QUALITY AND QUANTIFICATION IN ROCK DRILLING AND GROUTING

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ABSTRACT

This paper reviews "best of current practice" concepts under four broad categories. The concept of a Quantitatively Engineered Grout Curtain (QECG) is held to be the most responsive level for design purposes and its basic components are described. In rock drilling the principles of Measurement While Drilling (MWD) are reviewed to illustrate how maximum geotechnical benefit can be achieved from every production drill hole. An introduction is provided of contemporary standards for field testing of grouts. Fourthly, the advantages of using Advanced Integrated Analytical (AIA) systems to collect data, monitor progress, keep records and reports, and generate technical analyses are described.

1. INTRODUCTION

Notable advances have been made within the last few years in drilling and grouting processes used for rock mass treatment. These have markedly improved both the design and performance of grouting works. Many factors can be cited as contributors to this remarkable rate of progress, including the technical challenges posed by the projects themselves (typically remedial in nature and frequently conducted in quite adverse conditions), developments in equipment, deeper understanding of grout mix design and performance issues, and far more rigorous approaches to QA/QC and verification.

This paper reviews what the authors consider to be "best of current practice" under the following major topics:

- design philosophy,
- drilling operations,
- field testing of grouts, and
- automated grouting monitoring and analysis.

2. DESIGN PHILOSOPHY

2.1 Historical Perspective

Prior to the 1980's, grout curtains were not assigned specific engineering properties that could be used in design and in subsequent construction so as to achieve specific performance results. At the lowest end of design sophistication,

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the curtain configuration was selected only on the basis of empirical rules of thumb related to applied hydraulic head and type of dam. Frequently, the curtain configuration had little relevance to the actual geologic conditions, and consequently they were often neither technically- nor cost-effective. At the highest end of design sophistication, the curtains were designed on the basis of sound experience coupled with a good understanding of the geologic conditions.

Shortcomings of curtains designed prior to the 1980'sincluded the following :

1. Subsurface investigations were performed to explore the stratigraphy and structure, but boring depths were often set at predetermined depths rather than tailored to define the relevant geologic conditions. Curtain configurations were often symmetrical across the site even though this geometry frequently bears little resemblance to the geologic conditions relevant to grouting. This resulted in curtains being deeper than necessary in some areas and of insufficient depth in others, thereby being neither technically- nor cost-effective.

2. Water pressure testing may have been incorporated in the program, but the results were rarely incorporated into design in a meaningful or rational manner.

3. Geologic investigations sometimes delineated fracture orientations, but little attention was ordinarily paid to fracture spacing, fracture size, or fracture characteristics. Holes were not always oriented so as to intercept primary fractures, and the interval over which critical fracture systems was intersected was often inadequate.

4. Specific design parameters and project performance requirements were not generally established (e.g., specific residual seepage rates and pressure distributions). Therefore, the grouting goals were often unclear and the programs subject to curtailment solely on the basis of economics when construction budgets were exceeded.

5. Grout curtain performance, at the time of design, was assumed not to be materially affected by the quality of work, the contracting procedures, or the quality of inspection procedures.

Houlsby (1982, 1990), Weaver (1991) and others through the 1980's and into the 1990's published a wealth of information that promoted a much more rational approach to grouting based on careful site investigation and site characterization, matching high quality field techniques to the site conditions, and performing at least semi-analytical approaches to grouting design and analysis of field results. Wilson and Dreese (1998) first coined the term Quantitatively Engineered Grout Curtain (QEGC) to describe a methodology whose goal is to take the design approach to an advanced level, in which all elements of the design are performed based on quantitative analyses and considerations.

2.2 Quantitatively Engineered Grout Curtain (QEGC)

It is first essential to properly characterize the site, with particular regard to those properties which will impact the grouting, including lithological, geostructural and hydrogeological properties. Only then can the project performance requirements be logically and realistically set, regarding acceptable residual seepage rates, flow paths and/or pressure distributions. The many factors impacting these decisions were listed by Wilson and Dreese (1997). Such decisions are best made by the Designer in concert with the Owner and any Board of Consultants which may have been convened.

