CURRENT TECHNOLOGIES IN GROUND TREATMENT AND IN-SITU REINFORCEMENT

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ABSTRACT

Ground treatment by grouting has been conducted in the United States since the nineteenth century, although most of the techniques used for soils have been imported much more recently. The principles of in-situ ground reinforcement featuring the use of small diameter soil nails or pinpiles have only been exploited for the last 25 years of so, but already provide a potent tool for the foundation engineer. This paper summarizes the state of practice in both ground treatment and reinforcement at a time when significant developments are occurring in each category, aided by the evolution of innovative contracting and procurement processes.

1. INTRODUCTION

According to Weaver (1991), the first application of rock grouting for consolidation was at New Croton Dam, NY, in 1893, while the first hydraulic cut-off was executed at Hinkston Run Dam, PA, in 1901. By the mid-thirties, major works were being carried out (e.g. at Hoover (Boulder) Dam) under specifications and practices which "quickly became the unofficial grouting standards" (Karol, 1990) and have in part persisted to the present day.

Soil grouting by permeation with chemicals only truly emerged in the fifties, by which time compaction grouting had been conceived by Warner and co-workers (Warner, 1982). Jet grouting was imported in the early eighties, followed by mechanical mix-in-

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place methods such as SMW Seiko. Most recently hydrofracture grouting has been heavily promoted, especially on the West Coast.

Despite this long history of usage, and the impressive scale and complexity of many of the works, grouting in some quarters still has a less than flattering reputation, totally at odds with its standing in other countries as a valued and respectable engineering tool. Frequently one meets owners who feel duped by grouting contractors, whom, of course they have elected to pay by the bag mixed and not the end 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 had turned to it when all else had failed and the situation had totaly deteriorated, both technically and contractually. In short, one can summarize this poor reputation as arriving from bad conception, poor execution and inappropriate contracting and procurement practices.

Construction activities in the United States are now becoming much more amenable to the benefits of grouting, as the market expands towards urban, industrial, and infrastructure development and redevelopment. Many of these activities have to be conducted in areas of difficult soil and hydrogeological conditions, restricted access and severe performance criteria. There is therefore a rapidly growing demand for innovative techniques and methods, often offered by specialty contractors, backed by European or Japanese resources. These new approaches, aided by more appropriate contracting and procurement practices, are helping elevate the status of grouting, so that it is being more widely perceived as a reliable engineering tool from the onset, rather than a last resort when all else has been tried and failed. This paper provides an overview of current practice in each of the major grouting methodologies.

Another aspect of ground engineering technology is the principle of in-situ earth reinforcement. As identified by Bruce and Jewell (1986) three basic classes can be recognized (Figure 1):

a) Soil nailing refers to reinforcing elements installed horizontally or sub-horizontally into the cut face, as top down staged excavation proceeds. The inserts improve the shearing resistance of the soil by being forced to act in tension.

b) Recitulated pinpiles are similar inserts, but steeply inclined in the soil at various angles, both perpendicular and parallel to the wall face. The overall aim is to provide a stable block of reinforced soil to act as a gravity retaining structure, holding back the soil behind.

c) Soil dowelling is applied to reduce or halt downslope movements on well defined shear surfaces. The principle exploits the large lateral surface bearing area and high bending stiffness of the dowels that are of far larger diameter than nails or pinpiles. The use of soil dowelling is rare in urban environments, although it can prove attractice when combined with linked deep drainage in arresting massive land movements (e.g., in eastern Italy and southern California). (Bianco and Bruce, 1991).

Soil nailing is primarily used in excavation or cut slope support and has become very popular, well documented and well researched (ASCE, 1987) in the United States. Dowelling is equally as well known, although has a less frequent application. Reticulated pinpiles, however, are a relatively recent development. These bored, cast in place elements are from 4-8" in diameter. The composite soil-pile structure then constitutes an in-situ barrier to arrest actual or potential slope movements.

When this structure is considered in cross section, it somewhat resembles a letter 'A', and so is popularly referred to as Type A Wall. Important advances are being made (Bruce, 1992b; Pearlman et al., 1992) towards creating more rational design

