

## CONTEMPORARY DRILLING AND GROUTING PRACTICES FOR DAM REMEDIATION

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### ABSTRACT

The paper provides generic classifications for the various methods used in drilling rock and overburden; the range of grouting materials that are available; and the different grouting methods that can be adopted. Such classifications are especially appropriate to the field of dam remedial grouting. Summary details are provided from two recent, major U.S. dam remedial projects to illustrate the principles of selection and application of the various methods and materials, and to provide an indication of the high level of performance which can be obtained in properly designed, executed, and monitored projects.

### RÉSUMÉ

Ce publication présente une classification générale sur les différentes méthodes de forage à travers le sol et la roche; la gamme des produits et coulis d'injection disponibles et les différentes méthodes d'injection qu'on peut utiliser ou adopter. Ces classifications sont spécialement propices dans le domaine des travaux de restaurations des barrages, utilisant les techniques d'injection. Les détails de deux projets de rehabilitation des barrages dans les Etats Unis, complétés récemment, sont résumés ici et illustrent les principes de sélection et d'application des différentes méthodes et matériaux ainsi que les niveaux de performance qu'on peut obtenir avec les méthodes bien conçues, bien exécutées et bien dirigées ou observées.

### 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 that 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.

Three of the key elements in designing and constructing an appropriate grouting solution are:

- The drilling method;
- The grouting method; and
- The grouting materials.

It is an accurate reflection of the intense level of global interest in dam rehabilitation that there is a plethora of information available from contractors, consultants, and manufacturers on each of these three key elements. Even for specialists intimately involved in the industry, the sheer volume of information provided via conferences, seminars, books, papers, and electronic databases, can be overwhelmingly voluminous, and frequently self-contradictory to the point of confusion: wasted time and squandered opportunities to solve problems logically result.

This paper, however, presents generic classifications for each of the three key elements. These classifications have been tried and proven for over a decade now (Bruce 1989a; Naudts, 1996; and Bruce *et al.* 1998a) and are intended to provide comfort and value to practicing professionals called upon to deal with the particulars of dam remediation by grouting.

## DRILLING METHODS

### Rock

There are three generic methods of rock drilling:

- 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 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.
- 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 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 (Fig. 1), and 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

100mm in diameter to depths of 50m 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; Bruce *et al.* 1991). Such methods are still, of course, wholly applicable for drilling grout holes to locate and fill large voids such as karstic features.

