SAMPLE

Keeping Water Out of the Quarry Floor

Part 2: Effective construction techniques and design considerations for grout curtains.

By Donald A. Bruce, Ph.D.

Aggregate producers all face the challenge of keeping water out of the quarry floor, but those working in heavily karstified limestone deposits are especially susceptible to water concerns. The second installment of this water control series focuses on construction techniques and design considerations for dealing with the issue. (For information on emergency procedures, see the January/February 2004 issue.)

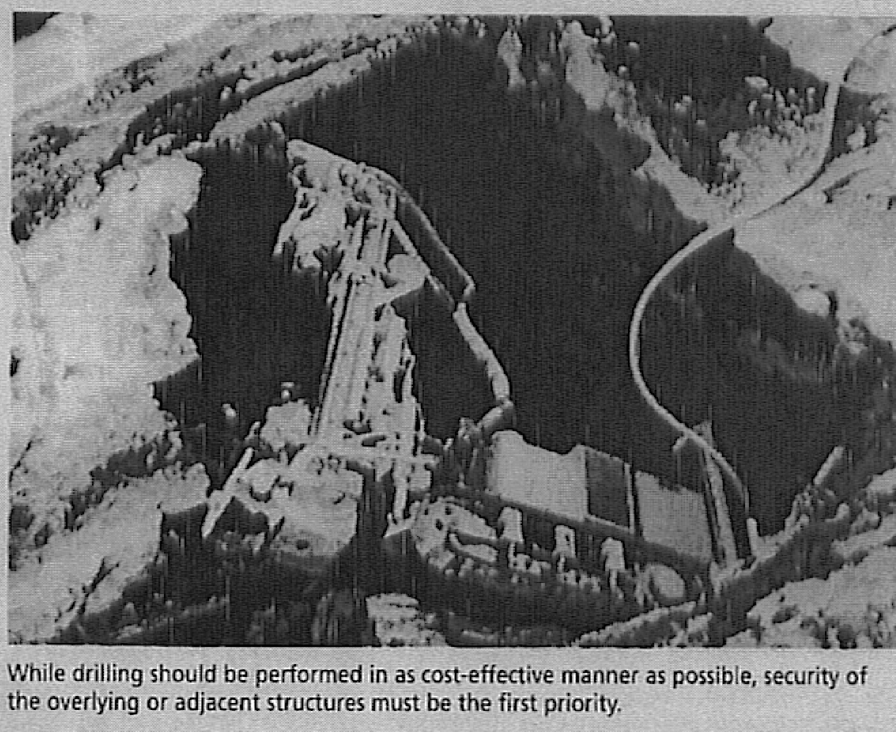
From a practical standpoint, restoring the condition to its previous state is a sensible goal. Occasionally, improvement can be achieved, but often it is found not cost effective or even necessary to attempt such relative improvement. In addition to clearly stating what the post treatment, residual flow should be, other project specific goals, if applicable, should be precisely set, e.g., attaining certain key piezometric levels, longevity of the curtain, and so on.

Drilling

Since much will already be known in precise geological terms about the lithology and structure of the rock mass, and it is generally the goal only to locate and fill major conduits (as opposed to treating microfissures), 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. This usually means using a direct circulation down-the-hole hammer (Bruce, 2003) powered by compressed air, which will help greatly in "cleaning out" clay from karstic features. More recently, the use of sonic drilling techniques has proved extremely advantageous.

Holes should be drilled at least 150 mm in diameter to permit the later installation of grouting-related pipework. Depending on the rock mass structure, holes may be most effectively inclined 10 to 15° off vertical. At least two rows of holes are necessary, for geological and operational reasons, with the holes in each row not spaced more than 3 meters 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.



While drilling should be performed in as cost-effective manner as possible, security of the overlying or adjacent structures must be the first priority.

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, color changes, and the presence of compressed air (if used as drill flush) are critical observations. Any interconnections between holes must be accurately recorded (depth and distance) since they will be vital to consider in designing the grouting operation.

Grouting materials

In the case of fast, large volume flows in very large conduits, conventional "slurry" grouts — also known as high mobility grouts (HMG) — will simply be washed away. Even thoughtfully formulated HMGs fail to perform in these circumstances, and even have the potential to cause an environmental problem downstream of the curtain [High Mobility Grouts: HMG (Chuaqui and Bruce, 2003)].

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.

