DRILLING AND GROUTING TECHNIQUES FOR DAM REHABILITATION

by

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ABSTRACT

With the increasing emphasis being placed on dam rehabilitation and repair, more dam engineers are being faced with the need to interface with drilling and grouting specialists. Regretfully, it is often the case that these specialists execute their work rather better than they explain their intentions, especially at the pre-award stage. This may lead to personal conflicts and professional disputes during the work, and so an unwillingness among dam engineers to entertain drilling and grouting techniques as favored options for future problems.

This paper provides generic classifications of drilling and grouting methods and materials for both rock and soil, so that the non-specialist can have a basic framework of reference. An extended bibliography is provided so that readers can research particular points of interest.

1. INTRODUCTION

The drilling and grouting techniques have many applications in the remediation of existing dams and their foundations (Bruce, 1990, 1992; Weaver, 1989). These applications can be broadly summarized as follows:

- Seepage Control
  - Concrete/Masonry Dams
    - a) grouting of the structure
    - b) grouting of the foundation rock
  - Embankment Dams
    - a) grouting within the structure
    - b) grouting of the foundation rock or soils

- Settlement Control
  - Concrete/Masonry structures on rock

- Liquefaction Control
  - Improvement of embankment dams and/or their foundation soils

There are also numerous other miscellaneous applications, such as the placing and sealing of geotechnical instrumentation, but most of the work focuses on these three groups of applications.
For many decades, the market demand and the procurement/ contracting procedures resulted in the drilling and grouting of U.S. dams being conducted according to relatively simple, rigid standardized specifications. Indeed,

these principles still form the core of the specifications being adopted for rock mass grouting on new dams today (Aberle, et al., 1990; Weaver, 1991).

However, within the last few years, the difficult and typically original problems associated with major existing structures, and a certain and welcome flexibility in contracting practices (Nicholson and Bruce, 1992) have demanded the use of innovative and varied techniques. For example, drilling may have to be conducted in unstable rock masses or heterogeneous soils, usually below the water table, and without causing further damage to the foundation, while grouting techniques and materials have had to be adapted to the sealing of water pathways ranging from microfissures to karstic voids. And, of course, the grouting usually has to be done in a high pressure/high flow seepage regime from locations which are not logistically ideal.

Geotechnical drilling and grouting is only one of the many technologies which impact engineers involved in dam safety and the associated remediation. It is an extremely dynamic and rapidly developing science, which does, still, owe much for its successful execution to the knowledge and experience of the contractors. It is understandable, therefore, if the non-specialist dam engineer feels intimidation, or despair, when trying to unravel the mysteries of the drilling and grouting fraternity.

The purpose of this short paper is to provide a generic framework to facilitate understanding and optimize selection.

2. ROCK DRILLING

There are three generic methods of rock drilling:

1. High Rotation Speed/Low Torque Rotary: relatively light drill rigs can be used to extract core samples, when using a core barrel system, or can also be used simply to drill holes, using "blind" or "plug" diamond impregnated bits. Typically for holes up to 4" diameter.

2. Low Rotational Speed/High Torque Rotary: used with heavier rigs to drill holes of greater diameter to considerable depths. The penetration rate also depends on the thrust applied to the bit. Uses a variety of drag, roller or finger bits depending on the rock.

3. Rotary Percussive: the drill bit (cross- or button-) is both percussed and rotated. In general the percussive energy is the determinant of penetration rate. There are two options:
   - Top drive, where the drill rods are rotated and percussed by the drill head on the rig.
   - Down-the-hole hammer, where the (larger diameter) drill rods are only rotated by the drill head, and compressed air is fed down the rods to activate a percussive hammer mounted directly above the bit.

In principle, the prime controls over choice of drilling method should ideally be related to the geology, the hole depth and diameter (Figure 1), bearing in mind always the question of lineal cost. Hole linearity and drill access restraints may also have significant impact.

Overall, drilling is largely and traditionally conducted by rotary methods although the insistence on diamond drilling is no longer so prevalent. Top drive rotary percussion is growing in acceptance in certain quarters - with the increasing availability of higher powered diesel hydraulic drill rigs - as long as water or foam flush is used. Holes up to 4 inches in diameter to depths of 200 feet can be drilled economically. Somewhat perversely, certain specialists are beginning to allow air flushed rotary-percussive drilling for routine grout holes. Even when the air is "misted" with some inducted water, most specialists agree that this medium has a detrimental effect on the ability of the fissures to subsequently accept grout (Houlsby, 1990; Weaver, 1991; Bruce, et al., 1991).