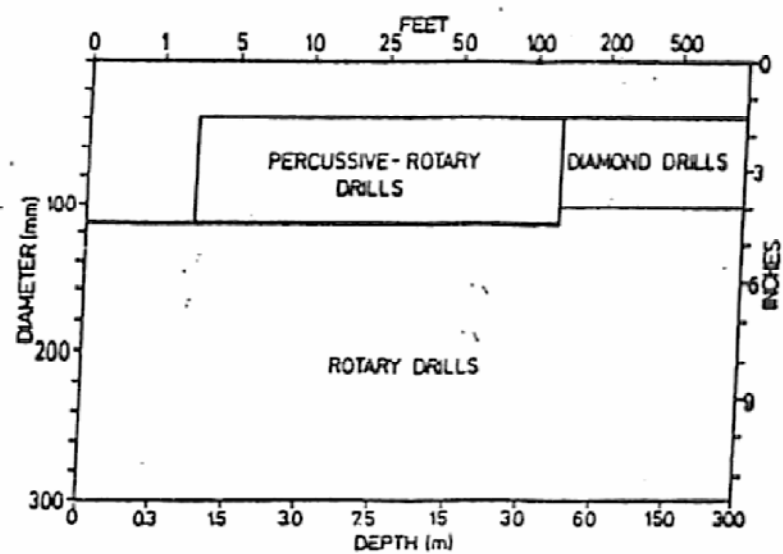
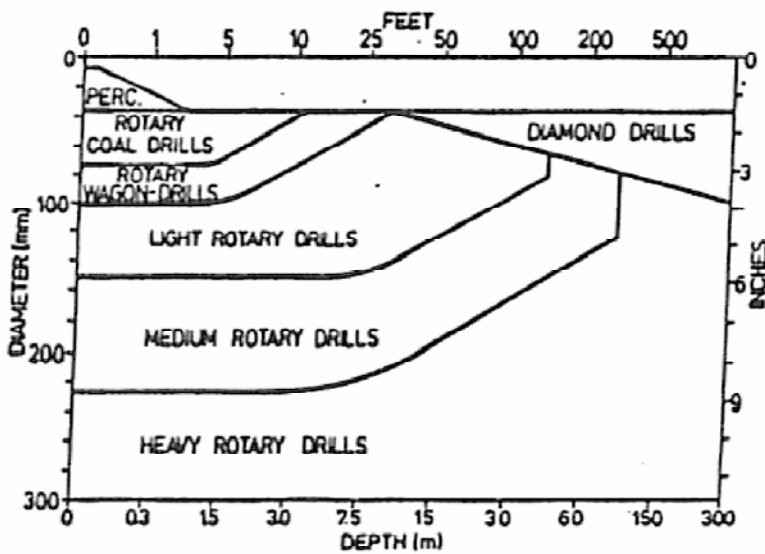
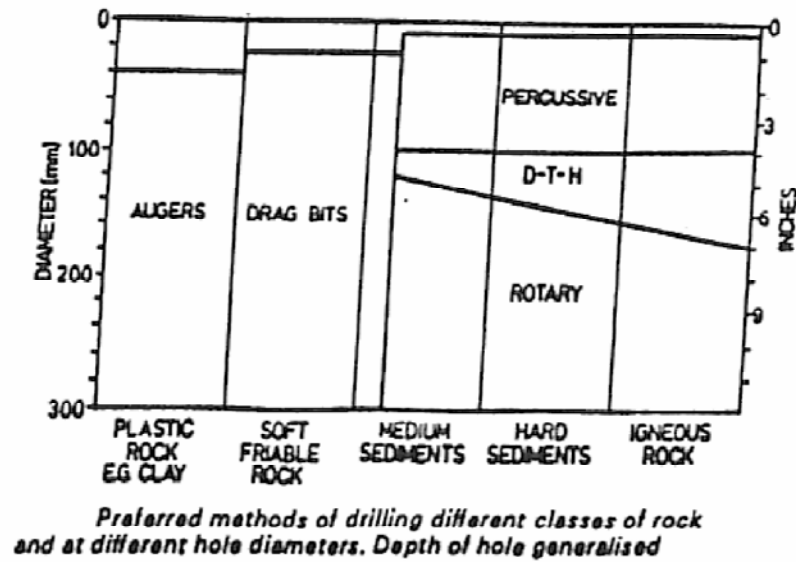


FIGURE 1. General guides for selecting drilling method and equipment for rock drilling (McGregor, 1967).

## Soil and Overburden Drilling

There are six generic techniques, discounting vibrodrilling (which has major geological and environmental restraints), and the use of bentonite slurry supported open holes (often considered a potential hydrofracturing problem in embankment dams) (Bruce 1989a and b). As summarized in Table 1 and Fig. 2, these are as follows:

- Group 1: Single tube advancement: This is the most simple principle. In the drive drilling variant, the casing is percussed and pushed into the soil, without flush, and with a “knock-off” disposable bit. With external flush, the casing terminates in an open shoe or “crown” and is rotated into the soil using a strong flushing action (usually water). The flush emerges from the casing and (hopefully) travels to the surface between the casing and the soil.
- Group 2: Rotary Duplex: The term “duplex” means the simultaneous advancement of an outer casing (with crown) and inner drill rod (with bit). The flush is passed down the drill rod, but then is allowed to emerge to the surface through the annulus between rod and casing. In this particular category, the rods are casings are simultaneously rotated in the same sense.
- Group 3: Rotary Percussive Duplex (Concentric): Similar to Group 2 except that the rods are also percussed. When a top hammer is used, the casings are simultaneous percussed, whereas if a down-the-hole hammer is used, only a drill bit experiences the percussive action, and the casing is merely rotated.
- Group 4: Rotary Percussive Duplex (Eccentric): Similar to Group 3 except that an eccentric drill bit reamer device on the rods is used to oversize the hole, to permit the casing to follow without rotation. After the duplex has reached target depth, the reamer is retracted into the casing so permitting the extraction of the rods. Both top drive and down-the-hole versions are available.
- Group 5: “Double Head” Duplex: Similar to Groups 2 and 3 except that the rods are casings are rotated and advanced simultaneously but in opposite senses. This maximizes the penetration action for any given rig energy, and encourages hole straightness. It is especially useful in very difficult ground conditions (Bruce and Kord 1991). Pure rotary, top drive or down-the-hole rotary-percussive options can be employed.
- Group 6: Hollow Stem Auger: High torque and thrust are used to advance a screw with a hollow core (protected during penetration by a bottom plug). This is a traditional method of drilling cohesive soils and soft argillaceous rocks.

