Grouted Seepage Cutoffs in Karstic Limestone

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Abstract

Four types of seepage cutoffs have been successfully utilized in limestone formations: open-cut excavated cutoffs, diaphragm wall cutoffs, secant pile cutoffs, and grouted cutoffs. After falling somewhat out of favor due to lack of success on some projects, recent advances in materials, procedures, and techniques have resulted in practitioners regaining confidence in grouting.

This paper examines cutoff methods with respect to geologic compatibility and the issues, problems, and limitations for each type of cutoff. Four recent case histories of successfully grouted seepage cutoffs are discussed: the reservoir rim cutoff at Tims Ford Dam, Tennessee, the Patoka Lake spillway in Indiana, Wujiangdu Hydroelectric Project in China and a multi-material cutoff in an operating quarry in West Virginia.

Introduction

Any construction in or on karstic geology is very complex and the desired results are frequently difficult to achieve. When voids and cavities are encountered in the excavation operations for foundation preparation in the initial construction, the conventional method for providing the necessary cutoff is by open cut excavation with conventional earth and rock excavating equipment. This has proved to be a successful method. In the past, many reservoir projects in the United States have been constructed on karstic limestone foundations with only limited grouting and foundation treatment. Over time, the head created by the reservoir can cause increased seepage by continuing to wash out the clay or soil filled joints and cavities. Traditionally, when this happened seepage cutoffs were installed using the diaphragm wall and secant pile methods of construction. Grouting methods had

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fallen out of favor due to lack of success on several projects. However, recent advances in grouting technology, materials and grouting procedures have resulted in the profession regaining confidence in grouting as a cost effective method of constructing cutoffs in karstic limestone.

Karstic Topography and Geology

Karst topography is the landform that develops in areas of exceptionally soluble carbonate rock (limestone and dolomite). It is characterized by the presence of sinkholes, closed depressions, enlarged fracture systems, caves and underground rivers. The sinkholes and depressions allow soil to fill or partially fill some of the voids. Unique surface and subsurface drainage patterns develop and large quantities of water flow beneath the surface.

The major problem for seepage control is the presence of red clay from the chemical degradation of the rock. This clay usually occupies large cavities and is highly erodible. As the erosion of the clay or soil material continues, these conditions become more extensive and present a real challenge for the construction of infrastructure projects.

Cutoff Types

Excavated Open Trench: This method consists of excavating and removing the rock and joint materials to the required depth and length. The excavation is then backfilled with the appropriate concrete mix to form a thick and continuous wall. It results in a positive cutoff since the termination points can be visually inspected before backfilling operations begin. This method is applicable when the voids are discovered during the initial construction, when the overburden or fill above the rock surface is shallow and the required depth is easily obtained by conventional drilling, blasting and excavation equipment. This is a traditional method used for many dams worldwide.

Diaphragm Wall: This method consists of excavating a narrow trench that is temporarily stabilized by a slurry fluid in a series of continuous panels. After the excavation for a primary panel is completed, the excavation is then backfilled with concrete. Reinforcing is added if required. After completion of several primary panels, secondary panels are then excavated between the existing primary panels and backfilled with concrete to form a continuous wall. It is important that the completed diaphragm wall have adequate structural strength and integrity as well as to provide a positive cutoff for differential hydraulic head.

Secant Pile Wall: This method consists of drilling large primary and secondary piles, in sequence, and then backfilling them with tremied concrete. After two primary piles have been drilled and the concrete has cured, a secondary pile is drilled between them and backfilled with concrete to form a continuous concrete cutoff wall. This is an effective method where the depth of overburden is shallow and the depth of penetration into the rock is significant.

Grouting: Historically, grouting operations in limestone have not been very successful because of our lack of understanding of the characteristics of limestone foundations and with the conventional equipment and procedures, it was difficult to control the grout mixes and injection pressures needed to ensure that the grout filled all of the voids. Monitoring of grout takes and the results were accomplished manually after a zone had been grouted. After a hole was completed an assessment was made. This process made it difficult to measure the degree of success of grouting an area or the project as a whole. While grouting was successful in stopping muddy water from flowing from the toe of the Wolf Creek Dam between 1968 and 1970, additional studies concluded that because of the high head on the foundation, grouting could not be considered as permanent long term treatment and a diaphragm cutoff wall was then installed.

