INNOVATIONS IN AMERICAN GROUTING PRACTICE

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ABSTRACT

Rock grouting has been conducted in the United States for almost a century and soil grouting is well into its fifth decade of application. However, for a number of well documented reasons, American grouting practice is often perceived as somehow lagging behind that of certain other countries. This paper reviews progress in methodologies, materials and contracting practices which demonstrate that the industry is enjoying a period of considerable innovation and strong development.

INTRODUCTION

In his book "Dam Foundation Grouting", Weaver (1) provides a concise history of rock grouting in the United States. He describes that the earliest reported usage was in 1893 for consolidation of the fissured rock mass beneath New Croton Dam, NY, while the first hydraulic cut-off was executed at Hinkston Run Dam, in Pennsylvania in 1901. The work at Estacada Dam, Oregon, from 1910 to 1912 was the "first *major* usage of cement grouting" for a curtain, while by the early thirties a massive drilling and grouting program had been carried out at Hoover (Boulder) Dam, NV, as a "normal feature" (2) of the overall construction. The specifications and practices developed then "quickly became the unofficial grouting standards" (3) and have in part persisted to the present day.

Soil grouting featuring permeation with chemicals had a much later start, only truly emerging in the fifties. This market until 1978 largely revolved around the marketing efforts of the American Cyanamid Company with their now banned AM-9 acrylamide grout, and Diamond Alkali Company's silicate grout SIROC. Since then a wide variety of products have been developed or imported, although Karol stated in 1990 that "at present, virtually all construction (chemical) grouting in the United States is done with silicates", reflecting environmental, cost and health reasons. Generally, however, the most popular form of soft ground treatment remains compaction grouting, the "uniquely American" process (4) first conceived by Jim Warner and co-workers over forty years ago. Jet grouting is being aggressively marketed, and "controlled fracture" grouting is being promoted principally on the West Coast. The advantages of mechanical mix-in-place methods such as SMW Seiko (5) are becoming increasingly exploited in both geotechnical and environmental fields.

And yet, it is only in 1991 that the current author felt obliged to write an albeit pythonesque article entitled "Equal Rights for Grouters" (6) in an oblique attempt to remind dam remediation engineers in particular of the overlooked benefits of contemporary drilling and grouting expertise. Given the long and

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(mostly) successful history of grouting in America, this may have appeared a strange task. However, it often seems that the national status of grouting as a reliable engineering tool simply does not match the popularity it enjoys in other countries, especially in Western Europe, the Far East and Southern Africa.

Frequently one meets Owners who have been duped by grouting contractors whom, of course, they elected to pay by the volume injected instead of by the result achieved. One hears Contractors who have lost heavily on certain projects as a result of the rigid application of obsolescent specifications by hamstrung inspectors. One reads of projects where "we tried grouting - it didn't work", after the Engineer turned to the technique when all else had failed and the situation had totally deteriorated, both technically and contractually.

The simple consequence is that grouting in many circles does not enjoy a good reputation. The reason is often threefold: bad conception, poor execution, and inappropriate contracting and procurement procedures. Allied to these factors are certain natural causes. The United States of America is an extremely large country: structures could therefore be located to best geological advantage. As a consequence it was just not necessary to devise new, sophisticated ground treatment methods to combat poor geotechnical conditions - which could generally be avoided by the "walkaway solution". The ingenuity displayed by European and Japanese engineers, for example, faced with extreme problems of urban engineering in coastal cities, dam construction on previously discarded sites, or transportation engineering through softish Tertiary upheavals was not required. It is no surprise to find that virtually all of the current wave of grouting technologies and concepts have originated outside the U.S., where, as well, the business atmosphere is less litigious and the players rather more pragmatic about cooperation and the sharing of research and development burdens.

At the same time, the demands of national focus are equally important to consider: during the times of European and Japanese enforced inventiveness, American engineering technology was being extended in other directions to make particular strides in structural, chemical, transportation, hydraulic, and aeronautical engineering, as examples. Recent decades, however, have begun to see an increasing demand for the skills of the grouting engineer, in the same way, and for the same reasons as his foreign counterparts twenty years before. Mass transit systems are being created through and under older cities, usually built on alluvial or marine deposits and often with high water tables; sewage and stormwater tunnels are being formed deep in areas of horizontal, "soft" geology; existing hydraulic and waste containment structures require sealing; and mining operations are extending deeper into "difficult" lithologies.

The outcome of all these factors places the status of the grouting industry in the United States in a fascinating and extremely ironic position. On the one hand there remains a hard core of disenchanted disbelievers, soured by bitter experience and the connotations of grouting being "all smoke and mirrors". On the other hand, there is truly a growing appreciation of, and market for, the potential of contemporary grouting practice. Led by specialty contractors, often linked to overseas resources, backed by high quality university and government research, and encouraged by incrementally more progressive contracting procedures (7), this innovative spirit is touching facets of geotechnical, environmental and mining activities all over the country.

This paper summarizes the trends and developments in the American grouting industry in the early nineties. It reflects the proceedings of recent ASCE Conferences (8)-(13) the activities of the ASCE and ACI Grouting Committees, and the author's personal observations and experiences.

METHODOLOGIES

Rock Grouting

As inferred above, rock grouting practice largely follows traditional lines although within the last few years it would seem that publications by such as Houlsby (2) and Weaver (1) have had a refreshing and innovative impact. Their moves towards change, coupled with a wider appreciation of overseas developments have been aided by the international flavor of many of the annual short courses (e.g., at Univ. Missouri - Rolla, and Univ. Wisconsin - Milwaukee), the active contributions of foreign specialists in domestic industry, and the experiences shared with U.S. grouting consultants in foreign works (14). In addition, the technical demands of grouting new sites of difficult geology (15) and the increasing amount of remedial grouting at existing sites (16) has forced challenges to old paradigms. In general the following broad statements can be made to reflect typical current practices.

- Drilling is still largely conducted by rotary methods, although the insistence on diamond drilling (including full coring) is no longer so prevalent. Top drive rotary percussion is growing in acceptance in certain quarters - with the increasing availability of diesel hydraulic crawler rigs, as long as water flush is used. Somewhat surprisingly, certain consultants are beginning to allow air flushed down-the-hole hammers to be used for routine grout hole drilling. Even when the air is "misted" with some inducted water, most specialists believe that this medium has a detrimental effect on the ability of fissures to subsequently accept grout (2, 17).
- Water testing is not so rigorously or intensely conducted as, for example, Houlsby (2) would advocate, and in the vast majority of cases, stage water tests are run at a single, relatively low, excess pressure and results are expressed in units of cm/sec as opposed to Lugeons.
- Grout mixes have traditionally been "thin" by European standards and composed of only cement and water, but, again, change is evident. For example certain Government agencies (18, 19, 20) have been systematically experimenting with fluidifiers and plasticizers, while work continues with pozzolans and silica fume and other modifiers. The systematic use of stable, bentonitic grouts, in accordance with the current European theories (21) is not yet widespread.
- Grouting equipment has changed little, except that tighter controls are being exercised at batching stations over mix proportioning. Grouting pressures remain conservative by foreign standards - although often exceeding the old "one psi per foot" rule - and "constant pressure" progressive cavity pumps such as Moynos are specified over "fluctuating

pressure" piston or ram pumps. Grout consumptions still tend to be recorded in "sacks per foot".

