffs under existing dams, it may be stated that karst is either stratigraphically driven, or structurally related. Figure 1 shows a case where the major horizon of concern for long-term seepage and erosion is limited to the 30 feet or so of epikarst; Figure 2 is the case where the seepage and erosion concern is in a certain deep stratigraphic member; and Figure 3 shows the condition where the karstification has developed along discrete, vertical structural discontinuities. For the sake of illustration, it may be assumed that the final cutoff has to be 1,000 feet long, the cost of drilling and grouting is $30 per square foot, the concrete wall costs $120 per square foot, and the maximum vertical extent of the cutoff is 110 feet since a shale aquiclude exists at 100 feet below ground surface (b.g.s.). The dam itself is "invisible" in this exercise.

In the configuration of Figure 1, the original design featured a concrete cutoff wall extending 10 feet into the aquiclude. The cost would therefore be 1,000 feet X 110 feet X $120 = $13.2 million. This would, of course, assume (or worse, ignore) that construction of the wall through the epikarst would be feasible without its pre-treatment by grouting. Alternatively, if the entire alignment were to be predrilled and pre-grouted, it would be revealed that there was no need to construct the wall deeper than, say 35 feet. The total cost of this composite cutoff would therefore be:

- drill and grout: 1,000 feet X 110 feet X $30/square foot = $3.3 million
- concrete wall: 1,000 feet X 35 feet X $120/square foot = $4.2 million

TOTAL $7.5 million

This represents a cost savings of $5.7 million on the original estimate. This represents the case at Clearwater Dam, MO.

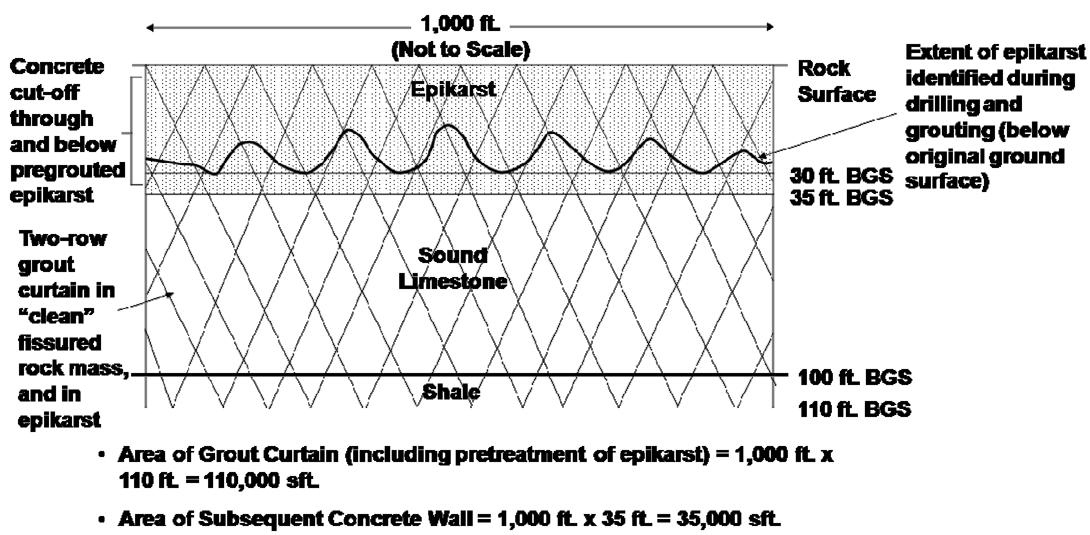

FIG. 1. Epikarst is found during pregrouting to an average of 30 ft. b.g.s. Therefore, the concrete cutoff is installed only to 35 ft. b.g.s., and the grouting provides the cutoff in the "clean" rock below.