3. SOIL AND OVERBURDEN DRILLING

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

1. Single Tube Advancement. This is the most simple principle. In the drive drilling variant, the casing is percussed and pushed into the soil, without flush, and with a "knock-off" disposable bit. With external flush, the casing terminates in an open shoe or "crown" and is rotated into the soil using a strong flushing action (usually water). The flush emerges from the casing and travels to the surface between the casing and the soil.

2. Rotary Duplex. The term "duplex" means the simultaneous advancement of an outer casing (with crown) and inner drill rod (with bit). The flush is passed down the drill rod, but then emerges to the surface through the annulus between rod and casing. In this particular category, the rods and casings are simultaneously rotated.

3. Rotary Percussive Duplex (Concentric). Similar to Group 2 except that the rods are also percussed. When a top hammer is used, the casings are simultaneously percussed, whereas if a down-the-hole hammer is used, only the drill bit experiences the percussive action.

4. Rotary Percussive Duplex (Eccentric). Similar to Group 3 except that an eccentric drill bit reamer device on the rods is used to oversize the hole, to permit the casing to follow without rotation. After the duplex has reached target depth, the reamer is retracted into the casing so permitting the extraction of the rods. Both top drive and down-the-hole versions are available.

5. "Double Head" Duplex. Similar to Groups 2 and 3 except that the rods and casings are rotated and advanced simultaneously but in opposite senses. This maximizes the penetration action for any given rig energy, and encourages hole straightness. It is especially useful in very difficult ground conditions (Bruce and Kord, 1991). Pure rotary, top drive or down-the-hole rotary-percussive options can be employed.

6. Hollow Stem Auger. High torque and thrust are used to advance a screw with a hollow core (protected during penetration by a bottom plug). This is a traditional method of drilling cohesive soils and soft argillaceous rocks.

The logic of choice is perhaps even more obscure than in rock drilling, and history and habit have ensured that not all methods are used by any one contractor, or in any one geographical region. Hollow stem augers are common around the Lakes and on the West Coast, while simple flushed casing and rotary duplex are favored in the East. The emergence of foreign-backed drill rental companies offering percussive duplex and double-head duplex capabilities has spread these techniques nationwide. Percussive duplex (eccentric) is in general decline for grout holes, although is still regarded in certain 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. The better contractors, at least, are adopting a refreshing degree of technical responsiveness to replace traditional paradigms.

4. ROCK GROUTING

Rock grouting practice largely follows traditional lines (Ewart, 1985), although it would appear that more recent publications by specialists such as Houlsby (1990) and Weaver (1991) have had a refreshing and stimulating impact. As illustrated in Figure 2, there are three basic methods used for grouting stable rock masses:

1. Downstage (Descending stage) with top hole packer
2. Downstage with down hole packer, and
3. Upstage (Ascending stage).

Circuit grouting is, to the author's knowledge, no longer used.

The advantages and disadvantages of each method are summarized in Table 2. The competent rock available on most dam sites was ideally suited for upstage grouting and this has historically been the most common. Downstage methods have recently had more demand reflecting the challenges and difficulties posed by more difficult site and geological conditions posed by the remedial and hazardous waste markets. The work described by Weaver, et al. (1992), describing 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 2700 feet 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 tube (Figure 3). 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 (Bruce and Gallavresi, 1988).

5. SOIL GROUTING

Although it has been traditional to identify only four basic methods of soil grouting (Figure 4), the rapidly growing popularity of the SMW method has resulted in a fifth bona fide member.

1. Permeation Grouting. Involves the infiltration of existing voids and pores with grouts. The granulometry of the soil largely dictates the choice of materials and so, to a large extent, the cost. Various methods of placement exist (Bruce, 1989a) but the most common range from the simple end of casing injection, to the sophisticated but precise tube à manchette (sleeved pipe) system. Interested readers are referred to the Proceedings of the ASCE Specialty Conferences (1982, 1992) and Karol's textbook (1990). The forthcoming European conference in London in November, 1992, will provide a similarly rich source of modern data.