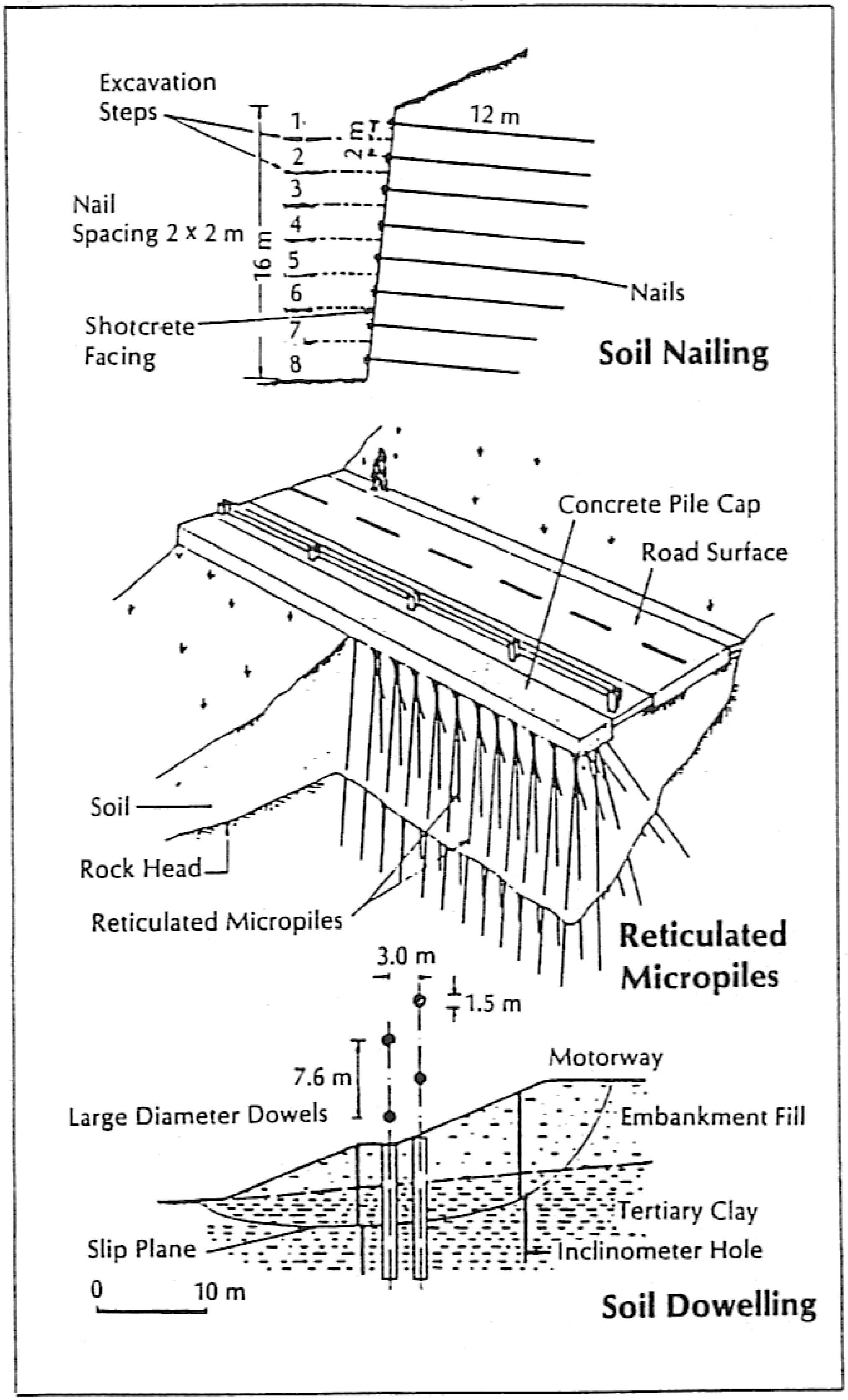


Figure 1. The family of in-situ soil reinforcement techniques. (Bruce and Jewell, 1986)

methodologies. Given the considerable potential of Type A Walls, they are therefore the subject of the latter part of this paper.

2. GROUND TREATMENT

2.1. 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 (1990) and Weaver (1991) 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 (Anthony, et al., 1992). In addition, the technical demands of grouting new sites of difficult geology (Aberle, et al., 1990) and the increasing amount of remedial grouting at existing sites (Bruce, 1990) 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 (Houlsby, 1990; Bruce, et al., 1991a).
- Water testing is not so rigorously or intensely conducted

as, for example, Houlsby 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 (USCOE, 1984; USBR, 1984, 1987) 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 (Deere and Lombardi, 1985) 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 (Aberle, et al., 1990). 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. 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. 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. (1992) relating 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 (Bruce, et al., 1992) 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 2800 ft 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. 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 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 pipe (Figure 2). After placing the pipe 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 (Bruce and Gallavresi, 1988).

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.

2.2 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

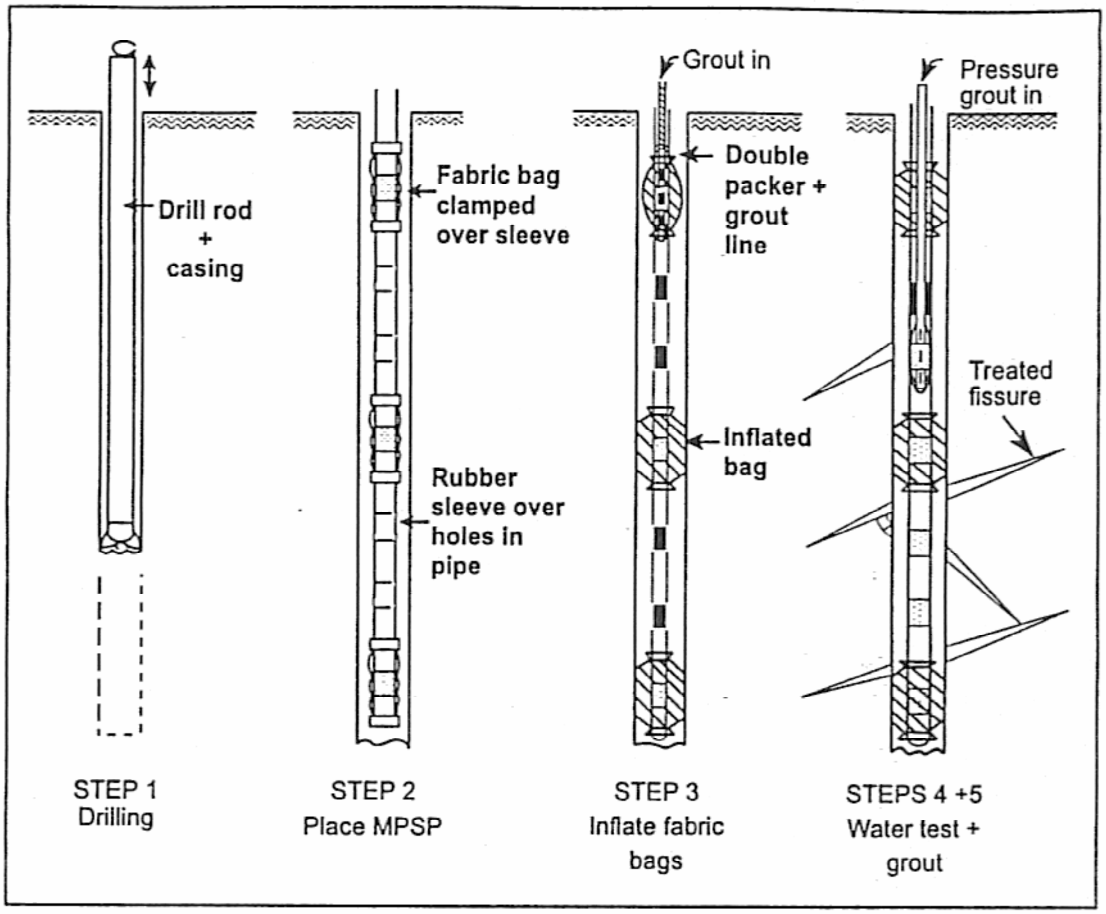


Figure 2. The MPSP grouting method.

RHEOLOGICAL CLASS	PARTICULATE SUSPENSIONS (BINGHAMIAN FLUIDS)			SOLUTIONS (NEWTONIAN FLUIDS)			GASEOUS EMULSIONS	
	UNSTABLE	STABLE		COLLOIDAL SOLUTIONS (EVOLUTIVE)		PURE SOLUTIONS (NON-EVOLUT.)		
MAIN TYPES OF GROUTS				CHEMICAL GROUTS			SWELLING GROUTS	
	CEMENT ONLY	CEMENT WITH BENTONITE OR CLAY	DEFLOCCULATED BENTONITE	BASED ON SODIUM SILICATE		BASED ON ORGANIC RESINS	BASED ON CEMENT	BASED ON ORGANIC PRODUCTS
				HIGH STRENGTH	MEDIUM-LOW STRENGTH			
FIELDS OF APPLICABILITY	FISSURED ROCK AND MASONRY			MICRO-FISSURED AND POROUS ROCK			LARGE VOIDS OR CAVITIES	CAVITIES WITH FAST FLOWING WATER
		GRANULAR SOILS						
		PREVAILING GRAVEL	COARSE SANDS	MEDIUM-FINE SANDS		FINE SILTY SANDS (SANDY SILTS)		
COEFFICIENT K OF PERMEABILITY (m/s)		$> 5.10^{-4}$	$> 5.10^{-5}$	$> 5.10^{-5}$	$> 1.10^{-5}$ ①	$> 1.10^{-6}$ ②		
SPECIFIC SURFACE S_s (m²/N)		< 0.5	< 1.5	< 1.5	< 4	< 10		
BASIC INJECTION PRINCIPLES	HIGH PRESSURE	CONTROLLED QUANTITY AND PRESSURE					LOW PRESSURE (FILLING)	

① LIMIT GOVERNED BY VISCOSITY/TIME EVOLUTION ② NORMAL LIMIT FOR UNIFORM IMPREGNATION

Figure 3. Classification of grouts related to groutable media. (Gallavresi, 1992)

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" (Clough, 1981) 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 (Figure 3). Much of the smaller, simpler work is executed by end of casing injection (or lancing: Bruce, 1989) 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 (Karol, 1990). 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 ft. diameter tunnels under the Hollywood Freeway in Los Angeles is a fine example of the state of practice (Gularte, et al., 1992). 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 (1990) at Rocky Reach Dam, Washington, in the late 1950's apparently remaining the largest. Smaller applications in remedial works are summarized by Bruce (1990, 1992a).

