

Grout Line

Paolo Gazzarrini

Overture

We are at the 26th edition of the Grout Line (more than 4 years have passed since the first edition) and a lot of material for this issue.

I start with very sad news that I would like to share with you; A. Clive Houlby, a very renowned rock grouting expert passed away last September. I didn't know him personally but I am very well aware, as is everyone in our industry, of all the enormous work and dedication he provided for the grouting industry. I thank Jim Warner for preparing the following.

In Remembrance of A. Clive Houlby

Renown rock grouting expert A. Clive Houlby passed away peacefully at age 82, on September 17, following six weeks of hospitalization in his ongoing battle with cancer. Houlby revolutionized North American grouting practice through presentation of his well documented case history data, as an instructor at the annual Short Course on Grouting Fundamentals and Current Practice, now sponsored by the Colorado School of Mines, and as an Invited Keynote lecturer at the once each decade International Conference on Grouting in 1982. He leaves his wife of 55 years Betty and two daughters Susan and Janet. He is to be honored as a "Grouting Great" at

the awards ceremony of the upcoming International Conference on Grouting and Deep Mixing to be held in New Orleans, in February 2012. A citation previously prepared for that ceremony follows.



A. Clive Houlby.

A. C. Houlby Sydney, Australia

A keen interest in engineering and construction came naturally to Clive Houlby. As a child he reveled in constructing sand castles and dams on the beaches of his native Australia, where he became keenly aware of the importance of the ratio of water to the sand, too much and the shape slumped, too little, it wouldn't stand. But his greatest delight (and future

career) were established at age 9, when he discovered "*This stuff which could be mixed with sand to form all sorts of interesting shapes. And a day later the shapes were hard and were permanent! Glorious enjoyment limited only by the supply of cement from father's small resources.*" Based on his prior experience on the beach, "*it came naturally to apply appropriate water:cement ratios to the cement molding.*"

And so, his life of playing with cement continued until graduation from Sydney Technical college in 1952, with a Diploma in Civil Engineering. He then entered the real world, working in a design office for a few months. But he couldn't play with cement in a design office, so in 1953, he transferred to the Sydney Water Board as a Construction Engineer assigned to the new Warragamba Dam construction. Grouting wasn't well established in Australia and experienced people were lacking, besides it was considered dirty and beneath their dignity by most engineers. So young Clive was assigned to oversee the grouting work where he "was given free hand by the bosses".

Warragamba Dam was to be the largest concrete gravity dam in the southern hemisphere and serve as the main source for Sydney's water supply. It's a 351 meter long, 142 meters high, with a thickness of 8.5 meters at the top and 104 meters at the base, and

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was cast in massive blocks, which due to drying shrinkage, requiring grouting of the joints.

The joint grouting became of most interest to Clive; unlike the foundation, movement of the grout could be followed and observed in the exposed joints. The massive undertaking continuing for about four years with "a crew of 60 men operating the various valves under my direction from a control centre. It was ticklish work!" He did a lot of experimentation including the use of dye testing to identify leakage paths, pre and post injection observation by use of a borehole periscope, use of different grout consistencies, and vacuum injection. But the periscope examination was of most interest; even though the thinnest grout used was 3:1 water to cement (thick by U.S. standards of the time), he observed many bleed pockets which convinced him that thicker grouts were better.

Clive became the Countries grouting expert. As such he became embroiled in a huge controversy in 1962.

An American engineer from the USBR was consulting on the Snowy Mountains Hydroelectric Project and insisted very thin (12:1 w/c) grout should be used. Clive was adamant; nothing thinner than 3:1! This led to an extensive test program wherein subsequent inspection disclosed the thicker grouts provided superior results. Clive went on to oversee all grouting operations at his agency, but his duties expanded to directing all site investigations, specification preparation, and head of the Dam Safety Unit.

He has consulted on projects throughout the world, was a speaker at numerous technical events, and from 1980 to 1995, provided the rock grouting portion of the week long Annual Short Course on Grouting, now sponsored by the Colorado School of Mines. He was a Keynote Speaker at the 1st International Conference on Grouting in 1982. He is the author of numerous technical presentations and the landmark book, Construction and Design of Cement Grouting, a Guide

to Grouting in Rock Foundations, John Wiley & Sons, 1990. But perhaps most notable is his internet presentation ROCKGROUT (www.users.tpg.com.au/houlsby1) which in spite of failing health, he continued to improve until his recent hospitalization. The comprehensive ROCKGROUT site even includes a variety of grouting simulators, and can also be accessed through the ASCE Geo-Institute, Grouting Committee website (www.grouters.org). Clive Houlsby is truly a Grouting Great!

Jim Warner

The Gin Method Discussion Continues

I received also an additional comment from Dr. Donald Bruce related to the past 2 articles about the GIN Method, as an answer to Dr. Lombardi article published in September 2011 issue.