In the QEGC design approach, the grout curtain is not treated as a vague "impervious barrier." Rather, it is treated as an engineered structure with a specific geometry and specific hydraulic conductivity that interacts with the natural geologic materials.

The issue of assigning design parameters to a grout curtain is highly complex because the parameters are controlled by design, construction, and inspection factors. The achievable results are dependent on many elements of the grouting process including the grouting materials, grout mixes, construction equipment, field technique, number of lines utilized, hole spacing, hole orientation, experience and diligence of the contractor, experience and diligence of the inspection staff, the field monitoring and analysis techniques utilized in evaluating the completed work, contractual incentives and disincentives, climatic conditions, and other factors. While extensive information and discussion of the importance of each of these parameters is readily available, the factors have not, in general, been combined into specific design recommendations.

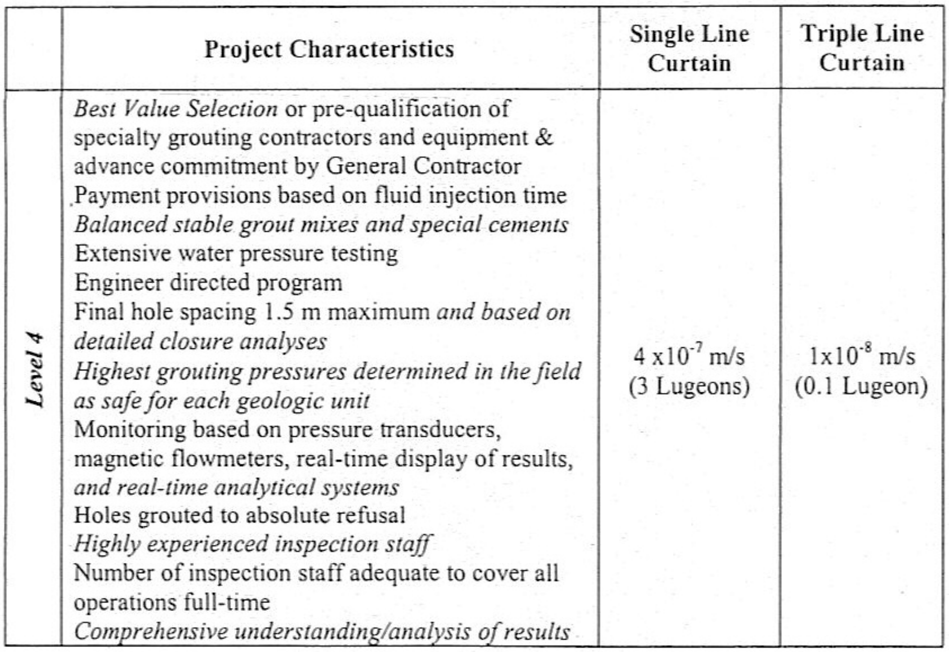
With these factors in mind, Wilson and Dreese (2003) identified four successive levels of reasonable design performance expectations for both single- and triple-line curtains, assuming that in all cases the virgin permeability was supportive of grouting being a viable option. The expected results achievable when best practice is utilized in all elements of design, construction and verification are summarized in Table 1.

3. DRILLING

3.1 Historical Perspective

The quality of the drilling process is fundamental to the successful and timely execution of a grouting project. Effective drilling systems must be capable of permitting continuous, adequately straight penetration in materials which may vary from very soft to extremely hard and from homogeneous to heterogeneous.

Table 1. Expected Performance Results for Best Grouting Practice: Level 4 (Wilson and Dreese, 2003).



