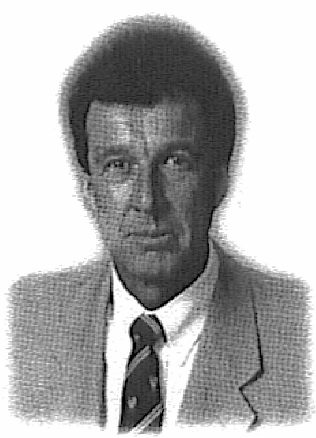
Crisis Management: Dealing with Massive Underflows in Karstic Limestone



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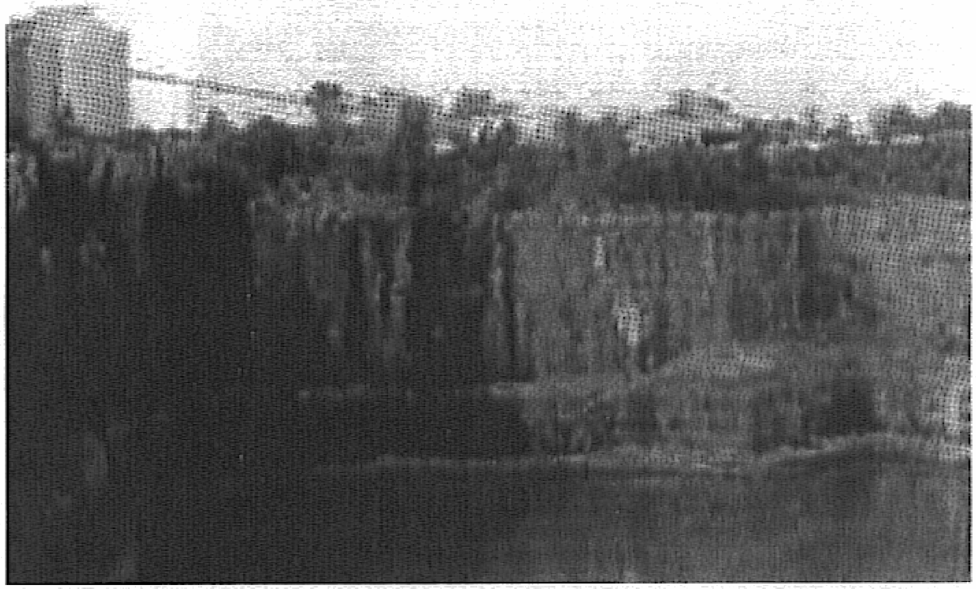
Introduction

Dams must often be founded on karstic limestone terrain, or on other soluble rock types. Whereas it is typical practice to install a grout curtain under a new dam, such an operation cannot be guaranteed to comprehensively treat a karstic rock mass to a degree that seepage under long term service conditions may not – eventually – result in channels being opened through features in the karst filled with residual clay or other erodable or weathered materials. This long term deterioration may be superimposed on any short term disturbance to the karstic terrain created by construction activities, such as blasting, excavation, and the local alteration of piezometric levels. Grout curtains in karst have a finite effective life, the length of which depends on the rock mass characteristics, the intensity and quality of any grouting conducted, and the prevailing hydraulic gradients. Unfortunately, this life expectancy cannot be reliably or precisely predicted.

Massive sudden inflow through karstic features under an existing dam could well create a dam safety situation (if the overlying or adjacent structures were adversely affected) or could cause severe financial consequence if lake levels could not be maintained. In this case, power generation, flood regulation, and/or recreational impacts would be felt and the project purpose not met.

Although it is conventional wisdom to state that dams in the U.S. were invariably built on "good" sites, since the country was so large, and engineers always had the "walk away" solution of relocating the structure elsewhere, this view can be quickly discredited. A significant percentage of the United States' large dams — identified in a 2002 study by *Hydropower and Dams* as being 6724 in number — had to be founded on sites with less than perfect geology. The magnificent vision of the Tennessee Valley Authority could not have been realized if an embargo had been placed on sites with limestone bedrock. Construction of the great U.S. Army Corps of Engineers' and private utility structures of later decades in Indiana, Tennessee, Missouri, Georgia, and Alabama in particular would also have been denied if fears over karstic response had overridden the contemporary social and economic needs of the community.