(2) Compaction Grouting: this "uniquely American" process has been used since the early 1950's and is still attracting an increasing range of applications. In summary, very stiff, "low mobility" grouts (Warner, 1992) are injected at high pump pressures (up to 500 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 (1983).

Indeed, the earlier applications were largely for leveling slabs and light buildings on shallow foundations (ASCE, 1977; Warner, 1982). Prior to the pivotal Bolton Hill Tunnel project (Baker, et al., 1983) 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 (Lyman, et al., 1988) 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 (1992) and Graf (1992), and the lucid case histories presented openly by contemporary contractors such as Bandimere (Sealy and Bandimere, 1987), Berry (Berry and Grice, 1989), 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 (Salley, et al., 1987), the combatting of sinkhole damage in karstic limestone areas (Welsh, 1988), and talus slope stabilization (Weaver, 1989).

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 (1992) unveiled a new design theory for constructing "compaction grout mats" in karstic conditions. Warner and colleagues (1992) 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 not 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 gallons/minute to enhance the development of regularly shaped bulbs.

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

(3) Hydrofracture Grouting: 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. (1988) note that hydrofracture *naturally* occurs with conventional cement-based grouts in soils with a permeability of less than 10^{-3} m/sec.

Graf (1990) 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 (Eckerlin, 1992). 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 450 ft. deep diaphragm wall through the dam. Over 5000 yds^3 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 yds^3 of grouts were injected into over 19,000 ft 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.

<u>(4) Jet Grouting:</u> 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 excellent effort put forward by certain specialty contractors (Burke, et al., 1989; Welsh and Burke, 1991), independent authorities (Kauschinger, et al., 1992), Federal agencies such as the Corps of Engineers and the Bureau of Reclamation (Paul, 1988), and educators at short courses.

Both the one-fluid (i.e., cement) and the three-fluid (i.e., cement, water and air) methods have been used successfully in a range of applications including water cut-offs, structural underpinning (probably the most common), hazardous waste containment (Gazaway and Jasperse, 1992), pile support (Andromalos and Gazaway, 1989), and tunnel presupport (Kauschinger, et al., 1992). 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 (Imrie, et al., 1988), jet grouting was even conducted through the core of an existing embankment dam as part of a seismic retrofit program.

There are many obstacles in the path of universal application and acceptance. Firstly, it must be admitted that there have been disappointing experiences 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.

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 (Jasperse and Ryan, 1992). 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 (22 to 40 inches) discontinuous flight augers as they are rotated to target depth (Figure 4). Each rig may have multiple augers (up to a maximum of four), although the role of the central units is often just to encourage

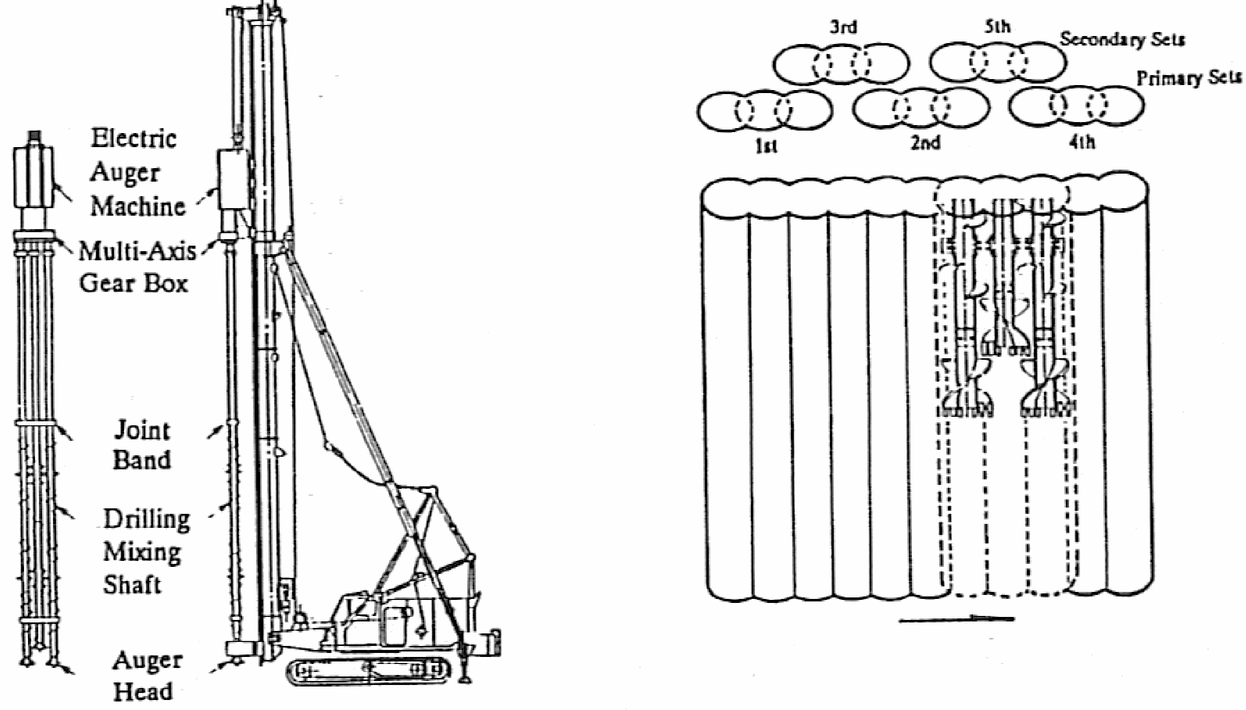


Figure 4. Equipment and procedure for SMW system. (Taki and Yang, 1991)

