CONTEMPORARY PRACTICE IN GEOTECHNICAL

DRILLING AND GROUTING

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ABSTRACT The history and applications of grouting in geotechnical construction are well known in the ground engineering community. Today, more than ever before, there is great dynamism in the industry reflecting both the increasingly onerous demands of clients and site conditions on the one hand, and the inventiveness and competitiveness of practitioners on the other. This paper provides an overview of the state of practice in the drilling and treatment of rock and soil. It provides generic classifications for the large number of methods used in drilling and grouting, so that readers can supplement the framework with knowledge and experience of their own. The paper also touches upon contemporary methods of quality control and assurance- always key factors in the promotion and execution of grouting techniques.

1. PREAMBLE

For attendees at a gathering such as this, it is unnecessary to reach back and recount the history, applications and definitions of grouting. Virtually all engineers involved in some aspect of geotechnical construction have direct knowledge of grouting in some form or another. In addition most specialists in hazardous waste control and fixation, in structural and in mining engineering can boast contact or experience, as can their colleagues engaged in remediation projects. Suffice it to state that in these later years of the twentieth century, grouting is established worldwide as a reliable and often vital tool in an immense array of applications, only some of which can be touched upon in this, and later presentations. Grouting is the subject of major and authoritative text books (eg. Karol, 1983), the prime topic at international conferences (eg New Orleans, 1982), and is regulated by national standards as in Germany. It remains a target for tremendous research efforts in all corners of the engineering profession, and is the raison d'etre of specialist engineering firms of major scale. Being such a dynamically evolving science, a state of the art is immediately obsolescent- especially as much of the current research and development is being conducted for commercial "edge" and so is unlikely to emerge early. Equally, the ever widening range of applications, each with its own parameters and methods, further frustrates the possible goal of compiling such a comprehensive review. Instead, it is viable to attempt a state of practice, if this is limited to one particular facet of the industry. This is what is attempted in this publication.

The classic application of grouting is in the treatment of rock and soil, for the purposes of reducing permeability, increasing strength parameters, or otherwise filling large voids, both natural and artificial. This introductory review therefore restricts itself to such applications, and refers to contemporary practice with respect to methods, materials, equipment and quality assurance. Major references are provided for further research, although it may be noted at this point that Committee 552 of the American Concrete Institute is currently finalizing a major work on geotechnical grouting, intended for publication in 1990 (Graf, 1989). It is equally pertinent to relate current practice in drilling techniques associated with such grouting works. Especially in the realm of overburden drilling there is a potentially bewildering range of techniques, the use of which often reflects less on the geotechnical characteristics of the soil than the background of the contractor. This review concentrates on methods used to drill holes within the typical limits of geotechnical construction, namely diameters from 50 to 250mm, and depths to100m. While concentrating on classic drilling and grouting for ground treatment, the data of this review are equally valid for those involved in ground anchors (Littlejohn and Bruce, 1977), pin piles (Bruce, 1988), in situ reinforcement (Bruce and Jewell, 1986) or large diameter piling (Bruce, 1986).

As a final word of introduction, it will be noted that in the course of the paper, numerous references are made to specific companies, systems or products. No endorsement or favoritism is implied in this although care has been taken to name reputable and representative sources.

2. METHODS OF DRILLING

In every grouting project a major concern is, of course, the penetration of the ground to permit the subsequent introduction of grout at the desired depth and location. Methods must be selected to ensure holes are drilled as quickly and economically as possible while ensuring minimal damage to the environment both above and below ground.

2.1 Rock Drilling

It is fair to say that the debate continues (Deere, 1982) as to the "best" way to drill rock formations to permit grouting of the fissures. Traditionalists in North America still tend to lean towards the use of rotary drilling though appearing to relax their insistence on core drilling throughout. Elsewhere in the world, if the rock strata permit, the most popular choice is rotary percussive which is typically several times faster, and more economic than pure rotary drilling. Evidence remains at best inconclusive as to the real danger of this type of drilling leading to fissure clogging and, so, inefficient grouting. Most engineers do, however, agree on stipulating that grout hole drilling can be accomplished with water flush during - and often after-penetration. It is interesting that on a major dam currently being constructed in Western Canada, the use of air powered down-the-hole hammers is being permitted, although periodic water flushing is required.