There are two areas especially where major change is evident, and where rock grouting practice has undergone rapid changes: parameter recording and staging philosophies.

- Parameter recording by electronic means has become standard practice on all federal jobs and on most others also. This may range from a simple "in the field" chart recorder, to the telemetric system, devised by the Bureau of Reclamation at their massive New Waddell Dam project in Arizona (15). There, electronic pressure transducers, magnetic flow meters and density meters in the field constantly relay data via a Remote Telemetry Unit to a Central Telemetry Unit, where all the grouting parameters are displayed in real time. Graphical data consist of flow rate, pressure, bag rate, and water-cement ratio. Numerical data include hole and stage number, target pressure, volume, density, w/c ratio, take rate, depth, cumulative take, date and time. Numerical data from six stages can be monitored instantaneously. The field inspector is in constant communication via radio with the CTU office to exchange information and instructions. Data are stored for future technical analyses and reports, and also for payment purposes. Aberle et al. (15) concluded that these systems are extremely valuable and greatly help to direct and optimize the grouting. This is to be warmly applauded given their earlier statement that "in Reclamation, drilling and grouting is the most thoroughly inspected construction which is performed on a dam project."
- Regarding staging practices, the competent rock available and selected for past sites was ideally suited to ascending stage operations, and this method has become the traditional standard (<u>Table 1</u>, <u>Figure 1</u>). Descending stage grouting is becoming more common, reflecting the challenges posed by more difficult site conditions in the remedial and hazardous waste markets. The work described by Weaver et al. (22) related to the sealing of dolomites under an old industrial site at Niagara Falls, NY, represents a statement of the best of American practice.

In some cases of extremely weathered and/or collapsing bedrock, even descending stage methods can prove impractical, and two recent projects illustrate innovative trends. Firstly, at Lake Jocassee Dam, SC, a remedial grouting project was conducted (16) to reduce major seepages through the Left Abutment of the dam. *Given the scope of operating within innovative contracting procedures*, the contractor was able to vary his methods in response to the extremely variable ground conditions actually encountered. Some holes permitted ascending stages, others needed descending stages, while the least stable had to be grouted through the rods during their slow withdrawal.

A second example is the grouting of poorly cemented hard rock backfill 2600 feet below ground level in a copper mine in Northern Ontario, Canada (23, 24). This medium proved so difficult to drill that none of the conventional grouting methods could be made to work. Instead, the first North American application of the MPSP system, devised by Rodio, in Italy, was called for. The Multiple Packer Sleeved Pipe System is similar to the sleeved tube (tube à manchette) principle in common use

	DOWNSTAGE	UPSTAGE
ADVANTAGES	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. 2. Depth of hole need not be predetermined: grout take analyses may dictate changes from foreseen, and shortening or lengthening of hole can be easily accommodated. 3. Stage length can be adapted to conditions as encountered to allow "special" treatment.	1. Drilling in one pass. 2. Grouting in one repetitive operation without significant delays. 3. Less wasteful of materials. 4. Permits materials to be varied readily. 5. Easier to control and program. 6. Stage length can be varied to treat "special" zones. 7. Often cheaper since net drilling output rate is higher.
DISADVANTAGES	1. Requires repeated moving of drilling rig and redrilling of set grout: therefore process is discontinuous and may be more time consuming. 2. Relatively wasteful of materials and so generally restricted to cement-based grouts. 3. May lead to significant hole deviation. 4. Collapsing strata will prevent effective grouting of whole stage, unless circuit grouting method can be deployed. 5. Weathered and/or highly variable strata problemmatical. 6. Packer may be difficult to seat in such conditions.	1. Grouted depth predetermined. 2. Hole may collapse before packer introduced or after grouting starts leading to stuck packers, and incomplete treatment. 3. Grout may escape upwards into (non-grouted) upper layers or the overlying dam, either by hydrofracture or bypassing packer. Smaller fissures may not then be treated efficiently at depth. 4. Artesian conditions may pose problems. 5. Weathered and/or highly variable strata problemmatical.

Table 1. Major advantages and disadvantages of downstage and upstage grouting of rock masses (Ref. 26).

for grouting soils and the softest rocks (25). The sleeve grout in the conventional system is replaced by concentric polypropylene fabric collars, slipped around sleeve ports at specific points along the tube (Figure 2). 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 potential is foreseen in loose, incompetent, or voided rock masses, especially karstic limestones (26).

As a final note, there remains considerable activity in bulk infill, principally associated with older, shallower mining operations in the Appalachians, and in Wyoming. Rotary and rotary percussive drills, often of water well drilling type, are common, with the void filling (either partial or total) being executed with cementitious grouts or concrete prepared in large scale site batching plants. Innovations are restricted to improved automated parametric recording and the development of special foamed grouts intended to extinguish mine fires.