The problem of providing long term security to dams on karst has been assiduously addressed by many Federal and private owners for over 80 years. In particular, in recent years,



Sudden development of large flow (over 30,000 gpm) through karst into the base of an operational quarry. Nearby river provides infinite source and driving head of over 300-feet.

major rehabilitations have been funded to a number of large and vital existing structures owned by the U.S. Army Corps of Engineers, including Beaver Dam, AR; Walter F. George Dam, GA; and Mississenewa Dam, IN. All have been protected by constructing "positive" concrete cut off walls – overlapping large diameter piles in the case of Beaver Dam (Bruce and Dugnani, 1996), and diaphragm walls in the latter instances. A notable exception to this pattern has been the repair of the foundations of Patoka Lake Dam, IN, where a relatively innovative grout curtain (Dreese et al., 2003) was selected over a concrete wall for overwhelming cost reasons. Similarly, the recent karst related seepage problem of a major TVA structure was also resolved by the use of contemporary grouting principles (Bruce et al., 1998).

Dams, founded on bedrock containing potentially erodible material, can develop an increasingly severe and sudden problem at any time in their useful life. Bruce and Gillon (2003) describe the performance of a 70-year old dam in New Zealand where the recent erosion of clay infilling in fissures resulted in the need for a very precise remedial grouting operation. It is also known that certain dams in Ordovician terrain south of the Mason-Dixon line are recording massive under seepage which is either being "managed," or is being closely monitored with the confidence that the seepage constitutes no imminent threat to life, structure, or profitability.

This paper addresses the actions that may be taken when the particular flow velocity and/or volume reaches a level that simply demands that action be taken. Such events are typically highly stressful for all parties, especially given the potential consequences of "failure." They invariably present a technical scenario which is extremely challenging to resolve. It is at this time that logic often is lost in the rush, and the "fire, aim, ready" syndrome kicks in.

The Fundamental Elements of Crisis Management

This article focuses on the short term response to emergency conditions which can be resolved by grouting. The following 8-step sequence reflects the three fundamental stages in the implementation of any successful remedial grouting operation:

- Exploration and situation assessment.
- Responsive execution.
- Verification and monitoring of performance.

Sudden, significant and obvious changes to the preexisting structural and hydrological regimes characterize a karst related flow event. Flow or seepage rates may increase substantially – by an order of magnitude or more — the flow may be discolored, new seepage entry and exit points develop

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(e.g., "eddies" and "boils"), piezometric surfaces drop, and/or surface manifestations may occur in the form of depressions in embankments or sinkholes in overlying overburden.

At such times, normal facility operations are interrupted or suspended, and depending on the severity of the situation, a fundamental structural safety issue may be declared and a wide range of technical, operational, managerial, financial, and regulatory bodies may become involved. Time will be of the essence in order that resolution is achieved as quickly and cost effectively as possible, and that any safety-related issue is correctly and firmly managed. The following steps reflect the approach the author has developed over the course of several such events, where flows of the order of 40,000 gpm at differential heads of up to 300 feet have suddenly developed.

Step 1. Appoint a Project Manager to act as a coordinator of the short term emergency and the subsequent longer term remediation efforts. This Manager should be from the ranks of the facility owner, and should have long and direct experience with the construction and operation of the site and with the modus operandi of the ownership. The Manager should be divorced from his prior routine duties as far as possible, and should be fully empowered to seek further assistance, both from internal resources and external consultants. He must have authority to act independently. A separate "mission control" room should be established for his use, wherein all data are collected and analyzed and all technical meetings are held. Every meeting should be formally documented.

Step 2. Evaluate exactly what the situation is, via analysis of all available data sources, but at this time paying special attention to documenting verbal accounts from actual witnesses. Such accounts can be of great benefit in subsequent analysis, but their value depends on their accuracy and completeness, both of which will rapidly recede with time.