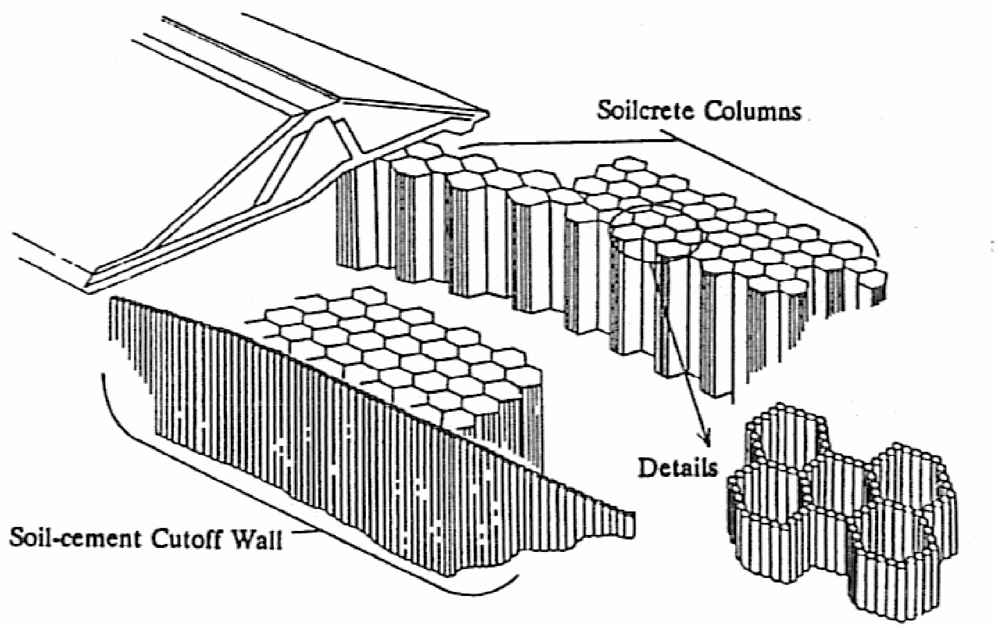


Figure 5. Soil-cement mixing work for Jackson Lake Dam modification project. (Taki and Yang, 1991)

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 (Rodio, 1992).

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 lin. ft. of columns were installed in a cellular, sexagonal pattern to improve the liquefaction resistance of a major dam foundation and a 230,000 ft^2 curtain to a depth of 105 ft. was similarly formed (Figure 5).

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 ft. (although 200 ft. 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 7-25 ft. (Jasperse and Ryan, 1992). This system permits the use of dry reagents and an effective vapor collection apparatus. It can be used with cementitious, chemical or even biological reagents as required. One variant uses steam or hot air to extract volatile pollutants from the subsoil.

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.

2.3 Miscellaneous Trends and Developments

There are many other aspects of the drilling and grouting market which are undergoing rapid and important development. As detailed at the ASCE Specialty Conference on Grouting, Soil Improvement and Geosynthetics, held at New Orleans, LA, in February 1992, and as summarized by Bruce (1992c) these can be categorized as follows:

- Improvement in the various types of overburden drilling equipment and methods (Table 1), and a greater inclination amongst the drilling community to free themselves from local or traditional paradigms in selecting the most apposite approach to each site's demands.
- Microfine *cements* have been imported into the States since 1984 and have been well marketed (Clarke et al., 1992) and researched (e.g., Schwarz and Krizek, 1992). There remain, however, certain problems associated with timely availability (in large quantities), handling, preparation and cost, and much favorable attention has recently been focused on an alternative principle.

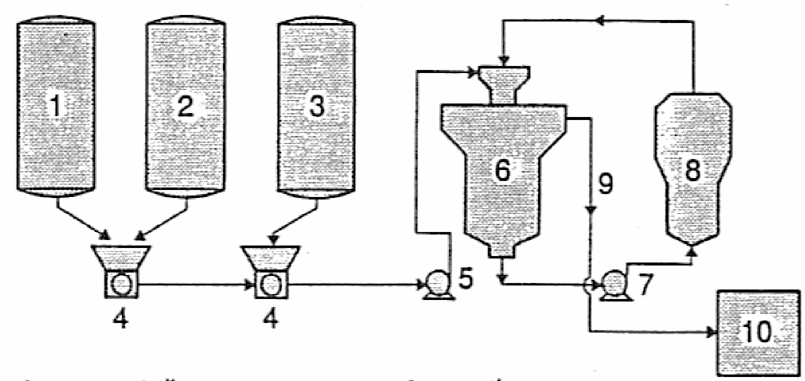
The Cemill® technology (DePaoli, et al., 1992a) permits microfine grouts to be produced, on site, from normal cement grouts, in a wet regrinding process (Figure 6). Excellent grain size characteristics are produced (Figure 7), resulting in enhanced penetrability characteristics (Figure 8). Yet to be exploited in the U.S., this method is proving highly successful - technically and economically, in Italy.

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

DRILLING METHOD	PRINCIPLE	COMMON DIAMETERS AND DEPTHS	NOTES
1. Single Tube Advancement a) Drive Drilling	Casing, with "lost point" percussed without flush.	2-4" TO 100'	Hates obstructions or very dense soils.
b) External Flush	Casing, with shoe, rotated with strong water flush.	4-8" to 150'	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" to 200'	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.	3-1/2 -7" to 120'	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" to 200'	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" to 200'	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" to 100'	Hates obstructions, needs care in cohesionless soils. Prevents application of higher grout pressures.

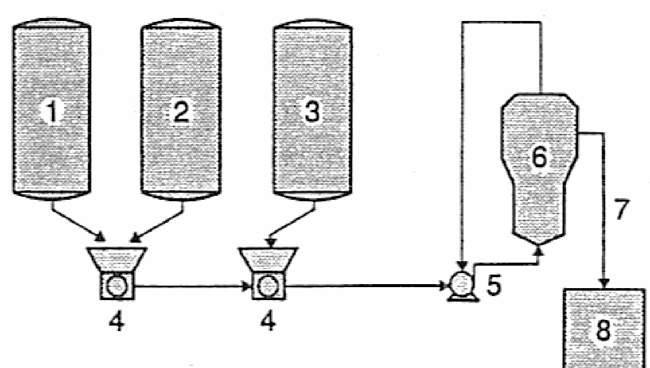
Table 1. Summary of overburden drilling methods.

a



1 cement silo
2 water tank
3 additive silo (optional)
4 mixers
5 starting mix inlet
6 continuous separator
7 recirculation pump
8 colloidal refiner
9 CEMILL® I mix exit
10 storage tank

b



1 bentonite silo
2 water tank
3 cement silo
4 mixers
5 recirculation pump
6 colloidal refiner
7 CEMILL®S mix exit
8 storage tank

Figure 6. Layout of production plants for (a) CEMILL-I (unstable grouts) and (b) CEMILL-S (stable grouts). (DePaoli et al., 1992a)

	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

ⓐ ⓑ ⓒ sands for injection tests
ⓐ $\gamma = \gamma_{max} = 1.713$ g/cm^3
ⓑ $\gamma = \gamma_{max} = 1.701$ g/cm^3
ⓒ $\gamma = \gamma_{max} = 1.690$ g/cm^3