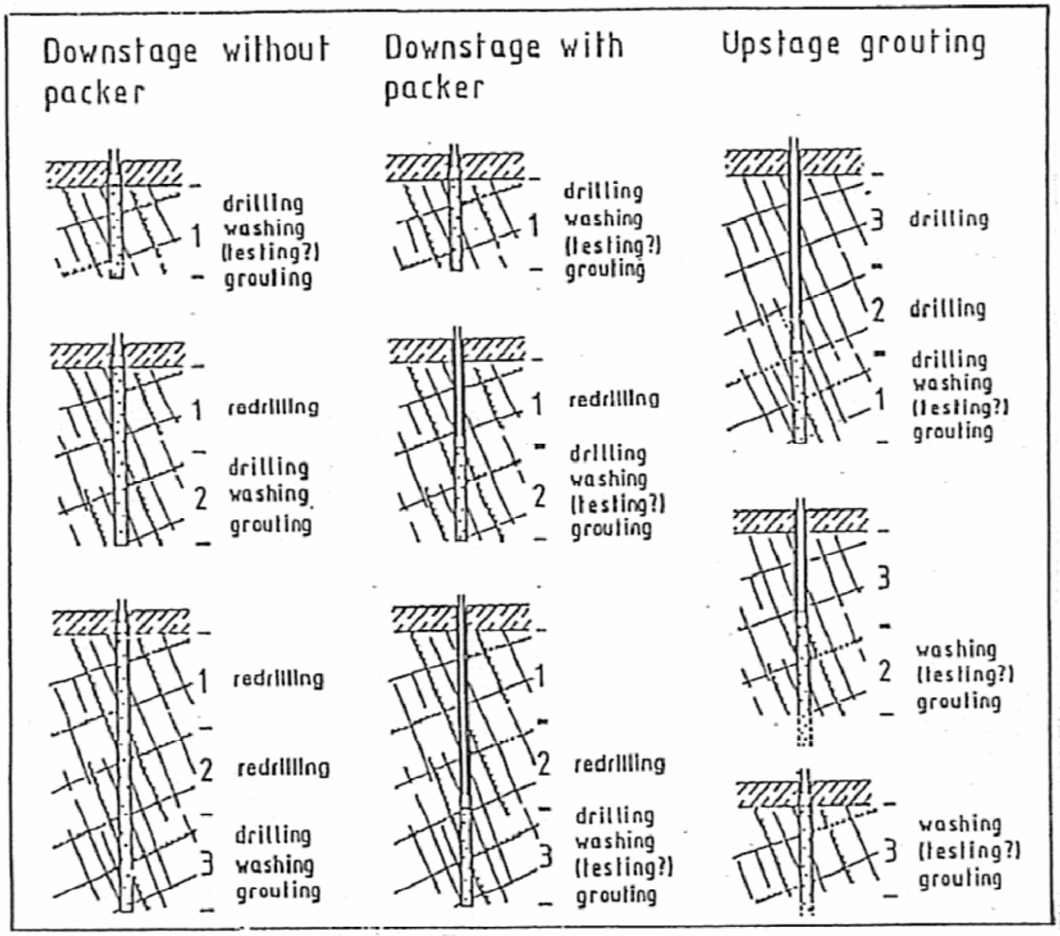


Figure 1. Conventional stage grouting methods for rock fissure grouting (After Ref. 2).

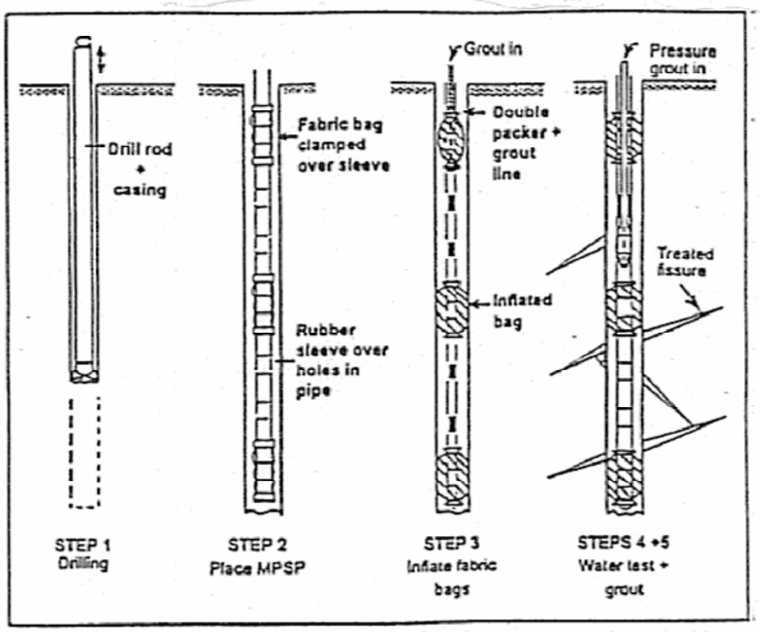


Figure 2. MPSP installation and grouting steps (Ref. 24)

Soil Grouting

Five fundamental categories of soil grouting methodologies are being used in the U.S. to various extents and the industry is rapidly evolving. Technological advances are being made by chemists, physicists and geotechnical engineers on the one hand, and are being prompted by the increasingly severe demands made by structural engineers, environmentalists and property developers on the other. Such has been the pace of recent developments that soil grouting is fast achieving the status of the "design tool, as it should be from the onset" (27) instead of a final remedial option when "conventional" techniques have failed.

(1) Permeation Grouting: probably the oldest and most widely used principle, covering a wide range of applications, materials and injection methods. Much of the smaller, simpler work is executed by end of casing injection (or lancing: Ref. 28) using cement based grouts. However, largely through the efforts of a limited number of specialty contractors, there has survived an important if sporadic market in sophisticated chemical grouting using the tube à manchette system (3). This has been executed principally in association with new Metro systems, and the major work conducted to prevent run-ins and control settlements during the subsequent excavation of the twin 20 feet diameter tunnels under the Hollywood Freeway in Los Angeles is a fine example of the state of practice (29). On this project, incidentally, a fire which occurred in the lining of the tunnel during its construction provided a unique (and successful) test of the surrounding treated ground.

Applications for dam grouting have been far less frequent, with the work described by Karol (3) at Rocky Reach Dam, Washington, in the late 1950's apparently remaining the largest. Smaller applications in remedial works are summarized by Bruce (30, 31).

(2) Compaction Grouting: this "uniquely American" process has been used since the early 1950's and is attracting an increasing range of applications. In summary, very stiff, "low mobility" grouts (32) are injected at high pump pressures (up to 600 psi) in predetermined patterns to increase the density of soft, loose or disturbed soil. When appropriate materials and grouting parameters are selected, the grout forms regular and controllable 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 (33).

Indeed, the earlier applications were largely for leveling slabs and light buildings on shallow foundations (34, 35). Prior to the pivotal Bolton Hill Tunnel project (4) compaction grouting had been used on such subway projects to compensate tunnel induced settlements after completion of the tunnel. The philosophy changed fundamentally at that time, however, so that grouting was executed during the excavation of the tunnel at locations just above the crown: soil decompressions were therefore prevented from migrating up to cause surface settlements. This principle has been adopted for more recent major tunnelling schemes including those in Phoenix (36) and currently on the Los Angeles Metro.

The popularity of the technique continues to grow, in no little way due to the active preachings of the "founding fathers", such as Warner (32) and Graf (37), and the lucid case histories presented openly by contemporary contractors such as Bandimere (38), Berry (39), Welsh, and their co-workers. The technique has now been exported to Japan and to Europe and so is the only native American grouting technique to be so recognized.

