

Rock Grouting: Contemporary Concepts in Materials, Methods, and Verification

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ABSTRACT: The paper provides a broad overview of contemporary aspects of rock grouting practice. Generic classifications for the various materials and drilling and grouting methodologies are provided, and observations on qa/qc and verification procedures are given. Details are provided of recent seepage prevention works at two major U.S. dams to further illustrate the general principles.

1 INTRODUCTION

The use of drilling and grouting methods to locate and seal all manner of fissures and voids in rock masses has been common throughout the world for over a century. While the goals of such programs have largely remained unchanged, the materials and methods have undergone remarkable change in response to technological advances and increasingly onerous site specific demands. These changes, however, have not been constant in their rate of evolution in any given part of the world. For example, little advance seems to have been made during the 50 year period of intense activity on U.S. Federal dams from the 1920's onwards. One may cite extremely restrictive, prescriptive specifications as the main reason for the languid rate of innovation.

During the last few years, however, the art of rock grouting has entered a new phase of progress, rapidly drawing it towards the status of an engineering science. This paper reviews contemporary methods, highlighting those areas where the most significant advances have occurred, and indeed are still occurring. These developments are then illustrated with reference to two recent U.S. projects - one an existing dam seepage remediation, the other a new dam curtain.

2 MATERIALS

2.1 General Classification

There are four categories of materials (Bruce et al., 1997) which can be listed in order of increasing rheological performance and cost:

1. Particulate (suspension or cementitious) grouts, having a Binghamian performance.
2. Colloidal solutions, which are evolutive Newtonian fluids in which viscosity increases with time.
3. Pure solutions, being non evolutive Newtonian solutions in which viscosity is essentially constant until setting, within an adjustable period.
4. "Miscellaneous" materials.

Category 1 comprises mixtures of water and one or several particulate solids such as cement, flyash, clay, or sand. Such mixes, depending on their composition, may prove to be stable (i.e., having minimal bleeding) or unstable, when left at rest. Stable, thixotropic grouts have both cohesion and plastic viscosity increasing with time at a rate that may be considerably accelerated under pressure. Category 1 grouts are most common in rock grouting and are undergoing rapid development as a result of a markedly increased understanding of basic rheological and hydration principles.

Category 2 and 3 grouts are now commonly referred to as solution or chemical grouts and are typically subdivided on the basis of their component chemistries, for example, silicate based (Category 2), or resins (Category 3). They are rarely used in rock grouting, having application largely in "fast flow" sealing operations.

Category 4 comprises a wide range of relatively exotic grout materials, which have been used relatively infrequently, and only in certain industries and markets. Nevertheless, their importance and significance is growing due to the high performance standards which can be achieved when they are correctly used. The current renaissance in the use of hot bitumen grouts is a good example, in cases of extreme seepage conditions.

2.2 Developments in Particulate Grouts

Due to their basic properties and relative economy, particulate grouts remain the most commonly used for both routine waterproofing and ground strengthening. The water to solids ratio is the prime determinant of their basic characteristics such as stability, fluidity, rheology, strength, and durability. Five broad subcategories can be identified:

1. Neat cement grouts
2. Clay/bentonite-cement grouts
3. Grouts with fillers (Including low mobility or "compaction" grouts)
4. Grouts for special applications (Such as for antiwashout conditions)
5. Grouts for special applications
6. Grouts with enhanced penetrability.

It should be borne in mind that many particulate grouts alone are unsuited for sealing high flow, high head conditions: they will be diluted or washed away prior to setting in the desired location. However, the recent developments in rheology, stability, and hydration control technologies, and the major advances made in antiwashout additives have offered new opportunities to exploit the many economic, logistical, and long term performance benefits of cementitious compounds (Gause and Bruce, 1997). Water cement ratios are now typically in the range of 2 or 3 as a maximum, many times lower than the "traditional" mixes of the 1930's. These developments have drawn largely from experience with the wide range of additives developed primarily for the concrete industry. It is now common for a routine fissure grouting operation to feature a suite of grout mixes containing several components (in addition to cement and water), to satisfy site specific fluid and set property requirements, (Table 1), while the use of finer grind materials (e.g. DePaoli et

al., 1992) has further enhanced penetrability efficiency. At the other end of the aperture spectrum, economic bulk infill mixes (e.g. for karsts, old mineral workings) are being refined using large volumes of relatively inexpensive materials such as flyash, and naturally occurring soils from gravels to clays. Admixture technology is again valuable in such mixes, providing stability, rheology and anti washout properties.