Increasingly, engineers are adopting a more pragmatic approach to the choice of rock drilling method. The decision is left to the contractor, based on his own experience, but often supported by a brief on site test program designed to show that the drilling method is appropriate - from a grouting viewpoint - to the rock mass in question.

2.2 Overburden Drilling

In certain conditions the soil characteristics and the hole geometry may permit the hole to be "open holed" i.e. it will stand open after drilling with air or water. In other cases it may be possible to temporarily stabilize holes by using a mud flush or some type of drilling foam - both of which are displaced out of the hole prior to subsequent grouting activities. Usually, however, the conditions are such that the hole must be stabilized against collapse during drilling by some form of liner or casing, typically retrieved at some later point. There is a large number of such systems developed and promoted by suppliers and contractors. However, it is possible to condense these into seven major categories (Bruce, 1984).

It should be noted that only contemporary "production" methods are reviewed and that systems synonymous with excessive cost (eg. diamond coring) or very limited geological capacity (eg. vibratory) are excluded.

2.2.1 Drive Drilling (Lancing)

In appropriate ground conditions, to fairly shallow depths, drive drilling is the simplest, cheapest and fastest method. It is, in principle, a percussive system in which a tube is drilled with the leading end terminating in either a "knock off" drive shoe, bit or crown (Figure 1). No flush need be used. A little rotation is necessary to prevent the string uncoupling during driving and to reduce deviation potential (recorded for the 76.1mm size as being as much as 1 in 7.5). A standard range of sizes is shown in Table 1.

Rarely, however, are sizes over 101.6mm o.d. practical, except in particularly loose, gravelly or sandy conditions, and the 76.1mm System appears to be the optimum in terms of cost effectiveness. Production figures of up to 250m/day are claimed for this size in "favorable" conditions, to maximum depths of 40m.

System Designation: o.d. (mm)	i.d. (mm)	Recommended tube lengths *(must be portable by 2 men)*
42.4	15	3.0m
51.0	18	3.0m
63.5	35	3.0m
76.1	50	3.0m
88.9	64	2.5m
101.6	72	2.0m
108.0	82	2.0m
114.3	88	2.0m
133.0	108	2.0m
177.8	150	1.5m

Table 1 Standard Drive Drilling sizes (Hutte)

2.2.2. Rotary Duplex

In the most common situations, when ground conditions and job requirements combine to eliminate the "easy option" of single tube advancement some method featuring the simultaneous advancement of rod (with bit), and casing (with

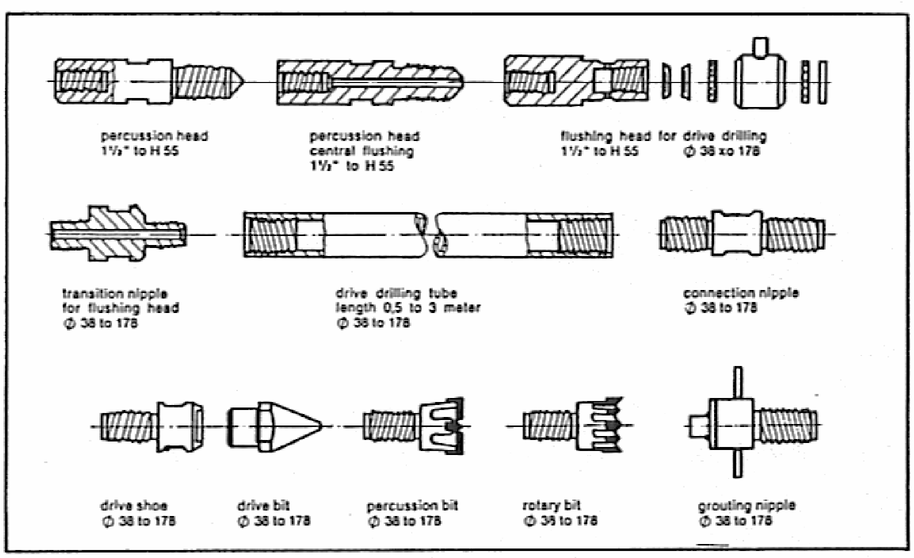


Figure 1 Components of Drive Drilling System (Hutte)

shoe) must be adopted. Such methods may collectively be referred to as "Duplex".