Considerations for Selecting the Type of Cutoffs in Karstic Limestone

In the evaluation of alternative methods for constructing cutoffs, there are many factors to consider. A basic and sound characterization of the site and foundation is very important and many times difficult to obtain due to the nature of karstic limestone. It is often difficult to determine the locations and extent of the voids and cavities. The physical properties of the limestone or dolomite will have a significant impact on the type of cutting heads used to cut through the rock. Selection of the wrong type of head and equipment can result in major change orders or termination of the contract.

An example of the difficulty in assessing the insitu properties of the rock foundation occurred at Beaver Dam, AK. The contractor started constructing a diaphragm cutoff using a hydrofraise built especially for the job. A large sample of the rock from a quarry was tested to refine the cutting head design. The hydrofraise had two cutter heads with 32 cutting picks per head and cut a 9-foot by 33-inch panel. After 500-600 picks were used and only a small fraction of the wall was excavated, the contractor stopped work after less than a month and the contract was terminated.

In the evaluation and design phase, it can be difficult to establish the depth and length of a cutoff wall to achieve the desired reduction in seepage or flow of groundwater. This can have a significant impact on the investigation costs. Mobilization and construction costs can be high for a wall constructed by the diaphragm or secant methods. For wall construction the alignment is critical to ensure continuity of the wall and at times can be costly to accomplish.

Today, the use of computer monitoring systems clearly provides an improvement and is characterized by totally integrated systems of data analysis and management and real time monitoring and adjusting the grouting operations. Recent experience has shown that properly designed and constructed high pressure grouting can successfully provide a seepage cutoff in karstic limestone.

Recent Developments and Current Grouting Methods

Grouting is an especially unique type of construction. It is the process of injecting mixes of water, cement, fillers and additives into open or soil filled cracks and voids in rock with the intent of stopping the movement of water or to improve the physical characteristics of the rock. It involves managing and performing many simultaneous operations, each of which requires a high degree of care. Grouting is further complicated by the fact that we cannot see the formation to be grouted or see grout permeating the voids or fractures. In the past, this has led people in the profession to commonly describe grouting as an "art", based on rules of thumb.

Recognition of the potential benefits and experimentation with "automated" monitoring or data recording systems for grouting started in the 1960's. Use of electronic measurement devices mated with computers was recognized as having significant potential almost as soon as desktop computers came into being in the late 1970's. Since the mid-1990's, there have been dramatic improvements in both the number and type of flow and pressure measuring devices, computer hardware, data acquisition software, and data management and display software. The dipstick and pressure gage method is becoming a practice of the past. Using proper investigation, evaluation, design and construction techniques, we now have the ability to design and build Quantitatively Engineered Grout Curtains (QEGC) for seepage control with a high degree of confidence and reliability. This system is now sufficiently reliable and user friendly that grouting can now be considered as a very efficient and cost effective method to provide a cutoff for future projects.

Karst Grouting Issues, Theory and Methods

There are a number of issues in confidently constructing a durable and reliable grout curtain in karst formations. However, successful procedures have evolved that address these problems. These items are discussed in subsequent paragraphs.

Irregular Top of Rock Surface. The first problem that must be dealt with is the enlarged joints, seams and soil filled voids that create an irregular top of rock surface. For new dams, this problem is usually solved by variation in the depths of foundation excavation to expose a groutable rock surface. The excavation depth is established based on the experience and judgment of the engineer or geologist, and the seam is backfilled with concrete before grouting.