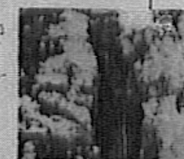
In contrast, I've experienced success using either low mobility grouts (LMG) [Cadden et al., 2000] in lower head, low-velocity conditions, and hot bitumen (together with HMG and LMG) in particularly adverse conditions. Various additives and admixtures, including accelerators, antiwashout agents, viscosifiers, and polypropylene fibers are used by better contractors to tailor both LMG and HMG grout combinations to the precise project requirements.

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 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.

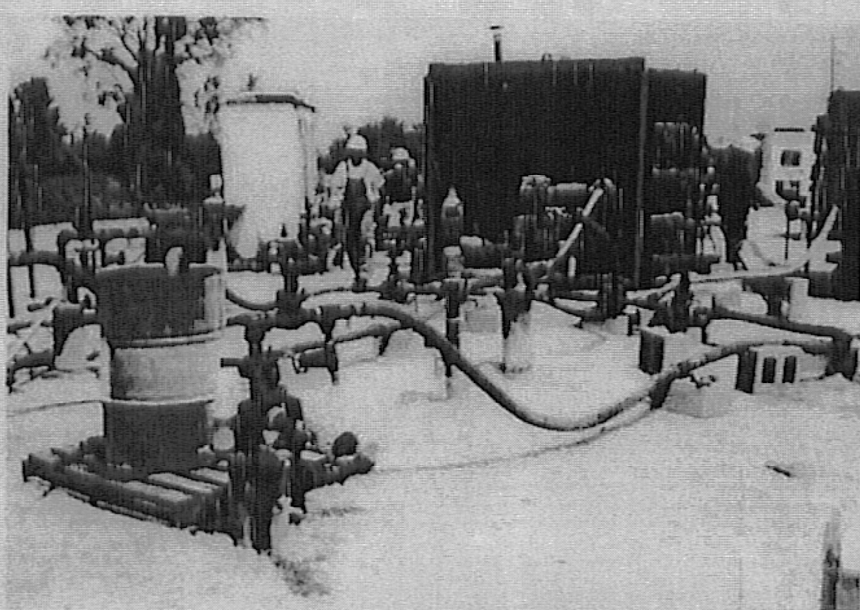
Typically, little benefit — in terms of flow or pressure reduction — is found at this time, even though it is absolutely essential to conduct this work at this juncture (i.e., at a time when the water flow rate in this part of the final grout curtain is minimal).

***The most** critical and dramatic phase of the grouting program is plugging the conduit after the surrounding rock mass has been protected.*



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 more than 100 ft., 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 higher). 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 (temporarily) plugged 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 should eventually resist the hydraulic gradient applied to the temporary plug. Failure to conduct sufficient HMG and LMG grouting at this time will simply ensure the ultimate failure of the operation because the temporary bitumen plug will continue to cool and shrink and so permit the water to exploit the growing gap between the conduit boundary and the bitumen. The plugging operation must be continued without interruption until completion unless bitumen is pumped continuously down through the specially installed pipework at high temperatures, the system will freeze prematurely, and the conduit will not be accessed.



When dealing with flows of 40,000 gpm or more and head differentials of more than 100 ft., hot bitumen — along with HMG and/or LMG — has proven reliable.

The organization and management of the plugging operation is an exercise in detail and logic and must involve the skills, input, and cooperation of all parties. Clear field leadership is essential.

Recent case studies

West Virginia (Bruce et al., 2001) — An inflow of about 40,000 gpm suddenly developed into the floor of this fully operational quarry, originating in a river about 1,500 ft. away. The head differential was over 160 ft. Remediation had to be undertaken since:

a) the quarry was an integral part of a major commercial organization, having long term aggregate supply contracts to satisfy; and
b) it would have been prohibitively expensive to pump on an ongoing basis.

Desk studies were supplemented by programs of geophysical testing (fracture trace analysis, EM surveys, and dipole-dipole) and exploratory drilling. These holes were sampled for water chemistry, pH, and temperature. The result was that the likely flow path was identified, being — at its most intense —

more than 50 ft. wide and at two elevations (60 to 100 ft. down; and as deep as 200 ft.). However, other karstic features, as yet not transmitting water, were found over a far larger lateral and vertical extent. Following an assessment of the viability of other options, a two-line grout curtain was designed, about 1,200 ft. long, 230 ft. deep, and within 70 ft. of the river bank.