"I am delighted that my article has stimulated debate on the current challenges facing the evolution of

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the dam grouting industry in North America, and am obliged to Prof. Lombardi for his most thoughtful contribution. In 2003, I invited Prof. Lombardi to present the keynote lecture (on rock grouting) at the New Orleans International Grouting Conference. At its conclusion, I, as session chair, stated that if he had given this “GIN Lecture” in the U.S. in the 1980’s or 1990’s, then contemporary practices in North America would likely be so very different from what they had evolved into. I still believe that opinion to be true. However, *res ipsa loquitur*, and the *res* is that today our best practices

are now somewhat different from those based on advanced GIN theory, even as implemented by the experienced and knowledgeable contractors in such non “remote” countries such as Switzerland and Austria. In this regard, I personally appreciated very much the details of the newer GIN developments.”

Donald Bruce

We continue with an interesting article from Michael Byle D.GE, F.ASCE about grouting in karst. Mike is the National Discipline Lead for Civil/Geotechnical Engineering at Tetra

Tech EC, Inc. He holds both Bachelor and Master of Science degree from the University of Michigan. He has more than 30 years of experience in dealing with geologic hazards including karst. He is a past Chair of the Geo-Institute Committee on Grouting and current President of the International Conference Organization for Grouting. He is also the Co-chair of the 4th International Conference on Grouting and Deep Mixing to be held in New Orleans in February, 2012. (Michael.byle@tetrattech.com – Tetra Tech-Langhorne, PA)

Managing Risk for Grouting in Karst

Michael J. Byle

Grouting in karst is fraught with difficulty and uncertainty that increase performance risks for grouting operations. Managing this uncertainty is essential in producing a successful result when seeking to stabilize or provide hydraulic cutoff in karst. Uncertainty is due to the unpredictable nature of the solution process and inability to detect the resulting openings with great certainty. The greatest risk results where grouting methods selected are either inappropriate or not adaptable to the conditions present. This paper will discuss the nature of karst features, methods to evaluate formations for their presence and methods to assess the performance and make adjustments to the grouting process to optimize performance. The approaches will include a discussion of geophysical methods and intrusive drilling and boring methods and how to integrate results statistically and geologically to better characterize the formation, as well as, including the Observational Method to reinterpret the characterization based on grouting performance data.



Figure 1. Vertical solution feature in flat lying limestone.



Figure 2. Isolated karst conduit in otherwise intact rock.

Introduction

The risks to a grouting project in karst are manifold. These include the potential for delays and cost overruns due to difficulty in drilling, reduced productivity during grouting for various reasons, material overruns, and equipment problems; as well as the risk of failure of the process to achieve the required objectives, or to provide long term performance. Risks can be effectively managed if they are adequately understood. Conversely, the risk to the project is greatest when uncertainty is greatest. The combination of all of the above uncertainties taken together with normal project risks (i.e. labor issues, material pricing, weather, etc.) will reveal the total project risk. This paper will deal exclusively with the risks associated specifically to karst, since the other normal project risks are routinely managed and covered elsewhere in the literature.

Uncertainty in Karst Grouting

Risk analysis has been applied to subsidence risk in karst (Kaufmann, 2008; Doctor et al., 2008, Perlow, 2008, Zisman, 2008, etc). Most of this type of work has been focused on development risk and not on identifying the specific risk of karst features being present at any specific location, though similar approaches can be used, provided sufficient site specific data is available. There are a number of categories of uncertainty associated with the planning and execution of a grouting program that must be addressed and managed for successful grouting outcome. These can be divided into site uncertainties, methodological uncertainty and temporal behavior uncertainty.

Site Uncertainties

For the purposes of this discussion, the term site uncertainties is defined as those unknown conditions present in the subsurface of the site that will affect

the grouting performance and outcome. Site uncertainties would affect the rate and difficulty of drilling grout holes, the number of grout holes and injection locations, the quantity and distribution of grout in the subsurface and the overall effectiveness of the grouting program. The site uncertainties include site geologic variability, formational structural variability (i.e. the occurrence of fractures, folds or other features), the degree of weathering and karstification, the maturity of the karst, the presence of infilling, caves, etc., as well as, the depth and condition of soil overburden and the geo-hydrologic conditions.

Geological uncertainty relates to the nature of the formation as defined in geologic terms. That is the type of rock, rock material properties. This occurs where the nature of the geologic formation is either not known, or poorly defined. An example of this would be where a formation is mapped that consists of alternating beds of differing rock types, without a defined sequence

or where bedrock mapping is incomplete. Bedrock mapping is often incomplete where it is overlain by a thick mantle, or where surface geomorphology is not residual, such as where the karst stratum is overlain by an alluvium, glacial deposits, or other such soils that would mask the presence and nature of the underlying bedrock. This can obscure contacts between formations. Another instance of geologic uncertainty would be where complex faulting or folding results in local disruption of the regional geology that may not be completely mapped.