Water Loss During Drilling. The recommended practice for drilling grout holes in rock is to use water for removal of cuttings (Houlsby, 1990 and Weaver, 1991). When open joints or voids are encountered during drilling, water loss will occur. This is a frequent occurrence in grouting karst foundations, particularly in the early stages of the program. The frequency of occurrence will decrease dramatically as the grouting progresses. When water loss occurs, the drilling is suspended a short distance past the point of loss and the fracture is washed and grouted before continuing with further drilling of the hole (Weaver 1991). There are multiple reasons for this procedure:

1. The hole has encountered precisely the type of feature being sought, and a significant opening has been encountered that deserves special treatment.

2. Continuing to drill without having cuttings brought to the surface means that the cuttings are entering the fracture and potentially reducing the ability to later inject grout into the fracture.

3. Drilling difficulties are likely to occur without return of water including possible damage to the bit, losing the hole, or losing drilling equipment in the hole.

4. Continuing past that point and grouting later is highly likely to result in grouting in of packers resulting in loss of equipment and likely the drill hole itself.

Large Voids. When a void is encountered during drilling, the size of the void is unknown. Rod drop may have little meaning, since it is not known whether the center or edge of the void has been penetrated or perhaps the drill has encountered an enlarged vertical seam of limited horizontal dimensions. A downhole camera system is of great value in assessing the conditions, and it is recommended that one be kept onsite full time for that purpose. In the absence of a camera, and sometimes even with image information, the recommended procedure is to still begin grouting at a relatively fluid mix, but to proceed through a sequence of thicker grouts relatively quickly. The grouting should be brought to refusal with whatever grout mix is found to be necessary. Low mobility grouts (LMG) will usually perform adequately when large voids are encountered. The use of sanded mixes and concrete mixes should be limited to those voids where the condition is known by camera inspection.

Large Water Flows in Fractures. When fractures with large water flows are encountered, the flows must be reduced by whatever means necessary to allow later high quality grouting to be performed. A staggering variety of materials have been used for this purpose including any and all materials readily available (Bruce et al

1998). After the flow has been initially blocked, extensive grouting is performed with proper materials.

Soil Filled Fractures. Clay, silt or sand filled fractures and solution features are extremely common and have always been the major source of concern for the quality of grout curtain construction in karst conditions. The concern is heightened by the fact that these infilled materials are frequently soft and loose and are clearly erodible under even moderate flow conditions. Houlsby (1990) and others, including the authors, have concluded that removal of all of these infilled materials is neither possible nor necessary. Simply from an intuitive standpoint, it is clear that the relatively small diameter of the water washing pipes makes it impossible to inject enough water through the drilling system to clean out a major infilled seam. At best, it might erode an opening through the material of sufficient diameter to accommodate the inflow rate. Accordingly, it is recommended that washing continue until the return flow becomes clean, but it should not be assumed that the infilling has been removed to a significant degree. In the absence of any return flow, the fracture should be washed for a pre-determined and limited amount of time, typically 5 to 10 minutes.

A critical question remains, however, regarding how an effective grout curtain can possibly be constructed in the presence of such materials. In fact, it is precisely this question and the combination of unsatisfactory grout curtain performance on some projects that has given rise to the loss of confidence in grouting as a solution. However, despite the "horror stories" about grouting limestone sites, there are a larger number of success stories, including effective grouting of foundations with major cave systems for dams with applied heads as high as 165 m (540 feet) (Weaver, 1991; Zuomei and Pinshou, 1982; Houlsby 1990). Why grouting works under these circumstances is one of the most intriguing and least understood technical issues because it is such a deviation from the normal concepts of what is required for successful grouting. Clearly, there must be alternate mechanisms involved that allow successful grouting of karst despite these conditions. These alternative mechanisms are discussed in the following case histories.

Patoka Lake Dam, Indiana

The recent seepage remediation project at the Corps of Engineers Patoka Lake Dam required grouting of a vertically fissured limestone unit with considerable soil infillings. A 3-line grout curtain was used, and real-time computer monitoring of grouting was employed. As the grouting progressed, it was clear that in these enlarged, infilled fractures a common pattern was a gradual build-up of pressures followed by one or more episodes of hydrofracturing of the clays. The grouting pressure being used was well in excess of the head that would eventually be applied to the completed curtain, and each stage was brought to refusal at that pressure.