Step 3. Implement all necessary short term measures which legally, administratively, or practically have to be taken. From the technical viewpoint, this may include installing additional, simple instrumentation (to help quantify the issue, e.g., structural movement monitoring, flow measurements); increasing the frequency of reading existing instrumentation; site inspection; relocating equipment that is threatened by inundation; or even rapid reduction in reservoir level. These actions help to create a baseline, mitigate the immediate impact, identify if the situation is deteriorating further, and/or help the Project Manager determine the level of imminent danger.

Step 4. Design and conduct a focused program of new site investigation, the purpose of which will be to establish the exact path of the flow (typically it is in a massive conduit as opposed to in a widely dissipated network of small conduits), its rate and velocity, and the nature of the rock around the conduit. If the conduit is found to be in a zone surrounded by other clay-filled karstic features which have not, as yet, been "flushed out," this will represent a severe problem during subsequent remediation and service. This study will permit a remedial design to be conducted and priced. It will also highlight if the flow has the potential to create further distress to overlying or adjacent structures. During this time, the reading instrumentation schedule of Step 3 is maintained.

The site investigation should comprise the following two tasks, which are complimentary:

- Desk study: review all relevant construction records; historical performance data; instrumentation data; regional, local, and site geology; climatic and seismic records; aerial photographs; personal recollections; and, published technical papers. At this stage, the input of personnel involved in the original construction and contributions from a "local" engineering geologist can be most useful.
- Field study: install investigation holes by the fastest and most economical method to try to physically locate the conduit and the possible existence of "latent" channels. This should be done as far "upstream" as possible. These holes can then be instrumented to

provide ongoing data on groundwater levels, chemistry, temperature and pH, or can be used for various types of geophysical testing, e.g., seismic tomography, or can in fact be used as grout holes in the subsequent remediation. Other types of geophysical testing such as Ground Penetrating Radar, Spontaneous Potential, Electrical Resistivity (Dipole-Dipole or Wenner Schlumberger), and magnetic or gravimetric surveys can be conducted. Dye testing, if properly and thoughtfully conducted, can be extremely useful (Bruce and Gillon, 2003).

It may happen that despite the best of efforts and intentions, the exact source or path of the flow cannot quickly be determined with accuracy. Perseverance is essential: the subsequent steps should not be commenced until closure on Step 4 is satisfactorily concluded.

Step 5. Assuming the situation is to be positively rectified, as opposed to merely being monitored and/or managed by other means (e.g., ongoing pumping from the quarry floor), the Project Manager and his advisors develop the design for remediation. At this stage, input from specialty contractors and other specialists should be sought, and the technical literature reviewed for case histories of similar nature. It is essential that the design clearly identifies the "measure of success" of the project in terms of, for example, the residual flow rate or piezometric levels at various locations following treatment. It is common to find that few contractors will have faced such a severe problem before, and unfortunately, most will tend to initially underestimate the difficulty of the remediation. Considerable amounts of time and money have been lost by firstly employing local contractors in haste, using simple and conventional methods which are later proved to be wholly inadequate. It is also usually the case that such contractors have been hired on a "cost plus" or "time and materials" basis and so may not be highly motivated to achieve a quick and definitive solution, even if they did possess the technological resources.

Step 6. With the design and contract terms approved, the contractor is hired. This should be done on the basis of "best value" as opposed to "low bid," although the two may be the same. Emphasis should be placed on the experience, expertise, and work plan of the contractor, as opposed to his estimated price. Engaging the "wrong" contractor will certainly lead to disappointment and dispute over schedule, performance, and cost, and indeed inappropriate construction methods may worsen the situation and make further remediation attempts even more challenging. It is very difficult to accurately estimate the cost of such works at this stage.

