SEEPAGE CONTROL: A REVIEW OF GROUTS FOR EXISTING DAMS

D.A. Bruce[1], W.G. Smoak[2], and C. Gause[3]

Abstract

One of the major concerns facing dam owners is the rehabilitation of their structures to prevent seepage through, under, or around them. Most often, reservoirs cannot be drawn down completely, and so repairs must be conducted in the presence of high flow volumes and/or heads. Over the years, many existing dams have been treated by grouting but with varying degrees of success. One of the major reasons for this erratic performance has been the inappropriate selection of the grouting material. This paper provides a general review of the major families of grout used in such applications:

1. Particulate (suspension or cementitious) grouts;
2. Collodial solutions;
3. Pure solutions;
4. Other grouts.

Background

As noted by USCOLD (1997) the most complete source of information on dams in the United States is the National Inventory of Dams, completed by 76 state, territory and Federal agencies, in coordination with the Federal Emergency Management Agency, for the U.S. Army Corps of Engineers. The states regulate over 100,000 dams although only 75,187 are actually listed in the Inventory. Of these, 6386 are considered as high dams (i.e., over 15m). Table 1 shows the distribution of dam ownership.

Dam Owners	All Dams (%)	> 15 m (%)
Private	58	32
Local Government	17	28
State Government	5	7
Federal Government	3	14
Utilities	2	9
Unknown	15	10

Table 1. Distribution of ownership of U.S. dams (USCOLD, 1997).

1 Principal, ECO Geosystems, Inc., Venetia, PA.
2 Principal, ECO Structural Systems, Lakewood, CO.
3 Sales Manager, Underground Division, MasterBuilders Technologies, Cleveland, OH

Private interests funded the early years of dam construction, but as government influence increased, several agencies sponsored and constructed dams to meet their respective public missions. For example, the Bureau of Reclamation began constructing in the early 1900s, as did the Corps of Engineers, while the Tennessee Valley Authority started in 1933, and state government agencies, notably California's Department of Water Resources, have long been active. However, the majority of dams in the United States have been built since 1960, although since 1990, only 186 large dams have been completed and barely 40 remain under construction.

The trend is clearly to less new construction but an increasingly necessary emphasis on dam remediation and rehabilitation. Such works are conducted for a variety of reasons, the majority not reflecting foundation conditions and defects. Nevertheless, as the average age of the bulk of our dams increases, and the measures originally constructed to prevent seepage through, under and around these structures are further exposed to the ravages of hydraulic gradients acting on erodible materials - both natural and artificial - so the occurrence of major seepage problems continues to increase.

In certain cases where, for combinations of technical and political reasons, "positive" cut offs have been required, the application of diaphragm (slurry) walls (Bruce, 1990a) or overlapping large diameter bored piles (Bruce and Stefani, 1996) has provided very effective, if also very costly, solutions. However, there remains a great potential for the use of grouting technologies, as described by Bruce (1990b), the successful use of which in recent years has been greatly enhanced by developments in grouting material knowledge (Gause and Bruce, 1997). Bearing in mind that such repairs are typically conducted in cramped conditions, e.g., galleries) against seepages of cold water flowing at high velocity and volume under significant head, then the complexity of the issue can be appreciated, and the skills of successful practitioners justly acknowledged.

There is a plethora of grouting materials available, and the purpose of this paper is simply to provide the reader with a generic framework to simplify his selection of the most appropriate material. In considering his selection of material, the reader should also recall that different placement methods and techniques will be required for the different materials: the "conventional" staging processes used in the creation of particulate grout curtains are not suitable, for example, to the intricacies needed for the injection of hot melts and their associated materials (Naudts, 1996).

Bruce (1992) describes the drilling and grouting principles and methods used for dam rehabilitation. This companion paper covers the materials that can be used.

Basis of Classification

This paper divides the materials into four categories listed in order of increasing rheological performance and cost:

1. Particulate (suspension or cementitious) grouts, having a Binghamian performance (Figure 1a).
2. Collodial solutions, which are evolutive Newtonian fluids in which viscosity increases with time (Figure 1b).