Water pressure testing was performed at a lower, uniform pressure adequate to locate fractures and to calculate the Lugeon (Lu) value for the stage.

Early in the project, the theory of successful grouting at this site was based only on a containment concept. A 3-line curtain would be constructed, but the primary mechanism for success would be that a wide zone of rock would have all the open fractures filled, thereby keeping gradients relatively low and simultaneously protecting and containing the infilled materials left in place. However, as the program evolved, extensive observations and analyses of the developing behavior were performed. In particular, the effects related to the hydrofracturing were considered, and a revised closure criterion was developed. Previously, closure of a line was considered to occur when analysis of series of grouted holes suggested line closure had occurred and when the lower pressure water tests in supplemental holes indicated that open fractures had been completely filled. When that condition was found to exist, the supplemental holes were simply gravity grouted since they were absolutely tight as per the water testing. As the program progressed, the criterion for closure of a line was modified such that drilling and grouting of supplemental holes continued until closure had been obtained. When the lower water pressure tests of supplemental check holes indicated absolutely tight conditions, and when grouting of supplemental holes showed no hydrofracturing. This modified closure criterion resulted in total confidence that a fully effective grout curtain had been created, because it now showed that not only had containment been achieved, but also that it was not possible to hydrofracture through the infilled materials even at elevated pressures.

Wujiangdu Hydroelectric Project, China

The work by Zuomei and Pinshou (1982) has added more information on the mechanisms related to hydrofracturing and other factors. The Wujiangdu Hydroelectric Project in China required effective grouting of extensive karstic caves filled with soft clay to be able to withstand heads of up to 165 m (540 feet). Grouting was accomplished under high pressures (60 kg/cm^2), and hydrofracturing was observed. After grouting, specimens were removed from the grouted caves in the curtain line. Based on examination and testing of soil samples from the voids, they concluded that multiple mechanisms were at work that allowed the curtain to be successful under very adverse conditions. Specifically, they concluded the following:

1. Hydrofracturing occurred in a radial pattern that created an extensive network of cement veins within the clay. There was also evidence that the grouting created circumferential fracturing. This resulting network acts as an effective barrier to confine the clay from erosive flows. In order to verify the effectiveness of the grouting, specimens from the voids were obtained and tested. A secondary benefit of the hydrofracture cement network was a chemical alteration and hardening of the clay from calcium carbonate formed

by the grout. This produced a measurable increase in strength and slaking resistance that improved the fundamental erosion resistance of the infilled materials.

2. While the hydrofracturing effects are the most important items, two other beneficial effects were also observed. The first is that grouting did displace some of the softer materials by extrusion under the high grouting pressures, thereby increasing the efficiency of the grouting. Secondly, by using the natural water content and density of the clay and the volumetric ratio of the cement grout in the specimens, consolidation of the clay in the voids was calculated to be 6.5% of the grout volume.

Combining the information from these two projects provides both a reasonable explanation of the mechanisms (hydrofracturing, displacement and consolidation), as well as the importance of adopting a dual closure criteria for the curtain lines based both on demonstration of tight stages by water pressure testing and by cessation of hydrofracturing at elevated grouting pressures.

Tims Ford Dam, Tennessee

The Tennessee Valley Authority's (TVA) Tims Ford Dam is a 175-foot high rock-fill darn, located on the Elk River, Tennessee. The rock at the Tims Ford site consists of thinly bedded, nearly horizontal layers of limestone and shale. The reservoir rim near the right abutment of the dam is comprised of red residual clay from the Fort Payne formation underlain by three limestone formations - the Brassfield limestone containing numerous solution cavities along bedding planes and near-vertical joints; the Fernvale limestone, also containing solution cavities along bedding planes and joints; and the Catheys-Liepers limestone, containing shale lenses, fossilized layers and displaying a prominence of clay seams.

