High Flow Reduction in Major Structures: Materials, Principles, and Case Histories

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Abstract

The paper firstly presents a structured classification of the four different categories of grouting materials: particulate, colloidal, solutions, and miscellaneous. Three case histories are then summarized to illustrate the application of these materials to produce optimum results in projects where the goal is to reduce or eliminate high seepage flows, usually at high hydrostatic pressures. The case histories are drawn from recent works conducted by the authors at Dworshak Dam, ID, Tims Ford Dam, TN, and at a potash mine in New Brunswick, Canada. Conclusions are drawn on the eight elements common to the achievement of a satisfactory result in such programs.

Introduction

One of the most difficult challenges facing the grouting industry is the reduction or elimination of high volume water inflows into or through major civil engineering structures such as dams, tunnels, and quarries. Often these flows are occurring at high velocities, under high heads, and in locations which render treatment logistically and practically very awkward. Of particular concern are those situations such as karstic limestone formations, where there are often networks of orifices, as well as zones with potentially erodible or soluble material that must also be treated to prevent future reoccurrence of the problem.

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Over the years, many existing major structures have been treated by remedial grouting operations, but with varying degrees of success. One of the major reasons contributing to this erratic performance has been the inappropriate selection of the grouting materials. The first part of this paper provides a generic classification of the major families of grout that can be used in such applications.

The second part of the paper provides summary accounts of three major recent case histories, which illustrate a systematic approach that can be adopted towards analyzing the issues and problems, executing the work, and optimizing and verifying the results.

Generic Classification of Grouting Materials

There is a plethora of grouting materials available which, given the broad range of their chemical compositions, and trade names, can be bewildering even to specialists in the field. In addition, it should also be noted that different placement methods and techniques will be required for different materials: the "conventional" staging processes used in the construction of cementitious grout seepage barriers may not be suitable, for example, to the special intricacies of injecting hot melts (e.g., bitumen) and their associated materials. More details on the materials introduced below can be in found in Naudts (1996) and Bruce et al. (1997). A companion paper by Bruce (1992) describes the drilling and grouting construction principles used in dam rehabilitation, although these can be extended to cover other applications.

Basis of Classification

There are four categories of materials, 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 nonevolutive 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, pozzolans, clays, sand or viscosity modifiers. 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 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). The outstanding rheological properties of certain Category 3 grouts, together with their low viscosities, permit permeation of soils as fine as silty sands ($k = 10^{-4}$ cm/s).

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.

Category 1: Particulate Grouts

Due to their basic characteristics, and relative economy, these grouts remain the most commonly used for both routine waterproofing and ground strengthening. The water to solids ratio is the prime determinant of their properties and 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.
4. Grouts for special applications.
5. Grouts with enhanced penetrability.

It should be borne in mind that many particulate grouts 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 and hydration control technologies, and the 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). Low mobility grouts ("compaction grouts") can be classified in the third subgroup, and can be very beneficial in flow reduction under appropriate conditions as noted below.

Category 2: Colloidal Solutions

These comprise mixtures of sodium silicate and reagent solutions, which change in viscosity over time to produce a gel. Sodium silicate is an alkaline, colloidal aqueous solution. It is characterized by the molecular ratio R_p, and its specific density, expressed in degrees Baumé (Bé). Typically R_p is in the range 3 to 4, while specific density varies from 30 to 42 Bé. Reagents may be organic or inorganic (mineral). The former cause a saponification hydraulic reaction that frees acids, and can produce

either soft or hard gels depending on silicate and reagent concentrations. Common types include monoesters, diesters, triesters, and aldehydes, while organic acids (e.g., citric) and esters are now much less common. Inorganic reagents contain cations capable of neutralizing silicate alkalinity. In order to obtain a satisfactory hardening time, the silicate must be strongly diluted, and so these gels are typically weak and therefore of use only for waterproofing. Typical inorganic reagents are sodium bicarbonate and sodium aluminate.

The relative proportions of silicate and reagent will determine by their own chemistry and concentration the desired short- and long-term properties such as gel setting time, viscosity, strength, syneresis, and durability, as well as cost and environmental acceptability.