The logic of choice is perhaps even more obscure than in rock drilling, and history and habit have ensured that not all methods are used by any one contractor, or in any one geographical region. Hollow stem augers are common around the Great Lakes and on the West Coast, while simple flushed casing and rotary duplex are favored in the East. The emergence of foreign-backed drill rental companies offering percussive duplex and double-head duplex capabilities has spread these techniques nationwide. Percussive duplex (eccentric) is in general decline for routine

DRILLING METHOD	PRINCIPLE	COMMON DIAMETERS AND DEPTHS	NOTES
1. Single tube advancement a) Drill drilling b) External flush	Casing, with "lost point" percussed without flush. Casing, with shoe, rotated with strong water flush.	50 - 100 mm to 30 m 100 - 200 mm to 60 m	Obstructions or very dense soils problematical. Very common for anchor installation. Needs high torque and powerful flush pump.
2. Rotary duplex	Simultaneous rotation and advancement of casing plus internal rod, carrying flush.	100 - 200 mm to 70 m	Used only in very sensitive soil/site conditions. Needs positive flush return. Needs high torque.
3. Rotary percussive concentric duplex	As 2, above, except casing and rods percussed as well as rotated.	89 - 175 mm to 40 m	Useful in obstructed/bouldery conditions. Needs powerful top rotary percussive hammer.
4. Rotary percussive eccentric duplex	As 2, except eccentric bit on rod cuts oversized hole to ease casing advance.	89 - 200 mm to 60 m	Somewhat obsolescent and technically difficult system for variable overburden.
5. "Double head" duplex	As 2 or 3, except casing and rods rotate in opposite senses.	100 - 150 mm to 60 m	Powerful, new system for fast, straight drilling in very difficult soils.
6. Hollow stem auger	Auger rotated to depth to permit subsequent introduction of reinforcement through stem.	150 - 400 mm to 30 m	Obstructions problematical; care must be exercised in cohesionless soils to avoid cavitation and/or loosening. Prevents application of higher grout pressures.

TABLE 1. Overburden drilling methods (Bruce, 1989b).