3. Pure solutions, being nonevolutive Newtonian solutions in which viscosity is essentially constant until setting, within an adjustable period (Figure 1b).
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 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 are 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.

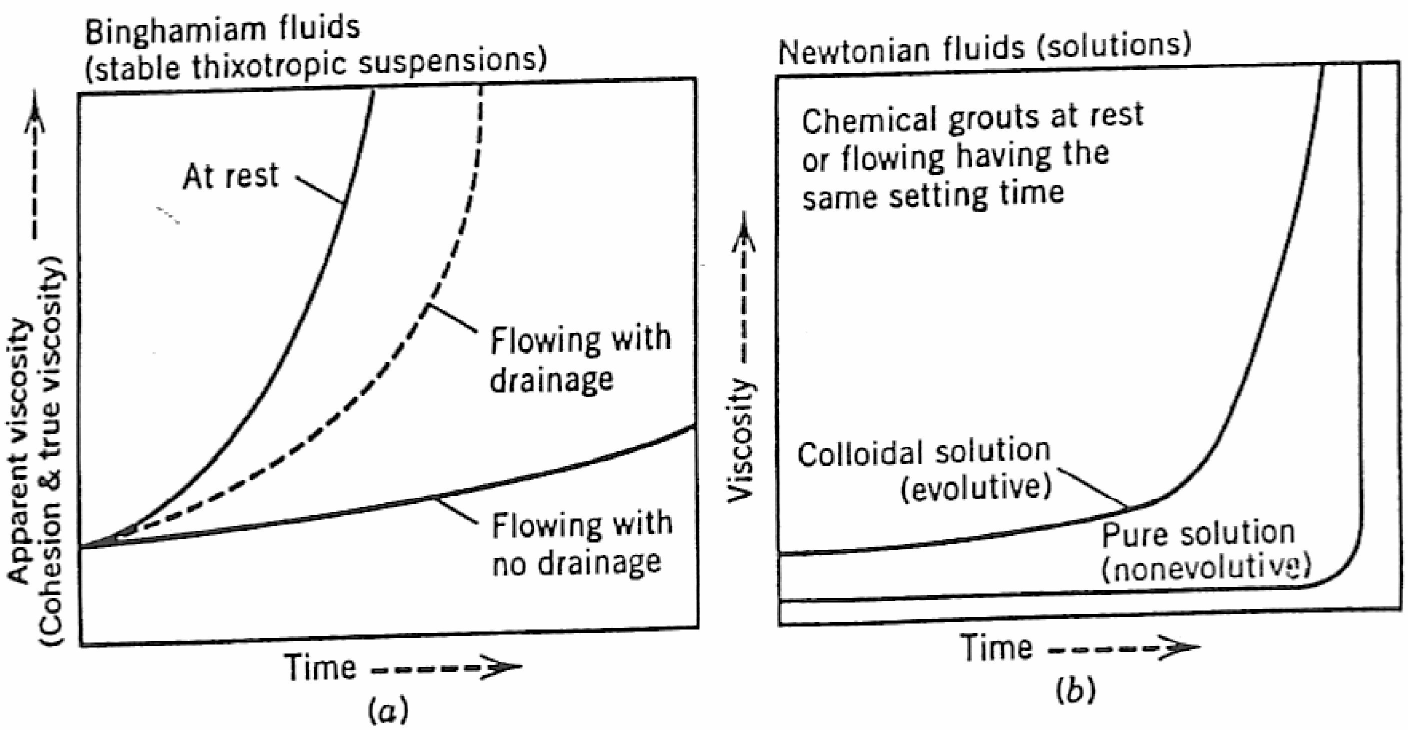

Figure 1. Rheological behavior of typical grouts (Mongilardi and Tornaghi, 1986).

Particulate Grouts

Due to their basic characteristics (including economy) these grouts remain the most commonly used for both 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.

Details on the properties of each of these subclasses are provided in Bruce et al. (1997). It should be borne in mind that most of these particulate grouts - with the exception of those for "special applications" - are physically 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).