In general, sodium silicate grouts are unsuitable for providing permanent barriers against high flow/high head conditions, because of their relatively long setting time (20 to 60 minutes), low strength (less than 1 MPa) and poor durability. This is a different case from using sodium silicate solution (without reagent) to accelerate the stiffening of cementitious grouts - a traditional defense against fast flows.

Category 3: Pure Solutions

Resins are solutions of organic products in water, or a nonaqueous solvent, capable of causing the formation of a gel or foam with specific mechanical properties under normal temperature conditions and in a closed environment. They exist in different forms characterized by their mode of reaction or hardening:

- Polymerization: activated by the addition of a catalyzing element (e.g., poly-acrylamide resins, water reactive polyurethanes).
- Polymerization and Polycondensation: arising from the combination of two components reacting in stoechiometric proportions (e.g., epoxies, aminoplasts, two component polyurethanes, vinyl esters).

Mostly, setting time is controlled by varying the proportions of reagents or components. Resins are used when Category 1 or 2 grouts prove inadequate, for example when the following grout properties are needed:

- particularly low viscosity.
- very fast gain of strength (a few hours).
- variable setting time (few seconds to several hours).
- superior chemical resistance.
- special rheological properties (pseudoplastic).

- resistance to high groundwater flows.

Resins are used for both strengthening and waterproofing in cases where durability is essential, and the above characteristics must be provided. Four categories can be recognized: acrylic, phenolic, aminoplastic, and polyurethane (Table 1). Chrome lignosulfonates are not discussed, being, according to Naudts (1996), "a reminder of the dark, pioneering days of solution grouting" on account of the environmental damage caused by the highly toxic and dermatitic components.

Type of Resin	Nature of Ground	Use/Application
Acrylic	Granular, very fine soils	Waterproofing by mass treatment
	Finely fissured rock	Gas tightening (mines, storage) Strengthening up to 1.5 MPa Strengthening of a granular medium subjected to vibrations
Phenol	Granular, very fine soils	Strengthening
Aminoplast	Schists and coals	Strengthening (by adherence to materials of organic origin)
Polyurethane	Large voids	Formation of a foam that forms a barrier against running water (using water-reactive resins) Stabilization or localized filling (using two-component resins)

Table 1. Uses and applications of Resins (AFTES, 1991).

Of these four subclasses, only the two groups of polyurethanes are usually appropriate for remedial grouting given cost, performance and environmental implications:

- Water-reactive polyurethanes: Liquid resin, often "reactively diluted" or in a plasticizing agent, typically with added accelerator, reacts with groundwater to provide either a flexible (elastomeric) or rigid foam. Viscosities range from 50 to 1,000 cP (at 25°C). There are two subdivisions:

1) Hydrophobic - react with water but repel it after the final (cured) product has been formed.
2) Hydrophillic - react with water but continue to physically absorb it after the chemical reaction has been completed.

- Two component polyurethanes: Two compounds (polyol and isocyanate) in liquid form react to provide either a rigid foam or an elastic gel. 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).

Category 4: Miscellaneous Grouts

The following grouts are essentially composed of organic compounds or resins. In addition to waterproofing and strengthening, they also provide very specific qualities such as resistance to erosion or corrosion, and flexibility. Their use may be limited by specific concerns such as toxicity, injection and handling difficulties, and cost. Categories include hot melts, latex, polyesters, epoxies, furanic resins, silicones, and silacsols. Some of these (e.g., polyesters and epoxies) have little or no application for ground treatment. Others such as latex and furanic resins are even more obscure and are not described.

For certain cases in seepage cut off, hot melts can be a particularly viable 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 over 200°C). They are used in particularly challenging water-stopping applications (Bruce, 1990a and b; Naudts, 1996), remain stable with time, and have good chemical resistance. Contemporary optimization principles (Section 3.3) requires simultaneous penetration by stable particulate grouts to ensure good long-term performance.