2.3 Developments in Other Grout Families

Given that the sodium silicate based grouts are never used in rock grouting, and that cost and environmental concerns rule out the regular use of most solution grouts in rock grouting (with the exception of certain acrylates), major developments have revolved around two groups of materials:

- Polyurethane
 - Water-reactive polyurethane: Liquid resin, often in solution with a solvent or in a elasticizing agent, possibly with added accelerator, reacts with groundwater to provide either a flexible (elastomeric) or rigid foam. Viscosities range from 50 to 100 cP. There are two subdivisions:
 - 1) Hydrophobic - react with water but repel it after the final (cured) product has been formed
 - 2) Hydrophilic - react with water but continue to physically absorb it after the chemical reaction has been completed.
 - Two component polyurethanes: Two compounds in liquid form react to provide either a rigid foam or an elastic gel due to multiple supplementing with a polyisocyanate and a polyol. Such resins have viscosities from 100 to 1,000 cP and strengths as high as 2 MPA. A thorough description of these grouts was provided by Naudts (1996).
- Hot Melts
 - For certain cases seepage cut off applications, hot melts can be a particularly attractive option. Bitumens are composed of hydrocarbons of very high molecular weights, usually obtained from the residues of petroleum distillation. Bitumen may be viscous to hard at room temperature, and have relatively low viscosity (15 to 100 cP) when hot (say 200 degrees C plus). They are used in particularly challenging water-stopping applications (Bruce et al., 1998), remain stable with time, and have good chemical resistance.

Table 1. Contemporary typical cement grout additives (Wilson and Dreese, 1998).

ADDITIVE	BENEFICIAL EFFECTS	ADVERSE EFFECTS	OTHER COMMENTS
Flyash Type C or Type F	Improves grain size distribution of cured grout, Cheap filler with pozzolanic properties. Can be used as a replacement for some of the cement and reacts with the free lime resulting from the cement hydration process. Increases durability and resistance to pressure filtration.	Increases viscosity and cohesion.	Concentrations of Type C flyash in excess of 20% by weight of cement should be avoided.
Bentonite	Reduces bleed and increases resistance to pressure filtration. Slight lubrication and penetrability benefits.	Increases viscosity and cohesion. Weakens grout.	Should be added as pre-hydrated suspension
Silica Fume	Fine grained powder which improves pressure filtration resistance and reduces bleed. Improves water repellency and enhances penetrability. Improves grain size distribution of cured grout.	Increases viscosity and cohesion.	Difficult to handle due to fineness.
Viscosity Modifiers (Welan Gum)	Makes the grout suspension more water repellent, provides resistance to pressure filtration, and reduces bleed.	Increases viscosity and cohesion.	At higher doses, provides some thixotropy to the grout which is helpful for artesian conditions.

Contemporary optimization principles require simultaneous penetration by stable particulate grouts to ensure good long-term performance. Although the concept is decades old, it is only in the last three years that the process has been completely “reinvented” to provide a tool of extraordinary value.

3 METHODS

Drilling

There are three generic methods of rock drilling which have been used routinely in rock drilling (the rotasonic method has not yet met wide application for grouting):

- High Rotation Speed/Low Torque Rotary: relatively light drill rigs can be used to extract core samples, when using a core barrel system, or can also be used simply to drill holes, using “blind” or “plug” diamond impregnated bits. Typically used for holes up to 100mm diameter.
- Low Rotational Speed/High Torque Rotary: used with heavier and more powerful rigs to drill holes of greater diameter to considerable depths. The penetration rate also depends on the thrust applied to the bit. Uses a variety of drag, roller, or finger bits depending on the rock, and relates closely to water well or oil field drilling technology.

- Rotary Percussive: the drill bit (cross- or button-) is both percussed and rotated. In general the percussive energy is the determinant of penetration rate. There are two different options:
 - Top drive: where the drill rods are rotated and percussed by the drill head on the rig.
 - Down-the-hole hammer: where the (larger diameter) drill rods are only rotated by the drill head, and compressed air is fed down the rods to activate the percussive hammer mounted directly above the bit.

In principle, the prime controls over choice of drilling method should ideally be related to the geology, the hole depth, and diameter, bearing in mind always the question of lineal cost. Hole linearity and drill access restraints may also have significant impact.