New important fields of application include the mitigation of liquefaction potential for dams (40), the combatting of sinkhole damage in karstic limestone areas (41), and talus slope stabilization (42).

Whereas the ASCE grouting conference in 1982 largely provided an overview of the past, the corresponding conference in 1992 provided insights into the future. For example, Schmertmann and Henry (43) unveiled a new design theory for constructing "compaction grout mats" in karstic conditions. Warner and colleagues (44) presented accounts of fundamental field and laboratory research into the basics of compaction grout, and the conclusions are regarded in certain circles as revolutionary. For example, they conclude that the "control of slump alone is <u>not</u> a valid means to assure adequate low mobility grout", and further that "irrespective of slump or pumpability" criteria, grouts that are too mobile can result in hydraulic fracturing of the soil and loss of control over the operation. High mobility can result from excessive clay and/or water, whereas the addition of coarse aggregate has been observed to be advantageous to rheology. They also found that injection rates should be maintained at less than 10 gal/min. to enhance the development of regularly shaped bulbs.

It is against this backdrop of opportunity and challenge that compaction grouting expands into its fifth decade of applications.

<u>(3) Hydrofracture Grouting:</u> the concept is that stable, high mobility cementitious 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. It has been rare to find this principle deliberately exploited outside the French grouting industry, although there is no doubt that the effects have often been achieved, unintentionally, in the course of other methods of grouting: Warner, as noted above has identified the possibility in compaction grouting operations, while Tornaghi et al. (45) note that hydrofracture *naturally* occurs with conventional cement-based grouts in soils with a permeability of less than 10^{-1} cm/sec.

Graf (46) has described recent tests conducted in the U.S. towards rationalizing certain parameters. Apparently polypropylene fibers have been incorporated into the grout to provide a degree of tensile and flexural strength to the grout bodies after setting. In California especially, certain contractors are actively promoting the application of "controlled fracture" grouting for applications involving slope stabilization, loose fill consolidation, expansive soil treatment and soft ground tunneling. Despite the potential, the term "controlled fracture" remains nevertheless for many American grouting engineers a contradiction in terms.

Most recently, however, tube à manchette techniques were used to reconstitute the clay core of Mud Mountain Dam, WA (47). Loose zones and voids had developed as defects in the core which then experienced severe hydraulic fracturing by the bentonite slurry being used in the attempted construction of a 420 feet deep diaphragm wall through the dam. Over 5000 c.y. of slurry were rapidly lost into the core while excavating the early panels, and the dam was longitudinally split. A phase of gravity grouting was first undertaken to fill the voids and fissures caused by the bentonite slurry. A program of "recompression" grouting was then undertaken to recompact the core and improve the soil stress conditions. "The recompression technique created soil cracks in multiple directions by hydraulically fracturing with grout forming structures that provided cohesion and resistance to further fracturing". Cement bentonite grouts were used with sodium silicate added to vary setting time from 2 to 60 minutes. Over 5000 c.y. of grouts were injected into over 19,000 l.f. of grout holes, and this remedial program, during which the drilling and grouting parameters were electronically monitored, "practically eliminated" slurry losses during the remainder of the diaphragm wall work, intended to seal the core.

(4) Jet Grouting: the tremendous upsurge in jet grouting throughout the world since the late 1970's has not been reflected by its rather subdued market volume in the U.S. This is despite the strong effort put forward by certain specialty contractors (48, 49), independent authorities (50), Federal agencies such as the Corps of Engineers and the Bureau of Reclamation (51), and educators at short courses.

Both the one-fluid (i.e., cement) and the three-fluid (i.e., cement, water and air) methods (Figure 3) have been used successfully in a range of applications including water cut-offs, structural underpinning (probably the most common), hazardous waste containment (52), pile support (53), and tunnel presupport (50). In the last named application, two significant case histories have to date been recorded: on the D.C. Metro, and on an Atlanta Metro tunnel under an active interstate highway. In Canada (54), jet grouting was even conducted through the core of an existing embankment dam as part of a seismic retrofit.

There are many obstacles in the path of universal application and acceptance. Firstly, it must be admitted that there have been disappointing applications to set against the successes: these have been perpetuated by some contractors who have allowed certain operational subtleties to escape them in the translation from the original German, Italian or Japanese; by other contractors whose advantage in high pressure grouting equipment has alone not been a match for the vicissitudes of low bid geotechnical contracting; and by certain engineers who have simply, but unfortunately, specified the wrong technique. Secondly, and as referred to in the Introduction, it is doubtful if the state and direction of the construction industry truly needs the particular advantages of jet grouting on a large scale. And thirdly, it would seem that most of the benefits which jet grouting can impart, can be supplied by other techniques (such as pinpiles or Soil Mixed Wall) at a considerably lower cost.