The basic method, which most frequently carries the term "Duplex" is purely rotary, and relies for its penetration performance on variations of rig thrust, head torque and speed, and flushing characteristics, other factors being equal. The major components are illustrated in Figure 2 for a typical size , and are

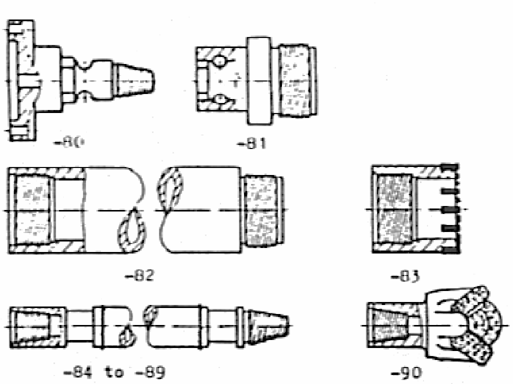
- Outer casing (rotated)
- Casing crown
- Inner drill rod (rotated)
- Drill bit (usually tricone)
- Duplex head/transition flange, connecting to the rotary head of the rig.

If a large number of hard obstructions are foreseen, it is possible to exchange a down-the -hole hammer for the tricone bit, to hopefully fragment the obstruction and so permit the casing to be rotated down with less resistance (eg. Bruce and Yeung, 1983). Equally, in other difficult ground conditions, reverse circulation may be used. Duplex is most commonly used as a high production tool in what are often "difficult" ground conditions, and usually with powerful hydraulic rotary heads. As a consequence, some British contractors, for example, favor rather more robust systems than as illustrated in Figure 2 and, as example, Figure 3 shows the "Heavy Duty" range manufactured by Euro-Drill. However, where conditions are less onerous, or environmental restraints are significant, Standard Flush Coupled or Jointed Casing, or Water Well Casing with appropriate rod types may be used, in accordance with local national standards.

2.2.3. Rotary Percussive Concentric Duplex

This method, typified by the Atlas Copco OD72 System, is a duplex method wherein both rods and casings are simultaneously percussed and rotated (Figure 4). In its early years of use it was driven by mainly airpowered hammers with relatively restricted torque capacity. Therefore, applicability was regarded as limited, and other methods, notably ODEX, with far less emphasis on rotational power were developed. More recently, however, there is clear evidence of a resurgence of the method as a result of the increasing availability of higher torque hydraulic top hammers. By way of illustration, it may be noted that rotary percussive duplex was the preferred production drilling tool of all the major contractors on MTRC related works in Hong Kong, where ground conditions were extremely onerous, featuring gritty decomposed granites with large fresh rock relicts. This market for grout hole installation alone, was conservatively estimated at about 200,000m of drilling per year.

Although the Atlas Copco System is available in only one size, other manufacturers can supply sizes as in Table 2.



Order-no.	Name
178-80	transition flange with Wirth-thread 63,5
178-81	ejection flushing head 63,5 x 177,8
178-82	tube 177,8 x 900mm
178-83	casing crown button type 178 x ∅ 180mm
178-84	tube 63,5 x 900mm
178-85	tube 63,5 x 1500mm
178-86	tube 63,5 x 2000mm
178-87	tube 63,5 x 2500mm
178-88	tube 63,5 x 3000mm
178-89	tube 63,5 x 3500mm
178-90	rotary bit ∅ 149,2mm with transition to tube 63,5

Figure 2 Components of 177.8mm Rotary Duplex System (Hutte)