During the initial planning of the dam project, it was decided to treat only those portions of the rims that showed leakage after impoundment. In March 1971, when the pool reached approximately 865 feet in elevation, leakage developed in both left and right reservoir rims, as well as in the left abutment adjacent to the dam. Over time leakage from the Fernvale limestone on the right reservoir rim increased steadily to about 4,000 gallons per minute (gpm) at maximum pool by 1995. Later that year the rate of flow increased dramatically to just less than 8,000 gpm.

This leakage prompted TVA to evaluate the need for remedial action at the right rim of the reservoir. Several alternatives were evaluated. Grouting from the top of the rim was selected. The advantages of this scheme were: the area to be treated could be fairly well defined; the likelihood of success was good; the work could be done with the reservoir a few feet below normal minimum pool elevation; standard drilling and grouting equipment could be used; and the effectiveness of the grouting could be monitored by observing the leakage.

Results from a site investigation indicated that a multi-row, remedial grout curtain having a length of 800 feet would be adequate. The holes penetrate all three limestone formations, were inclined at 30 degrees to the vertical to ensure intersection of sub-vertical features and were oriented in opposite directions in the two outside rows. Primary holes in each row were located at 40-foot centers, with conventional split spacing methods to be employed (to reduce interhole spacing to 10-foot centers). The central tightening row was vertical.

TVA's goals were to reduce the peak seepage to about 1,000 gpm and to focus only on the major features. Holes that did not encounter voids or active flow were to be grouted with fluid, cementitious grouts. The grouting was designed to be performed using upstage methods, although it was anticipated that poor foundation conditions could require localized utilization of downstage methods in conjunction with polyurethane resin. However, because larger than anticipated were encountered, low mobility grout (LMG) was used to fill the major voids in lieu of the polyurethane resin.

Actual field conditions varied from what was anticipated. The work progressed as scheduled, but several major modifications were made.

1. This project had to comply with a restricted schedule due to reservoir drawdown constraints. The LMG (slump 2 to 6 inches) was batched onsite, using a two-conveyor, three-component, trailer-mounted batch plant, with hydraulic-driven mixer/conveyor auger.

2. When the reservoir was drawn down to elevation 859 feet, the flow from the major seepage exit point stopped. This "no flow condition eliminated the need for the polyurethane grouts and extending the applicability of cement-based formulation (including LMG).

3. Larger-than-anticipated open or clay-filled features were encountered, especially in the upper 20 feet of the curtain. For technical, commercial, environmental, and scheduling reasons, such features were treated with LMG.

4. A suite of four cement-based grout mixes were developed to permit the appropriate match of mix design and "thickening sequence" to the particular stage conditions as revealed by drilling and permeability testing (both multi- and single-pressure tests). In summary, about 2,000 cy of LMG, 400 gallons of polyurethane, and 790 cy cement-based grouts were injected into a total of 250 holes (comprising 11,000 linear feet of rock drilling)

Real-time performance monitoring during the grouting operations included the results of drilling, water pressure tests, calculating reduction ratios and dye testing. This monitoring allowed onsite engineers to track the development of the integrity of the grout curtain and focus grouting efforts on specific zones along the grout rows. Monitoring also included data from 1) discharge from the rim leak; 2) groundwater elevations down gradient from the grout curtain; and 3) headwater elevations. Engineers used results from water tests to evaluate permeability of the rock in Lugeon (Lu) values. The water tests confirmed more open void stages in two certain areas, and another order holes were added to these zones. Grout takes closely followed trends observed in the water test data. To evaluate grouting progress, reduction ratios were calculated by dividing the average take of one order of holes by the average take of the previous order of holes. By completion of the program, total seepage at full head had been reduced to less than 300 gpm and has remained at that level since completion of the grouting.

Limestone Quarry, West Virginia

A large operational dolomitic limestone quarry is situated in West Virginia less than 1,500 feet (460m) from the Shenandoah River. In April 1997, a major sudden inflow developed into the southwest corner of the quarry pit following production blasting activities and several abnormally severe precipitation events that caused flooding of the river and nearby sinkhole formation. An observed vortex in the river appeared to be the point source of the flow. The initial magnitude of the flow, estimated at over 35,000 gpm (132,500 L/min) was far greater than the capacity of the existing pit pumping facilities.