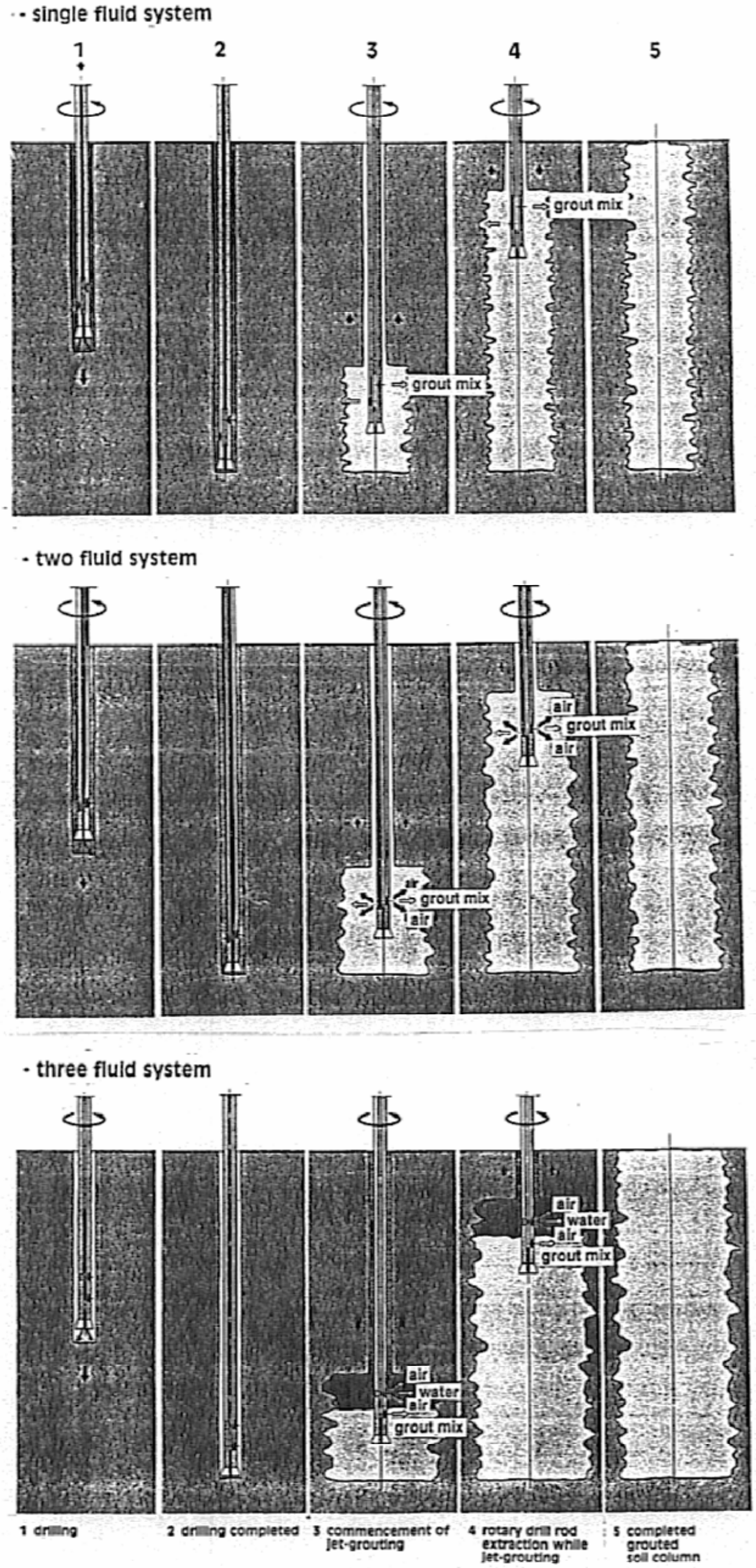


Figure 3. Three basic jet grouting systems.

From an American viewpoint, possibly the single biggest attraction of jet grouting is probably that it has the opportunity to be "designer driven". This would give it a unique position in an industry where experience and "feel" are key elements, and most of the knowledge - to universal suspicion - lies in the hands of the specialty contractors. In short, it could become a "by the book" technique, greatly reducing economic, technical, and operational risk, and providing a certain predictable level of reliability in the final product, even in the poorest soils.

It will be fascinating to see the outcome of this debate, for the market remains small but expectations and awareness remain high. The future could well be decided on the outcome of one major, high profile application: as grouters we trust it will be an extravagant success.

(5). Mechanical Mix in Place: by convention, this method typified by proprietary names such as SMW (Soil Mixed Wall), and DSM (Deep Soil Mixing) is not regarded as soil grouting, even though its origins are over 30 years old (55). However, it does fulfill certain criteria for inclusion in this review: it uses conventional cement based grouts; it certainly improves the mechanical and hydraulic properties of the treated soil; and, importantly, it is challenging conventional grouting methods in a wide range of applications. The fact that it does not feature injection, sensu strictu, into the soil is not sufficiently overbearing to delete it from discussion.

The method features the introduction of cementitious grouts down the stems of large diameter (20 to 40 inch) discontinuous flight augers (Figure 4) as they are rotated to target depth (5). Each rig may have multiple augers (up to a maximum of four), although the role of the central units is often just to encourage breakup of the soil by injecting air or water. A smaller amount of grout is placed during withdrawal of the auger. The result is the formation of soil-cement columns, which by proper selection of equipment and sequencing can be combined into continuous in-situ walls. Developments are being made with the injection of dry materials which react in place, e.g., the RODEM^{S} method (56).

Applications in the U.S. include support of excavation structural walls (when appropriately reinforced), waste containments, and hydraulic cut-offs for dams (Cushman Dam, Washington) and levees (Sacramento, California). The single largest example to date was for the seismic retrofit of Jackson Lake Dam, Wyoming. Here over 430,000 l.f. of columns were installed in a cellular, hexagonal pattern to improve the liquefaction resistance of a major dam foundation and a 230,000 s.f. curtain to a depth of 100 feet was similarly formed.

Mix in place methods are proving extremely competitive in appropriate conditions. Less attractive circumstances include a) very dense, bouldery or obstructed overburden, b) low headroom, difficult access, c) depths over about 100 feet (although 200 feet is claimed as the maximum), and d) projects of limited scope.

The advantages of the concept have been further exploited in the sister technique of SSM (Shallow Soil Mixing) wherein larger diameter mixing heads are used for fixing hazardous materials to depths of 6-25 feet (55). This system permits the use of dry reagents and an effective vapor collection apparatus. It can be

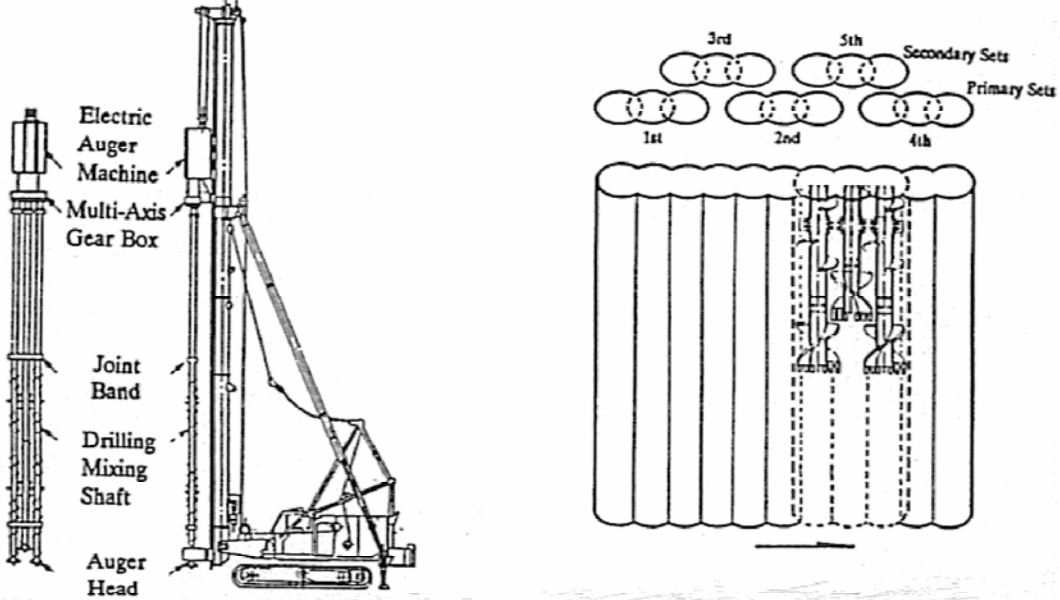


Figure 4. The concept of mechanical soil mixing (Ref. 5).

used with cementitious, chemical or even biological reagents as required. One variant uses steam or hot air to extract volatile pollutants from the subsoil (57, 58).