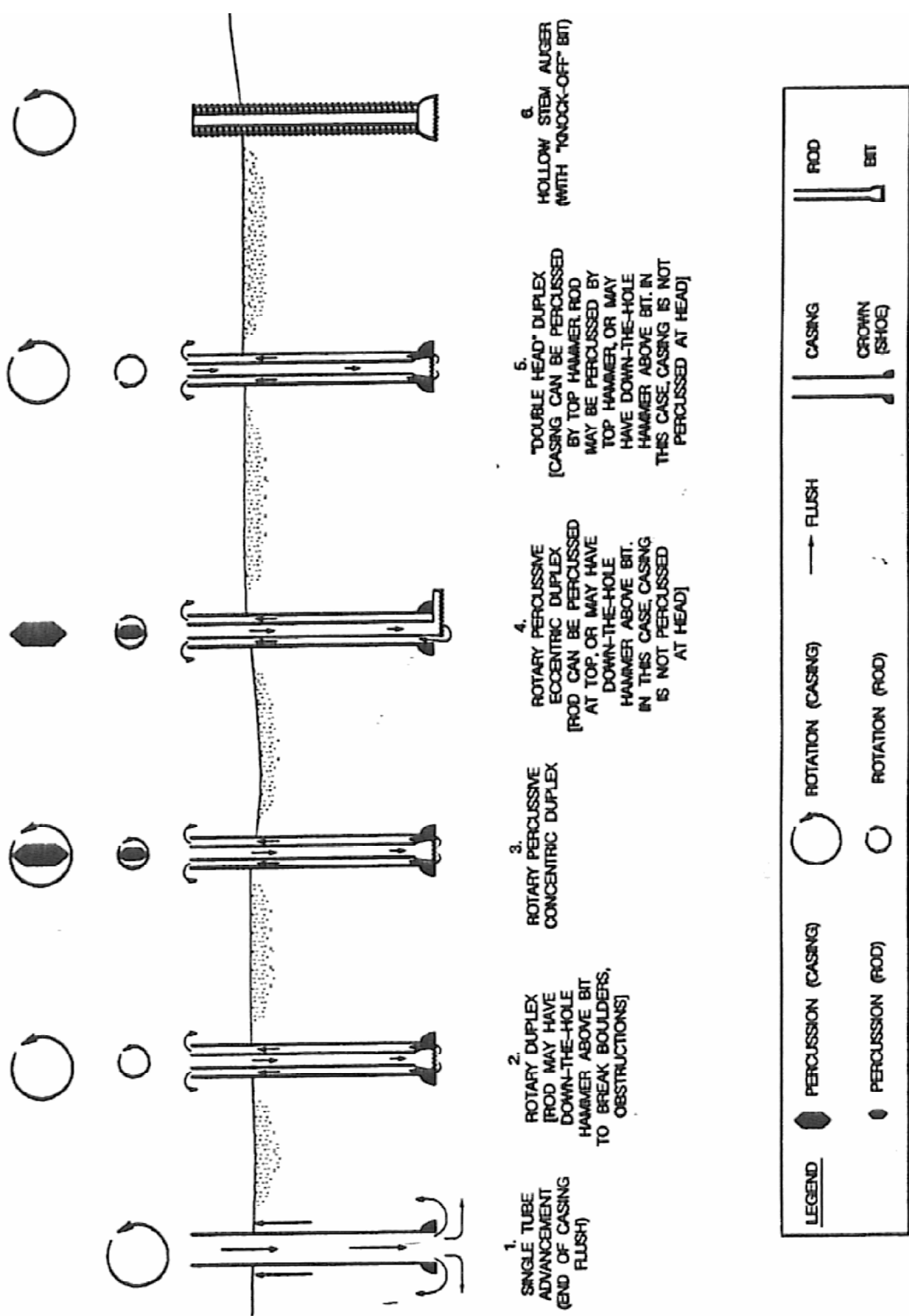


FIGURE 2. Schematic representation of the six generic overburden drilling methods (Bruce, 1989b).

production grout holes, although is still regarded in certain quarters as the premier overburden drilling method, in very difficult conditions.

Despite the resistance towards innovation apparent in every stratum of the industry, it does seem that domestic demand plus the easy availability of foreign technology is forcing major changes in attitudes towards soft ground drilling. The better contractors, at least, are adopting a refreshing degree of technical responsiveness to replace traditional paradigms.

## **GROUTING METHODS**

### Rock

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. As illustrated in Fig. 3, 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 advantages and disadvantages of each method are summarized in Table 2. 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 reflecting the challenges and difficulties posed by more difficult site and geological conditions posed by 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.

A recent example is the grouting of poorly cemented hard rock backfill 823m below ground level in a copper mine in Northern Ontario, Canada (Bruce and Kord 1991). This medium proved so difficult to drill that none of the conventional grouting methods could be made to work. The MPSP system is similar to the sleeved tube (tube à manchette) principle in common use for grouting soils and the softest rocks (Bruce 1982). The sleeve grout in the conventional system is replaced by concentric polypropylene fabric collars, slipped around sleeve ports at specific points along the tube (Fig. 4). 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 major projects involving the authors in the Philippines, Canada, and the U.S.

TABLE 2. Major advantages and disadvantages of downstage and upstage grouting of rock masses (Bruce and Gallavresi, 1988).