Structural uncertainty refers to uncertainty related to the geologic structure. This includes location and condition of joints, faults, as well as, voids in the bedrock formation which comprise the secondary porosity of the formation. Structural geology informs the search for voids, since solution is typically more pronounced in areas of higher transmissibility where rock is fractured or broken and along discontinuities such as unconforming geologic contacts. Resolving or reducing structural uncertainty probably has the greatest impact on setting up the drilling patterns for a grouting program.

Hydrologic uncertainty arises from complexity of groundwater flow in karst. The impact of groundwater hydrology on the grouting can be profound. Injecting grout above the water table, below the water table or into flowing water will have quite different results that can seriously affect both the quantities of materials needed and the performance of the completed grouting.

Geomorphology is the study of the processes, characteristics and configuration and evolution of rocks and land forms. It is important to know what stage of the geomorphologic process the formation is in. Karstification is a geomorphologic process involving many stages from the initial dissolution of rock minerals, and formation weathering, to the erosion and infilling of voids, to the ultimate decomposition of the rock matrix. Understanding this process in a particular formation is necessary to assess whether voids are active conduits, plugged paleo-karst, or something in between. An excellent

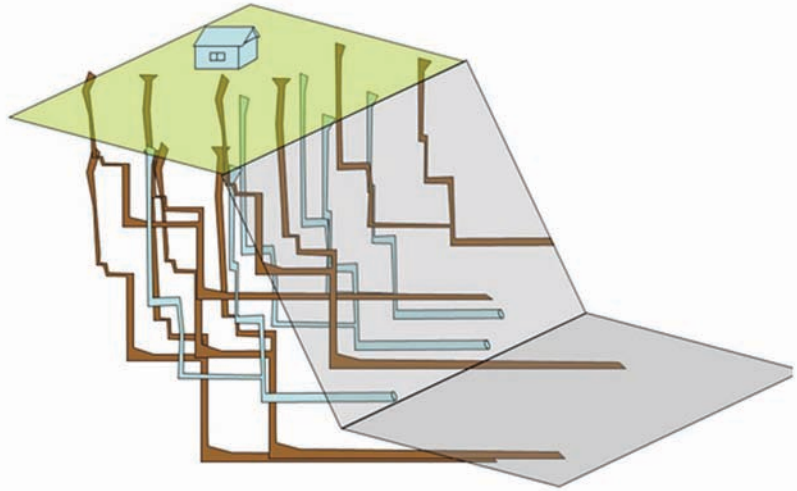


Figure 3. Karst conduits can be connected or isolated, soil filled, air filled or water filled.

discussion of karst conditions and their formation is included in Waltham et al (2005) and White (1988).

Methodological Uncertainty

The application of this methodology used in grouting poses its own uncertainties. Whether a low or high mobility grout is selected; whether displacement by compaction

grouting, replacement by jet grouting, displacement by fracture grouting, or void filling. Void filling would seem to be a relatively simple process, but it can be complicated where the voids are interconnected, where flowing water is present, the voids are partially filled with soil, or other factors. Grouting controls and materials can radically affect the performance of the grout. If the geology, structure and geomorphology are sufficiently understood, the grouting method and materials should be selected to provide effective performance. The method must allow versatility to accommodate uncertainties and adapt to varying subsurface conditions.

The temporal factor is one that is often ignored in grouting solutions. The passage of time will allow natural processes to continue that can alter the long term performance of the grouted formation. Erosion and transport of sediments around the grout may continue, albeit at a slower pace, but can undermine the effectiveness of the grout by opening new passages through previously plugged conduits, or through soils surrounding the hardened grout (Lolcama, 2009). To be effective, the grouting design and execution must consider the full consequence of the

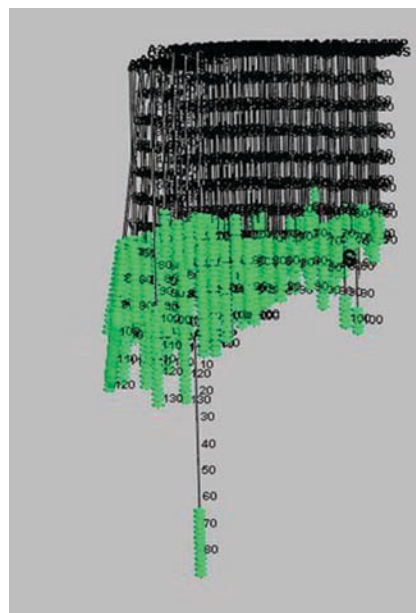


Figure 4. Results of grouting 20 ft into top of rock in karst with battered holes.