Outside the environmental market, however, there is considerable potential for the SMW technique, for it seriously threatens the former preserves of diaphragm walling, conventional "beams and lagging" support, jet grouted cut-offs, and a whole range of ground improvement technologies (including compaction grouting) which may be considered for liquefaction control.

MISCELLANEOUS TRENDS AND DEVELOPMENTS

Overburden Drilling

The continuing shift away from projects on prime hard rock sites has thrown greater demands on the skills of drillers now faced with the whole range of soils and artifical fill materials. All of the six generic techniques (59) are in use (Table 2), although history and habit ensure that not all are used by any one contractor, or in any one geographical region. Large diameter hollow stem augers are common for anchoring practice around the Lakes and on the West Coast, although problems have occurred when poorly controlled drilling practices have turned augers into screw conveyor belts causing considerable cavitation. Simple flushed casing, or rotary duplex are more common in the East, while the emergence or 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, although it still regarded in obsolescent quarters as the premier overburden drilling method.

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, and that the better contractors at least are adopting a refreshing degree of technical responsiveness. Despite the incrasing awareness of the potential benefits of automated drilling parameter recording

DRILLING METHOD	PRINCIPLE	COMMON DIAMETERS AND DEPTHS	NOTES
1. Single Tube Advancement			
a) Drive Drilling	Casing, with "lost point" percussed without flush.	2-4 in. to 100 ft.	Hates obstructions or very dense soils.
b) External Flush	Casing, with shoe, rotated with strong water flush.	4-8 in. to 150 ft.	Very common for anchor installation. Needs high torque head and powerful flush pump.
2. Rotary Duplex	Simultaneous rotation and advancement of casing plus internal rod, carrying flush.	4-8 in. to 200 ft.	Used only in very sensitive soil/site conditions. Needs powerful flush return. Needs high torque.
3. Rotary Percussive Concentric Duplex	As 2, above, except casing and rods percussed as well as rotated.	3-1/2 -7 in. to 120 ft.	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.	3-1/2 -8 in. to 200 ft.	Obsolescent, expensive and difficult system for difficult overburden. Largely restricted to water wells.
5. "Double Head" Duplex	As 2 or 3, except casing and rods rotate in opposite senses.	4-6 in. to 200 ft.	Powerful, newer system for fast, straight drilling in worst soils. Needs large hydraulic power.
6. Hollow Stem Auger	Auger rotated to depth to permit subsequent introduction of tendon through stem.	6-15 in. to 100 ft.	Hates obstructions, needs care in cohesionless soils. Prevents application of higher grout pressures.

1 in. = 25.4 mm
1 ft. = 0.305 m.

Table 2. Summary of overburden drilling methods for grout holes (59).

(60), the only known example was at Mud Mountain Dam (47) where the work was conducted by a European contractor. With an increasing emphasis being devoted to quality at all stages in the construction process, one must assume that the use of these recorders such as Papero or Empasol will become much more common over the next few years.

Materials

Microfine cement grouts were introduced into the United States in 1984. Manufactured in Japan, the earliest example (MC500) is a mixture of finely ground Portland cement and slag in the ratio of about 4:1 (3). It can be used like a conventional cement grout with 4-5 hour setting time, or with sodium silicate to accelerate set to 1-3 minutes. It has been used on many relatively small projects in North America.

Clarke, et al., (61) describe the use of two new products, MC300 (an ultrafine Portland of Greek origin) and MC100 (ultrafine slag) which can be mixed in varying amounts with dispersant to give a range of hardening times. Both are finer ground than MC500, and so have enhanced penetration potential. Other foreign manufactured materials are also available, including the aptly named "Stealth" grout. All these prebagged materials, however, despite their technical attractions, do share certain problems associated with availability, handling, preparation and cost, and much favorable attention has recently been focused on an alternative principle.

The Cemill[R] technology (62) permits microfine grouts to be produced, on site, from normal cement grouts, in a wet regrinding process. Excellent grain size characteristics are produced (Figure 5), resulting in enhanced penetrability characteristics (Figure 6). Yet to be exploited in the U.S., this method is proving highly successful - technically and economically, in Italy.

	grain size (μmm)					
	D 95	D 85	D 60	D 50	D 15	D 10
CEMILL® 6	15.0	9.0	6.0	5.0	1.3	0.9
CEMILL® 9	9.0	5.5	3.5	2.5	0.6	0.4
CEMILL® 12	6.0	4.0	3.0	2.2	0.4	0.3
ONODA MC-500	8.0	60.0	4.5	4.0	2.5	2.0
Portland 525	40.0	22.0	11.0	8.0	2.5	2.0
bentonite	60.0	40.0	15.0	10.0	1.7	1.2

(a) (b) (c) sands for injection tests
(a) $\gamma = \gamma_{max} = 1.713$ g/cm³
(b) $\gamma = \gamma_{max} = 1.701$ g/cm³
(c) $\gamma = \gamma_{max} = 1.690$ g/cm³
(d) bentonite
(e) Portland 525 cement
(f) ONODA MC-500 cement
(g) (h) (i) CEMILL® mixes

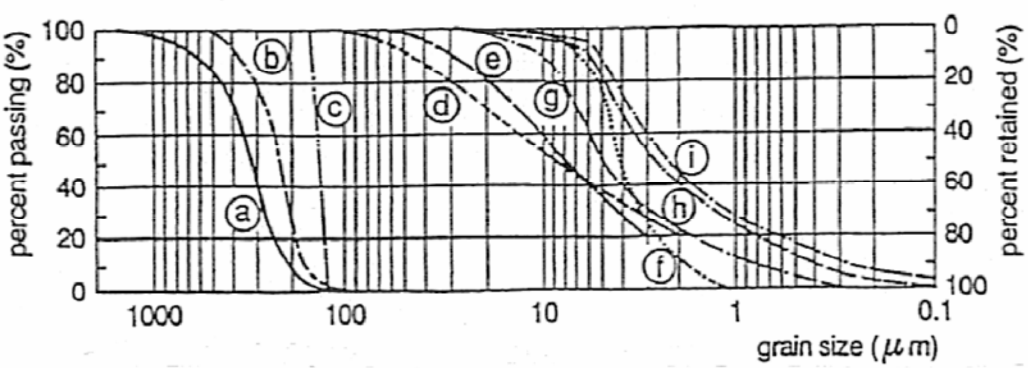
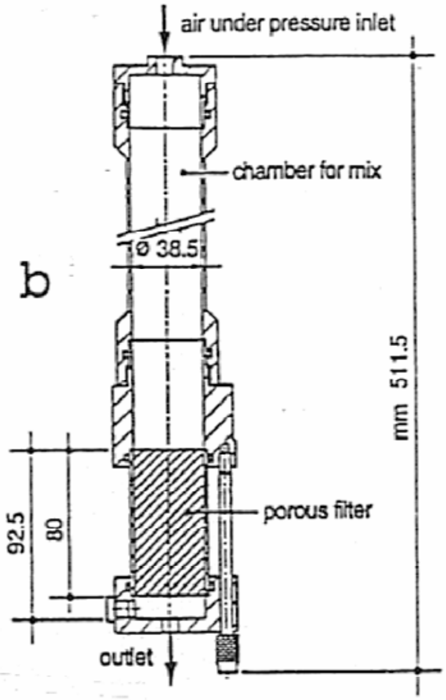


