Practical Aspects of Water Pressure Testing for Rock Grouting

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ABSTRACT

Rock mass permeability testing has been performed to characterize rock formations since the early 20th century. It was further popularized by Maurice Lugeon (1933) after he defined a standard unit for quantifying the transmissive ability of rock discontinuities. As the dam and grouting industries developed and flourished in the latter half of the 20th century, more attention was devoted to better understanding water pressure testing and its application to rock grouting projects. Today, water pressure testing is a well-established practice and is one of many useful tools for characterizing rock formations. However, it seems the benefits of water testing may not be fully understood from a rock grouting perspective. In several recent grouting designs, the authors have observed that water pressure testing has been incorporated for the sole purpose of measuring the permeability of the untreated formation. Such a limited use of the test and results inhibits important evaluation of project quality and production efficiency. In the last two decades, the grouting industry has seemingly dedicated more effort toward technical interpretation of the water pressure test while not promoting its many practical and technical benefits. In this paper, the authors expound on numerous uses for water pressure testing which add to the overall value of a rock grouting program and advocate for increasing quality and production efficiency. To maintain such progress, geoprofessionals in these industries should maximize the application of available tools and continue promoting innovation in this dynamic field of work.

INTRODUCTION

The bulk of rock fissure grouting is conducted for seepage control, as opposed to some form of mechanical improvement of the rock mass. Therefore, it is natural and correct that the main acceptance criterion for a grouted cutoff should be some type of permeability test (to quantify the residual permeability of the treated rock mass). This is commonly known as a water pressure test. Such tests also have equal value in characterizing the site before construction begins and to monitor and control the intensity of the work during its implementation. Prior to the work of Maurice Lugeon, as described below, the intensity of grouting programs was principally dictated by an analysis of grout (not water takes), or by the available budget. Neither path is acceptable. However, the authors have begun to note a lack of awareness of the true needs for systematic water pressure testing in certain quarters, and seek to reaffirm its essential nature in this paper.

WHAT IS WATER PRESSURE TESTING?

Water pressure testing in rock consists of pressurized injection of water into boreholes drilled into the rock mass and recording the measured water flow rate under the applied pressure(s). The borehole is discretized into intervals, or stages, which are isolated through the use of single or double packers. Water pressure testing is typically performed in an “upstage” manner in a hole that has been drilled to full design depth. In such cases, the bottom stage may be tested using a single packer, and the stages above the bottom stage are tested using a double packer assembly which consists of two packers that are connected by a central perforated pipe.

RELATION TO CEMENT GROUTING

The grouting industry generally consents that water pressure testing data and pressure grouting data are generally not able to be directly correlated. The authors disagree, however, and think that there is much that can be gained from a qualitative comparison of water testing and grouting data. This paper describes multiple uses for water pressure testing results during the course of rock grouting projects, including comparison with rock grouting results. The authors consider it imperative to note that the qualitative comparison between water pressure testing and cementitious rock grouting results relies largely on consistency of grout properties (e.g. density, viscosity, etc.) during the grout injection process. Therefore, cement grouts mentioned in this paper refer to stable grouts, also known as high mobility grouts (HMG), which have a superior resistance to bleed and pressure filtration.

PERMEABILITY AND THE LUGEON VALUE

The measured data and observations recorded during water pressure tests are used to calculate the permeability of the stage. It is important to qualify and clarify the use of the term “permeability”. The terms “permeability” and “hydraulic conductivity” are more accurately applied to soils which typically contain a relatively regular network of pore spaces which allows fluid to be transmitted uniformly through the soil mass. As noted by Quiñones-Rozo (2010), a rock mass transmits seepage through discrete discontinuities. Therefore, it is more accurate to consider that the data collected during water pressure testing reflect the ability of the discontinuities in a rock mass to transmit water. While the authors note this distinction as an important concept to be recognized, the term “permeability” is used herein to refer to the average transmissive ability of rock mass discontinuities.