Also of considerable potential is the use of silacsols. Silacsols are solution grouts formed by reaction between an activated silica liquor and a calcium-based inorganic reagent. Unlike the sodium silicates discussed above - aqueous solutions of colloidal silica particles dispersed in soda - the silica liquor is a true solution of activated silica. The reaction products are calcium hydrosilicates with a crystalline structure similar to that obtained by the hydration and setting of Portland cement, i.e., a complex of permanently stable crystals. This reaction is not therefore an evolutive gelation involving the formation of macromolecular aggregates, but is a direct reaction on the molecular scale, free of syneresis potential. This concept has been

employed in Europe since the mid-1980s (Bruce, 1988) with consistent success in fine-medium sands. The grout is stable, permanent, and environmentally compatible. Other important features, relative to silica gels of similar rheological properties, are:

- their far lower permeability;
- their far superior creep behavior of treated sands for grouts of similar strength (2 MPa);
- even if an unusually large pore space is encountered, or a large hydrofracture fissure is created, a permanent durable filling is assured.

Finally, the concept of "preciptation grouts," as addressed by Naudts (1996), may have major, if infrequent, application. Solutions are injected into the groundwater which trigger a chemical reaction with metal ions in the groundwater, producing a precipitation of durable crystals or complex metal agglomerations, which block flow paths.

Illustrative Case Histories

During the last few years, the authors have consulted on a large number of major projects involving the stopping of high velocity, high head flows under and into major structures. These are not problems that are unique to dams (quarries, mines, tunnels, and deep basements are equally susceptible), and they are problems that are encountered worldwide, as witnessed by recent projects in the Philippines, Argentina and Malaysia. Often such projects become highly political and sensitive such are the technical, commercial, public safety, and environmental and scheduling consequences they generate, and for this reason, clients are frequently loath to allow details of the work to be publicized. Though understandable, this approach does not help advance the state of knowledge in the industry since it denies access to extremely valuable case histories, frequently executed using innovative techniques and methods. Given also the space restrictions, this paper provides summary data from only three recent projects:

- Dworshak Dam, ID;
- Tims Ford Dam, TN; and
- Potash Mine, New Brunswick, Canada.

More detailed information on Dworshak Dam is provided by Smoak and Gularte (1998), and on Tims Ford Dam by Bruce et al., (1998).

Background

Dworshak Dam had been constructed for the Corps of Engineers on the North Fork of the Clearwater River, approximately 55 km east of Lewiston, ID by 1972. The dam has a structural height of 219m, is the highest straight axis concrete gravity dam in the Western Hemisphere, and the third highest dam in the U.S. The dam crest is 1002m long at elevation 492m. The dam provides flood control, power generation, fish migration, and recreation.

The bedrock under the left abutment is composed of competent granite gneiss with foliations dipping 15 to 30 generally to the west. Features that were nearly vertical and striking northeast to southwest are also present. Inspection of the foundation from the dam adits revealed very competent rock that is slightly to very slightly fractured and jointed with widely scattered shearing. The fractures/joints are commonly infilled with clay and mica.

Foundation permeability as determined by pressure testing in boreholes, was moderate to very low, progressively decreasing with depth from 1×10^{-3} cm/s (10-m depth) to 5×10^{-7} cm/s (75-m depth). During dam construction, a single line grout curtain was created from a basal grouting gallery using contemporary methods, and a drainage curtain was constructed downstream of this curtain from the same gallery.

The Problem

Seepage flows at full reservoir elevation from the left abutment drains were relatively constant until mid 1984 with flows from the drains in Monoliths 14 through 17 totaling about 2,300 l/min. After 1984, a significant increase in rate of flow began. Seepage by 1987 had increased to 4,500 l/min, and measurements taken in mid 1996 revealed a total flow of 9,500 to 11,500 l/min from the drains in Monoliths 14 through 17. More than half that total was coming from the drains located within Monoliths 16 and 17. The flow from the drains seemed to be clear but observation of the various collection flumes showed that fracture infill material was being eroded. Although foundation uplift pressures remained well below the original design assumptions, there was concern that if flows increased beyond drain capacity an increase in uplift pressures could occur. Such flows exceeded the capacity of the left abutment drainage gallery, overtopping stairs, landings and gallery walkways causing personnel safety concerns. In addition, vertical joint drains located between Monoliths 14/15, 15/16, 16/17 and 17/18 showed significant leakage into the gallery directly through their waterstops. This was possibly due to waterstop failure or improper installation, or inefficiencies in concrete placement.