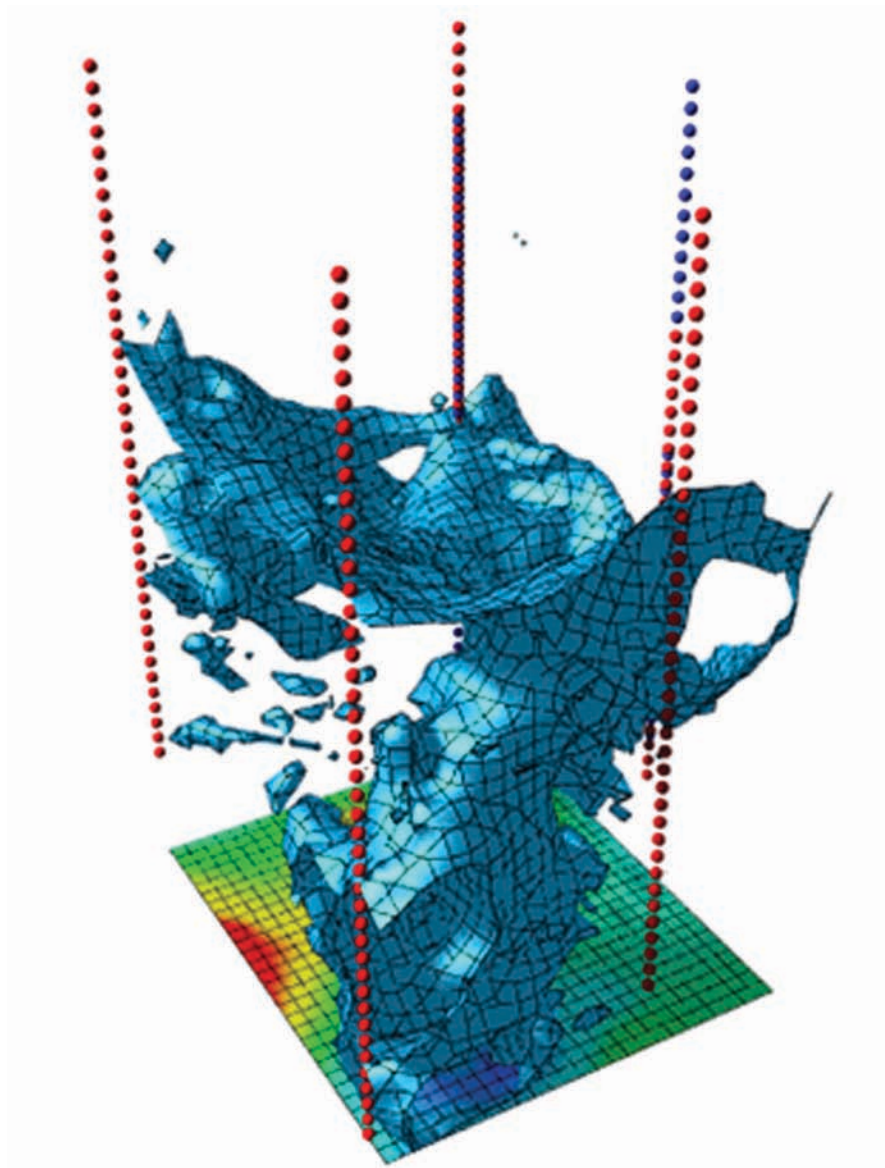


Figure 5. Crosshole seismic tomography image of sinkhole.

grout on the subsurface conditions, the long term stability of the grout material, and time dependent processes that can undermine the effectiveness of the grouting solution.

Managing Site Uncertainties

Uncertainties associated with site conditions can be effectively managed through proper site investigations in advance of the grouting program design. The investigation must be tailored to each site and should include the following:

1. Geologic Assessment
2. Hydrogeological Assessment
3. Subsurface Exploration

4. Karst Assessment

The Geologic Assessment must include an evaluation of the formations present including identification of the rock type, behavior, and layering; frequency of fractures and orientations; strike and dip of the rock beds, locations and orientation of dikes, faults, and unconforming contacts; presence and types of karst features present, and geomorphologic history of the materials at the site. Often times this can be accomplished by a review of technical publications and maps together with a site visit. The literature review should include review of previous studies and maps of the project site, and review of

well drilling logs, a review of historic and current aerial photos can provide input on the distribution of karst features and changes in them over time as well as, enable fine tuning of the geologic data through identification of lineaments and other features.

A key factor in the geologic assessment is to develop a geologic site characterization. This characterization must include an evaluation of the distribution of identified karst features, faults, fractures and other features that can be related to karst activity or rock variability. The geologic assessment should characterize the type and distribution of karst features and the expected pattern of weathering.