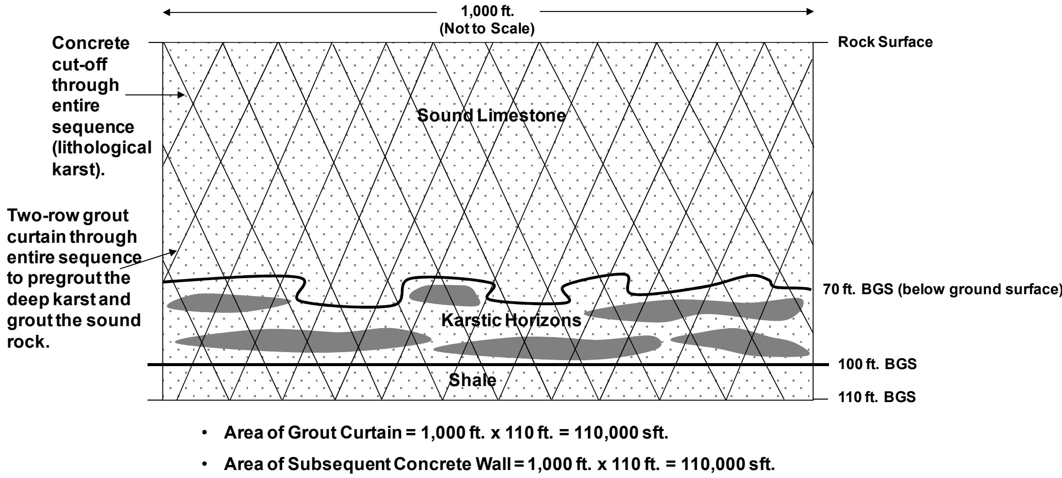

FIG. 2. Heavily karstified horizons are found at depth during predrilling and grouting. Therefore the concrete cutoff is required for the full extent. The grouting has pretreated the karstic horizons to permit safe concrete cutoff construction.

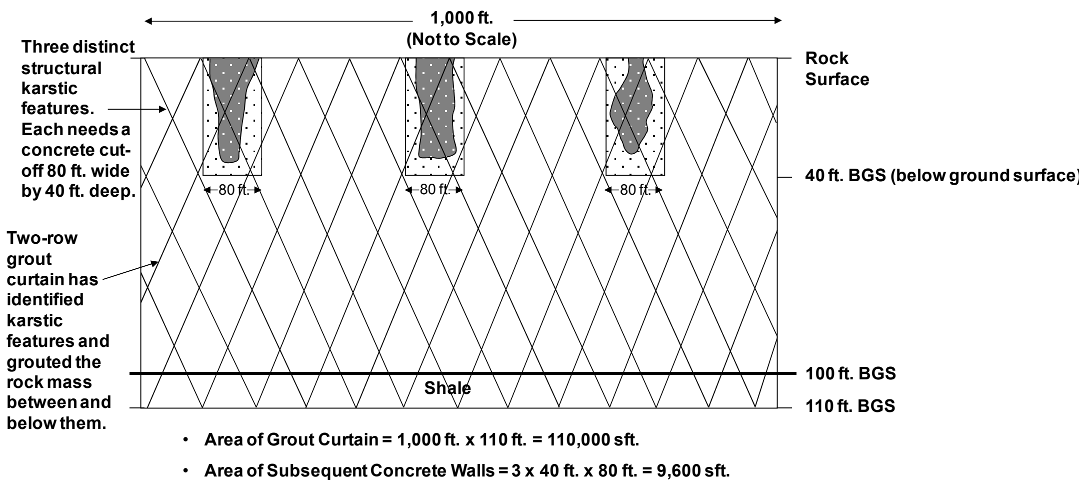

FIG. 3. Discrete karstic features have been found during the drilling and grouting, driven by major structural lineations. Thus, individual concrete cutoff panels can be installed, after drilling and grouting have confirmed the extent of these features and have pretreated them to permit safe concrete cutoff construction.

For the configuration of Figure 2, the cost of the pre-drilling and grouting would be the same, i.e., \$3.3 million. However, in this case, the concrete wall would still have to be \$13.2 million, since the critical zone is at depth. The overall cost of the composite cutoff would therefore be \$16.5 million. However, the pre-treatment in advance of the concrete wall would assure that the wall could in fact be built in a cost-effective, safe, and timely fashion, i.e., without interruptions caused by massive slurry loss. The overall (high) project cost would simply be a reflection of a uniquely challenging geological situation, i.e., a continuous horizon of erodible material at depth. This mirrors the case at Wolf Creek Dam, KY

For the configuration of Figure 3, the pre-treatment cost would be the same (i.e., $3.3 million). It would result in the identification of three discrete zones of structurally defined karst of combined area 3 X 80 feet X 40 feet = 9,600 square feet. Therefore, the cost of the concrete wall actually needed to cutoff these features would be 9,600 square feet X $120/square feet = $1,152,000. The total cost of the composite wall is $3,300,000 + $1,152,000 = $4.5 million, which would represent a savings of $8.7 million on the original "full cutoff" cost estimate. This scenario is represented by the recent works at Bear Creek Dam, AL (Charlton et al., 2010; Ferguson and Bruce 2010).