Numerous investigations and evaluations of the problem water flows were performed during the period 1984 through early 1995. The overall conclusions from the investigations were that:

1. The flow was coming through fractures intercepted by the left abutment foundation drains in Monoliths 15 through 19. These fractures were interconnected and drain hole cross communication was common.
2. Some individual drains had flow as high as 750 l/min and pressures as high as 0.7 MPa. Most drain hole flows, however, were significantly less than 400 l/min and the pressures were below 0.3 MPa.
3. Vertical rock fractures may not have been intercepted and grouted during construction of the original grout curtain.
4. Some clay infill material from the foundation fractures was being piped into the grouting gallery.

The Solution

A remedial program was initiated between May and December 1997, with three main actions:

1. Installation of additional dam instrumentation to continuously monitor uplift pressure and leakage flows and the setup of an instrumentation database to manage the instrumentation data generated during and after remedial grouting.
2. Remedial foundation drilling and grouting in Monoliths 15 through 19 from the gallery with the pool reduced from elevation 488 to 457m.
3. Repair leaking upstream monolith joint waterstops by grouting, including reestablishing any grout sealed downstream monolith drains.

An innovative procurement system was used by the Corps of Engineers focusing heavily on the technical proposal of the contractor, Partnering, and full technical cooperation between all parties. The specifications contained the following requirements of the contractor:

1. Furnish and install additional and replacement uplift pressure instrumentation, crack/joint displacement meters, seepage flow monitoring instrumentation and open tube piezometers complete with a database monitoring system capable of presenting the instrumentation data in spreadsheet form.

2. Remedial Foundation Grouting

   a. Perform remedial grouting using 45 m^3 of water reactive, fast setting solution grout, injected in the existing foundation drains, to construct a temporary downstream curtain.

   b. Drill, and inject with cementitious grouts, a multi-row permanent upstream grout curtain including 6,000 lin. m of grout hole drilling.

   c. Drill 2,500 lin. m of relief drain holes to establish a new row of downstream foundation pressure relief drains to replace those grouted during formation of the temporary grout curtain.

3. Controlling Monolith Joint Leakage

   a. Install packers in leaking monolith joint drains to reduce and/or control leakage to less than 38 l/min. (This work was specified because testing had verified that there was connection between the leaking relief drains and the foundation bedrock joints and fractures.)

   b. After completion of curtain grouting, repair upstream leaking monolith joint waterstops by grouting the upstream vertical drain holes.

   c. After grouting the upstream vertical monolith drains, reestablish the downstream monolith joint drains by cleaning, or by drilling replacement downstream joint drains.

Highlights of Construction

- The work was constructed under extremely difficult working conditions in the steeply dipping 1.8 x 2.4m gallery, inundated with cold seepage water.
- An extensive environmental protection program was successfully instituted.
- An extensive Contractor Quality Control Plan was successfully implemented.
- Data from instrumentation recording uplift pressure, hydraulic head, and gallery flow were monitored by laptop computer in the gallery, continuously during the work, and also after its completion.
- Sealing of the monolith joint drains (through which 50% of the flow was occurring) was effected by using the Multiple Packer Sleeve Pipe (MPSP) system (Bruce and Gallavresi, 1988), and polyurethane and modified cementitious grouts.
- The 63 existing NX drain holes (as deep as 67m) were first sealed using the MPSP system polyurethane and accelerated cementitious grouts. Remnant flows were minimal.

- The 2-row remedial grout curtain (upstream of the original) was then installed to a depth of 40m using conventional stage grouting and modified cementitious grouts.
- The replacement drainage curtain was then installed in the line of the original holes to a depth of 30m.

Effect of Treatment

Total gallery flows had been reduced to less than 100 l/min by December 1997, following the drilling of 6,000 lin. m of grout and drain holes, and the injection of over 45 m^3 of polyurethane and 170 tonnes of cement, within a 150-calendar day schedule. No uplift pressures were recorded on the foundation. These observations were made with the reservoir elevation at about Elevation 466m.