	Project Characteristics	**Single Line Curtain**	**Triple Line Curtain**
Level 4	*Best Value Selection* or pre-qualification of specialty grouting contractors and equipment & advance commitment by General Contractor Payment provisions based on fluid injection time *Balanced stable grout mixes and special cements* Extensive water pressure testing Engineer directed program Final hole spacing 1.5 m maximum *and based on detailed closure analyses* *Highest grouting pressures determined in the field as safe for each geologic unit* Monitoring based on pressure transducers, magnetic flowmeters, real-time display of results, *and real-time analytical systems* Holes grouted to absolute refusal *Highly experienced inspection staff* Number of inspection staff adequate to cover all operations full-time *Comprehensive understanding/analysis of results*	4 x10^{-7} m/s (3 Lugeons)	1x10^{-8} m/s (0.1 Lugeon)

They must be capable of providing a constant diameter, stable (or temporarily stabilized) path full depth, from which the drilling debris has been wholly removed. In conjunction with rock mass fissure grouting, the drilling must leave every fissure which is intercepted in as clean a condition as possible to facilitate entry and travel of the grout. The choice of drill system must ideally be dictated by the ground conditions, hole depth and diameter, cost notwithstanding, although historical bias and regional experience are often powerful factors.

Other project specific considerations may include hole deviation potential, drill access constraints and the generation of vibrations. Methods must also satisfy project environmental restraints including noise, and flush control and disposal. Above all, the drilling process must not cause harm or distress to any structure being penetrated, or any adjacent structure.

Traditionally little attention has been paid to the geotechnical aspects of grout hole drilling, other than the tedious, long-running argument about the relative merits of percussion versus rotary drilling. More significant, of course, is the argument which favors water as opposed to air as the drill flush of choice in fissured rock.

There are many textbooks including those by Acker (1974), Australia (1997) and Rao Karanam and Misra (1998), principally dealing with rock drilling. These works, though extremely valuable as detailed references, focus on the mechanical or geomechanical aspects, mainly as related to blasthole, water well drilling or site investigation. On the other hand, contemporary textbooks on grouting tend to provide little guidance beyond providing descriptions and illustrations of rock drilling equipment (and drill bits).

3.2 Quantification of the Drilling Process: Measurement While Drilling (MWD)

Bruce (2003) provided practical guidance on drilling systems, equipment, circulation characteristics, deviation, and specifications — all details relating to the goals of providing straight, cost effective, stable boreholes in the correct positions. He also discussed Measurement While Drilling (MWD) concepts, an issue which is simple in philosophy, relatively straightforward to implement, and potentially invaluable to the grouting program designer.

The fundamental concept of MWD is that every hole that is drilled in the ground is a source of geotechnical information on the actual or probable response of the rock mass to treatment. This concept applies, of course, to site investigation holes, but equally to every production drill hole. The information can be collected by two basic methods: manual and automatic. To be most useful, the data must be studied and responded to in real time. Data provided by MWD can be correlated with information from nearby conventional exploratory holes to enhance its "stratum recognition" ability. The most informative insights when studying MWD records relate to the "exceptions and unexpecteds" (Weaver, 1991).

For manual monitoring of drilling parameters, the information value of otherwise routine driller's logs will be considerably enhanced by careful and periodic monitoring of:

- penetration rate
- thrust
- torque
- flush return characteristics (cuttings, volume)
- drill "action"
- interconnections between holes, or to the surface
- hole stability
- groundwater observations

Such data can be easily recorded by a good driller or an experienced inspector who has been previously briefed about the overall purpose of the exercise. Readings should be taken as frequently as possible, and in any case at no more than 5 feet intervals in each hole. Regarding automated monitoring, industry has benefited for over 20 years from several successive generations of "black boxes" fitted to drill rigs. These record in real time the parameters necessary to quantify the "drillability" of the ground, as quantified by e, the specific energy:

$$e = \frac{F}{A} + \frac{2\pi N T}{AR}$$

where

e = specific energy (kJ/m^3)

F = thrust (kN)

A = cross sectional area of hole (m^2)

N = rotational speed (revolutions/second)

T = torque (kN-m)

R = penetration rate (m/sec)

Such records, coupled with information from other in situ investigations, e.g., borehole TV and permeability testing, provide a very high diagnostic ability to the grouting specialist during the work and allow him to make rational decisions regarding the possible need for modifications to assure that the design intent of the curtain is met.