	DOWNSTAGE	UPSTAGE
<b>A D V A N T A G E S</b>	<ol style="list-style-type: none"> <li>1. Ground is consolidated from top down, aiding hole stability, packer seating and allowing successively higher pressures to be used with depth without fear of surface leakage.</li> <li>2. Depth of hole need not be pre-determined; grout take analyses may dictate changes from foreseen, and shortening or lengthening of hole can be easily accommodated.</li> <li>3. Stage length can be adapted to conditions as encountered to allow "special" treatment.</li> </ol>	<ol style="list-style-type: none"> <li>1. Drilling in one pass.</li> <li>2. Grouting in one repetitive operation without significant delays.</li> <li>3. Less wasteful of materials.</li> <li>4. Permits materials to be varied readily.</li> <li>5. Easier to control and program.</li> <li>6. Stage length can be varied to treat "special" zones.</li> <li>7. Often cheaper since net drilling output ratio is higher.</li> </ol>
<b>D I S A D V A N T A G E S</b>	<ol style="list-style-type: none"> <li>1. Requires repeated moving of drilling rig and redrilling of set grout; therefore process is discontinuous and may be more time consuming.</li> <li>2. Relatively wasteful of materials and so generally restricted to cement-based grouts.</li> <li>3. May lead to significant hole deviation.</li> <li>4. Collapsing strata will prevent effective grouting of whole stage, unless circuit grouting method can be deployed.</li> <li>5. Weathered and/or highly variable strata problematical.</li> <li>6. Packer may be difficult to seat in such conditions.</li> </ol>	<ol style="list-style-type: none"> <li>1. Grouted depth predetermined.</li> <li>2. Hole may collapse before packer introduced or after grouting starts leading to stuck packers, and incomplete treatment.</li> <li>3. Grout may escape upwards into (non-grouted) upper layers or the overlying dam, either by hydrofracture or by-passing packer. Smaller fissures may not then be treated efficiently at depth.</li> <li>4. Artesian conditions may pose problems.</li> <li>5. Weathered and/or highly variable strata problematical.</li> </ol>

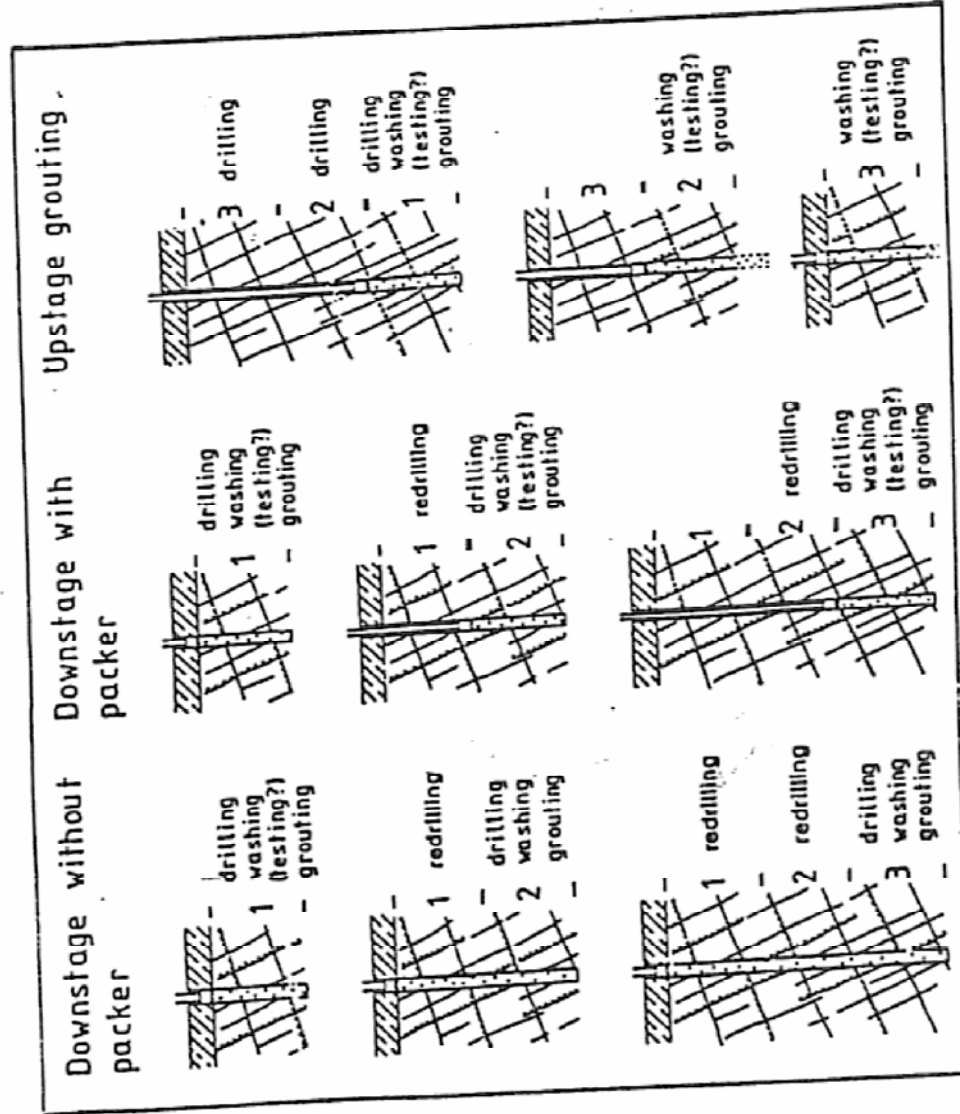


FIGURE 3. Conventional stage grouting methods for rock fissure grouting (Ewert, 1985).