Tims Ford Dam, TN

Background

Tims Ford Dam is an embankment structure constructed 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 277.4m. The right (west) abutment of the dam is a ridge running nearly north-south (Figure 1), 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

In May and June 1971, two leaks designated Leaks 8 and 6 appeared on the downstream side of the right rim during initial filling. Leak 8 was approximately 45m upstream of the dam base line. Exploratory drilling and dye testing were performed along the right rim for a distance of 630m upstream of the dam baseline. This work led to grouting a curtain line of holes using cement based grouts containing calcium chloride accelerator to withstand the water flow velocity. At that time, dye connection times from curtain to Leak 6 were recorded in the range of 4 to 8 hours. No attempt was made to seal it. The major outflow from Leak 6 emitted from two vertical features at Elevation 260m, some 290m upstream of the dam baseline, and formed an unnamed stream traveling approximately 1000m to the Elk River. An outflow monitoring program was begun and data from that program showed that the outflow varied directly with reservoir level. During the period 1971 through 1994, Leak 6 peak outflow volume slowly increased to about 15,000 l/min. In 1994, however, following record drawdown of the reservoir, the Leak 6 outflow volume increased dramatically in 1995 to over 29,000 l/min. TVA determined that

remedial grouting should be performed to reduce the Leak 6 outflows to less than 4,000 l/min at maximum pool.

An exploratory drilling program was performed during February to April 1997 to better define the existing foundation conditions and provide information necessary to design the remedial grout curtain. This program consisted of drilling a total of 20 vertical and inclined holes, permeability testing in stages, and dye testing to develop flow connection times and paths to Leak 6. The exploratory program provided the following conclusions:

1. Progressive erosion of collapsed and/or desiccated karstic feature infill material was the likely cause of the increased seepage. These features were controlled by solutioning along bedding planes and vertical or near vertical joint sets. Open features in excess of 6m deep were detected. Several dye test connection times of only minutes were encountered to the seep.
2. The bottom elevation of the remedial grout curtain as indicated by the geology and permeability, was estimated as Elevation 256m.
3. The southerly extent of the remedial grout curtain was geologically well defined.
4. The middle and north end of the exploratory area was less uniform with high water takes, cavities and open features, very fast dye connection times and the possibility of an undetected open channel to Leak 6. (The possibility of an open channel was reinforced by the occurrence of low permeability areas near the north end on either side of a high permeability area, thus leaving the location of the north end of the curtain somewhat questionable).

There was strong evidence that there would be substantial water flow through the features of the foundation rock during remedial grouting.

The Solution

A multirow remedial 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). 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 Owner's goal was to reduce the peak seepage to about 4,000 l/min and to focus only on the major features (i.e., not to specifically treat the smaller fissures).

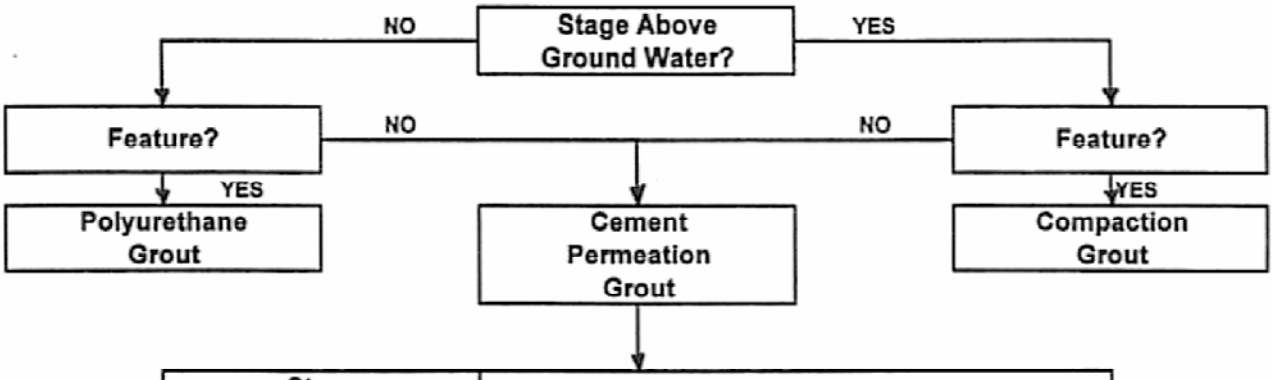
The Specifications contained provisions that required monitoring and limitations to outflow pH and turbidity to protect the downstream environment. TVA agreed to draw down the reservoir to Elevation 260.6m (3m below minimum normal pool) to minimize hydraulic gradient and flow through the rim. The curtain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

Highlights of Construction

- When drawdown of the reservoir reached Elevation 261.8m the outflow from Leak 6 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 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).
- A suite of cement-based grouts were developed to permit the appropriate match of mix design and "thickening sequence" to the particular stage conditions as revealed by drilling and permeability testing (both multi- and single-pressure tests). Details of the initial mixes and their application are provided in Tables 2 and 3.