4. FIELD TESTING OF GROUTS

4.1 Historical Perspective

As is widely known, rock grouting practice in North America traditionally used only two grout mix components (water and cement) except where particularly open conditions and/or flowing water necessitated the use of mineral (and other) fillers, and/or chemical admixtures. This pattern persisted until the late 1990's, some ten years or more after European practice had evolved towards the routine incorporation of bentonite and other admixtures to provide stable multicomponent formulations of far superior fluid and set properties (Deere, 1982; DePaoli et al., 1992). The simple mixes were field tested using standard API test apparatus originally developed for the petrochemical industry, with heavy emphasis placed on the accuracy of batching, not necessarily on the properties of the mixed grout.

4.2 Routine Field Quantification of Mix Properties

Contemporary grout mixes may often comprise six or more components (Chuaqui and Bruce, 2003). They are specially formulated on a site specific basis to provide favorable properties such as low bleed, superior resistance to pressure filtration, and controllable rheology. The development of mixes on any particular project is best done in a three-phase process.

During the first phase, a series of formulations, each suited for injection under the specific site conditions, is developed through a laboratory-testing program. In the second phase, on site and prior to production, the mix designs are replicated to investigate any changes in properties due to differences in materials, mixing equipment or procedures between the laboratory testing and production grouting. During this phase the baseline data for the quality control program are also established. In the third phase (production grouting) the properties of the grouts are verified regularly to ensure that grouts are consistent, and of acceptable characteristics.

It is common to find that contractors will provide on site a well-equipped QA/QC facility, run by a QC technician or manager, on all but the smallest projects. They are therefore able to quantify and verify the standard fluid grout properties, as shown in <u>Table 2</u>, as well as to conduct unconfined compressive strength testing of hardened samples. Specific project challenges can also be addressed. For example, Gause and Bruce (1997) describe a simple device for quantifying the washout potential of grouts placed in flowing water conditions.

Table 2. Standard Field Quality Control Tests for High Mobility Grouts (HMG's) (Chuaqui and Bruce, 2003).

EQUIPMENT	TEST	DESCRIPTION
Marsh Funnel	Apparent Viscosity	The Marsh time of the grout can be measured in accordance with the method described in API Recommended Practice 13B-1 with a Marsh funnel and a calibrated container. The test is performed by filling the Marsh cone to the bottom of the dump screen and then measuring the time for 0.26 gallons (1 liter) of grout to flow through the funnel.
Penetrometer/ or Shear Vane	Cohesion and Time to Initial/Final Gelation	Either a penetrometer or shear vane type test will be used to measure the amount of time required for the grout to reach initial gelation (cohesion of 100 Pa) and final gelation (cohesion of 1000 Pa).
API Filter Press	Pressure Filtration Coefficient	The pressure coefficient can be measured with an API filter press. The test is performed by pouring a 0.42-quarts (400-ml) grout sample into the top of the filter press. The sample is then pressurized to 0.7 MPA. The test is run until all the water is expelled from the sample. The value of the pressure filtration coefficient is then calculated with the following equation: $K_{pf} = \frac{\text{volume of filtrate} \times 1}{\text{volume of sample} \times (\text{time in minutes})^{(1/2)}}$
250-ml Graduated Cylinder – Glass	Bleed	The bleed capacity of the grout can be measured in accordance with the method ASTM C940 with a 0.26-quart (250-ml) graduate cylinder. The test is performed by pouring grout into the cylinder to the 0.21-quart (200-ml) level. The sample is then left undisturbed for two hours before the amount of bleed water is measured.
Baroid Mud Balance	Specific Gravity	The specific gravity of a grout can be measured in accordance to the method described in API Recommended Practice 13B-1 with a Baroid Mud Balance. The Baroid mud balance is a calibrated scale that is used to measure the specific gravity. Micromotion flow/density meters and hydrometers are also used in practice.
Vicat Needle	Initial and Final Set Times	The initial and final set times can be determined with the Vicat needle testing apparatus. The vicat needle is set at the surface of the grout sample and released. Initial set is reached when the needle only penetrates 1-inch (25-mm). Final set is reached when the needle does not penetrate the surface of the grout sample.