Figure 5. Grain size distribution curves for sands, dry materials and grouts (62)

filter no.	permeability (m/s) theoretical Hazen (C = 1.45)	permeability (m/s) experim. (permeam.)	grain size (μm) D 95	D 60	D 15	D 10	U	porosimetry (μm) theoretical (Kozeny) D 80	D 50	D 30	porosimetry (μm) experim. (Hg porosimetry) D 95	D 85	D 15	D10	specific surface cm^2/g	retaining capacity (μm)
07	$5.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	1500	900	700	640	1.41	300	240	150	380	300	170	160	28	70
06	$2.3 \cdot 10^{-3}$	$8.3 \cdot 10^{-4}$	750	620	450	400	1.55	160	133	90	360	260	130	124	37	60
04	$7.7 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$	700	480	250	230	2.09	110	90	60	300	140	70	64	56	40
01	$2.8 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	400	230	160	140	1.64	58	49	32	120	64	46	44	111	10
005	$1.4 \cdot 10^{-4}$	$9.5 \cdot 10^{-5}$	180	120	110	100	1.20	35	25	18	90	46	32	30	125	5

a



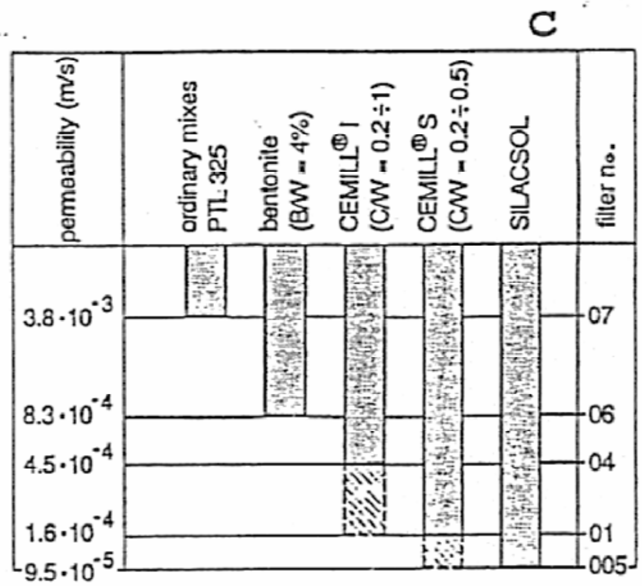


Figure 6. Injection test details: a) porous stone filter characteristics, b) apparatus, and c) penetrability limit of different mixes into filters (62).

Equally attractive to the U.S. market is the concept of improving the penetrability of cementitious grouts by fundamentally examining their rheological and internal stability characteristics. The Mistra[R] series of grouts (63) has already been successfully exploited in Europe (64) and provides extremely stable mixes with greatly reduced cohesion (Figure 7). Both these features generate major technological and economical benefits, and the concept is attracting favorable interest in the U.S.

Regarding chemical grouts, and as noted in the Introduction, sodium silicate bases remain the most popular for general purpose. Other materials such as phenoplasts, aminoplasts, chrome lignins and acrylamides are well known in the U.S. (3) but are not very common due to environmental concerns, and, simply, cost. Urea formaldehydes have been used (65) but require meticulous preparation and may not always be permitted by "regulatory circumstances" (1). Several specialty formulators are promoting a variety of polyurethane grouts, and water reactive prepolymers, but to date their application has been somewhat limited by cost to small (albeit very challenging) applications.

The Environmental Protection Agency is considering a ban on acrylamides and methylolacrylamide grouts currently used extensively in rehabilitation of sewer lines and manholes, while

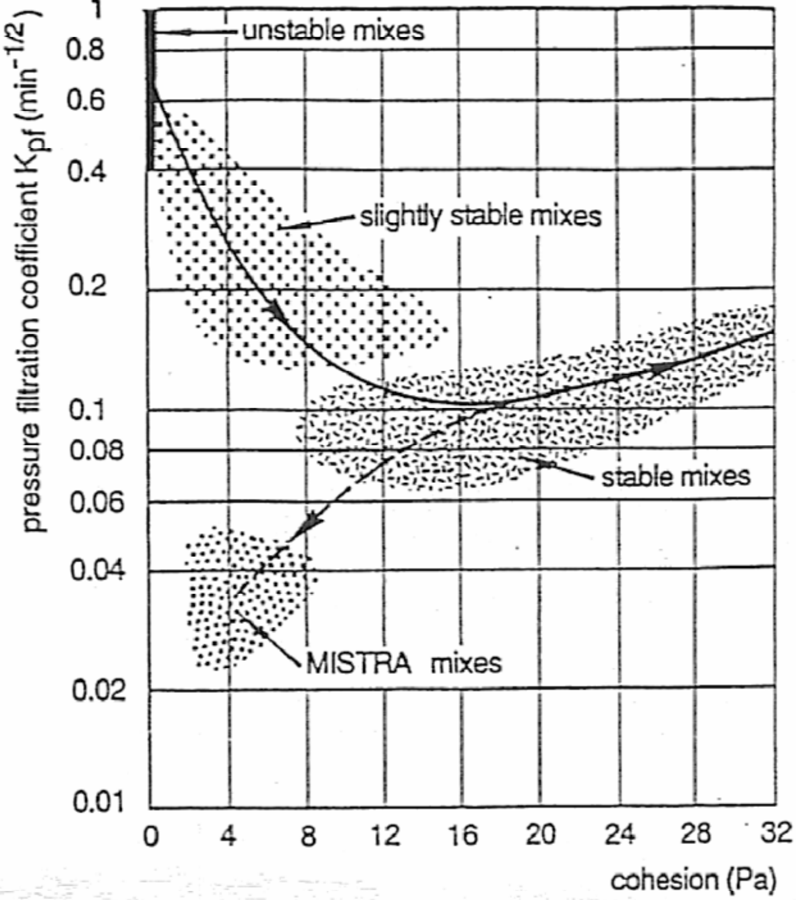


Figure 7. Relationship between stability under pressure and cohesion for the different types of mixes (63).

according to McIntosh (66), a possible acrylate monomer replacement, AC-400, "has essentially been rejected by the industry" despite attracting the interest of excellent research efforts (67). The use of epoxy resins has been limited to the structural repair of concrete structures (68) while there remains a sporadic market (30) for hot asphalt injection for the interim sealing of fast and large seepages.