ⓓ bentonite
ⓔ Portland 525 cement
ⓕ ONODA MC-500 cement
ⓖ ⓗ ⓘ CEMILL® mixes

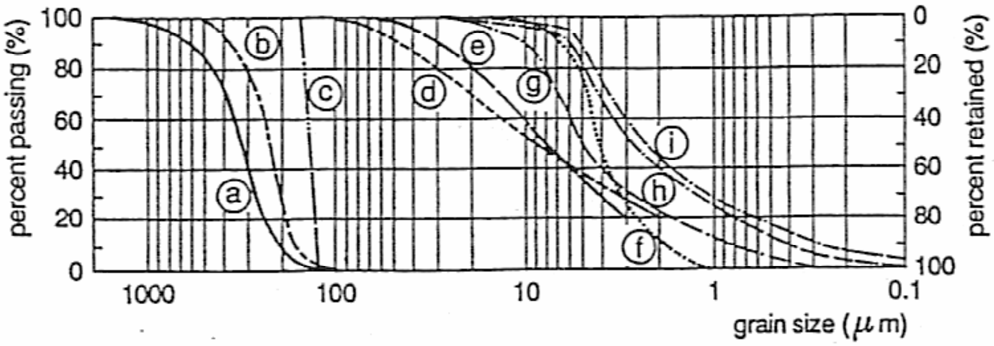
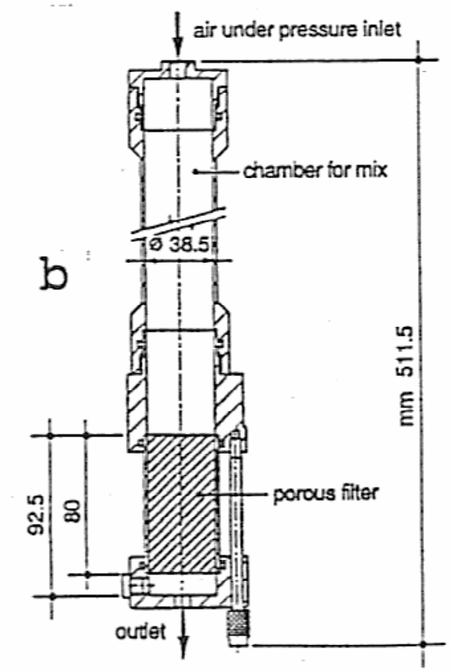


Figure 7. Grain size distribution curves for sands, dry materials and grouts. (DePaoli et al., 1992b)

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	experim. (Hg porosimetry) D 95	D 85	D 15	D10	specific surface cm²/g	retaining capacity (μm)
07	$5.9\cdot10^{-3}$	$3.8\cdot10^{-3}$	1500	900	700	640	1.41	300	240	150	380	300	170	160	28	70
06	$2.3\cdot10^{-3}$	$8.3\cdot10^{-4}$	750	620	450	400	1.55	160	133	90	360	260	130	124	37	60
04	$7.7\cdot10^{-4}$	$4.5\cdot10^{-4}$	700	460	250	230	2.09	110	90	60	300	140	70	64	56	40
01	$2.8\cdot10^{-4}$	$1.6\cdot10^{-4}$	400	230	160	140	1.64	58	49	32	120	64	46	44	111	10
005	$1.4\cdot10^{-4}$	$9.5\cdot10^{-5}$	180	120	110	100	1.20	35	25	18	90	46	32	30	125	5

a

b



c

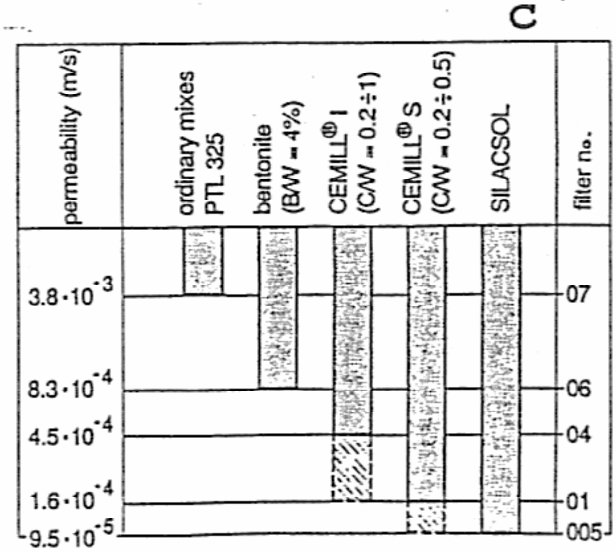


Figure 8. Injection test details: a) porous stone filter characteristics, b) apparatus, and c) penetrability limit of different mixes into filters. (DePaoli et al., 1992b)

characteristics. The Mistra[R] series of grouts (DePaoli, et al., 1992b) has already been successfully exploited in Europe (Mongilardi and Tornaghi, 1986) and provides extremely stable mixes with greatly reduced cohesion (Figure 9). Both these features generate major technological and economical benefits, and the concept is attracting favorable interest in the U.S.

Regarding chemical grouts, 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. (Karol, 1990) but are not very common due to environmental concerns, and, simply, cost. Urea formaldehydes have been used (Graf, et al., 1985) but require meticulous preparation and may not always be permitted by "regulatory circumstances" (Weaver, 1991). 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 according to McIntosh (1992), a possible acrylate monomer replacement, AC-400, "has essentially been rejected by the industry" despite attracting the interest of excellent research efforts (Schwarz and Krizek, 1992). The use of epoxy resins has been limited to the structural repair of concrete structures (Bruce and DePorcellinis, 1991) while there remains a sporadic market (Bruce, 1990) for hot asphalt injection for the interim sealing of fast and large seepages.