The formation of karst features is always water related. The history of groundwater conditions over geologic time ultimately produced the karst conditions that remain within the rock at present. Except in the case of highly soluble formations, dissolution of rock is unlikely to be a significant ongoing problem; however, the current hydrologic conditions are likely to be a significant factor in the occurrence of activity in sinkholes and subsidence. The Hydrogeological Assessment must assess these items, from a geologic, historic, and current perspective. The Hydrologic Assessment should include an assessment of groundwater levels and flows, from both a static and dynamic perspective. The nature of groundwater flow should also be addressed, as to whether the karst voids are highly interconnected forming a ‘water table’ behavior or whether the voids form isolated conduits producing erratic water levels and potentially high velocity flows.

It is essential that the subsurface investigation be planned to consider the conditions identified in the geologic and hydrogeologic assessments to ground truth the conditions expected that should be treated by grouting. The subsurface explorations in karst are frequently conducted to refusal at the top of rock. This can be misleading, since karst is often pinnacled and may contain ‘floaters’, boulders that are remnants of prior collapse or differential weathering. The subsurface investi-

gation must penetrate rock sufficiently to assure that sound bedrock has in fact been reached, or that the condition of the rock meets the requirements for support or conductivity needed for the intended site use. This can be a significant risk factor where the intent is to grout the soil overburden and takes are grossly under estimated where grout can migrate into undiscovered openings in the rock below.

The number of borings/corings/test pits must be sufficient to be statistically significant relative the variability of the conditions. In order to do this, there must be good understanding of the geologic conditions. It is imperative to have some idea as to whether the surface of the rock is highly variable and pinnacled and at what spacing karst features might be expected. If the surface of the rock is pinnacled with large pinnacles spaced 10 m apart, or with tall narrow pinnacles 3 m apart, or if it is a relatively uniform flat rock surface with irregularly spaced vertical karst conduits, a different exploration is necessary. The objective of the investigation is not necessarily to identify and locate every karst opening, but should be sufficient to project the quantity, type and size of openings such that an appropriate grout hole spacing can be defined.

Where the exploration reveals conditions inconsistent with the geologic assessment, the geologic interpretation should be revisited and revised to provide the best picture of the subsurface. Where the purpose of grouting is

to control permeability, or where high velocity flows can be expected, wells should be included with appropriate measurements made. Where grouting in rock is required, it is necessary to assess whether voids detected by coring contain soil. This can be done using a small diameter split spoon that can be inserted through wireline coring drill stem.

Additional exploration tools such as borehole video, borehole geophysics, and other geophysical investigation methods should be used where appropriate. When using geophysics it is essential to understand the resolution and limitations of the methods used. Most methods cannot identify small voids more than a few meters deep. Even large voids can be difficult to identify at depth. When using electrical and compression wave methods it is essential to understand that the absence or presence of water can radically alter the result. All geophysical methods must be ground truthed using boring, and/or coring.

The Karst Assessment includes evaluation of all of the data and conclusions from the Geologic Assessment, Hydrogeologic Assessment, and Subsurface Exploration in concert to develop a unified model of conditions that fits all of the data and site conditions. To do this effectively requires a geotechnical engineer with a thorough understanding of geology, hydrogeology and karst processes. This model is used to design the grouting program.

Controlling Methodological Uncertainties

The effectiveness of a grouting methodology in karst is inextricably linked to site conditions. Without a proper understanding of the site conditions, it is impossible to select the correct method and approach to mitigation. That said, there are measures that can be taken to improve the prospect of obtaining a satisfactory result and reducing cost and schedule. The key issues come down to control:

- Control of materials
- Control of drilling
- Control of the grouting process

These control measures together with a clear focus on the goals of the grouting program and an understanding of the mechanism by which the goals are to be achieved will provide a higher likelihood of a successful outcome. A summary of karst grouting approaches can be found in Warner (2004) and Byle (2001).

Grouting Goal Setting

The materials and methods used in grouting in karst must be selected to provide the performance desired. The performance must be carefully defined so that success can be measured. Some big picture goals may include:

- Creating and impermeable barrier
- Stopping seepage
- Preventing sinkholes
- Stabilizing an active sinkhole
- Providing a sound structural base for foundations



Figure 6. Karst grouting approaches.

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The reader will notice the absence of ‘filling voids’ as an objective. This is because such an objective must be defined as to why it is desired to fill the voids. Such an objective is incomplete since it implies no clear endpoint and even if completed, may not yield the desired result.

For example, one may be willing to invest the huge sum necessary to completely fill all of the voids within a given area, but there is no assurance that doing this will prevent sinkholes, form and impermeable barrier, or provide long term structural support for foundations. Often voids are filled or partially filled with loose sediments and mud that can erode after grouting and undo the work of the grouting program. The complication with such an objective is that there is no practical way find and verify that all voids have been filled; and complete filling of all voids is seldom needed for satisfactory performance. One must view the filling

of subsurface openings as part of the solution and not the end goal.