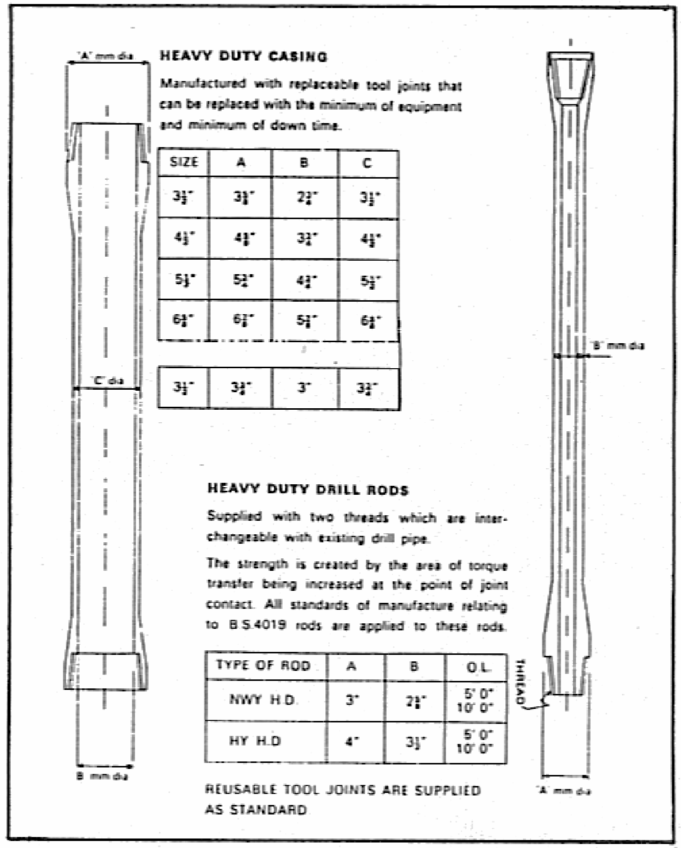


Figure 3 Heavy Duty Rotary Duplex System. Note that the recommended rock bit maximum sizes for the four major casing types are 2 5/8", 3 1/2", 4 1/2", and 5 3/4" respectively (Euro Drill)

Casing o.d. (mm)	Casing min i.d. (mm)	Casing Crown o.d. (mm)	Bit dia. (mm)
88.9	64	92	60
101.6	72	104	67
108.0 *	82	112	77
114.3	88	116	83
133.0 *	108	135	103
177.8 *	150	182	146

Table 2 Standard Percussive Duplex Sizes (Hutte)

(*denotes common sizes for Double Head Drilling- Section 2.2.6)

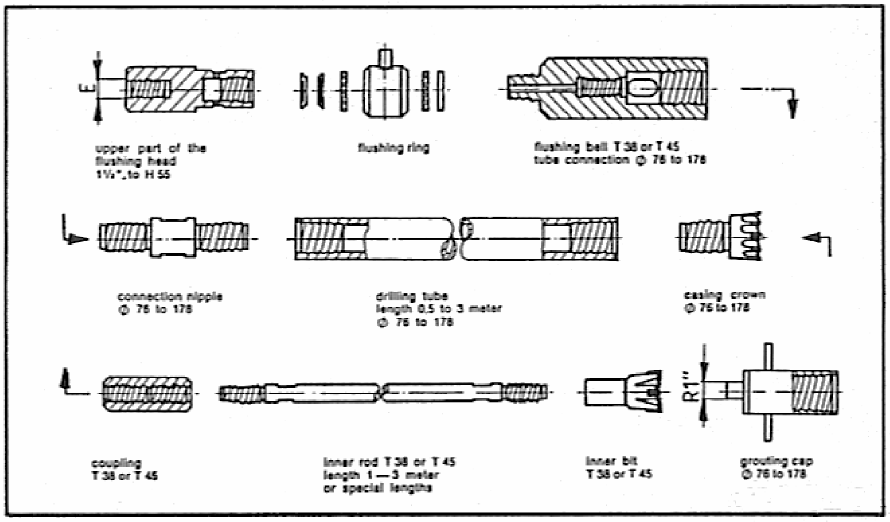


Figure 4 Components of Rotary Percussive Duplex System (Hutte)