Overall in the United States, rock drilling is largely and traditionally conducted by rotary methods although the insistence on diamond drilling is no longer so prevalent. Top drive rotary percussion is growing in acceptance in certain quarters - with the increasing availability of higher powered diesel hydraulic drill rigs - as long as water or foam flush

is used. Holes up to 100 mm in diameter to depths of 50 m can be drilled economically. Somewhat perversely, certain specialists are beginning to allow air flushed rotary-percussive drilling for routine grout holes. Even when the air is "misted" with some inducted water, most specialists agree that this medium has a detrimental effect on the ability of the fissures to subsequently accept grout (Houlsby, 1990; Weaver, 1991). Such methods are still, of course, wholly applicable for drilling grout holes to locate and fill large voids such as karstic features. It is common to have drilling rigs instrumented to provide real time accurate data on those drilling parameters which in some way reflect directly the geology and ground water conditions.

3.2 Grouting

Rock grouting practice largely follows traditional lines (Ewert, 1985), although it would appear that more recent publications by specialists such as Houlsby (1990) and Weaver (1991) have had a refreshing and stimulating impact. There are three basic methods used for grouting stable rock masses:

- Downstage (Descending stage) with top hole packer;
- Downstage with down hole packer; and
- Upstage (Ascending stage).

Circuit grouting is now only very infrequently used.

The competent rock available on most dam sites is well suited for upstage grouting and this has historically been the most common method. Downstage methods have recently had more demand in the U.S. reflecting the challenges and difficulties posed more difficult site and geological conditions in the remedial and hazardous waste markets.

In some cases of extremely weathered and/or collapsing ground conditions, even descending stage methods can prove impractical, and the MPSP (Multiple Packer Sleeve Pipe) Method is now the method of choice. (Bruce and Gallavresi, 1988). This has particular application in remedial rock grouting operations.

The MPSP system is similar to the sleeved tube (tube à manchette) principle in common use for grouting soils and the softest rocks. The sleeve grout in the conventional system is replaced by concentric polypropylene fabric collars, slipped around sleeve ports at specific points along the tube (Figure 1). After placing the tube in the hole, the collars are inflated with cement grout, via a double packer and so the grout pipe is centered in the hole, and divides the hole into stages. Each stage can then be grouted with whatever material

is judged appropriate, through the intermediate sleeved ports. Considerable use has been made of MPSP in loose, incompetent, or voided rock masses, especially karstic limestones in recent projects involving the authors in the Philippines, Canada, and the U.S. Such systems permit the use of a wide range of grouting materials, including the hot melts.

Regarding equipment, contemporary practice features the use of highly automated grout preparation and pumping stations. Mixers are high speed, high shear, high output and are capable of batching wide ranges of multicomponent particulate grouts with accuracy and consistency. Electricity is the power source of choice. Pumps must be capable of infinite stepping of injection rate and volume within their operating parameters and are usually electrically and/or hydraulically powered. Higher pressure operations (say above 2 MPa), require piston pumps, while progressive cavity pumps remain common for low pressure work. Other families of grouts require their own batching and delivery systems, usually provided by, or in conjunction with, the materials suppliers.

4 QA/QC & VERIFICATION

4.1 General

The fundamental approach to a correctly engineered grout curtain remains

- Investigate site and determine causes/paths of leakage;
- Execute grouting program; and
- Verify performance.

The traditional tools for investigation and verification such as coring, permeability testing, ground water characterization, dye testing, piezometric levels, and outflow monitoring have been supplemented by a range of geophysical tests in certain applications, and by sophisticated data collection, analysis and presentation instrumentation.

However, it is in the qa/qc programs now exercised during the execution of grouting works that the most significant progress is being made. As reported by Wilson and Dreese (1998), the potential of electronic measurement devices mated with computers was recognized almost as soon as