3. IN SITU EARTH REINFORCEMENT: TYPE A WALL

3.1 General Features

Early applications of conventional, axially loaded pinpiles

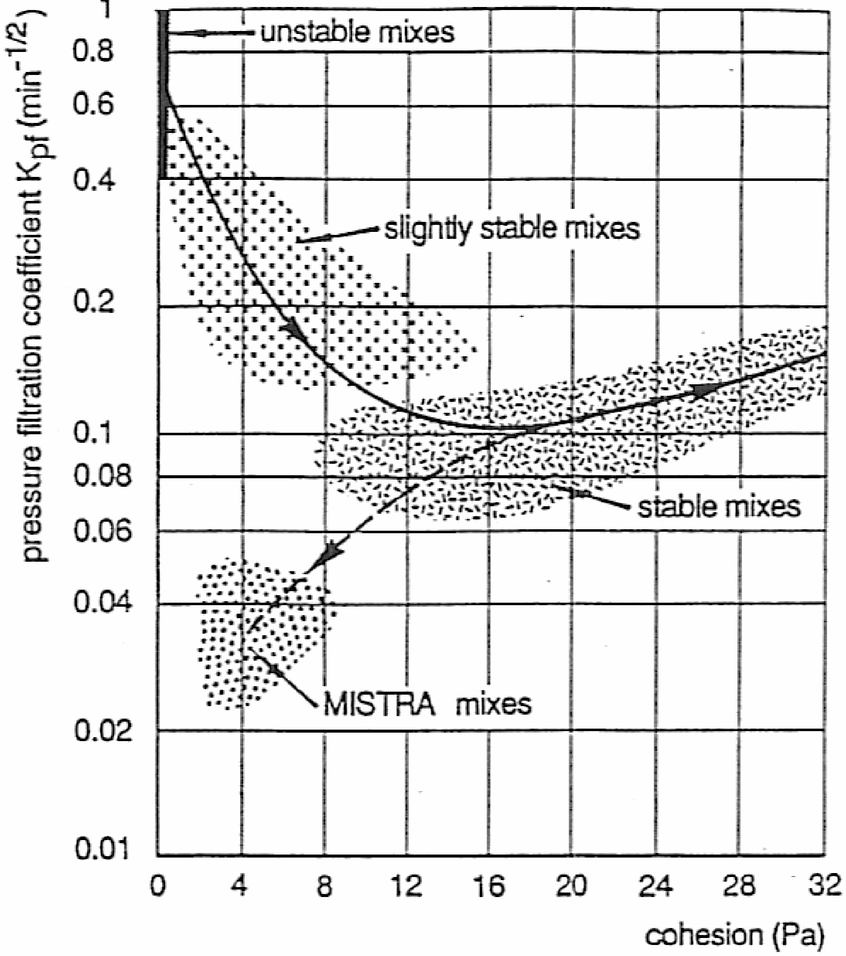


Figure 9. Relationship between stability under pressure and cohesion for the different types of mixes. (DePaoli et al., 1992a)

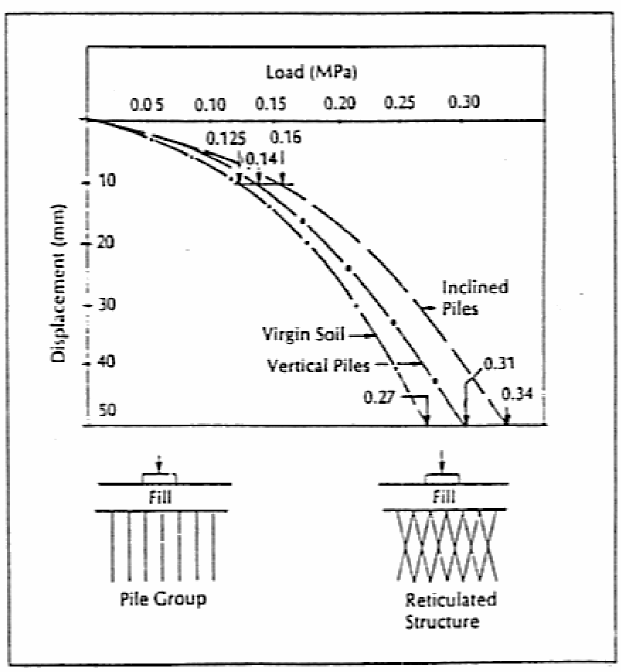


Figure 10. Field test data for different minipile arrangements. (Plumelle, 1984)

indicated, surprisingly, a positive "group effect", thought to be due to beneficial soil-structure interaction (Figures 10 and 11). This advantage was then exploited in slope stability applications in Western Europe and later - but infrequently -in the United States. In urban environments similar groups of pinpiles (or "INSERTS" in this context) can be used in cut and cover, as well as bored tunnel, construction. There the concept is to create protective structures in the ground to separate the foundation soil of the building from the zones that are potentially subject to disturbance (Figure 12). All these INSERT structures rely for their effectiveness on soil/pile interaction, and not on intergranular soil cementation. This composite structure - referred to as a "Type A Wall" because of its distinctive cross sectional appearance - is intended to stop loss of soil from behind it, and to prevent sliding along potential failure planes passing through it.

Design approaches continue to lag behind other aspects of the technology, but several instrumented field programs have confirmed that reinforcement stresses and overall wall movements in service are minimal, and that most probably designs have been highly conservative. Even their original proponent - Fernando Lizzi - confirmed in 1982 that "it is not yet possible to have at our disposal an exhaustive means of calculation ready to be applied with safety and completeness." In addition, an ASCE Committee (1987) also alluded to the great reliance placed on soil/pile interaction, the safe exploitation of "which is still subject to experience and intuition".

The typical approach to design is, of course, relatively simple, and involves standard basic steps:

- estimating loads (active and passive) on the wall;
- conducting a stability analysis to determine the shear force needed to maintain a required factor of safety;
- determining the number of INSERTS needed to provide the required shear resistance;