The casings are, of necessity, high quality steel, have modified rope form threads, and wall thicknesses of around 12mm (as opposed to 6mm for ODEX). One consequence is that the unit weight is high, and normally 2m casing lengths are used in the larger sizes. Drilling on with the rods into rock or other stable strata is accomplished without the necessity to change the bit. Both insert and button types are available for bits and casing shoes. As with other forms of concentric duplex, in especially sensitive ground, the bit can be retracted behind the casing shoe, to minimize cavitation of the ground and promote good flush return. The opposite is done in particularly competent ground. Flushing water is best introduced via an external flushing device and should have a minumum rate of about 100-150l/min at 15-20 bars. To further improve flush return, sleeving can be inserted between adjacent couplers on the rod string to present a constant annular volume and reduce local "pressure drops" and resultant blockages.

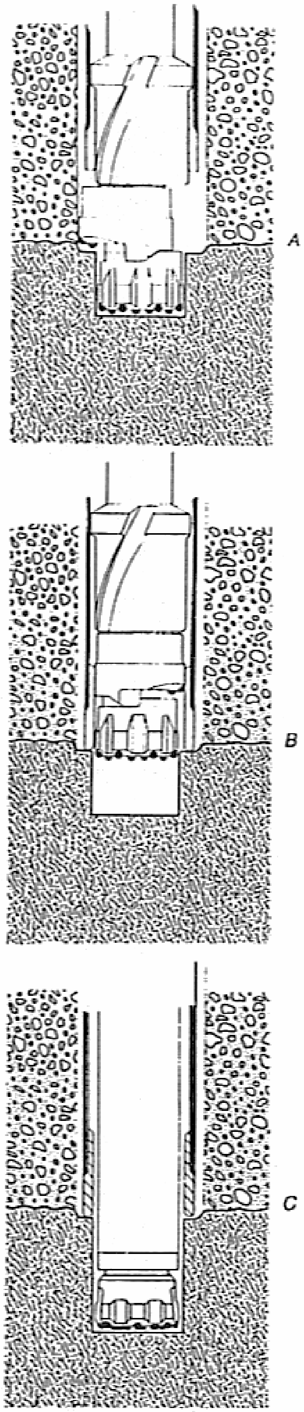
Assuming that sufficient torque (say to 6,000Nm) is available at the hammer, and adequate pull-up force can be applied (say around 4,000kg) then rotary percussive duplex may be regarded realistically as a viable and robust production method for holes to 60m depth. Clearly, however, for the deeper drilling associated with water well drilling or mineral prospecting it may not be the most cost effective option.

2.3.4. Rotary Percussive Eccentric Duplex

Restricted in terms of torque availability faced with the increasing demand for a system to reliably penetrate the difficult Scandinavian boulder clays, Atlas Copco and Sandvik jointly developed the very successful ODEX system in 1972. This percussive duplex variant features a pilot bit with eccentric reamer, which cuts a hole of diameter slightly larger than the casing. The manufacturers state that its performance is not impaired by gross changes in the ground from loose soil to fresh igneous rocks; the method cuts straight through obstructions or shoulders them aside. Early experience in Britain (Patey, 1977) also confirmed its ability to deal reliably with artificial obstructions such as slag and other foundry spoil, typical of fill deposits in old industrialized areas. Good results in loose scree type deposits, rip rap, and through old piled foundations have also been confirmed.

The principle of the operation is illustrated in Figure 5. In (a) the single piece pilot bit (concentric) is shown drilling beneath the casing; rotation has been applied, swinging out the reaming device (eccentric) which is enlarging the hole so facilitating the advancement of the casing (percussed only). The reamer is held in the correct position by stop lugs during drilling. Cuttings are transported upwards past the guide device, inside the casing to exit via ports at the driving cap. Flush is usually water, although air can be used, and foam is common for depths over 30m. When drilling is complete (Figure 5 (b)) the rods are counter-rotated, so closing the reamer and permitting the withdrawal of the rods and bit assembly. Drilling on into rock must then be done with a suitable rock bit (Figure 5c).ODEX is available with both top hammer and down-the-hole options and selection reflects ground conditions, hole diameter, hole purpose, and the type of rig and head available. In the former case, (Figure 6 (a)) part of the percussive energy is transferred from the top hammer, via a shank adaptor, to a driving cap above the casing. For down-the-hole drilling (Figure 6 (b))the percussive energy is transferred to the casing from the hammer by a special 'bit tube' with a driving (or impact) shoe. The casing is therefore pulled down, again without rotation, from its lower end.