Step 7. Execute the work. During this phase, all data relating to the contractor's operations (e.g., drilling, water testing, and grouting records, and progress) and impact on the overall structure/bedrock system (e.g., flow characteristics, piezometric levels, structural movements, changes in groundwater chemistry, temperature, etc.) must be collected and studied in real time by the Project Manager and his team in "mission control." Only in this responsive, integrated fashion can the effect and effectiveness of the work be revealed progressively, and a sound engineering basis created upon which to instruct changes to the program if required (e.g., need for additional or deeper holes; different grout mixes; etc.). Such data are also invaluable in the ongoing process of reevaluating the soundness of the design (Step 5). This step continues until the remediation has been completed and a short term (e.g., 7 days) confirmation period has successfully elapsed. A fully comprehensive "as built" report covering all the relevant data from Steps 1 through 7 should be prepared as soon after the remediation as practical.

Step 8. Long term monitoring. Many – if not all – the piezometers and other monitoring devices installed beforehand should still be functional at this point. The Project Manager must establish a regular schedule for reading these instrumentation sources and analyzing their data, and for conducting any relevant revised site or structural inspections. A database must be established, together with a well

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defined series of protocols to follow if certain instrumentation trigger and threshold levels are reached, or if any significant flow or pressure aberrations should reoccur. These protocols should include details of the responsible person(s) to be notified, and appropriate emergency response plans.

It must be stated that the most effective a grout curtain in karst will ever be is immediately after its construction. In service, as the full hydraulic gradient is applied to the grout curtain (i.e., the normal operating lake level is restored), pockets of ungrouted and/or ungroutable weathered material will be exposed to pressures which may prove sufficient, over time, to cause such pockets to "blow out." This will occur despite the very best efforts of the design and construction teams. However, there is no predictive capacity as to how severe this increase in residual permeability will be, or how fast it will develop. Clearly, such deterioration will depend on the nature of the karst (i.e., how much erodible material such as residual clay remains in the voids), the applied hydraulic gradient, and the length of time over which it acts.

Basic Construction Considerations for Grouted Cutoffs

Definition of the Measure of Success

Pragmatically, a restoration of the conditions status quo ante is a sensible goal. Occasionally, betterment can be achieved, but often it is found not cost effective or even necessary to attempt such relative improvement. In addition to clearly stating what the post treatment, residual flow should be, other project specific goals, if applicable, should be precisely set, e.g., attaining certain key piezometric levels, structural movement thresholds, longevity of the curtain and so on.

Drilling

Because much will already be known in precise geological terms about the lithology and structure of the rock mass, and because it is generally the goal only to locate and fill major conduits (as opposed to treating microfissures), the drilling should be conducted with the most cost effective method available – provided always that it is compatible with maintaining the security of overlying or adjacent structures. In this regard, the potential of sonic drilling (Bruce, 2003) is beginning to be exploited in major dam remediation. Holes should be drilled at least 150 mm in diameter to permit the later installation of grouting-related pipework or downhole instrumentation. Depending on the rock mass structure, holes may be most effectively inclined 10° to 15° off vertical to intersect vertical joints. At least two rows of holes are necessary, for geological and operational reasons, with the holes in each row not spaced more than 3 m apart on centers. It is essential to log carefully the drilling conditions encountered in each hole, so that a simplified geological profile can be established, identifying, as a minimum, the locations and extents of the following:

- Overburden,
- Hard massive rock,
- Fissured rock,
- Very weathered rock,
- Clay infilled karst, and
- Voided karst.

Variations of flush return (especially total loss conditions, and interconnections between holes) should also be carefully recorded. During the drilling of each hole, the exit point of the flow, if accessible, must be continuously monitored to determine if the conduit has been influenced. Flow volume and/or color changes or the presence of drill flush are critical observations. Any interconnections between holes must be accurately recorded (depth and distance) since they will be vital to consider in the subsequent injection program.

Grouting Materials

In the cases of fast, large volume flows in very large conduits, conventional "slurry" grouts (High Mobility Grouts: HMG (Chuaqui and Bruce, 2003), even when thoughtfully formulated, will simply be washed away, perhaps even causing an environmental problem downstream of the curtain. Similarly, the potential benefits of highly sophisticated – and expensive – chemical grouts (Bruce et al., 1997) are rarely exploitable since they lack the short term gelling and strength characteristics to mechanically resist the hydrodynamic forces in the conduit. In contrast, the author has experienced success using either Low Mobility Grouts (LMG) (Cadden et al., 2000) in lower head, low velocity conditions, and hot bitumen (together with HMG and LMG) in particularly adverse conditions. Various additives and admixtures including accelerators, antiwashout agents, viscosifiers and even polypropylene fibers are used by better contractors to "tailor" both LMG and HMG grout suites to the precise project requirements. In certain conditions, coarse aggregate can be preplaced in the void to provide a "skeleton" for later grouts to permeate.