2. Compaction Grouting. This "uniquely American process" (Baker, et al., 1983) has been used since the early 1950's and continues to attract an increasing range of applications (Warner, 1982). In summary, very stiff "low mobility" grouts (Warner, 1992) are injected in predetermined regular patterns to increase the density of soft, loose or disturbed soil. When appropriate materials and grouting parameters are selected (Warner, et al., 1992) the grout forms regular and controllable coherent volumes, centered on the point of in-jection. Near surface injections may result in the lifting of the ground surface and associated structures, akin to the principle of slabjacking described by, for example, Bruce and Joyce (1983). Unlike other types of grouting, compaction grouting does not aim to reduce overall soil mass permeability; rather the densification it provides can be an important guard against liquefaction for example (Salley, et al., 1987).

3. Hydrofracture Grouting. Features the concept 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. However, the process is

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

4. Jet Grouting. Was primarily developed in Japan in the early 1970's (Bruce, 1988) but was introduced into the States at the end of that decade. Restricted opportunities and a litigious mistrust of innovation have somewhat limited its national popularity despite the efforts of a small and determined band of proponents (Andromalos and Gazaway, 1989; DePaoli, et al., 1989; Kauschinger, et al., 1992; Welsh and Burke, 1991). There are three basic types of jet grouting in popular use but all feature the use of a high pressure fluid jet ejected laterally during the rotation and extraction of the drill rod to erode and/or grout the soil. The result is a column of "soilcrete", the diameter and strength of which reflects the virgin soil, the grout mix design, and the operational parameters (Table 3). Jet grouting has many inherent advantages as a ground treatment method especially its ability to be applied in all types of soil, and its reliance on cement based grouts only. However, many remain concerned about the high pressures employed, and remain skeptical about its economic competitiveness. Only one North American dam (John Hart Dam, BC) has had (minor) jet grouting, for a hydraulic cut-off (Imrie, et al., 1988).

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 grouting, even though its origins are over 30 years old (Jasperse and Ryan, 1992). However, it is fast becoming a popular process and can fulfill the same tasks as some of the other grouting methods (Taki and Yang, 1991). It features the introduction of cementitious grouts down the stems of large diameter (20-40 inch) discontinuous flight augers as they are rotated to depth (Figure 5). Each rig may have up to 4 augers working in unison to encourage continuity of the soilcrete. Developments are being made with the injection of dry materials which react with the in-situ moisture of the soil (RODEM^S).

6. FINAL REMARKS

The topic of drilling and grouting techniques for dam rehabilitation is widely complex and challenging. However, as an introduction, various generic classifications can be established as a framework. The classifications identified in this paper should prove useful to put in perspective the new developments which continue to occur in this important science. This paper is a very brief synopsis, and the interested reader is encouraged to pursue further details in the referenced publications.