In both cases, however, the steel must be strong enough to resist the percussive energy of the hammer either in compression (top hammer), or in tension (down-the-hole). Also, where it is to be extracted, the threaded casing must also have sufficient tensile strength, particularly in the threaded zones, and this parameter often dictates the practical depth to be drilled under any given conditions. Indeed, where ODEX 76 has been employed as a production drilling tool under adverse conditions, the typically thin-walled rotary casing of the standard system has had to be altered by specialist contractors, within, of course, the limits imposed by the geometry of the other elements of the system.



A When drilling, the reamer of the ODEX bit swings out and drills a hole larger than the external diameter of the casing tube.

B When the required depth has been reached, the drill is reversed and the reamer swings in to its minimum diameter, allowing the bit to be lifted up through the casing, which is left in the hole.

C Drilling can continue with an ordinary DTH drill bit.

Figure 5 Operating Principle of ODEX (Atlas Copco)

Regarding the anticipated longevities of the key components of the ODEX and OD systems (for comparison), Atlas Copco have published the indicative guidelines reproduced in Table 3. It should be noted however, that the relatively recent developments of high torque rotary and percussive drill heads have breathed new life back into conventional and simpler concentric duplex systems, as described above. Therefore the use of top drive eccentric duplex is becoming rare. On the other hand the demand remains strong especially in the water well industry for the drilling of large diameter holes in which the casing may be left in permanently. In such cases the down-the-hole variants still have much to offer especially when the driller has available only a standard medium sized drill rig with rotary head, and has experience in down-the hole-drilling. Most recently Halco have developed their own eccentric duplex system called Sim Cas (Figure 7). As the reaming device is only in two pieces, the operation is claimed to be simpler and more robust than the three piece ODEX equivalent. A similar system is also offered by Hutte.

In summary, a major attraction of ODEX type systems is that the effective efficient depth of penetration is not primarily dependent on driving torque, since the presenter of the greatest steel/ground contact area, i.e. the casing, is not rotated. However, the system remains relatively sophisticated, and its success is very sensitive not only to operator skill and expertise, but to the quality of the casing and its joints, and the efficiency of the flush.

ODEX System	
Pilot Bit	200- 600 drilled metres
Reamer	100- 300 drilled metres
Guide	400-1200 drilled metres
The various items are normally consumed in the following ratios: 1 guide; 2 pilot bits; 4 reamers.	
OD System	
Extension Tube	1000-1500 drilled metres
Tube Coupling	800-1000 drilled metres
Ring Bit	150- 400 drilled metres
Adaptor Sleeve	1000-1200 drilled metres
Cross-Bit	300- 500 drilled metres
ODEX and OD Systems	
Shank adaptor, flushing head, driving cap	800-1000 drilled metres
Extension Rods	1000-1500 drilled metres
Coupling Sleeves	800-1000 drilled metres

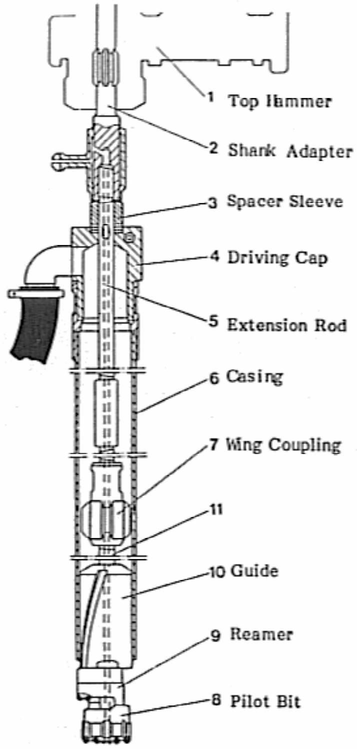
Table 3 Indicative Guideline Longevities for Atlas Copco OD and ODEX Systems components (Atlas Copco)

2.2.5. Rotary or Driven Duplex Underreaming

Several such systems have been conceived and employed with varying degrees of technical and commercial success in recent years. One of the more successful - the Casing Underreamer, of Acker Drill, - is taken as a typical example. In principle, an oversized hole is cut by a bit, and the following casing is either driven or rotated.