Thus, the investment in the predrilling and grouting program in this exercise generates significant savings in the cases of Figures 1 and 3, whereas for the case of Figure 2, it assures that the wall, which must be built to full depth, can be installed without massive delays, difficulties, or — at worst — creating dam safety issues.

Recommendations for Grouting as a Component of a Composite Cutoff Wall

Site Investigation Assessment and Design

The most important elements of this phase are as follows:

- Research and utilize all the historical data (including original construction photographs) that may have bearing on the development of a tentative geostructural model for the site. An excellent example is provided by Spencer (2006) for Wolf Creek Dam, KY.
- Conduct a new, thoughtful, and focused site investigation to test the tentative geostructural model and so provide prospective bidders with the kinds of information they truly need to estimate construction productivity and to quantify other construction risks.
- Develop an initial estimate of the extent of the composite cutoff and its contributory components, i.e., the concrete wall and the grout curtain.
- Assess the adequacy of the existing dam and foundation instrumentation, and design and install additional monitoring arrays as appropriate. Revise the reading frequency protocols as appropriate, especially in the vicinity of construction activities.

Preparation of Contract Documents and Contractor Procurement Methods

Major recommendations are as follows:

- Draft a Performance Specification (as opposed to a Prescriptive Specification), and clearly define the methods and techniques that are not acceptable. Performance goals must be explicitly defined, together with their means of verification.
- Procure the specialty contractor on the "best value" basis, not "low bid."
- Mandate "partnering" as a minimum; favor "alliancing" as the goal (Carter and Bruce, 2005).

- Perhaps separate general construction activities (e.g., office modifications, relocation of existing utilities and services) into a different contract, but always leave the design and construction of the working platform to the specialist contractor.

Technical Aspects

The following items are particularly important:

- If flush water has been lost during investigatory drilling, slurry will certainly be lost during wall excavation, without pre-treatment of those same horizons.
- The minimum pre-treatment intensity will feature two rows of inclined holes, one on either side of the subsequent wall location. The rows may be 10 to 20 feet apart, and the holes in each row will typically close at 5- to 10-foot centers (i.e., after all successive orders of holes are installed). The inclination (typically 15 degrees off vertical) will be oppositely orientated in each row.
- The curtain should be installed to at least 50 feet below and beyond the originally foreseen extent of the cutoff to ensure adequate coverage and to identify unanticipated problems. The treatment is to be regarded as an investigatory tool, equally as much as a ground pre-treatment operation and as a sealing of clean rock fissures.
- "Measurement while drilling" principles should be persevered with the philosophy being that every hole drilled in the formation (not just cored investigations) is a source of valuable geotechnical information.
- Special attention must be paid to the epikarst, which will typically require special grouting methods such as MPSP (multiple packer sleeve pipe), descending stages, and different grout mixes.
- A test section at least 500 feet long should be conducted and verified to allow finalization of the Method Statement for the balance of the grouting work. A residual permeability of 10 Lugeons or less should be sought in the area that is later to accept the cutoff, and 1-3 Lugeons in the "clean" rock below the future cutoff toe. Conversely, a falling head test in vertical verification holes, using bentonite slurry as the test fluid to simulate the diaphragm wall construction, is an appropriate test. Verification holes should be cored, and the holes observed with a televiewer to demonstrate the thoroughness of the grouting.
- In terms of the details of execution, the principles previously detailed to create quantitatively engineered grout curtains should be adopted. Thus, one can anticipate the use of stage water tests, balanced, modified, stable grouts, and computer collection, analysis, and display of injection data. When drilling the verification holes (at 25- to 100-foot centers between the two grout rows), particular care must be taken to ensure that no drill rods are abandoned within the alignment of the wall, since this steel will adversely impact subsequent wall excavation techniques.
- Grouting pressures at refusal should be in excess of the foreseen maximum slurry pressure to be exerted during panel construction.