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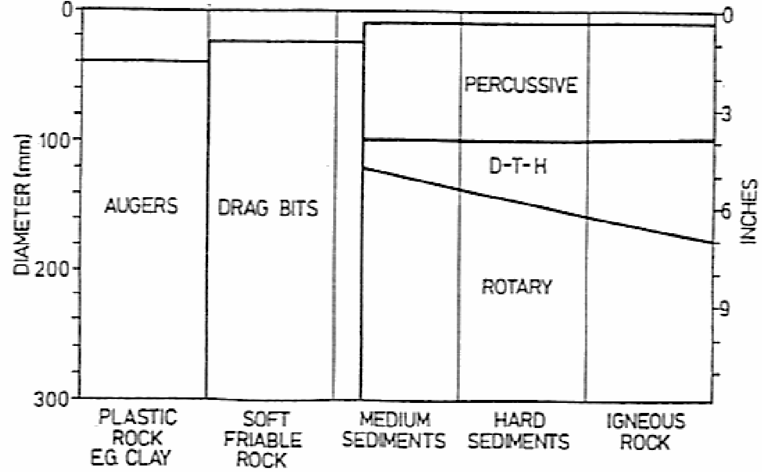
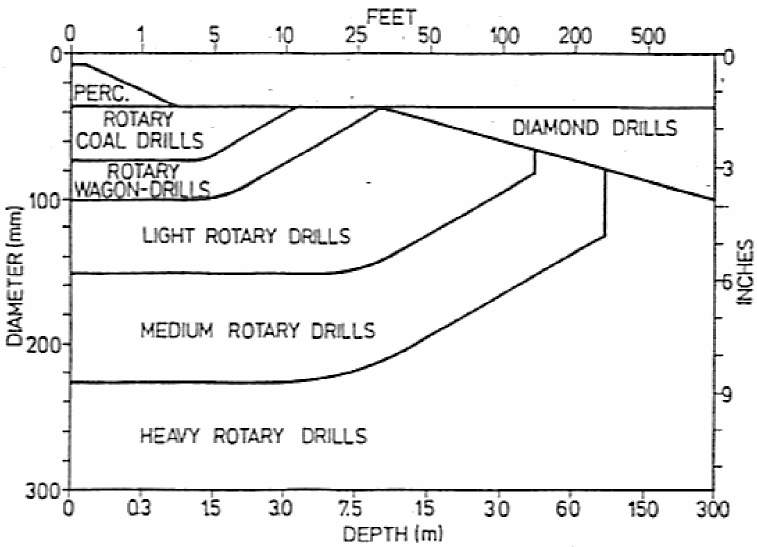
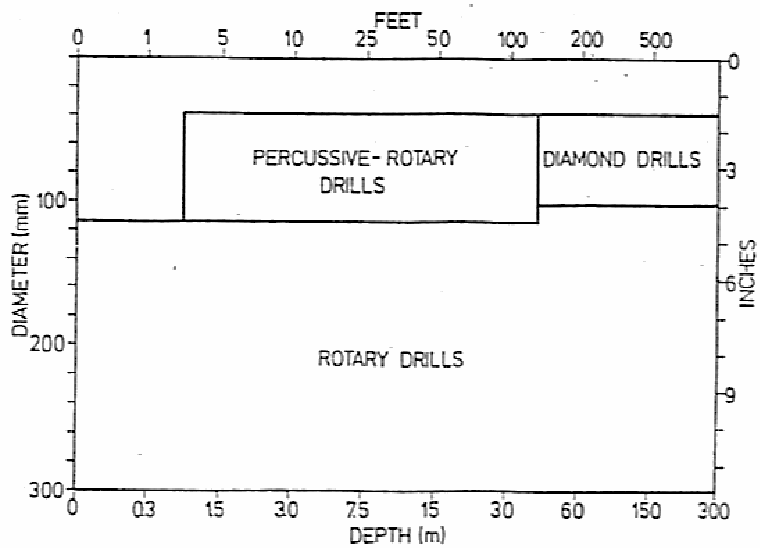


Preferred methods of drilling different classes of rock and at different hole diameters. Depth of hole generalised



Preferred methods in soft friable rocks



Preferred methods in variable strata

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

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 (Bruce, 1991).