One must set goals that reflect real measurable performance and that define the purpose of the subsurface improvement. One of the key reasons for grouting failure is using a grouting method where it is inappropriate. One must be careful not to presume the solution when setting the goal. In some cases, the most effective solution might be to excavate from the surface and complete the improvement with concrete and compacted fill with no grouting at all. Often times, a combination of methods will be most appropriate and these may include more than one type of grouting, or grouting in combination with another measure.

Tactical Planning

Once the overarching goal has been defined, the focus can shift to the tactical level, where methods and mechanisms are reviewed to select

the appropriate approach. In grouting, there is always more than one way to skin the proverbial cat. One can fill a void with anything using a variety of methods, from dumping gravel into a hole, to pumping through a tube á manchette and everything in between. The trick is to fill the hole with the right something in an economical way to achieve the project goal.

The first real step is identifying the type, frequency, and orientation of the voids in question and assessing what impact they will have on the end site use; and then to examine the distribution statistically to determine the probability of encountering a void that would adversely affect the end use within the project footprint. Once that has been established, it becomes a question of determining what approach will decrease this probability to acceptable levels. This then becomes the tactical objective. The presence, absence, and flow of water in voids will also affect the grouting method selection. High velocity flows may require special methods (Warner, 2008; Bruce et al., 1998).

With this understanding together with knowledge of drilling and grouting technology and achievable performance, one can conduct an economic analysis weighing the relative cost of drilling and grouting using various methods. Where voids are to be filled, the first job is to drill casings into them. This is where knowledge of the orientation and distribution of voids is critical. The grout holes must be spaced such that grout will travel the amount needed to effectively treat the area required.

Structural applications are often simpler, because high strength is easier to achieve than low permeability. For structural applications, it may not be necessary for 100% coverage, since high strength limited mobility grout can create structural columns within the rock mass that may be sufficient without filling of intermediate voids. An example of this approach is included in Berry et al (2001).

For a hydraulic cutoff, it will be necessary to completely seal all hydraulic connections across the barrier location. This can be complicated by the presence of sediments within the rock voids that can be difficult to dis-

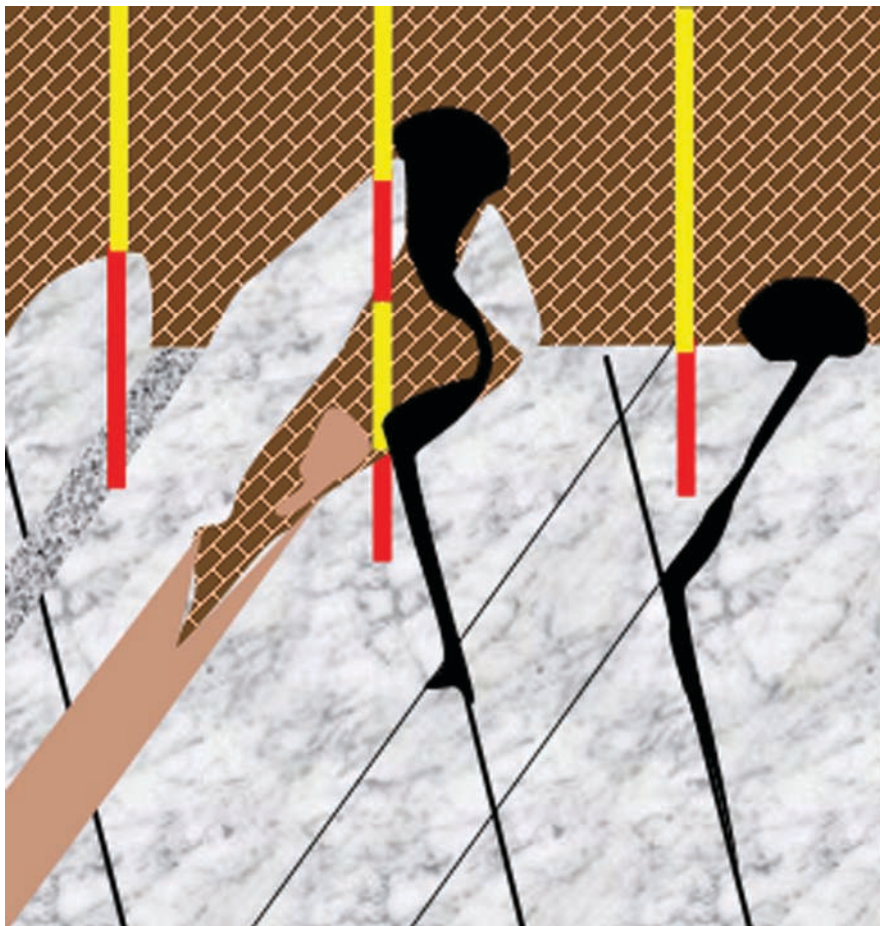


Figure 7. Vertical holes in karst can be ineffective orienting grout holes can increase success.

place or permeate. In such instances, the hole spacing must be close enough to permit overlap of grout injection between holes.