Construction

Every project is different, and the following basic recommendations must be supplemented on a case-by-case basis:

- The work must be conducted in accordance with the contractor's detailed Method Statement. This document, in turn, must be in compliance with the minimum requirements of the Performance Specification unless otherwise modified during the bidding and negotiation process. At the same time, modifications to the foreseen means and methods can be anticipated on every project in response to unanticipated phenomena. Prompt attention to, and resolution of, these challenges are essential.
- Special attention is merited to the details of the design and construction of the working platform. The contractor's site support facilities (e.g., workshop, offices, slurry storage and cleaning, concrete operations) can be completed and the utilities extended along the alignment (water, air, electricity, light, slurry) during the building of the work platform.
- The test section should be established in a structurally and geologically non-critical area that does not contain the deepest extent of the foreseen concrete wall. The test section should, however, be integrated into the final works if it is proven to have acceptable quality.
- The concrete wall excavation equipment must have adequate redundancy, and must be supported by appropriate repair/maintenance facilities. A variety of equipment is usually necessary (clamshell, hydromill, chisels, backhoe) to best respond to variable site conditions and construction sequences. Standard pre-installed mechanical features, such as the autofeed facility on hydromills, must not be disabled in an attempt to enhance productivity.
- Special protocols should be established to ensure that the flow of real time construction data (e.g., inclinometer readings from a hydromill) is regular, uncontaminated, and of verifiable provenance.
- The site laboratory must be capable of accurately and quickly conducting the whole range of material tests required. In addition, the contractor's technical/ quality manager, who is a vital component in any such project, must be fully conversant with all the principles and details involved in the monitoring of the construction, and of the instrumentation of the dam itself. In particular, expertise with panel or pile verticality and continuity measurement is essential, as is an awareness of the significance of piezometric fluctuations or changes.
- Emergency response plans must be established to satisfy any event that may compromise dam safety.

Assessment of Cutoff Effectiveness

The protocols established for observations and instrument readings during remedial construction must be extended after remediation, although usually at a somewhat reduced frequency. The data must be studied and rationalized in real time so that the remediation can be verified as meeting the design intent. Alternatively, it may become apparent that further work is necessary, a requirement that becomes clear only when the impact of the remediation of the dam/foundation system is fully understood. Finally, owners and designers should publish the results of these longer-term observations so that their peers elsewhere can be well informed prior to engaging in their own programs of similar scope and complexity.

CONCLUSION

U.S. engineering practice in rock grouting and concrete cutoff wall construction has reached very high levels of competence. However, even the best grouting practices cannot assure a robust, durable seepage barrier in terrains containing significant amounts of potentially erodible materials, particularly when these are concentrated in discrete features of considerable dimension and extent. Similarly, diaphragm wall operations will be vulnerable to voided conditions which have the potential to cause sudden and complete loss of the supporting slurry during excavation. This can have serious dam safety implications, quite apart from the prospect of losing extremely valuable equipment trapped hundreds of feet down in collapsed trenches. Furthermore, diaphragm walls, especially in rock, are costly, which is particularly galling when it is noted that oftentimes large volumes of excellent rock of appreciable strength and low permeability are being replaced with an engineered material (concrete) perhaps half its strength and of equivalent permeability.

It is time to squash the false debate as to which method — grouting or diaphragm wall — is best. The obvious way forward is to take the best from each camp: drill, water test, and grout (relatively cheaply) to prepare the ground for a concrete wall (relatively expensive), the extent of which is now properly defined. Then, build, in improved ground conditions with significantly reduced dam safety and cost risk, the definitive concrete wall only in those areas where the grouting cannot be expected to be effective in the long term.

Our dams must be repaired in a way that must be conceived to be "permanent." However, the goal remains that we should ensure that our designs and implementations are cost effective. Furthermore, there is simply insufficient industrial capacity in the United States to build the foreseen volume of cutoffs solely by concrete wall construction techniques in the time frame available. The concept of the "composite cutoff" is therefore logical, timely, and the obvious choice. This argument was expressed in somewhat different form by the irrepressible instrumentation specialist, John Dunnicliff (1991):

> "Equal rights for grouters,"
> cries Donald Bruce with glee.
> He challenges the doubters,
> with pungent repartee.
>
> Slurry wall or grouting?
> Which method works the worst?
> The brotherhood is touting
> that grouting should be first.
>
> Casagrande's basis

for sealing every crack
was "use both belt and braces"
to hold the water back.

So let's stop all the shouting
and use them, one and all:
the wall to seal the grouting;
the grout to seal the wall.

The brothers will be wealthy.
The grapevine will be sweet.
The dams will all be healthy,
and flow nets obsolete.

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