Maurice Lugeon (1933) developed a method for quantifying the permeability of rock based on a water pressure test performed in a discrete interval of a borehole. The method produced a permeability unit which became known as the Lugeon. The Lugeon (Lu) is defined as 1 liter per minute (L/min) of water flow into a water test stage with a length of 1 meter (m) under an excess pressure of 10 bars. This may be more clearly understood as follows:

$$1\,Lu = \frac{1\,L/min}{m}\ at\ 10\,bar$$

Weaver and Bruce (2007) noted that the method was originally devised by Lugeon for measuring water well inflow and that the applied pressure of 10 bars (about 145 psi) initially selected to mimic heads created by the Alpine dams of the day is excessive for shallower grouting projects. Adjustments for applied pressure (P), fluid flow (Q), and stage length (L_S), which may differ from the unit values in Lugeon’s method, are accounted for in the following equation for the Modified Lugeon (Lu_{Mod}):

$$Lu_{Mod} = 1000\left[\frac{Q\ (L/min)}{L_S\ (m)\ x\ P\ (KPa)}\right] = 1803.2\left[\frac{Q\ (gal/min)}{L_S\ (ft)\ x\ P\ (psi)}\right]$$

It is important to note that the Lu and Lu_{Mod} units only apply when injecting water. When a fluid other than water is injected, Lu_{Mod} must be adjusted to account for the difference in apparent viscosity. In rock grouting practice, the apparent viscosity of stable, non-sanded grouts is commonly represented by the marsh viscosity (v_{marsh}), which is defined as the amount of time, in seconds, for 1 quart of a fluid to flow from a filled marsh cone. The marsh viscosity of water is 26 seconds. A Lu_{Mod} value that is calculated when injecting a stable fluid other than water is referred to as an Apparent Lugeon (Lu_{App}) value and is calculated as:

$$\begin{aligned} Lu_{App} &= Lu_{Mod}\left[\frac{v_{marsh,grout}}{26\,sec}\right] \\ &= 38.5\left[\frac{Q\ (L/min)}{P\ (KPa)}\right]\left[\frac{v_{marsh,fluid}}{L_S\ (m)}\right] = 69.3\left[\frac{Q\ (gal/min)}{P\ (psi)}\right]\left[\frac{v_{marsh,fluid}}{L_S\ (ft)}\right] \end{aligned}$$

The Lu_{App} equation is rearranged as such to emphasize that the calculated value is exclusively based on the flow:pressure ratio when a single fluid is injected into a fixed stage.

Since Lu_{Mod} is intended to represent the in-situ permeability at the depth of the stage, the pressure value used in the Lu_{Mod} calculation should represent the actual pressure applied in the stage. In practice, the term “effective pressure” is used to describe the calculated net pressure applied to the stage and it should be used in the Lugeon equation. Effective pressure (P_{eff}) is a function of the gauge pressure (P_{gauge}) applied by a pump as measured at surface, the net hydrostatic pressure (P_{hydro}) due to weight of fluid in packer pipe above the stage and the pore pressure in the formation around the stage, and pressure loss, or "line loss" (P_{LL}), in the packer pipe due to friction, and is calculated as follows:

$$P_{eff} = P_{gauge} + P_{hydro} - P_{LL}$$

Readers are encouraged to consider that the magnitude of the Lugeon value should not be regarded in the same manner on all projects. As shown above, the Lugeon becomes dependent on the relationship between pressure and flow if the fluid viscosity and stage length are fixed. Using this convention to define maximum effective pressure for a deeper project as for a shallow project, a relatively high flow (e.g. 10 gallons per minute) will produce a considerably lower Lugeon at deeper depths as compared to the Lugeon produced from the same flow at shallower depths. Therefore, testing data should be evaluated with respect to project-specific constraints.

The length of the water pressure test stage can also have a misleading effect on the Lugeon value. The US Bureau of Reclamation (2001) noted that the measured flow during a water test may be transmitted through the rock mass by only a few discontinuities, and that the resulting calculated Lugeon may not accurately represent the permeability of the formation. Designers may want to specify the option to perform tests with reduced stage length in boreholes where drilling and testing data suggest the presence of large discontinuities.

WATER TESTING IN PRACTICE

Professionals in the rock grouting industry have endeavored in recent decades to converge in opinion on historically variable water pressure testing conventions. The USACE (2014) presented a comprehensive assembly of commonly accepted practices, but the authors have noted that such practices may not be widely recognized and that reiteration is warranted. Several notable concepts are discussed below.

Stepped Tests vs Single-Pressure Tests

As explained by Houlsby (1990), the behavior of fractures in a borehole interval can be interpreted from a test where a series of effective pressures are applied to the borehole interval. The Lu_{Mod} from each pressure step in the series can collectively suggest the relative number and size of the fractures, the suitability of the maximum design pressure, and the tendency for infilled particles in the fracture to be dislodged and carried by the pressurized flow. An alternative to the stepped test is the single-pressure test, where one pressure is applied for a brief period of time. Single-pressure tests typically provide time and cost savings, but further interpretation of the test results is limited. Weaver and Bruce (2007) recommended that every stage should be tested, regardless of the type of test. The authors encourage designers to specify a combination of stepped and single-pressure tests for production holes based on project constraints, and that stepped pressure tests be specified as a minimum for Primary and Verification holes.