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	oz	15	30	20	30
Rheomac UW450	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

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



Stage Permeability	Activity
0-1 Lu	Backfill hole with any stable mix
1.1-5 Lu	4 Batches of A Mix 4 Batches of B Mix Begin reducing content of Rheobuild 2000B by 5oz per mix in 2 bag steps for Mix B until refusal or until mix is too thick to mix easily.
5.1-15 Lu	4 Batches of A Mix 4 Batches of B Mix 6 Batches of C Mix Begin reducing content of Rheobuild 2000B by 3oz per mix in 4 bag steps for Mix C until refusal or until mix is too thick to mix easily.
15 Lu +	4 Batches of B Mix 6 Batches of C Mix 10 Batches of D Mix Begin reducing content of Rheobuild 2000B by 3oz per mix in 4 bag steps for Mix D until refusal or until mix is too thick to mix easily. Note: Engineer must be notified when stage approaches refusal or when reduction of Rheobuild 2000B anticipated.

1. Refusal will be defined as a flow of 1 gpm measured over a 10-minute period at the target pressure of 1 psi per foot of depth.
2. No more than 60 batches of cement grout will be injected into a given stage on one 12-hour shift.
3. Compaction grout may be used for features below the water table in the future but, until such a decision is confirmed, only polyurethane will be used in such features.

Table 3. Flow chart providing guide to mix selection and variation, Tims Ford Dam, TN.

- In response to conditions revealed during the treatment, observations of the seepage and further dye testing, extra groups of holes were added at the north end of the curtain, including 11 orthogonal to the original curtain, to allow specific treatment of key features.
- About 15,500 m^3 of compaction grout, 1530 liters of polyurethane, and 605 m^3 cement based grouts were injected into a total of 250 holes (comprising 3400 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 was 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 equivalent lake elevation prior to grouting. Data from piezometers and dye testing support the existence of an efficient curtain.

Potash Mine, New Brunswick, Canada

Background

During the late fall of 1996, minor leaks were detected in one of the highest areas of a major potash mine, near Sussex, N.B. This mine operates with the room and pillar method of excavation. In the area of the inflow, the back of the stopes was close to the shale caprock. At the time, the water inflow was judged insignificant as it did not affect production, and so was not treated, although an accelerated backfill program in this area was launched to provide more support and to try to prevent the problem from escalating. It was hoped that the seepage would drain a small isolated reservoir in the overlying strata and would eventually disappear.

However, the inflow continued to increase, as the roof started to deteriorate and collapse. Fresh water that enters a potash or salt mine is always a significant threat, since it can cause rapid solution. By late May 1997, the inflow had escalated, to a point that the mine was forced to shut down. Inflows were estimated to be in the order of 10,000 to 15,000 m^3 per day. The water was fresh, and believed to originate predominantly from a water-bearing zone located approximately 200 to 300m above the mining horizon. The inflow dissolved thousands of tonnes of salt per day and cut a pathway down to the basalt below the salt horizons. From there, it moved laterally to a point where it was intersected and pumped away. However, the mine's

dewatering system could only handle 5,000 m^3 per day, which resulted in a gradual flooding of the mine.

Solution

Following suspension of mining activities, the Owners selected the program proposed by ECO, even though it was understood that the chances of success were estimated at only 1 in 3, so severe was the structural deterioration caused by solutioning. The foreseen methodology featured the injection of hot bitumen in conjunction with modified cement based grouts, a long used concept that had been greatly refined and optimized in the course of more recent projects. Importantly this plan was to be implemented in conjunction with the simultaneous drilling of pressure relief holes, installed from the underground workings, to control the inflow and channel it to pump stations. These holes would also serve to provide data on the effectiveness of the grouting operation in real time. If pressure relief were not properly effected, then rapid build up of water pressure in the cavern and formation would otherwise lead to hydrofracturing of the formation, and so increased flow rates.