Research and Development

Innovation is largely driven by the specialty contractors and the materials suppliers, all of whom are seeking crucial competitive edges, and so do not initially publicize all the details of their researches. This proprietary cloak appears to work for a few years before the secrets gradually are exposed, or are given away through publication and other commercial promotion. Thereafter it is largely the government agencies and the universities who sponsor and conduct programs, although the latter are most often restricted by resources to documenting material properties.

However, the impact of the universities remains formidable, as witnessed by the NSF sponsored work at a group of mid-west centers header by Northwestern, into fundamental aspects of cement grout technology. This group, led by Dr. Krizek, has already made major contributions (e.g., New Orleans, 1992) while Dr. Borden's group at North Carolina is equally active in sodium silicate studies and Professor Karol's efforts have made Rutgers another center of excellence in this field.

Significant advances are also being made into cement grout technology at the Bureau of Reclamation, the Corps of Engineers, and at Sandia National Laboratories, New Mexico (in association with Atomic Energy of Canada in Manitoba).

Professional organizations bodies such as the grouting committees of ASCE, ACI and ASTM are also very active in disseminating information and encouraging future developments while American based engineers have initiated a new committee within ISSMFE devoted to grouting and related geosystems. Major national conferences provide regular opportunities for review and discussion. Another key facility is the annual short course format, such as organized by the University of Missouri - Rolla (since 1979) and the University of Wisconsin - Milwaukee (since 1988). These courses are taught by specialists in grouting from industry and academia and are important learning and sharing opportunities. Often these instructors are prolific technical authors, and such courses have given birth to recent books such as by Houlsby (2) and Weaver (1) which are of critical importance to an American grouting industry in metamorphosis.

Contracting Practices

Weaver (1) lists the elements necessary for a successful grouting project as follows:

- a design accommodating the site geological conditions;
- specifications that allow or facilitate modifications to the grouting program as the site conditions are revealed;
- an "experienced, competent, cooperative and honest" contractor;
- appropriate materials, equipment and techniques;
- knowledgeable inspection staff, and
- an effective quality assurance program.

While reviewing the history of grouting in the U.S., however, it is clear that rarely have these elements been simultaneously in place. The author believes that there are two fundamental reasons: inflexible specifications, and "low bid" procurement systems.

Regarding specifications, these must "be tailored to the project in hand and to the objectives to be accomplished" (1). Instead, successive generations of specifications have been cobbled together from sections lifted from previous documents, and often contain "boiler plate" sections which may be contradictory and always perpetuate the use of outmoded procedures and/or inappropriate materials. Specifications of this nature have dissuaded domestic contractors from innovating and have discouraged foreign specialists from competing.

The procurement system has proved equally stifling: the low bidder on a tightly specified job invariably wins the award, although he then operates as little more than a broker of labor, equipment and materials. However, in recent years there have been encouraging signs that a more enlightened approach is surfacing.

As a first step, stronger prequalification criteria are being applied to prospective bidders and their personnel. Specifications are being changed to "performance" types, so encouraging bidders to be creative and innovative, and most significantly, awards are being made not just on the basis of a low bid (7). In addition, many owners, including federal agencies, are promoting the concept of having "partnering" agreements between all the involved parties. This concept is a recognition that every contract includes an implied covenant of good faith. The process attempts to establish working relationships through a mutually developed formal strategy of commitment and communication. It tries to create an environment where trust and teamwork prevent disputes, improve quality, promote safety and continue to facilitate the execution of a successful project. Significantly, it is wholly endorsed by the Associated General Contractors of America, a group which has not always favored the more innovative procurement procedures.

Two recent examples can be cited to illustrate the operation and benefits of these newer contracting practices. The first example is the rock anchoring project recently completed at Stewart Mountain Dam, Arizona (69). This very delicate but critical dam stabilization was studied by the owner, the Bureau of Reclamation, for many years, during which time they interviewed various specialists from all facets of the anchorage industry. The result was a very challenging specification which set well defined targets but allowed the bidders a great deal of scope for original thought. Each bidder had to submit a very detailed Technical Proposal, which was closely graded by a Government team of specialists. A separate Price Proposal was submitted, but this was adjudicated by an independent group. The results were then combined, with a heavy weighting placed on the score from the Technical Proposal. As a result, the best qualified responsive contractor was chosen, having been encouraged to write and price an individual and extremely detailed method statement. In every respect the project was a stunning success, and was completed within program, under budget and without a hint of litigation.

The second illustration is a much smaller remedial grouting operation, also undertaken by Nicholson, at Lake Jocassee Dam, South Carolina (16). Seepage through the Left Abutment of this high embankment structure had to be addressed by the owner, Duke Power following an intervention by the Federal Energy Regulatory Commission. Again, a performance specification was set and a small number of prequalified contractors were permitted to bid. Again, a strong technical proposal proved crucial to securing the award. Using the new approach of "Responsive Integration^{SM}", the seepage was greatly reduced and the grouting deemed a major, and (in the light of previous local experience) surprising success.

Similar contracting and procurement principles have also recently been exploited at major remediation projects at Horse Mesa Dam, Arizona, and at the United Grain Terminal, Port Vancouver, Washington - to mutual advantage.

FINAL REMARKS

To many eyes, the American grouting market is perceived as extremely conservative and invariably parochial. However, there are strong signs that things are changing. One can cite the impact of foreign specialists, local "points of light", an active conference and training circuit, increasingly challenging applications and more enlightened contracting procedures. The consequence is that more grouting work is being conducted more effectively and with less legal intervention. This bodes well for the industry in the U.S. as it continues its path towards urban and industrial rehabilitation and infrastructure development and remediation.

ACKNOWLEDGEMENTS

The author welcomes this opportunity to cite the published works of his colleagues throughout the American grouting industry. He apologizes for the numerous oversights and the frequent generalizations, but hopes his sources will understand the restrictions which space enforces.

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