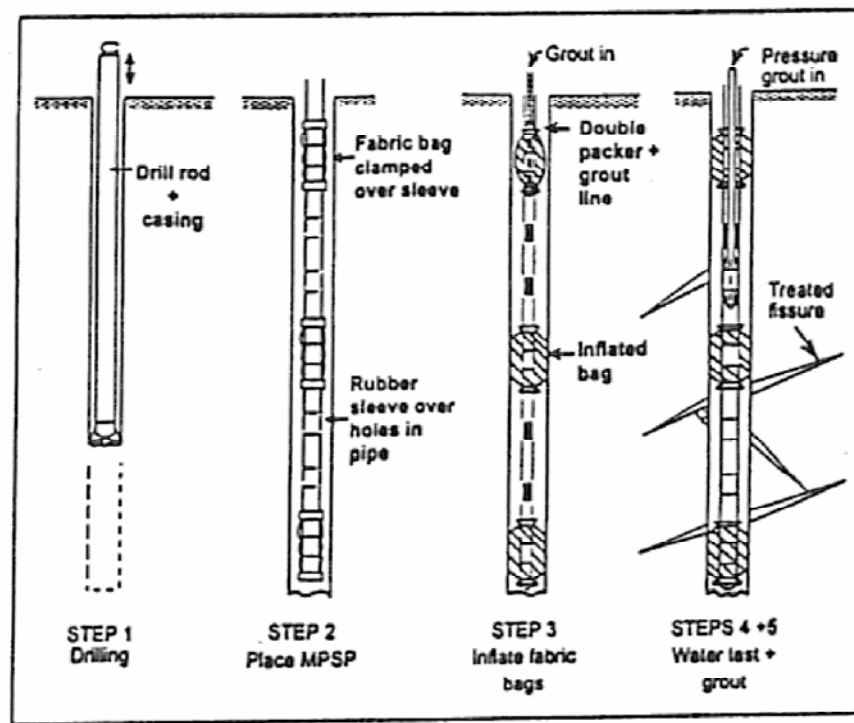


FIGURE 4. MPSP installation and grouting steps (Bruce and Kord, 1991).

## Soil

Although it has been traditional to identify only four basic methods of soil grouting (Fig. 5), the rapidly growing popularity of the Deep Mixing has resulted in a fifth bona fide member of the group.

1. **Permeation Grouting:** Involves the infiltration of existing voids and pores with grouts. The granulometry of the soil largely dictates the choice of materials and so, to a large extent, the cost. Various methods of placement exist (Xanthakos *et al* 1994; Naudts 1996) but the most common range from the simple end of casing injection, to the sophisticated but precise tube a manchette (sleeve pipe) system.
2. **Compaction Grouting:** This “uniquely American process” (Baker *et al* 1983) has been used since the early 1950s and continues to attract an increasing range of applications (Warner 1982). In summary, very stiff “low mobility” grouts (Warner 1992) are injected in predetermined soil. When appropriate materials and grouting parameters are selected (Warner *et al* 1992) the grout forms regular and controllable coherent volumes, centered on the point of injection. Near surface injections may result in the lifting of the ground surface and associated structures, akin to the principle of slabjacking described by, for example, Bruce and Joyce (1983). Unlike other types of grouting, compaction grouting does not aim to reduce overall soil mass permeability; rather the densification it provides can be an important guard against liquefaction for example (Salley *et al* 1987). Compaction grouts, properly formulated and injected, have also been used recently in void filling operations in major dams and quarries in both the U.S. (Tims Ford Dam, TN) and Canada (Bennett Dam, BC).
3. **Hydrofracture Grouting:** Features the concept that stable, high mobility particulate grouts are injected at relatively high rates and pressures to deliberately fracture the ground. The lenses, ribbons and bulkheads of grout so formed are conceived as increasing total stresses, filling unconnected voids, locally

consolidating or densifying the soil, and providing a framework of impermeable membranes. However, the process is relatively difficult to control, and may lead to unwanted ground heave or wasteful grout travels. It is rare outside the French grouting industry, although the work of one French contractor at Mud Mountain Dam, WA (Eckerlin 1992) is a clear demonstration of the methodology.