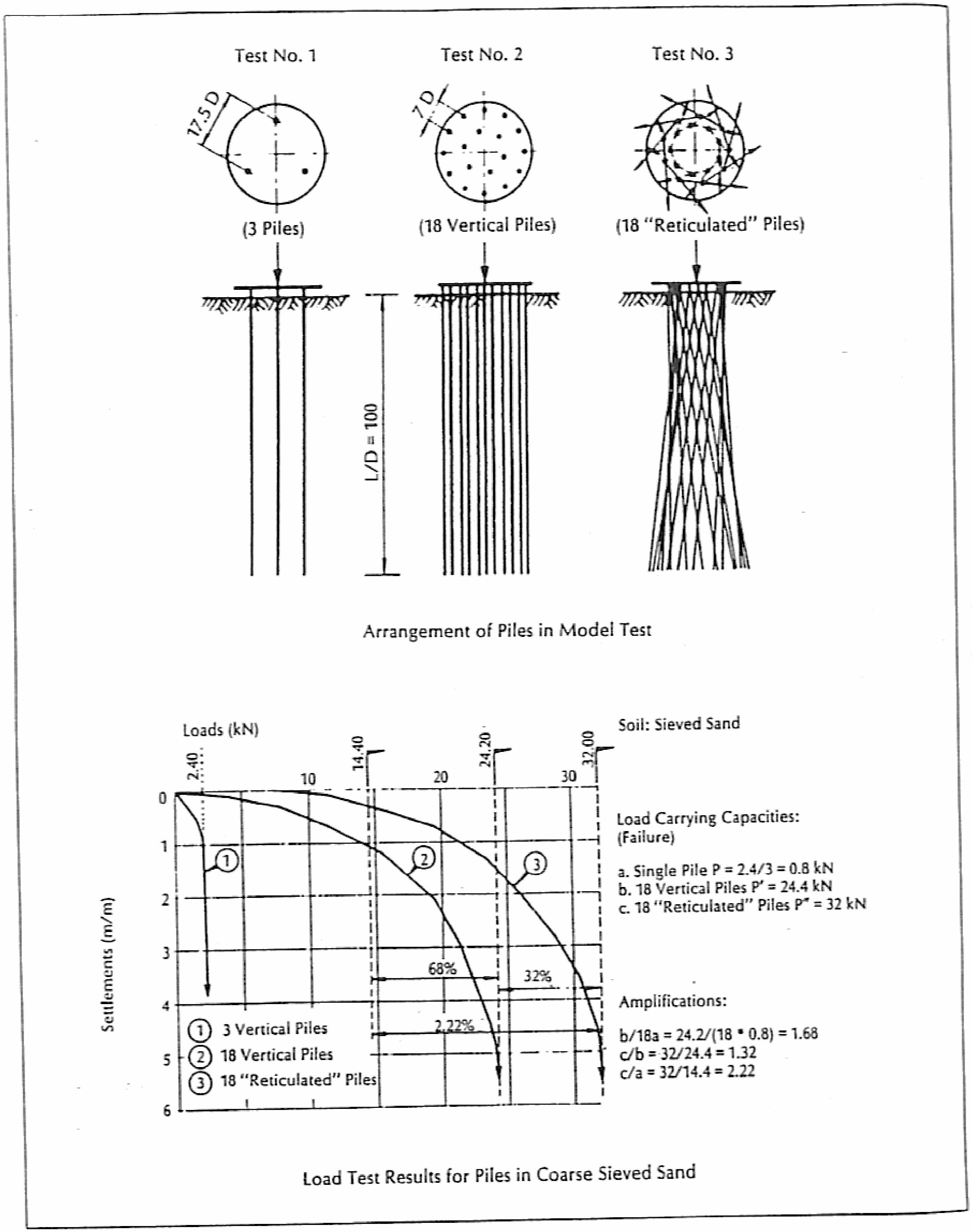


Figure 11. Model test data for different minipile arrangements in coarse sieved sand. (Lizzi, 1978)

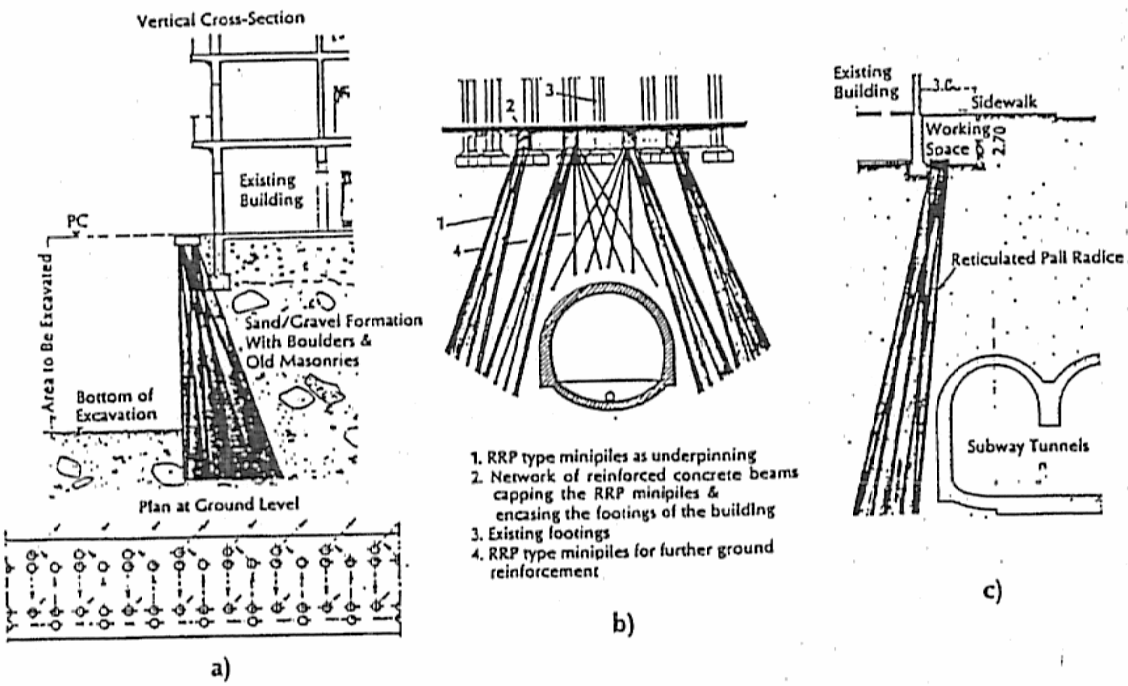


Figure 12. Applications of INSERTS a) for cut and cover and b) and c) around bored tunnels. (Bruce, 1989)