The orientation of grout holes should be selected to maximize the intersection of karst zones. This may involve steeply angled holes where steeply dipping or vertical features are present or vertical holes, where horizontal or horizontally connected features are present. Grout holes should be oriented across faulted zones or other areas within a project site where additional karst features would be expected.

The materials and methodology of grouting can be selected based on economics and performance. The effects of groundwater, where present, must be considered to prevent dilution and loss of grout effectiveness. A limited mobility grout should be selected where displacement and/or compaction of sediments is required, or where it is desirable to limit filling voids to specific areas without significant lateral spread of the grout. For very large voids, gravity filling with a concrete mix may be appropriate followed by secondary grouting with a finer or more fluid grout mix to seal remaining openings.

The key in successful planning is to anticipate variability. Even though large interconnected voids may not have been encountered, it is essential to have a plan to address them whenever grouting in karst. Identify volume alert levels so that the grouting plan may be changed to limit the loss of large volumes of grout. If grouting with a high mobility grout, be prepared to change to a limited mobility grout or other appropriate method, should an unanticipated large take occur.

Managing the Drilling

The drilling should be used as an investigative tool as well as a means to make grout injections. All holes should be logged and evaluated to verify that conditions are as anticipated and are appropriate for the methods planned. Automated drilling equipment that records down-pressure, torque, and depth can effectively communicate drilling conditions in real time without the delays and labor required for hand

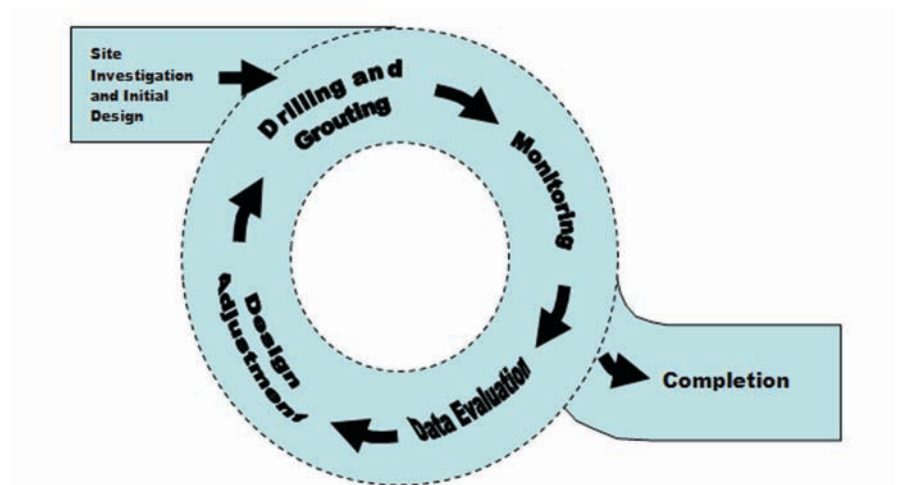


Figure 8. Grouting in Karst Design Cycle.

logging. Have a plan of action to adapt to changing conditions. For example, if it is anticipated to grout small fractures, and large cavities are discovered during drilling the notifications to the engineer and owner, must be immediate so that an evaluation can be made as to whether and how to proceed with handling this new condition.

The drilling should attempt, to the extent practical, to assess whether voids in rock are soil filled and continuous. The continuity of voids is often observable as lost circulation of drilling fluid (air or water) appearing in adjacent holes and should be recorded and reported where it occurs. The conditions in each hole should be evaluated by the project engineer prior to the grouting. A hole should never be terminated in a void without direction from the engineer, since it may be desirable to deepen the hole and it will shave cost to do this while the rig is already present than to have to move it back into place later.

In karst it is not uncommon to encounter rock drops that bind the drill casing or for the casing to become wedged due to drift of the drill string on sloping rock surfaces. In these instances, it may be of value to change the orientation of the boreholes. The boreholes should be oriented to be as close to perpendicular to the feature surfaces as possible. This can reduce the potential for casing drift and make it less likely for sections of rock to fall at an angle to the drill string.

Managing the Grouting

The actual injection of the grout may or may not achieve the desired result. It is essential to closely monitor and interpret the observed behaviors during grouting to assess whether the grouting is likely to meet the project objective. While the cost for engineering observation during the grouting is often considered excessive, the cost for a failure of the grouting or for later re-grouting the site will be considerably higher. The engineer in the field must have a clear understanding of the subsurface conditions, what the grout is expected to do in the ground, and what the overall objective of the grouting is, to be able to make good decisions.