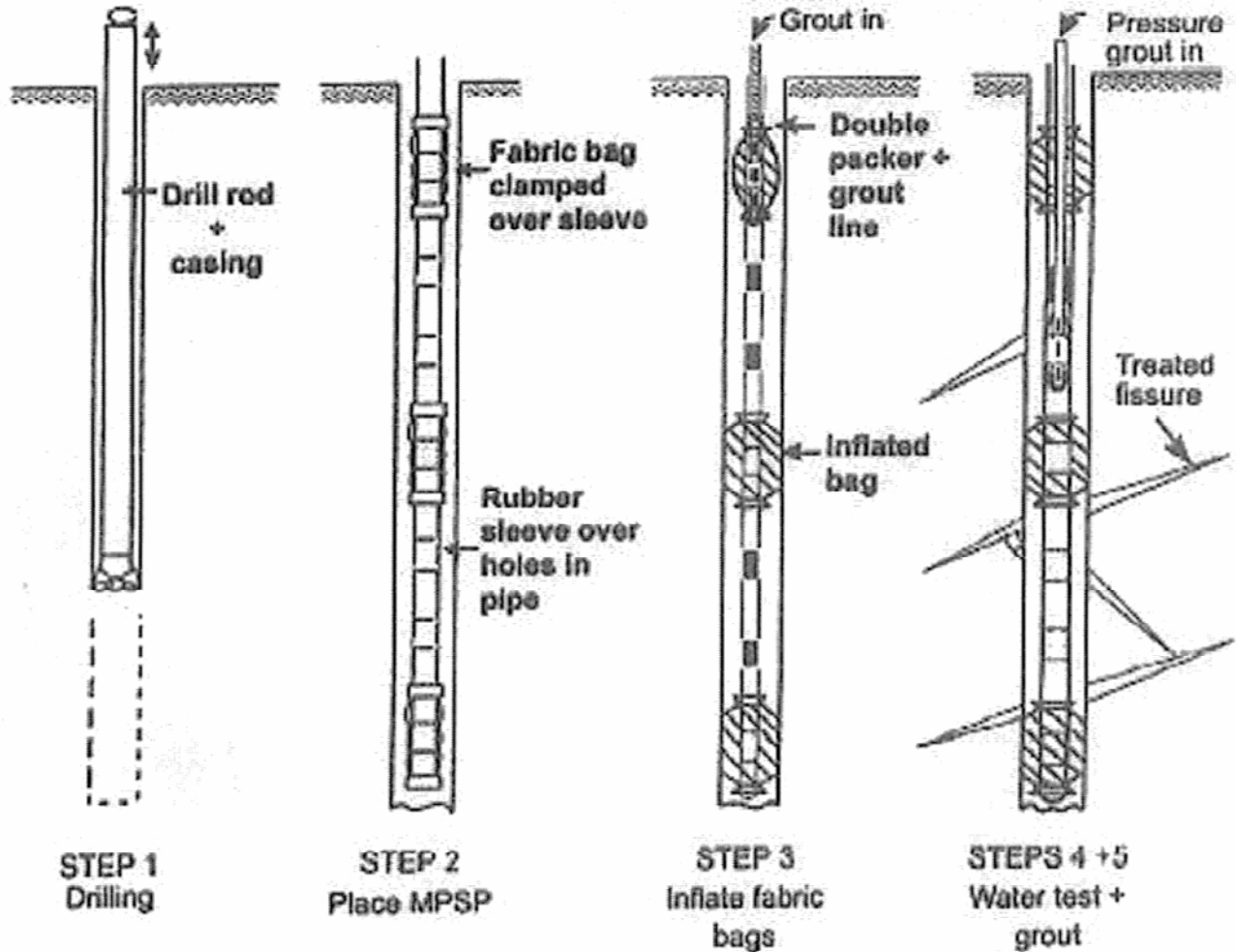


Figure 1. Multiple packer sleeve pipe system.

widespread use of computers came into being in the early 1980s. The first trials were conducted at Ridgeway Dam by the U.S. Bureau of Reclamation (USBR). The problems with the first system were numerous, but it led to the USBR embarking on development of 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). That system was written in Basic programming language by a USBR software subcontractor, who retained the proprietary rights to the software, and the USBR implemented its use at Stillwater Dam in 1985. Since that time, there have been dramatic improvements in both the number and type of electronic measurement devices, computers and data management software.

At the simplest level, readings from flow meters and pressure transducers are transmitted to an X-Y recorder and manual calculations are then conducted. However, potentially significant head losses and gains from the system and the environment are ignored. The manual manipulation can be erroneous and is usually cumbersome when head difference allowances must be made. The next level allows for computer display of

readings and spreadsheet calculations. Although head losses and gains are more easily accounted for, data entry from display to spreadsheet is still required.