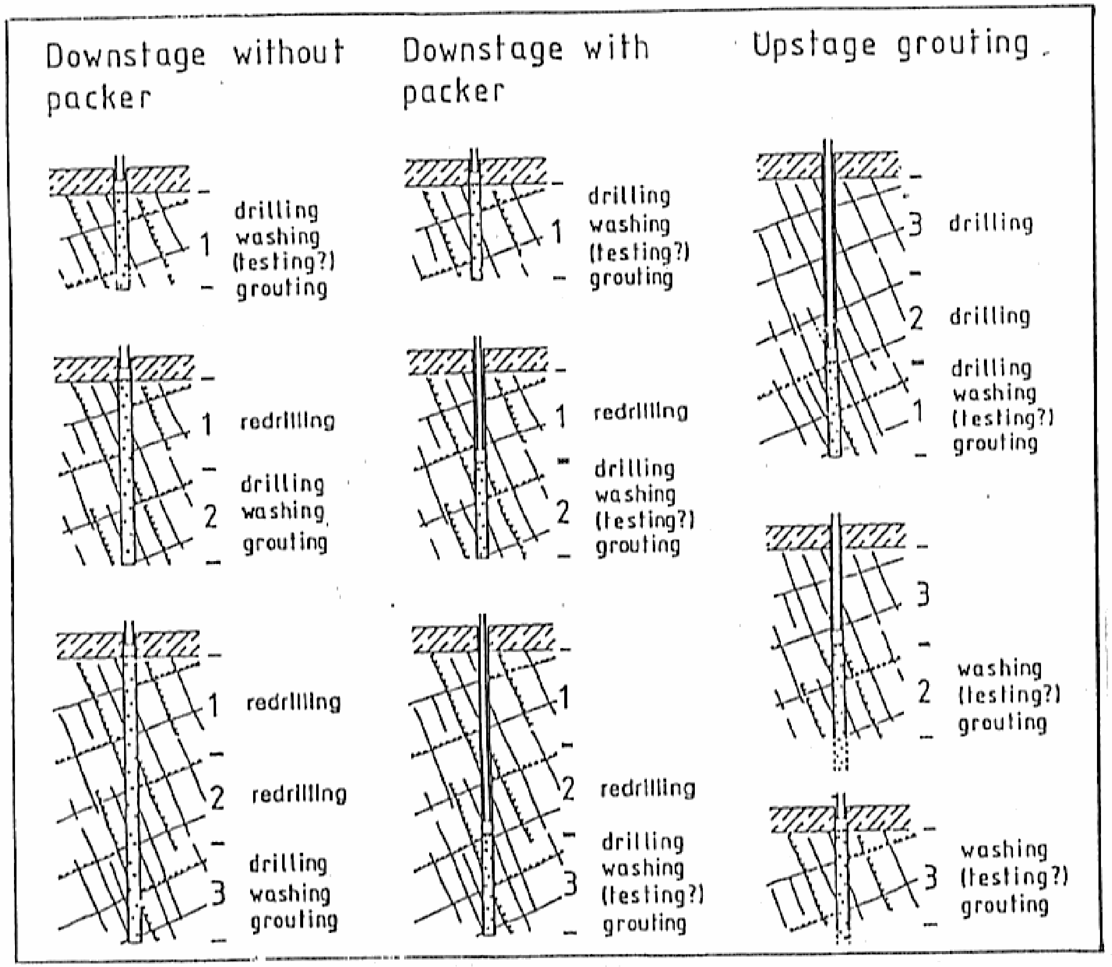


Figure 2. Conventional stage grouting methods for rock fissure grouting (Ewart, 1985).

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

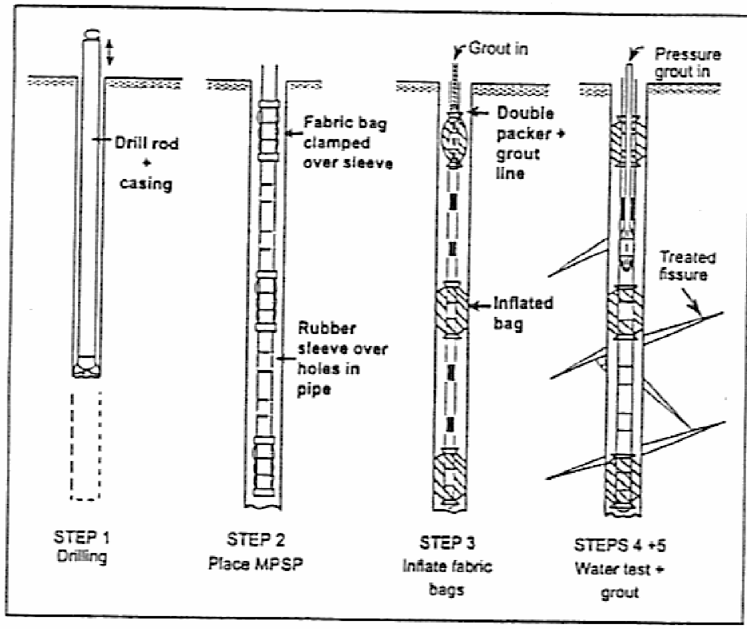


Figure 3. MPSP installation and grouting steps (Bruce and Kord, 1991).