4. **Jet Grouting:** This was primarily developed in Japan in the early 1970s (Xanthakos *et al* 1994) but was introduced practically into North America only in the mid 1980s. There are three basic types of jet grouting in popular use but all feature the use of a high pressure fluid jet ejected laterally during the rotation and extraction of the drill rod to erode and/or grout the soil. The result is a column of "soilcrete", the diameter and strength of which reflects the virgin soil, the grout mix design, and the operational parameters. Jet grouting has many inherent advantages in all types of soil, and its reliance on cement based grouts only. However, many remain concerned about the potential impacts of the high pressures employed, and remain skeptical about its economic competitiveness. The authors believe it has been used only twice on Canadian dams (John Hart, BC and Ste. Marguerite, QU) and equally sparingly elsewhere.
5. **Deep Mixing:** Originally developed simultaneously but separately in Scandinavia and Japan in the early 1970s, this method is now the most popular ground treatment and improvement technique for soft soils throughout the world. Cementitious products (either in dry form or in grouts) are introduced into the soil and blended with it in situ, using various types of rotary and jet assisted mechanical mixing methods (Bruce *et al* 1998b). The equipment is typically of large scale - treated columns up to 2m in diameter, 40m deep are not atypical results - and so needs good, unrestricted access. In the United States, its main applications have been for earth retention and ground treatment, principally in the softer marine soils of the coastal fringes. So far, the major dam related projects have been at Jackson Lake Dam, WY (for seismic upgrade) and at Cushman Dam, WA (cutoff).

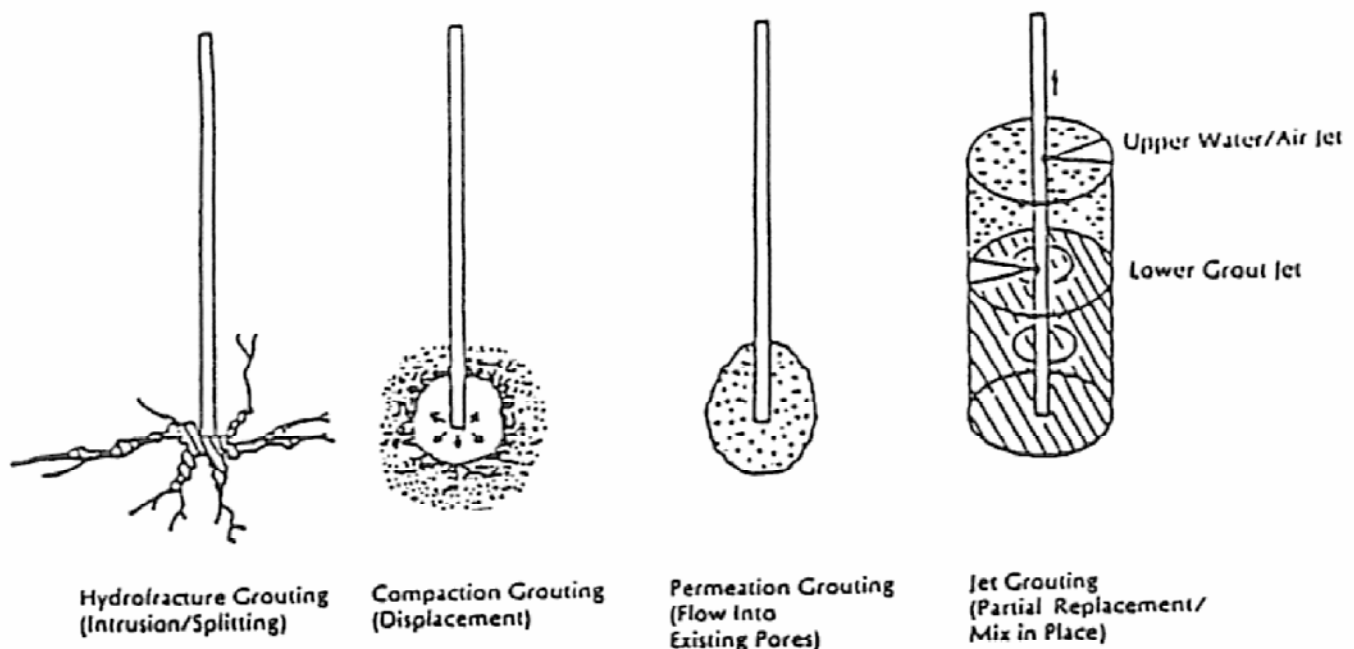


FIGURE 5. Four traditional categories of soil grouting.