The highest level is represented by CAGES - Computer Aided Grouting and Engineering System. The displayed data are automatically adjusted for all necessary correction factors to reflect actual parameters within the stage being grouted. The displayed data include real time plots of the pressure and flow values, and a time plot showing Apparent Lugeon value. This is a calculated Lugeon value adjusted for the viscosity of the grout and which allows evaluation of the geologic formation response during grouting. The software also generates final hole records comprised of actual and adjusted measurements and scaled time plots of all parameters throughout the entire grouting operation. A final level of sophistication, which is not in general use, includes remotely activated control valves to allow adjustment of flows and pressures during grouting. Computer assisted grouting combined with the application of the Apparent Lugeon Theory and Amenability Theory (Naudts, 1995) provides the knowledgeable grouting practitioner with real time data acquisition and a

sound, scientific basis for decision making. As a consequence, every stage in every hole can be correctly brought to a natural refusal by informed manipulation of grout pressure, injection rate, rheology and grain size.

5 CASE HISTORIES

5.1 Tims Ford Dam, TN (Bruce et al., 1998a)

Background. Tims Ford Dam is an embankment structure on the Elk River approximately 14 km west of Winchester, TN. This water regulating Tennessee Valley Authority (TVA) structure is about 460m long with the crest at Elevation 227.4m. The right (west) abutment of the dam intersects orthogonally a natural ridge running nearly north-south, and consisting of clay and weathered chert overburden overlying a karstic foundation of various limestones. The crest of this right rim abutment varies in elevation from 287m to about 292m with the top of rock generally around Elevation 274m. The maximum pool elevation is at Elevation 270.7m.

The Problem. Seepage through the right rim was recorded from first impoundment in 1971, prompting some local grouting. However, a major seepage at Elevation 260m, about 290m upstream of the dam center line persisted. It grew steadily each year until 1994 to about 15,000 l/min, but increased dramatically in 1995 to over 29,000 l/min following a record reservoir drawdown. TVA determined that a remedial grouting program be effected to reduce this flow to less than 4,000 l/min at maximum pool by sealing major karstic features thought to be present at that location.

An exploratory drilling and water testing program defined the geographic extent and depth of the remediation.

The Solution. A multirow grout curtain was designed, approximately 240m long. The holes were inclined at 30 degrees to the vertical to encourage intersection of (sub) vertical features and were oriented in opposite directions in the two outside rows. Primary holes in each row were foreseen at 12-m centers, with conventional split spacing methods to be employed (to 3-m centers or closer). The central, tightening, row was vertical. The grouting was to be executed between Elevations 270.7 and 256m - locally deeper if dictated by the stage permeability tests conducted prior to the grouting of each stage.

Because of the suspected high flow conditions, the downstream curtain row holes that encountered voids and active flow conditions were designated to be grouted with fast-setting (1 to 3 minute set time)

hydrophillic polyurethane resin to provide an initial semi-permanent flow barrier. Holes that did not encounter voids or active flow were to be grouted with cementitious grouts. Upon completion of the downstream row, it was anticipated that the active flow conditions would be mitigated, thus allowing the entire upstream row followed by the third, central, closure row to be grouted with cementitious grouts to form a permanent and durable grout curtain. The grouting was designed to be performed using upstage methods, although it was anticipated that poor foundation conditions could locally require utilization of downstage methods. The grout holes were to be cased through the overburden from the surface to the top of the curtain.

The Specifications contained provisions that required monitoring and limitations to outflow pH and turbidity to protect the downstream environment. TVA agreed to draw down the reservoir to Elevations 260.6m (3m below minimum normal pool) to minimize hydraulic gradient and flow through the rim. The curtain was to be constructed by first grouting the far ends, so conceptually channeling the flow through a middle zone which would then be treated.

Highlights of Construction

- When drawdown of the reservoir reached Elevation 261.8m, the outflow from the leak completely and naturally stopped. As a consequence, much of the grouting work could be done in "no flow" conditions, therefore, largely eliminating the need for the polyurethane grouts, and extending the applicability of cement based formulations.
- Larger than anticipated open or clay-filled features were encountered by the down-the-hole drilling methods, especially in the upper 6m or so of the curtain. For technical, commercial, environmental and scheduling reasons, such features were treated with a low mobility "compaction grout" (slump 50 to 150mm; containing also water reducing and antiwashout agents).

Table 2. Compositions and properties of cement grout mixes, Tims Ford Dam, TN.