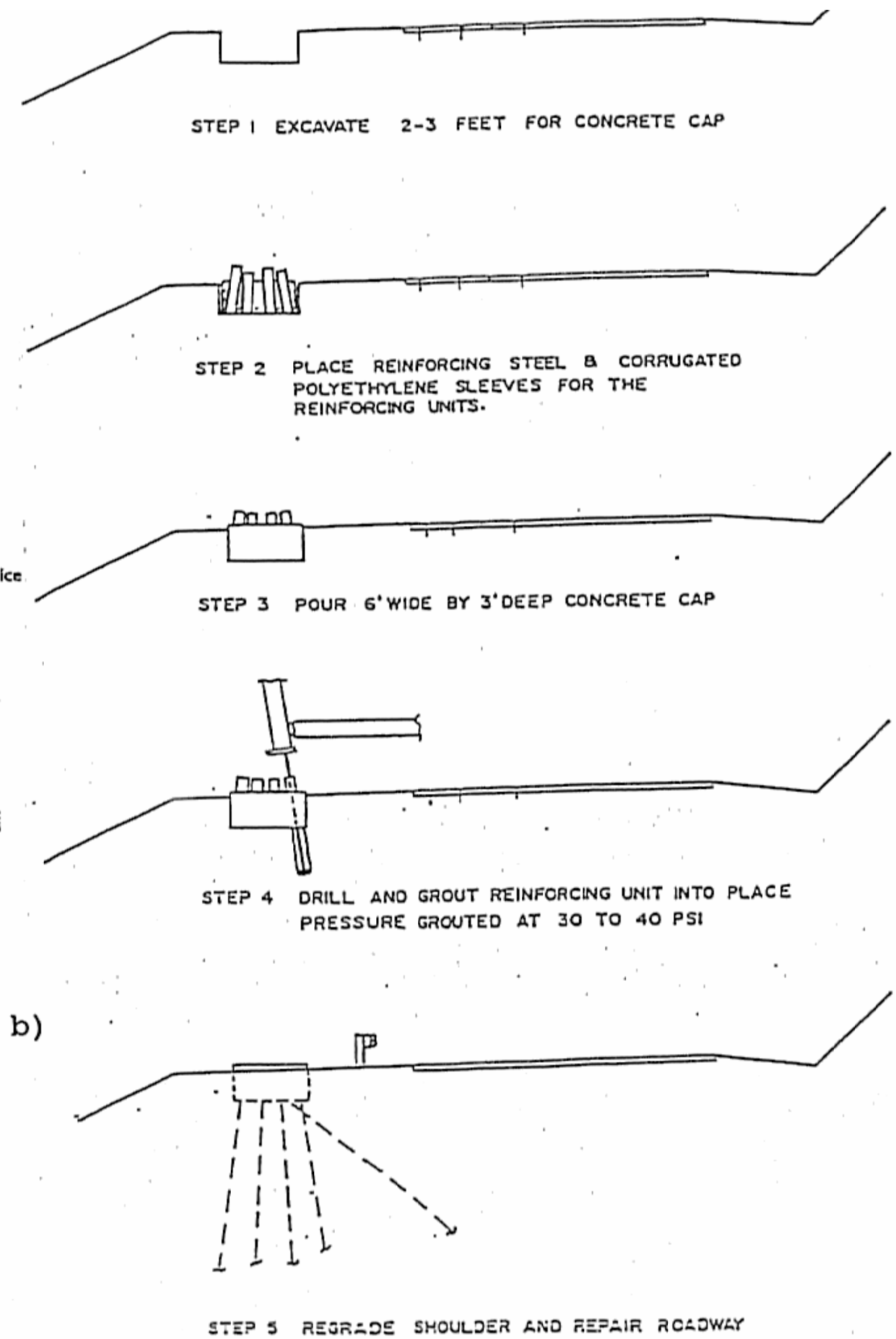


Figure 13. Typical steps in INSERT Wall construction

- calculatons (similar to those for a conventional gravity wall) to check stability against overturning, sliding and bearing failure at the base of the wall.

Usually the INSERTS are extended into bedrock where economically possible, but, in any event, always below the potential failure plane). INSERT Walls can be constructed in close proximity to existing buildings in relatively tight access locations without the need to excavate or underpin, and without causing any decompression of the foundation soil. Given their mode of construction, as detailed below, they can be installed in any type of ground, including through boulders, old foundations or other obstructions with no constructional limitation on hole inclination or orientation.

3.2 Construction Aspects

The successive steps involved in the construction of a Type A Wall are illustrated in Figure 13. The capping beam may be installed before or after the INSERTS are formed, although field evidence suggests that the latter option allows for an earlier benefit from the reinforcement. The drilling method is chosen to ensure minimal disturbance or upheaval to the soil. Of the six generic methods of overburden drilling, the most common method is rotary drilling with water flush, either via a single casing or by the duplex method, depending on ground conditions. Once the casing has been advanced to target depth it is filled with a stable, high strength cementitious grout, and the permanent reinforcement is placed. This may be a solid high strength steel bar, typically 1-2 inches in diameter, or a steel pipe of suitable dimensions, as dictated by the structural design requirements. The drill casing is then withdrawn from the hole as grout continues to be injected under pressure. The effect of the pressure grouting is three-fold in most conditions:

- it ensures all voids or drilling related disturbances to the soil are filled;

- it permeates a little into sands and gravels;
- it compacts somewhat soil around the pile that is too fine to be permeated.

Individual piles are oriented in different directions in each plane to promote the most effective soil/pile network. After installation of the INSERTS, the capping beam is simply graded over, or it can form the base of a guard rail or similar: the whole wall is thus wholly out of sight and maintenance free.

3.3 Case History: Road in Armstrong County, PA

Portions of State Route 4023 north of Kittanning, Pennsylvania, were constructed on a slope adjacent to the Allegheny River. A 240 ft. long section of the two-lane road, and the railroad tracks located upslope, experienced damage caused by slope movements toward the river. In June, 1988, and January and February, 1989, the owner conducted a subsurface exploration program and installed slope inclinometer casings to monitor the slope movements. The inclinometers indicated that a slip-plane was located approximately 26 to 36 ft. below the roadway and that the slope was moving at a rate of up to 0.75 inch per month downwards toward the river.

Boreholes showed that a significant amount (20-30 ft.) of fill had been placed at the site apparently during the construction of the roadway and/or railroad tracks. The fill consisted of intermixed loose to medium dense rock fragments and medium stiff silty clay. Underlying the fill was a 5-10 ft. thick layer of stiff colluvial clay with rock fragments, in turn overlying a 3-20 m. layer of weathered claystone. Competent rock was encountered at about 50 ft. below the roadway, and generally consisted of medium hard siltstones and sandstones.

The owner designed a repair of the failed section using an anchored caisson wall extending into competent rock. The earth pressures used for the design were based on the results of stability analyses, for which the soil along the slip-plane was assigned a residual friction angle of 17°. This design provided a minimum factor of safety with regard to the overall slope stability equal to 1.5 and 1.2 for the normal and rapid drawdown conditions, respectively. A row of 3 ft. diameter caissons were foreseen at a center-to-center spacing of 4.5 ft. and located immediately downhill of the roadway. The caissons were to be connected at the top by a cast-in-place reinforced concrete cap which was to have 90 ft. long prestressed rock anchors extending underneath the roadway at 7 ft. lateral intervals.

In 1989, the contractor proposed and the owner accepted an alternative design employing an INSERT Type "A" Wall. The wall consisted of four rows of pinpiles extending across the slip-plane and into competent bedrock. It comprised two equal length sections designated as Wall A and Wall B. Wall A contained a higher density of piles than Wall B, because the top of weathered rock dipped to a lower elevation in the area of Wall A which resulted in a larger volume of soil to be stabilized in this area. In general, Wall A contained 1.3 piles per lineal foot, and Wall B contained 0.9 piles per lineal foot. Besides providing a significant economic savings over the original design, the selection of the INSERT Wall allowed for one lane of roadway to remain open during construction (February to May, 1989). The wall was constructed as described above, with the cap poured after pinpile installation for practical reasons.

To monitor the INSERT Wall performance, two sections of the wall were instrumented with strain gauges, inclinometers, telltales, and survey pins. The inclinometers yielded the most useful information regarding the performance of the wall. The data for inclinometers located relatively close to and within the wall indicated that up to 1.5 inches of horizontal movement occurred during the 75-day construction period, but that a maximum of 0.3 inches of movement occurred in the 7-month period following the completion of the wall.

Overall, the inclinometer data indicated that the wall performed as expected, and had effectively stopped the slope movements at the site. These data also confirmed that some deflection of the relatively flexible INSERTS may be required to mobilize their lateral resistance.

4. CONTRACTING PRACTICES

Weaver (1991) addressed the elements necessary for a successful grouting project: they are equally valid for INSERT works

- a design accommodating the site geological conditions;
- specifications that allow or facilitate modifications to the works 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 particular, 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". 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 (Nicholson, 1990). 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 (Bruce, et al., 1991b). 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 (Bruce, et al., 1992). 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℠", 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.

5. FINAL REMARKS

In the fields of ground treatment by grouting, and in-situ reinforcement by Type A Walls, it is a period of considerable dynamism. In each field there is a long history of application in the United States but close examination reveals that the experience has not always been wholly satisfactory in either the technical or the contractural spheres. In recent years, various factors have conspired to improve the current situation and offer immense promise for the future. There factors include the impact of foreign technologies, the emergence of native "points of light", the changing demands of the American construction industry, and the heartfelt desire to move towards innovative contracting procedures and partnerships.

With these prospects in place, one can understand the new optimism of those involved in each corner of the business of ground treatment and reinforcement. With these people in place, one can foresee a new identify for our national efforts on the world stage.

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