Grout Injection and Sequencing

It is common to find all, or most, of the flow channeled into one or a small number of well defined conduits, although very soft, potentially erodible, or fissured rock conditions may still exist in the surrounding bedrock. The basic principle is to allow the flow to continue in these conduits, while treatment continues of the rock mass (through which water is not yet flowing) around the conduits. Depending on the nature of the rock mass, this "preemptive" treatment can be conducted by conventional open hole "staging methods," or by the MPSP (Multiple Packer Sleeved Pipe) system (Bruce and Gallevresi, 1988) – both of which use families of HMG – or by using LMG in upstage, end of casing applications. Again, observation of the flow outlet point is essential at all times, together with an ongoing assessment of any changes to piezometers and other instrument readings. Typically little benefit in terms of flow or pressure reduction is found at this time, even though it is absolutely essential to conduct this work at this juncture (i.e., at a time when the water flow rate in this part of the final grout curtain is minimal).

The last, and most critical and dramatic phase of the grouting program is to then put the "plug" in the conduit, given that the surrounding rock mass has now been "protected" against the danger of internal erosion when the curtain is functioning. When dealing with flows of 40,000 gpm or more, and head differentials of over 100 feet, cement based grouts – even those of high rheology and accelerated hydration – cannot be relied upon to resist the hydrodynamic situation in the conduit. In such extreme conditions, the use of hot bitumen, in conjunction with the simultaneous and adjacent injection of HMG and/or LMG has proved to be a most reliable solution.

Bitumen has been used in projects around the world for decades, but it is only within the last few years that full engineering value has been extracted from its extraordinary potential. In short, the hot bitumen encounters the flow which quickly removes the heat from the material (injected at temperatures of 200°C and over). The material begins to gel and congeal and thus, when pumped at sufficiently high rates, will begin to overwhelm the flow in the conduit. The simultaneous upstream injection of LMG or HMG causes these materials to be pushed against the cooling, but still relatively hot bitumen mass leading to a "flash set" of the cement based grouts in the conduit. This multi-material plug continues to form as injection continues. Eventually, the conduit is plugged (temporarily) with the gradually cooling (and shrinking) bitumen plug. At this point, further rapid injection of HMG and LMG is continued upstream of this temporary plug to create the "final" plug, which will eventually resist the hydraulic gradient applied to the temporary plug. Failure to conduct sufficient HMG and LMG grouting at this time will simply ensure ultimate failure of the operation since the temporary bitumen plug will continue to cool and shrink and so permit the water to exploit the growing gap between conduit boundary and bitumen. The plugging operation must be continued without interruption until completion: unless hot bitumen is pumped continuously down through the specially installed pipework at high temperatures, the system will "freeze" prematurely, and the conduit will not be closed.

The organization and management of the plugging operation is an exercise in detail and logic, and must

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involve the skills, input, and cooperation of all parties. Clear field leadership is essential. Recent examples of successful remediation are provided by Bruce et al. 1998, and 2001.

Final Observations

The reader should be cautioned from believing that such projects are anything other than extremely stressful for all the participants, demanding the highest levels of technology, administrative, engineering, management skills, commitment, and attention to detail. There is an old adage that "you find out about people in adversity." The development of a sudden and major flow into or under a major engineering structure founded on or in karstic limestone presents serious adversity in various forms to all concerned. It is hoped that this paper will in general provide comfort, confidence, and guidance to those who are faced with such events. In particular, it may form the basis for contingency plans or protocols that could be developed (and hopefully "left on the shelf"!) by managers of major facilities founded in karstic limestone terrain.

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