Monitoring of the grout properties is essential to interpreting the grouting records. The viscosity, and thixotropy of the grout will directly determine grout behavior. Low viscosity grouts will penetrate fine openings and travel farther than higher viscosity or limited mobility grouts under the same pressures and rates of injection. The grout material properties, both wet and in the hardened state, must be consistent with the planned injection procedures and controls, and with the final objective of the grouting.

Refusal criteria must be established to permit effective grouting while maintaining adequate control. The danger of causing damage with the grouting increases directly with the volume and pressure of grout injected. So, refusal criteria should include provi-

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sions to prevent high pressures applied to large volume injections. Additional criteria relating to the effectiveness of the grouting should be selected to identify when the resistance to the grouting (as measured by pressure) is consistent with the degree of penetration desired for the grout. Setting target values of grout injection in soil is helpful, where displacement and compaction are possible; but seldom appropriate in rock, unless the conditions of the karst are well understood and known to have a well defined distribution of openings for the grout to enter.

Setting criteria for changing grout type or consistency may also be of value. In some situations, compaction grouting, permeation grouting, and filling of open voids may be required at a single location at various depths within a hole. Anticipating the different mechanisms for grouting and establishing criteria for each is an important way to control grouting overruns and poor performance. Such a criteria must contain a diagnostic component such that the performance of one type of grouting is used to assess the need for another. In such instances, it is common

to start with a relatively fluid grout and step up to increasingly stiff or lower mobility grouts as various criteria are reached for volume and pressure.

All refusal criteria must include a rate of injection. The rate of injection will affect the pressure measured. Higher rates of injections will produce higher grouting pressures and may lead to early refusal due to viscosity effects and line pressures that may not be reflective of the ground conditions.

Closing the Loop

Once the planning is complete, controls are established and the work begins, it is essential to establish a feedback loop (Figure 8) whereby the additional information obtained by drilling and grouting is evaluated and employed to supplement the initial assumptions and conditions. This constant flow of new information will reveal conditions not identified in the original investigation. This is primarily due to the increased frequency of soundings over what can practically be accomplished during the initial investigations. Hole spacings are always closer in the execution of the grouting program than during

the investigation and this additional information can only be neglected to one's own detriment.

Likewise, the grouting records will indicate how effectively grout penetrates features identified during the hole drilling. This can provide useful information about the continuity of openings and infilling that may not have been detected. There may be cause to use a different grouting approach to determine if it can be more effective or to reveal additional information about the formation. For example, if limited mobility grouting is encountering repeated refusal with low volumes in identified voids, it may be worth attempting a more fluid grout to assess whether there is low or higher permeability infilling. It may also be worth considering using a borehole camera to visually assess the conditions prior to grouting.

It is essential to do this in real time. There is no point in injecting 150 points to depths of 10's of meters only to determine at the end of the work, that there was no real benefit and another approach is necessary. Such cases often lead to conflict among owners, engineers and contractors over who is



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responsible for the method and who will pay for the fix. It is far better to find out and handle such problems early. As a wise man once said, "Bad news does not improve with age."

Conclusions

Karst can be very complex and important features are largely invisible from the ground surface. Geologic investigations together with geotechnical engineering evaluations can produce a viable characterization of conditions, but rarely can they provide a complete 100% picture of conditions. The characterization is as important, if not more important, than the findings of the tests, borings and geophysics. Variable conditions are likely in karst and should be anticipated in setting the project criteria.

The grouting program must be based on a clearly defined goal for the grouting program and tactical selection of materials and methods to achieve that goal. The goal should relate to required performance and not just to an arbitrary objective such as filling voids. The tactical solution should focus on meeting the required performance with a composite economic evaluation of materials, drilling, and injection processes to meet the required performance goal.

Adequate controls must be in place to monitor all aspects of the grouting including the grout properties, drilling conditions and results, grouting parameters including rates, pressures, volumes and depth. Automated drilling records and grouting that can be easily communicated in real time enhances the ability to make on-the-fly adjustments to the grouting to achieve optimal performance and to adapt to unanticipated conditions.

All of the data collected from the initial investigation must be considered together with real-time field data from the drilling and grouting operations to form a feedback loop. Continuous evaluation of the actively acquired data must be used to evaluate the effectiveness and performance of the grouting operation and to make appropriate adjustments to improve the effectiveness where appropriate.

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Last but not least a reminder to everybody interested in Grouting, Jet Grouting and Soil Mixing. This is the last issue before the 4th International Conference on Grouting and Deep Mixing, so an important occasion before the next grouting conference that will be held in **10 years time, or 2022! Register now. (PS. I did!)**

With that I close this issue, wishing everybody a Merry Christmas and a phenomenal 2012.

Remember that, if you have additional comments or interesting grouting stories or case histories, you can write to me: Paolo Gazzarrini, fax 604-913 0106 or paolo@paologaz.com, paologaz@shaw.ca or paolo@groutline.com.

Ciao!