Consistency Between Water Testing and Grouting

The ability to identify trends between water test results and grout take relies greatly on consistency between equipment and methods used to perform water testing and grouting. The same types and sizes of equipment must be used to allow work crews to concentrate more on performing the work and less on using the correct equipment for each respective activity. The stage length and applied effective pressure range are two elements of methodology that have a greater effect on the numerical results and the response of the formation. Though effective pressure applied during water testing and grouting will vary with time during each respective activity, the data collected during water testing provides grouters with insight about how the formation responds to the range of specified pressures. Additionally, trends between water testing formation response and grout performance, which are often identified after the completion of many holes, allow grouters to make timely decisions about switching grout mixes. Using different pressures for water testing as compared to grouting hinders the ability to identify such trends and thus reduces the efficiency of the grouting program. The identification of trends and differences between water and grout performance cannot be accomplished unless the response of a discrete group of fractures to water testing and grouting can be evaluated. The USACE (2014) recommended that stage intervals selected for water testing be identical in length and position in a borehole to subsequent grout stages, and the authors concur with the recommendation.

Water Testing in Weak Rock or Near Soil/Rock Interface

Weak, weathered rock and materials encountered near the soil/rock interface can be unconsolidated and sensitive to low amounts of stress. Additionally, the susceptibility to deformation of these types of materials tends to increase when a pressure gradient is applied. If efficient reduction of permeability is the goal of a rock grouting project, then water testing in the vicinity of such materials should be approached with extreme caution. This can be a predicament in some cases where the upper portion of rock has a higher permeability and poses a significant challenge for seepage control. The USACE (2014) advocated for more conservative testing in weak zones, such as shorter stage lengths, reduced pressures, or elimination of water testing altogether (specifically near the soil/rock interface). If the design team determines that water testing of the upper portion of rock is not to be performed, the grouting permeability of and closure through the upper rock zone may still be evaluated based on $\mathrm{Lu}_{\mathrm{App}}$ and grout take.

Communication

Real time monitoring has become the standard for larger grouting projects over the last two decades. However, communication between experienced grouters observing the real time monitoring and experienced field personnel at the hole remains vital. A sophisticated program cannot replace experienced personnel or the ability to communicate observations at the subject hole. Clear communication, whether about a leaking packer, faulty pressure gage, water flowing from surface or adjacent holes, or any other issue, provides clarity to the task at hand and promotes overall project quality and efficiency.

Advancements in Technology – Downhole Pressure Transducers

On certain recent projects, downhole pressure transducers have been required to measure the pressure in the stage. Downhole pressure is collected in real time and displayed by the computer monitoring system. Based on recent results, the cost of outfitting a packer with a downhole pressure transducer is easily outweighed by the benefit of being able to "see" what is happening in the stage being tested or grouted. Since the variables used to calculate effective pressure are based on the testing system (i.e. filled hoses, valves, gages, etc.), the downhole transducer allows grouters to recognize flaws in the system upstream of the stage via comparison of the calculated effective pressure against the measured downhole pressure. The downhole pressure record additionally allows for communication of a more coherent explanation to designers or review panels not present at the time of testing. The authors recommend use of downhole pressure transducers and the measured downhole pressure to calculate Lugeon values on larger projects.

APPLICATIONS OF WATER PRESSURE TESTING DATA

The effectiveness of grouting designs and the efficiency of the grouting process are improved through pragmatic use of water testing data and participation of experienced grouting professionals. Accordingly, the authors recommend that designers and project owners employ the expertise of experienced grouters during each phase of a grouting project. The following paragraphs present applications of water pressure testing results that can add value to rock grouting projects.

Site Exploration

Drilling, water pressure testing, televiewing, and grouting processes implemented during the course of a grouting project provide a means to characterize the rock formation. Subsurface explorations are typically performed during the design phase of rock grouting projects, but the scale of the exploration scope is often limited by economics. As a result, exploratory borings are often widely spaced and designers are forced to make conservative design assumptions. Ewert (1985) recommended designers consider that local differences in permeability can affect a large area. Ewert further explained that the macro-scale permeability of a rock mass can differ greatly from the conductivity measured in a borehole. As a rock grouting project progresses, designers and contractors are afforded the opportunity to confirm design assumptions, to further characterize the rock formation, and to recognize various subsurface conditions. Enhanced understanding of subsurface conditions is facilitated, in part, by an increased number of borings, a decrease in distance between the borings, and water pressure testing procedures that promote recognition and interpretation of the various manners in which rock discontinuities respond to pressurized seepage flow.