Original Japanese Name	Principal of Operation	Jetting Pressure (N/mm²)	Jetting Nozzle Dia. (mm)	Revolving Rate (rpm)	Anticipated Column Dia. (cm)	Notes
Jet Grout (JG)	Upper water & lower grout jet	20	?	None	—	Panels only, soon obsolete
Chemical Churning Pile (CCP)	Single grout jet	20 - 40	1.2 - 3.0	20	30 - 60	1. Chemicals now replaced by cement 2. Similar to Rodinjet 1
Jumbo Special Grout (JSG)	Single jet of grout enveloped in air	20	3 - 3.2	6	80 - 200	1. Originally called Jumbo Special Pile (JSP) but name changed for patent reasons 2. Similar to Rodinjet 2
Column Jet Grout (CJG)	Upper water & air jet & lower grout jet	40 - 50	1.8 - 3.0 (upper) 3.0 - 5.0 (lower) (8 - 9 mm in Kajima system)	5	150 - 300	1. Referred to as "half replacement" 2. Similar to Rodinjet 3 or Kajima/GKN Keller system
Mini Max (MM)	Like CCP but uses special "chemi-colime" cement	20	1.2	20	80 - 160	Specially for very weak soil & organics (e.g., soft peaty clays under water)
Jumbo MiniMax (JJM)	As for MM except for addition of 20 - 40 cm wing jet	20	1.2	20	20	Specially for very weak soil & organics (e.g., soft peaty clays under water)
Super Soil Stabilization Management (SSS-Man)	Air water jet used to excavate volume completely underwater. This is then surveyed ultrasonically. If OK, then tremied full of desired material	20 - 60	2 - 2.8	3 - 7	200 - 400	1. To provide absolute control over shape & composition of column 2. Effective to over 70 m depth 3. "Complete replacement" 4. Most expensive technique, but ensures desired performance

Table 3. Major jet grout variants and their parameters (Bruce, 1988).

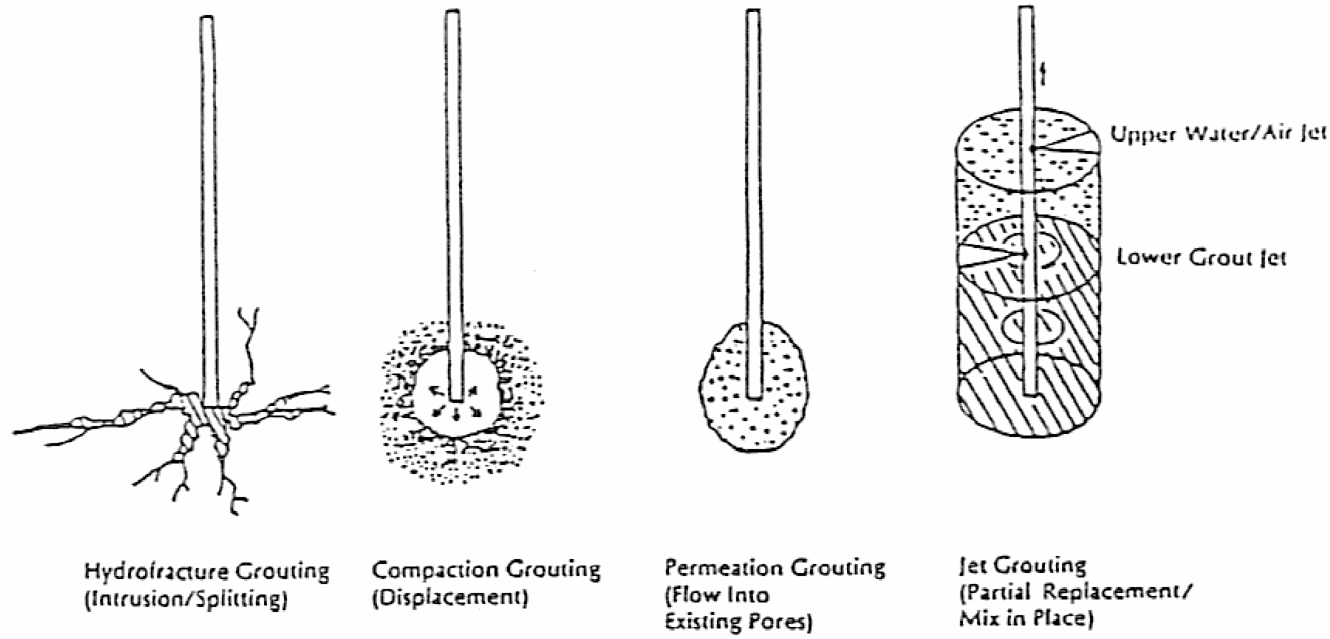


Figure 4. Four traditional categories of soil grouting.