The new inflow posed a severe threat to both the current and future viability of the quarry. Several unsuccessful attempts were made to construct a cofferdam with sandbags on and around the location of the vortex. In May 1997, pumping operations were discontinued, and the quarry water level was allowed to rise. Extensive investigations were conducted to determine the source and extent of the inflow. Prior to the design and construction of the remediation, it was agreed to "baseline" the hydrogeologic situation as closely as possible. Wells with deep piezometers were located between the river and the quarry to evaluate the water level, pH, conductivity, and temperature. This monitoring continued during and after the remediation.

The owner's goal of the remedial program was to reduce the total inflow into the quarry to a flow of 8000 gpm, (30,300 L/min*)* with the quarry completely dewatered. Later data would indicate this would require reducing the flow from the river to below 3000 gpm (11,400 L/min). Three specific options were considered:

1. Identify the specific solution cavities in the river and seal them.
2. Construct an intercepting cut off at some appropriate location between the river and quarry.
3. Treat the problem close to the quarry.

Option 2 was clearly favored, on logistical, technical, and environmental grounds, and it was decided to locate the cut off on a convenient road side location about 50 feet from the river bank

The main challenges were: the very high velocity and rate of the flow through potentially multiple conduits; mud filled karstic features, creating the possibility for erosion, piping, and "blow out" after curtain placement when the hydraulic gradient increased; and the possibility of grout migration "upstream", into the river. Several grouting technologies were studied to provide the curtain, in part or in whole jet grouting; polyurethane injection; LMG; hot bitumen injection; accelerated cement based slurries; use of the multi packer sleeve pipe (MPSP) system; and geotextile grout-filled bags. For the very severe geological and hydrogeological regimes to be accommodated, each technique was assessed based on technical feasibility, likelihood of successful treatment of the inflow in both short and long terms, and cost. Grouting was accomplished in nine phases. Throughout the grouting operation, several modifications were made to enhance control and responsiveness and allow simultaneous injection of both bitumen and slurry into the same hole. For example, stringers were used to allow the simultaneous injection of both slurry and bitumen into the hole. It was decided to first treat the "Cold Karst' zones (open voids without flowing water) with LMG and slurry grout via the MPSP system and then treat the "Hot Karst", i.e., the zones were water flowed, with hot bitumen from the downstream row of holes, backed up by slurry grouts simultaneously injected from the upstream row via further MPSP locations.

Monitoring of groundwater wells, water levels in the quarry, flow and visual observations of the river eddy indicated that the program was successful. By the end of the grouting, the flow from the river into the quarry had essentially stopped. This success of this case history clearly illustrates many important features, but three are particularly noteworthy. Firstly, this is an illustration of how contemporary grouting technology can be used, if correctly designed, implemented, analyzed, and closely monitored, to provide a successful result in even the most adverse conditions. Secondly, is that all sources of information must be studied before and during the operation in order to gain the best possible "picture" of what is really happening in the ground and the incremental changes actually brought about the grouting itself and changes in. the hydrogeological regime. Thirdly, and perhaps most importantly, this project illustrated the need for all stakeholders (owner, designer, consultants and the contractor) to partner fully and openly, and to provide mutual support at all times and in all aspects. In such circumstances, patience and trust are vital ingredients to successful teamwork in arduous and stressful conditions.

Summary:

Any type of construction in karstic geology is very complex and it is sometimes difficult to achieve the desired result. Establishing permanent seepage control can be difficult, expensive and requires monitoring and future evaluation. The recent advances in the approach to grouting now enable geologists and engineers to make significant improvements in the grouting practices and procedures to control seepage or the flow of groundwater. In summary, these advances in technology, materials and grouting methods have made grouted cutoffs in karstic limestone a reliable, efficient and cost effective method for permanent seepage control

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