Two inclined drill holes were to be advanced from the surface to the cavern deliver the substantial amounts of materials: one line for bitumen, the other for cement grouts. The cavern was located 700m below the ground surface.

Highlights of Construction

- Directional drilling was used to successfully drill the two nearly vertical but curved holes in the cavern.
- Dye and air tests were performed through these holes to verify connection to the inflow, establish the size of the rubble pile at the base of the cavern, and calculate the volume of the cavern (approximately 19,000 m^3).
- Injection of hot bitumen had never before been attempted to such depth, and the installation included grouting of the lower casing with insulting cementitious grout, hot oil circulation concentric piping systems, thermal expansion joints, bitumen delivery pipe with stringer and rupture discs, two thermocouples and wellhead attachment, bitumen reheating systems and heated storage tanks, and hot oil heating systems.
- For operational reasons, only two pressure relief holes had been completed prior to the grouting operation commencing.
- The bitumen plant was constructed to provide an average capacity of 20 m^3/hr without interruption to handle the foreseen volume of 6,000 m^3. The hot oil system was required for preheating the bitumen line to 125 C, as was the passage of a limited volume of "soft bitumen". Bottom hole temperatures exceeded 150 C before the "hard bitumen" could be injected.

- Six different modified cementitious grout formulations were used for void filling and formation grouting activities. These mixes had well defined performance characteristics (antiwashout, low pressure filtration coefficient, no bleed, high strength, durable, high abrasion and erosion resistance) within a wide range of viscosities and specific gravities. The antiwashout additive was added, for logistical reasons, downstream of the mixer.
- A fully automated and computerized colloidal mixing and pumping plant, capable of producing 60 m^3/hr of grout was specially developed. Continuous QA testing of grout properties was executed by the supervisory staff.
- An intensive manual and electronic monitoring program was implemented, with computers at the bitumen site, the cement site, and the main control center recording dozens of variables in real time on grouting progress, and the response of the groundwater.

Effect of Treatment

The mechanical execution of this enormous and difficult task was flawless. After three days of continuous injection, following a detailed program a combined total of 2,000 m^3 of bitumen and cement grout had been successfully injected. The inflow began to decrease within 24 hours and the formation pressure began to rise. By the end of the third day, the inflow was completely stopped and the formation pressure continued to rise. Grouting continued at the same injection rates (25 m^3 of bitumen per hour and 45 m^3 of cement based grouts per hour). Within 36 hours, there was no more washout of the cement based grout.

On Day 5, however, a major collapse and settlement of the rubble pile and eroded salt backfill took place triggered by the greatly increased hydrostatic pressure. Although this event was predicted and special measures had been taken underground for the occurrence of this event, the devastation caused by the resulting "tidal wave" was overwhelming. After generating an inflow rate of over 3,500 m^3/hr until the cavern had emptied itself, it returned to the pre-grouting flow rates within about 3 hours.

The grouting continued at slightly increased rates from both holes. Towards the end of Day 7, the rate of inflow started to decrease and the formation water pressures started to rise again. The increase of formation water pressure with time was much slower than during the first operation, indicative of a much larger cavern, caused by the collapse during Day 5. Towards the end of Day 10, the leak had again been reduced to a trickle and formation pressures were recovering faster. The inflow rates fluctuated for a few days: each slight increase in inflow triggered a decrease in formation pressure and vice versa.

Suddenly, during the thirteenth day of grouting, the entire area around the cavern collapsed. Most likely the undercutting, by solutioning of the salt layers at or near

the contact with the basalt had been too extensive. A large block of ground collapsed, followed by a tidal wave, which flooded thousands of cubic meters of water into the mine from the cavern in 5 hours. A last effort was made involving the injection of bitumen at pump rates of 40 m^3 per hour and cement grout in conjunction with sodium silicate (via 2 concentric pipes) at a rate of almost 60 m^3. However, the new cavern had become so large that the consultants, owners, and management all came independently to the same sad conclusion; the undermining by the fresh water had caused so much damage that the mine could not be salvaged, under these conditions.

So, after almost 15 days of continuous grouting, totally without down-time, the operation was terminated. A combined total of over 22,000 m^3 of bitumen and cement grout had been injected during this period.