Evaluation of the Work

The process of rock grouting consists of a continuous process of modification and evaluation. Typically, an initial grout hole series (i.e. primary) is drilled, water tested, and grouted prior to installing subsequent hole series (i.e. secondary, tertiary, etc.). Water testing is performed in the initial hole series to measure unmodified permeability, in part, as a baseline for comparison to future water test data. As each hole series is completed, the water testing data is evaluated to confirm design assumptions and evaluate the effectiveness of the materials, equipment, and methods which are used to perform the grouting work. In this way, water testing allows grouters to control the quality and value of the work during the course of the project.

Planning During Grouting Construction

The performance of water testing as part of a rock grouting program can provide grouters the opportunity to identify conditions that will affect the progress and nature of the work. Such conditions can indicate potentially large grout takes, connections between grout holes, challenges sealing stages due to leaks around the packer, and surficial leaks (when rock is near surface). Grouters must appropriately plan an approach to these types of situations and coordinate efforts accordingly to maintain the quality of the work, the progression of the project schedule, and the safety of construction staff. Through use of water testing data, grouters can plan to have sufficient materials for completing stages with a large Lu_{Mod} and to begin grouting such stages early in the day. Appropriate planning for large grout takes also promotes safety by reducing the chances of working past normal working hours. Sections of a grout row where multiple holes have produced low Lu_{Mod} can be grouted quickly to more efficiently progress the program sequence. Lastly, water test results can aid in avoidance of partially-grouted holes. When grouting in a hole is paused at the end of a scheduled work interval, such as a daily shift, the hole can become partially contaminated before grouting resumes at a later date. Such contamination could inhibit grout take. Common causes include emptying of the grout line as it is removed from the hole and grout rebound into the hole as injection pressures dissipate in the formation. The authors recommend that water testing data be used to avoid any situation where a portion of a grout hole could become compromised.

Amenability

The suitability of a stable particulate grout to move into fractures that are accessible to water is termed amenability. The Lu_{Mod} and Lu_{App} values calculated during water testing and grouting, respectively, are related to the aperture size of fractures in the subject stage. Amenability can be quantified by comparing Lu_{App} from grouting to Lu_{Mod} from antecedent water testing. Naudts (1995) presented the amenability coefficient (A_c) as a measure to evaluate the efficiency of the fractures to accept grout.

$$A_c = \frac{Lu_{App}}{Lu_{Mod}}$$

Note that a reasonably accurate A_c can only be obtained if the Lu_{App} and Lu_{Mod} are produced from the same borehole interval (i.e., same stage length and location in borehole). Additionally, the Lu_{App} value used for calculating A_c must be selected early during the grouting of a stage when the fractures are as unmodified as possible.

The maximum particle size and the viscosity of a particulate grout affect the ability of the grout to penetrate an aperture. Evaluation of amenability allows grouters to identify the need to modify viscosity or change one or more components in the grout. For example, a coarse cement may be selected during design and evaluation of amenability may lead to use of a finer cement or, in certain cases, a non-particulate grout. Amenability should be constantly evaluated throughout a grouting program, particularly in double or triple row grout curtains, because finer fractures tend to play a larger role as the project progresses. Naudts (1995) recommended a minimum A_c value of about 0.75. The authors note that amenability should only be evaluated for stages that intersect apertures that are large enough to accept typical cement grouts but are small enough to present a challenge to grout injection. Weaver and Bruce (2007) noted that stages producing Lu_{Mod} values of less than 10 are typically less likely to accept cement grouts and stages which produce Lu_{Mod} values of 100 or greater will almost certainly accept cement grouts readily. While these Lu_{Mod} values may vary from project to project, readers should be aware that apertures of a more intermediate size are more likely to create an amenability issue.