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 reflect in their own chemistry and concentration the desired short- and long-term properties including 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 longish setting time (20 to 60 minutes), low strength (less than 1 MPa) and durability concerns, 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 particulate grouts - a traditional defense against fast flows.

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 cement or silicate grouts prove inadequate. Examples of such situations would include the following requirements:

- particularly low grout viscosity.
- high rapid 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. Applications are summarized in Table 2. 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 2. Uses and applications of Resins (AFTES, 1991).

Of these four subclasses, only the polyurethanes are usually appropriate for remedial dam grouting. They have two basic classes:

- Water-reactive: 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. These resins have 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 Components: 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. Thorough description of these grouts is provided by Naudts (1996).

Other 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 below.

For extreme cases in seepage cut off, hot melts are a viable if rather complex 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, may have 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. Simultaneous penetration by stable particulate grouts is necessary to ensure good long-term behavior.

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 ("Colloidal Solutions") - 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: a complex of permanently stable crystals. This reaction is not therefore an evolutive gelation involving the formation of macromolecular aggregates (Figure 2), but is a direct reaction on the molecular scale, free of syneresis potential (Figure 3). 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 (Figure 3);
- 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.

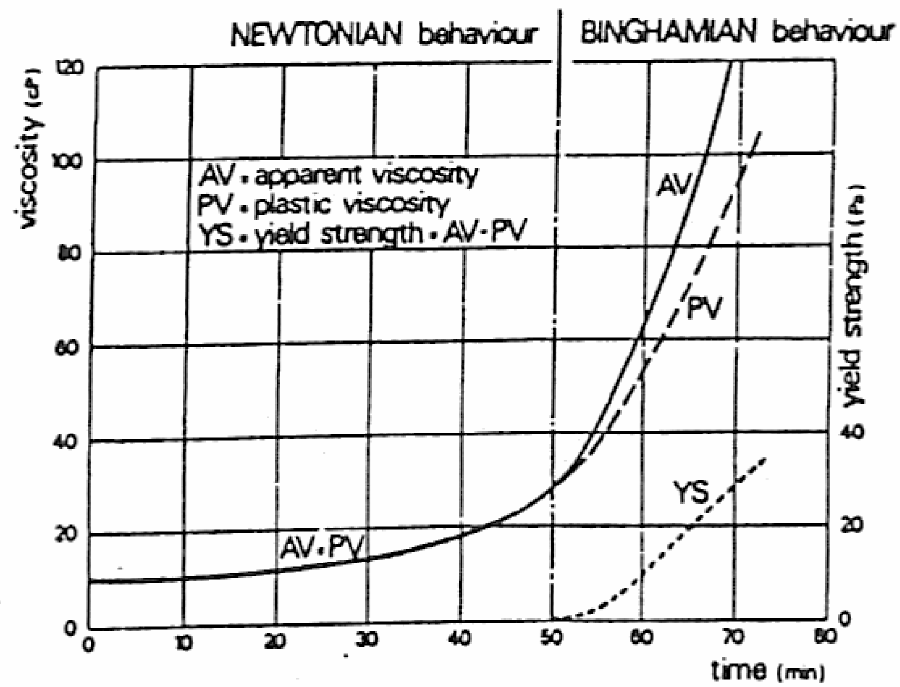

Figure 2. Typical viscosity-time behavior of Silacsol grout (Tornaghi et al., 1988).