## **GROUTING MATERIALS**

There are four categories of materials (Bruce *et al* 1997), 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, clays, 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 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 ( $k = 10^{-6}$  m/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 seepage reduction under appropriate conditions as illustrated 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, because of their relatively long setting time (20 to 60 minutes), low strength (less than 1 MPa) and poor durability, for providing permanent seepage barriers against high flow/high head conditions. 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 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).
- Polymerization and Polycondensation: arising from the combination of two components (e.g., epoxies, aminoplasts).

In general, 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 3). 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.

TABLE 3. Uses and applications of resins (AFTES, 1991).

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)

Of these four subclasses, only the two groups of polyurethanes are usually appropriate for remedial grouting:

- Water-reactive polyurethanes: Liquid resin, often in solution with a solvent or in a plasticizing 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).

#### 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 200 degrees C plus). 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 require 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.

## 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, as well as North America. 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 two recent projects:

- Dworshak Dam, ID; and
- Tims Ford Dam, TN.

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

## Dworshak Dam, ID

### 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 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  $15^\circ$  to  $30^\circ$  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  $1 \times 10^{-5}$  m/s (10-m depth) to  $5 \times 10^{-9}$  m/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 concrete compaction during construction.

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<sup>3</sup> of fast setting chemical 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 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<sup>3</sup> 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 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

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).
5. 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 4 and 5.
- 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<sup>3</sup> of compaction grout, 1530 liters of polyurethane, and 605 m<sup>3</sup> cement based grouts were injected into a total of 250 holes (comprising 3400 lin. m of rock drilling).

### Effect of Treatment

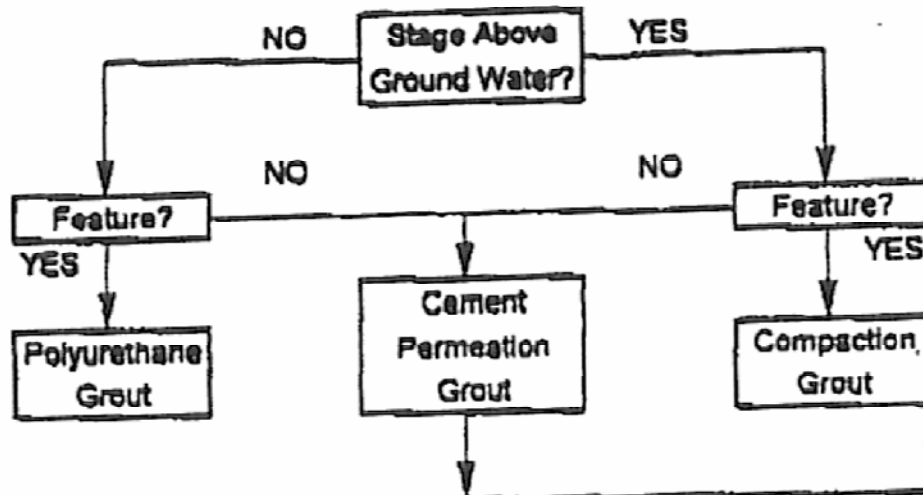
Throughout the work, closest attention was paid in real time to data from the drilling, water testing, and grouting activities in addition to information from leak monitoring, piezometers and dye testing. The curtain was thus brought to an engineered refusal. During refilling of the reservoir, the leak 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 the equivalent lake elevation prior to

grouting. Data from piezometers and dye testing support the existence of an efficient and durable curtain.

TABLE 4. 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	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 <sup>-1/2</sup>	<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 5. Flow chart providing guide to mix selection and variation, 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 5 oz 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 3 oz 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 3 oz 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.

## FINAL OBSERVATIONS

These two 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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