Ingredient	Unit	Mix A	Mix B	Mix C	Mix D
Water	lb	141	141	94	94
Bentonite	lb	4.7	9.4	4.7	4.7
Cement	lb	94	94	94	94
Rheobuild 2000 (water reducing agent)	oz	15	30	20	30
Rheomac UW450 (antiwashout agent)	oz	0	0	0	5
Volume of batch	Gal	20.8	21.0	15.1	15.1
Specific gravity		1.39	1.4	1.53	1.53
Bleed	%	<5	<1	<1	0
Kpf	min ^{-1/2}	<0.104	<0.042	<0.042	<0.042
28-Day Compress.	psi	500	500	800	800
Marsh time	sec	35	50	60+	100+
Stiffening time	hh:mm	4:30	4:30	4:00	4:00
Hardening time	hh:mm	10:30	8:30	8:00	8:00
Water and slurry volumes					
Bentonite slurry volume	gal	8.0	16.1	8.0	8.0
Additional water volume	gal	9.9	2.8	4.2	4.2

- A suite of cement-based grouts (Table 2) was 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 response to conditions revealed during the treatment, observations of the seepage and further dye testing, extra groups of holes were added the north end of the curtain, including 11 orthogonal to the original curtain, to allow specific treatment of key features.
- About 1,550m³ of compaction grout, 1,530 liters of polyurethane, and 605m³ cement based grouts were injected into a total of 250 holes (comprising 3,400 lin.m of rock drilling).

Effect of Treatment. Throughout the work, closest attention was paid in real time to data from the drilling, water testing, and grouting activities in addition to information from leak monitoring, piezometers and dye testing. The curtain was thus brought to an engineered refusal. During refilling of the reservoir, the leak had been totally eliminated with the level at Elevation 265m, when, for financial reasons, the work was terminated. The most recent reading, with the lake

at Elevation 269m, indicates a seepage of around 950 l/min (net of surface runoff contributions) - about 5% of the flow at the equivalent lake elevation prior to grouting. Data from piezometers and dye testing support the existence of an efficient and durable curtain.

5.2 Penn Forest Dam, PA (Wilson and Dreese, 1998)

Background. The new Penn Forest Dam is being constructed to replace the old Penn Forest Dam, which was a severely ailing earthen embankment dam. The new dam is being constructed with roller compacted concrete just upstream from the old dam, and is approximately 54m high and 600m long. It includes a three-line grout curtain, designed to have a maximum residual permeability of 3 Lugeons on a 4.5m width. The lines were 1.5m apart to a depth of 42m.

Construction Concepts. An accelerated construction schedule resulted in the grouting being split into two separate consecutive contracts, the first for one line (A); the second for the other two lines (B and C). Due to the short design period duration and other factors, the A-Line grouting contract was issued specifying conventional methods (for example, neat

cement grouts, agitator tank dipstick measurements, and pressure gages). However, sufficient time was available to design the second contract using "advanced"

Mix Design. Whereas Line A used neat cement mixes of w/c from 3 to 0.7, Lines B and C used a suite of multicomponent mixes comprising Type III cement, flyash, bentonite, welan gum and dispersant, as determined during extensive preconstruction field testing. Particular attention was paid to minimizing the pressure filtration coefficient (below $40 \times 10^{-3} \text{ min}^{-1/2}$) to promote efficient penetration and long term durability.

Injection Monitoring and Control. Lines B and C were injected using the CAGES software, which according to Wilson and Dreese, provided many advantages over the traditional manual methods:

- Real time data are obtained at much smaller time intervals (5 to 15 sec. frequency vs. 5 to 15 min. frequency).
- Eliminates potential for missing critical events such as pressure spikes.
- Data obtained are more accurate.
- Higher grouting pressures can be used with confidence.
- Formation response to procedure changes (mix or pressure) is shown instantly.
- Damage to formation due to over-pressuring can be easily detected and mitigated.
- Significant acceleration of pressure testing and grouting operations.
- More consistent grouting procedures due to central control location.
- Reduction in inspection manpower requirements.
- Provides detailed, permanent graphic records showing the entire time history for each operation on each stage.

The authors also found that the advanced system required less grout to reach the target permeability, largely as a result of the enhanced penetrability of these stable grouts. Financially, the construction cost savings were about 10%, the inspection cost savings 25%; and the construction schedule savings 25%, relative to those incurred during the previous, traditional grouting phase.

6 FINAL REMARKS

These two case histories illustrate how recent advances in rock grouting technology can provide treatment of the highest quality in a controlled, engineered fashion. The use of multicomponent, balanced particulate grouts, allied with computer aided

methods, such as balanced, stable cement based grouts and computer assisted grouting.

control and evaluation systems, has also proven to be highly cost effective when compared to traditional approaches. The engineer therefore has increased confidence in his ability to achieve stringent performance goals for the many applications of rock grouting.

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