Final Observations

These three case histories have many elements in common:

1. The advantage of having access to accurate historical records.
2. The necessity of careful research and exploration towards determining the nature and extent of the problem and so allowing engineered design of the solution.
3. The need to select efficient, knowledgeable, experienced, and committed specialists, as both consultants and contractors.
4. The need to select appropriate materials, equipment, and methods, and the possession of a fundamental level of understanding to modify these appropriately in the light of actual conditions on site ("Responsive Integration" - Bruce et al., 1993).
5. The need for real time monitoring and analysis of drilling and grouting data.
6. The need for the highest levels of QA/QC on materials and mixes.
7. The needs to establish appropriately quantified and measured " measures of success", and to "baseline" these prior to commencing the treatment.
8. The benefits of using contemporary cement grout admixtures.

Such works are typically conducted under adverse geological, site and logistical conditions and considerable financial, environmental and time pressures. However, these case histories illustrate quite clearly what can be achieved, assuming that the eight elements listed above are properly observed.

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Units

In this paper, the following "soft conversions" have been used:

1m ≡ 3.3 ft
1 liter ≡ 0.26 gallons
1 m^3 ≡ 35.3 cf
1 MPa ≡ 145 psi

References

1. AFTES, (1991). "Recommendations on Grouting for Underground Works," *Tunneling and Underground Space Technology*, Vol. 6, No. 4, pp. 383-461.
2. Bruce, D.A. (1988). "Developments in Geotechnical Construction Processes for Urban Engineering." Civil Engineering Practice 3 (1) Spring, pp. 49-97.
3. Bruce, D.A. (1990a). "Major Dam Rehabilitation by Specialist Geotechnical Construction Techniques: A State of Practice Review." Proc. Canadian Dam Safety Association 2nd Annual Conference, Toronto, Ontario, September 18-20, 63 p. Also reprinted as Volume 57 of the Institute for Engineering Research, Foundation Kollbrunner-Rodio, Zurich, September.
4. Bruce, D.A. (1990b). "The Practice and Potential of Grouting in Major Dam Rehabilitation." ASCE Annual Civil Engineering Convention, San Francisco, CA, November 5-8, Session T13, 41 pp.
5. Bruce, D.A. (1992). "Drilling and Grouting Techniques for Dam Rehabilitation." Proc. ASDSO 9th Annual Conference, Baltimore, MD, September 13-16, pp. 85-96.
6. Bruce, D.A. and F. Gallavresi. (1988). "The MPSP System: A new method of grouting difficult rock formations." ASCE Geotechnical Special Publication No. 14, "Geotechnical Aspects of Karst Terrains, " pp. 97-114. Presented at ASCE National Convention, Nashville, TN. May 10-11.
7. Bruce, D.A., Luttrell, E.C. and Starnes, L.J. (1993). "Remedial Grouting using Responsive Integration℠." Proc. ASDSO 10th Annual Conference, Kansas City, MO, September 26-28, 13 pp. Also in Ground Engineering 27 (3), April, pp 23-29.
8. Bruce, D.A. Littlejohn, G.S., and A.M.C. Naudts (1997) "Grouting Materials for Ground Treatment: A Practitioner's Guide", *Grouting* -

Compaction, Remediation, Testing, ASCE, Geotechnical Special Publication No. 66, Ed. by C. Vipulanandan, pp. 306-334.

9. Bruce, D.A., J.A. Hamby, and J. Henry. (1998). "Remedial Foundation Grouting at Tims Ford Dam, TN." Paper in preparation for 15th Annual Conference on Association of State Dam Safety Officials, Las Vegas, NV, September, 1998.
10. Gause, C. and D.A. Bruce, (1997). "Control of Fluid Properties of Particulate Grouts (1) General Concepts."*Grouting - Compaction, Remediation, Testing*, ASCE, Geotechnical Special Publication No. 66, Ed. by C. Vipulanandan, pp. 212-229.
11. Naudts, A.M.C., (1996). in Brown, Robert Wade, "Practical Foundation Engineering Handbook," McGraw-Hill, New York, NY. pp. 5.277-5.400.
12. Smoak, W.G., and F.B. Gularte. (1998). "Remedial Grouting at Dworshak Dam." This conference.