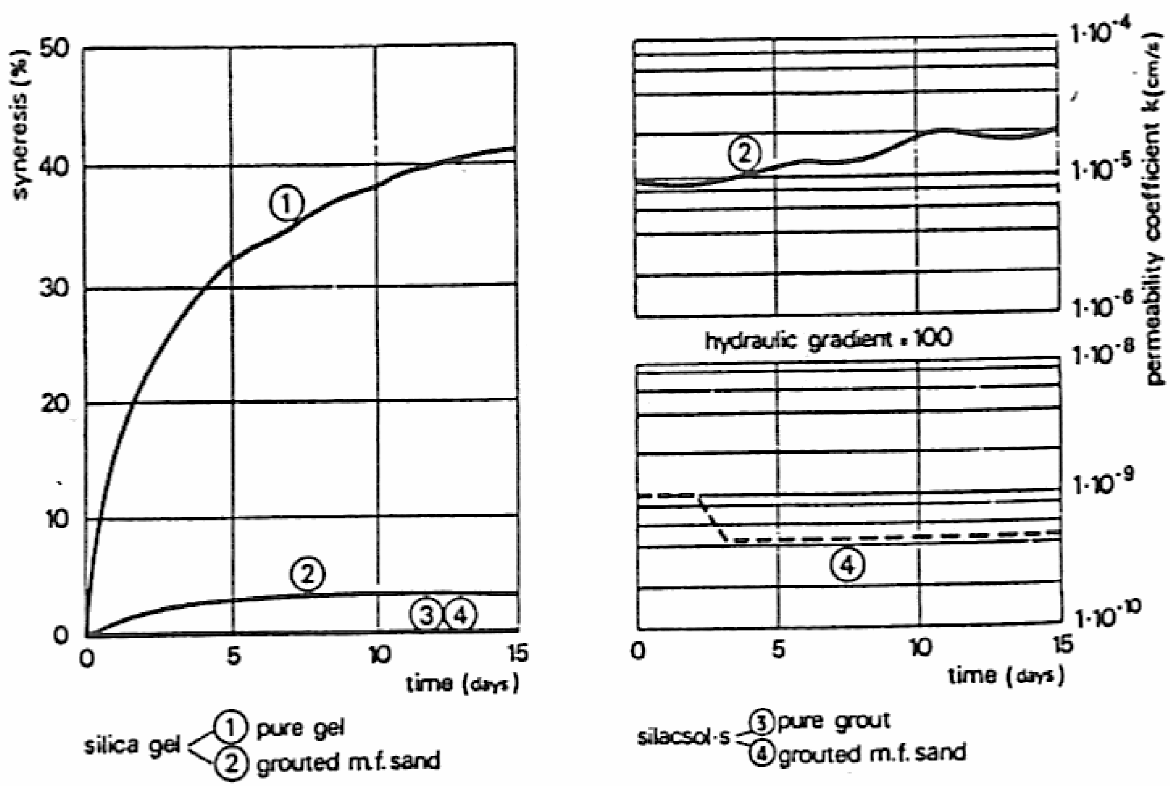

Figure 3. Effect of time on syneresis and permeability of typical silicate and silacsol grouts (Tornaghi et al., 1988).

Final Remarks

There is a potentially bewildering range of grouts which can be used in seepage cut off applications for existing dams. Of these, modified particulate grouts, polyurethanes and hot melts have enjoyed success and the silacsols' potential remains to be proved in the U.S. The efforts of material scientists in understanding and controlling the complex component interactions, and in continuing to improve the qualities of the materials they produce, are particularly timely for the dam engineering community: the next decade will most probably witness a major upsurge in seepage related "incidents" in our aging dam population.

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 S. Stefani. (1996). "The Rehabilitation of Beaver Dam: A Major Seepage Cut-Off Wall," *Ground Engineering*, Vol. 29, No. 5, June, pp. 40-45.
7. 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.
8. 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.
9. Mongilardi, E. and R. Tornaghi, (1986). "Construction of Large Underground Openings and Use of Grouts," Proc. Int. Conf. on Deep Foundations, Sept., Beijing, 19 pp.
10. Naudts, A.M.C., (1996). in Brown, Robert Wade, "Practical Foundation Engineering Handbook," McGraw-Hill, New York, NY. pp. 5.277-5.400.
11. Tornaghi, R., B. Bosco, and B. DePaoli, (1988). "Application of Recently Developed Grouting Procedures for Tunneling in Milan Urban Area," Proc. 5th Int. Symp. Tunneling '88, London, April 18-21, 11 pp.
12. USCOLD. (1997). "Dam Activity in the United States," May. 4 p.