A Case Study in Amenability – Rio Verde Dam

Rio Verde Dam is a small concrete gravity structure used to store drinking water in south central Kentucky, United States. A two-row grout curtain was installed in the dam’s right abutment in late 2013 in response to reported vortices upstream of the dam’s right abutment and seepage flows exiting the right stream bank downstream of the dam. A suite of Type III cement stable grouts were used to construct the curtain, and the thinnest grout mix had a marsh viscosity of 40 seconds. Initial Primary (PP) holes were installed 20 feet apart, Primary (P) holes were installed between PP holes, and Secondary (S) holes were installed between PP and P holes. Each hole generation was drilled, water tested, and grouted before adjacent hole generations were installed, and the downstream row was grouted to closure prior to the grouting of the upstream row. PP, P, and S holes were required on the downstream row, and PP and P holes were required on the upstream row. Additional holes were installed based on the results of water testing and grouting. A few indications of poor amenability issues were observed during the grouting of the downstream row. However, no changes to the mixes were made because observed Lu_{Mod} values and grout takes appeared to be more influenced by very small or very large apertures and because a general decreasing trend in Lu_{Mod} was observed. As the grouting of the upstream row commenced, water testing and grouting data suggested that some intermediately-sized apertures remained open and that the thinnest grout mix may not be able to penetrate such apertures. Figure 1 shows a comparison between calculated Lu_{Mod} and Lu_{App} values for stages where water take was observed.

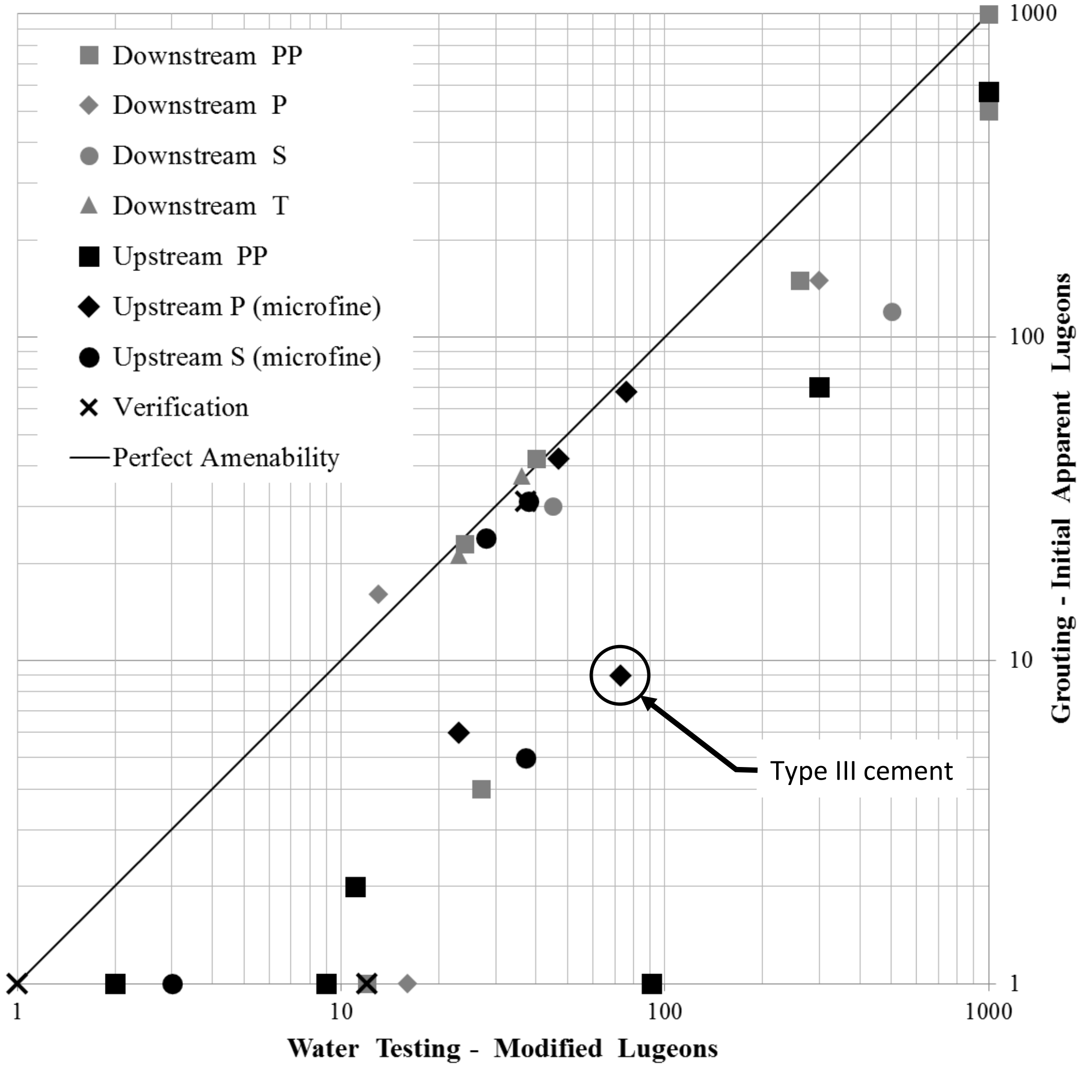

Figure 1. Comparison of Water Test and Grouting Lugeon Values at Rio Verde Dam.