Construction *of grout curtains can elimina water flow and restore piezometric levels upstream of the curtain.*

The work was conducted in several successive phases, each driven by the analysis of the results of its predecessor. Locally, the curtain was thickened or regrouted in response to the developing picture. Success, in this case the reduction to a total inflow of about 7,000 gpm, was achieved — temporarily — on several occasions, only for the integrity of the curtain to be compromised as a result of clay filled karsts being blown out under rising gradients. Eventually, however, success was achieved — inflow from the river was virtually eliminated under a differential head of 140 ft. This project required the injection of 8,400 cu. yd. of HMG, 2,140 cu. yd. of LMG, and 6,100 cu. yd. of hot bitumen.

Missouri — A virtually identical problem was encountered in Missouri three years after the West Virginia project. The same generic approach to assessing the problem and designing and executing the solution was adopted. Extensive use was made of electrical resistivity and spontaneous potential geophysical exploration, dye testing, aerial photography, and piezometric observations. The velocity of the underground flow reached about 80 feet per minute. In this case, the river created a maximum differential head of about 300 ft. on the base of the quarry, and the maximum recorded inflow was about 30,000 gpm.

A multi-row, 260-ft.-long grout curtain was constructed to a maximum depth of 350 ft. Intensive treatment of the incipient karstic features was first and systematically conducted to improve the ground around and under the location of the main conduit, found to be about 230 to 280 ft. down and 60 ft. wide. The major difference in the geology with the previous case was that the boundaries of the conduit were found to be relatively competent. As a consequence, the actual formation of the final plug — although it took several weeks to plan, organize, and prepare — took barely 48 hours. The result was total elimination of the flow and full restoration of piezometric levels upstream of the curtain. The overall curtain involved injection into about 77 holes of approximately 2,150 cu. yd. of LMG, 3,700 cu. yd. of HMG, and 215 cu. yd. of hot bitumen.

The relatively competent nature of the bedrock around the conduit permitted straightforward stage grouting procedures to be used with the HMG in the pretreatment phase of the operation, as opposed to the MPSP system necessary for the similar phase of treatment in the much less competent rock mass found in the West Virginia project.

Conclusion

Space restrictions prevent full descriptions being given of the two case histories summarized above. The reader should be cautioned from believing that these projects were anything other than extremely stressful for all the participants. They demanded the highest levels of technology, administrative, engineering, and management skills, as well as 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 article 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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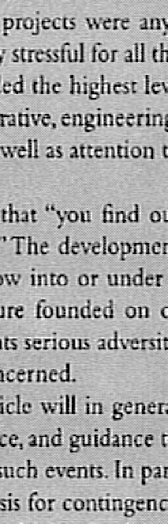

References

Bruce, D.A. (2003). "The Basics of Drilling for Specialty Geotechnical Construction Processes." *Grouting and Ground Treatment*, Proceedings of the Third International Conference, Geotechnical Special Publication No. 120, Ed. L.F. Johnsen, D.A. Bruce, and M.J. Byle, American Society of Civil Engineers, pp. 752-771.

Bruce, D.A. and Gallavresi, F. (1988). "The MPSP System: A New Method of Grouting Difficult Rock Formations." *Geotechnical Aspects of Karst Terrains*, ASCE Geotechnical Special Publication No. 14, Presented at ASCE National Convention, Nashville, Tenn. May 10-11, pp. 97-114.

Bruce, D.A., W.G. Smoak, and C.C. Gause. (1997). "Seepage Control: A Review of Grouts for Existing Dams," Proceedings of the Association of State Dam Safety Officials, 14th Annual Conference, Pittsburgh, Pa., Sept. 7-10, Compact Disc.

Cadden, A.W., D.A. Bruce, and R.P. Traylor. (2000). "The Value of Limited Mobility Grouts in Dam Remediation." Association of State Dam Safety Officials Annual Meeting.

Bruce, D.A., R.P. Traylor, and J. Lolcama. (2001). "The Sealing of a Massive Water Flow through Karstic Limestone." *Foundations and Ground Improvement*, Proceedings of a Specialty Conference, American Society of Civil Engineers, Blacksburg, Va., June 9-13, Geotechnical Special Publication No. 113, pp. 160-174.

Chuaqui, M. and D.A. Bruce. (2003). "Mix Design and Quality Control Procedures for High Mobility Cement Based Grouts." *Grouting and Ground Treatment*, Proceedings of the Third International Conference, Geotechnical Special Publication No. 120, Ed. L.F. Johnsen, D.A. Bruce, and M.J. Byle, American Society of Civil Engineers, pp. 1153-1168.