5. AUTOMATED GROUTING MONITORING AND ANALYSIS

5.1 Historical Perspective

Recognition of the potential benefits of "automated" monitoring or data recording systems for grouting started in the 1960's (Weaver, 1991). 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 early 1980's (Jeffries, 1982) (Mueller, 1982). The U.S. Bureau of Reclamation (USBR) was the first federal agency in the United States to experiment with the use of computers for monitoring of grouting. The first system was utilized at Ridgeway Dam in 1982, but had numerous problems. However, this experiment resulted in the USBR developing a comprehensive hardware and software system that would provide, generate, and record all the information that was needed for monitoring, control, and analysis of grouting (Demming et al., 1985). The USBR implemented its use at Stillwater Dam in 1985 although significant problems were experienced with consistently maintaining data signals to the recording equipment on this project. During the same time period, the U.S. Army Corps of Engineers began using portable site recorders to obtain real-time grouting data, but severe field reliability problems were also experienced (Houlsby, 1990).

Later years saw 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. It has been proven that the use of computer monitoring systems clearly allows rock fissure grouting to be more technically effective, performed at a lower cost, and in less time (e.g., Wilson and Dreese, 1998).

5.2 Advanced Integrated Analytical Systems (AIA)

Dreese et al. (2003) determined that there were fundamentally three levels of rock grouting technologies then in use. These can be summarized as follows:

Level 1: “Dipstick and gage” – general practice prior to 1997.

Level 2: “Real time data collection, display and storage” – electronic collection, display and limited analysis. Recommended as the minimum level acceptable for any project over $250,000 and/or of critical significance.

Level 3: “Advanced Integrated Analytical (AIA) System” – this represents a major advance on Level 2 by providing integration of data collection, real-time data display, database functions, real-time analytical and query capabilities, and CAD. The first operational system was introduced in the United States in 2001 and was recommended for use on projects over $750,000 in value or on any project with severe consequences of poor performance.

The system currently advocated by the authors is a totally integrated system for data collection, monitoring, record keeping, reporting and, most importantly, real-time on site and off site analyses. It not only contains all the features of Level 2 technology, but also includes real-time graphical display of geologic features and stratigraphy, hole geometry, water test data, and grouting data, which is provided through customized programming developed within AutoCAD. AutoCAD, like the real-time monitoring software, reads data from, and writes data to, a relational database. The database allows for the generation of standard and custom reports and also allows queries to the database to search for relevant information. In addition, the AutoCAD programming is also directly linked to this real-time database, which permits real-time graphical display of grouting results on a sectional profile. Utilizing the relational database, the system is able to perform practically unlimited, complex real-time grouting program analyses and can display the grouting results on a simple to understand and interpret, visual color display on a profile. Patterns, anomalies, compliance or non-compliance, and areas of special interest are immediately evident. The system is equipped with multiple monitoring stations, each with three monitoring screens to allow the operator to observe or perform multiple operations.

The concept of AIA is a major development in computer monitoring and analysis of grouting. It also further reduces on site inspection staff time and optimizes the results by decision makers via the data display options and the remote access capabilities.

6. FINAL REMARKS

It is not uncommon for all drillers to be associated with the "likeable rogue" stereotype that some of their brethren do, in fact, exemplify. Equally, grouters are routinely dubbed as practitioners of "black arts" where smoke and mirrors prevail and "trust me" is the basis for performance verification. To break this mould, the authors have attempted in this paper to identify, in four critical processes of rock treatment technology, the best current standards of quality and quantification. North American projects observing these standards will be at least on a par with those conducted anywhere else in the world.

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