The amenability of two upstream PP stages with Lu_{Mod} values over 100 was not concerning due to large respective grout takes when using the Type III cement grouts. However, an impeding amenability issue became apparent when one upstream PP stage and the first upstream P stage produced Lu_{Mod} of 91 and 73, respectively, and subsequently produced respective Lu_{App} of 1 and 9 when using the Type III cement grouts. The project team discussed the observed discrepancies between water testing and grouting and decided that the use of a microfine grout was warranted to improve the quality of the work. With agreement from the project owner, a microfine grout was developed with a marsh viscosity of 32 seconds and was used to grout the remaining upstream holes. The upstream P and S stages shown near the perfect amenability line in Figure 1 were grouted immediately following the change to microfine grout. The data collected in the remaining upstream P and S stages and verification holes indicated that the residual Lu_{Mod} could be reduced to no less than 20-30 Lu using the microfine grout. Exposed excavations around the site revealed localized pockets of silty sand which exhibited the relict structure of the non-soluble limestone formation upon which the dam was founded. The team concluded that similar silty sand pockets, which only non-particulate fluids may be able to penetrate, may exist in the right abutment. Despite higher localized residual Lu_{Mod} values, the previously observed seepage on the downstream right bank was no longer visible, no further vortices have since been reported, and the project owner has been satisfied with the results.

REDUCING ERRORS IN WATER TESTING DATA

Water testing procedures, equipment, and input variables affect the quality of water testing results. Errors in testing data can be reduced by experience observing real time data collection and by having an operational knowledge of the equipment being used and the engineering principles behind the test. Several scenarios that may contribute to error are discussed below.

Trapped air in the grouting/testing hoses can produce errors in instruments such as flow meters and pressure transducers. Air exists in the system initially and can enter the system when the packer is not submerged or if a leak occurs in the equipment. Water can be pumped through the system to purge air before testing. At a minimum, the theoretical volume of the hoses should be pumped. During testing, the measured downhole pressure can indicate if the packer line is full.

Water can flow around the packer and up the borehole if the packer is inflated in a fractured zone. This can be identified by water flow from the hole or a rising water level. The packer can be moved up or down in the borehole until a good seal is achieved.

Packers are pressurized through inflation lines that are connected to the bladders. Leaks at the connection or in the line can result in partial inflation. This scenario can be identified by rising water level or multiple consecutive large water takes (if bottom packer in double packer assembly is partially inflated). However, a clear indication is an observed decrease in packer pressure when shutting off the pressure source.

As stated previously, effective pressure is a function of the pore pressure in the formation, which is represented by the water level in the borehole. The amount of time between borehole drilling (using water) and water testing may not allow for the water level to settle to static level. This is a common source of error in water testing and grouting, and is often not avoidable without disrupting schedule. A reasonable representation of water level between holes can be developed from a series of overnight water levels collected from multiple holes along a grout line. However, ground water in the vicinity of a grout curtain should rise in elevation as the program progresses, and as such water levels will need to be collected through the course of the program.

The application of very low pressures requires that pumping equipment operate in the lowest range of design capacity. Additionally, instruments that measure pressure and flow may not function as well near the lower boundary of their calibrated range. Thus, data collected at very low pressures may be obscured by the mechanical limitations of testing equipment.

Higher Lu_{Mod} values calculated from relatively high flows may be misinterpreted if the formation is able to accept more water than can be supplied by the pump. In this case the resulting Lu_{Mod} value may represent pump capacity instead of formation permeability.

CLOSING REMARKS

Water testing is routinely performed as part of rock grouting programs, but may be underutilized. The quality and efficiency of a grouting program can benefit from appropriately specified and performed water testing, especially when performed consistently with grouting. As the grouting industry evolves, grouting professionals should take advantage of advancements in technology and methods while reinforcing the value of experienced personnel. Water testing is an important component to a rock grouting program and should be given careful consideration for the purpose of obtaining the most information and value from the test.

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