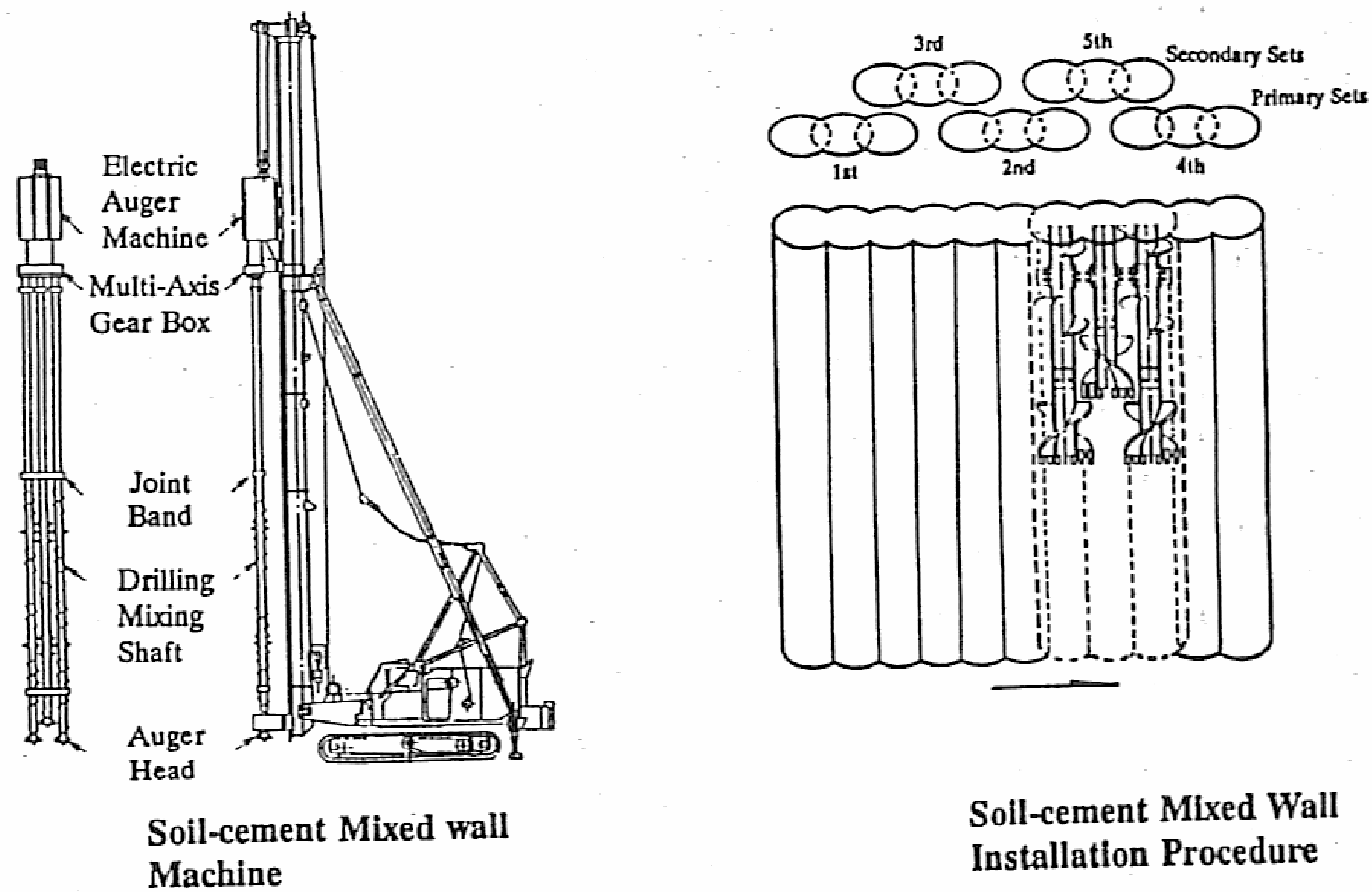


Figure 5. The concept of mechanical soil mixing (Taki and Yang, 1991).