Type*	Rock drill	Recommended casing dimensions metric standard (mm)	American standard (in)	Drill tube diam. mm	(in.)	Reamed diam. mm	(in.)
For top hammers							
ODEX 76 W/T	BBE 57 COP 1238	W: max. O.D. 89 min. I.D. 78 min. wall thickness 4.5 mm T: 88.9 × 77.8 R.H. thread	3 1/2 3 1/16 3 1/2 × 3 1/16	R 38	(1 1/2)	96	(3 25/32)
ODEX 127 W/T	BBE 57 COP 1238	W: max. O.D. 142 min. I.D. 128 min. wall thickness 5 mm T: 140 × 128 R.H. thread	5 19/32 5 1/16 5 1/2 × 5 1/32	R 38	(1 1/2)	162	(6 3/8)
For DTH hammers							
ODEX 90 W/T	COP 32 A 30–15	W: max. O.D. 115 min. I.D. 102 min. wall thickness 5 mm T: 114.3 × 101.6 L.H. thread	4 1/2 4 4 1/2 × 4	76	(3)	123	(4 13/16)
ODEX 115 W/T	COP 42 DHD 24 DHD 340 A A 34–15	W: max. O.D. 142 min. I.D. 128 min. wall thickness 5 mm T: 140 × 128 L.H. thread	5 19/32 5 1/16 5 1/2 × 5 1/16	76 or 89	(3) (3 1/2)	152	(6)
ODEX 140 W	DHD 15 DHD 350 A 43–15	max. O.D. 171 min. I.D. 157 min. wall thickness 5 mm	6 3/4 6 1/8	89 or 114	(3 1/2) (4 1/2)	187	(7 3/8)
ODEX 165 W	COP 62 DHD 16 DHD 360 A 53–15	max. O.D. 196 min. I.D. 183 min. wall thickness 5.5 mm	7 3/4 7 1/4	114	(4 1/2)	212	(8 11/32)
ODEX 215 W	DHD 380 A 63–15	max. O.D. 257 min. I.D. 241 min. wall thickness 6 mm	10 9 1/2	114 or 140	(4 1/2) (5 1/2)	278	(10 15/16)

*T = threaded casing tubes
W = welded casing tubes



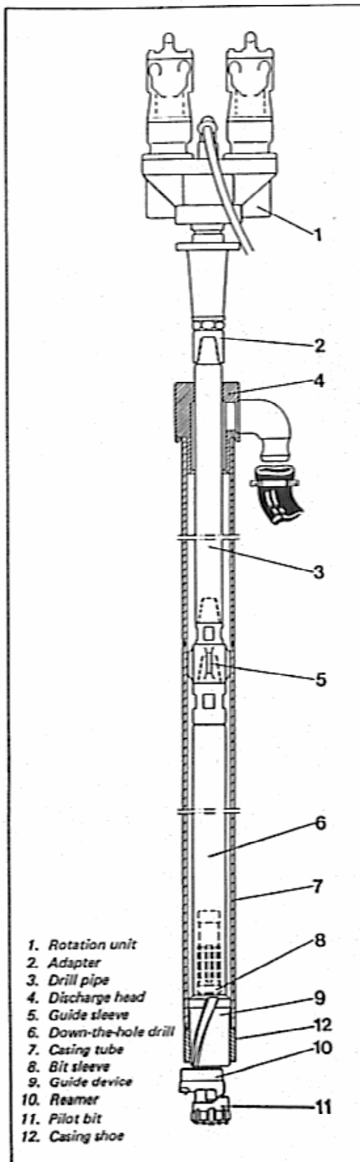
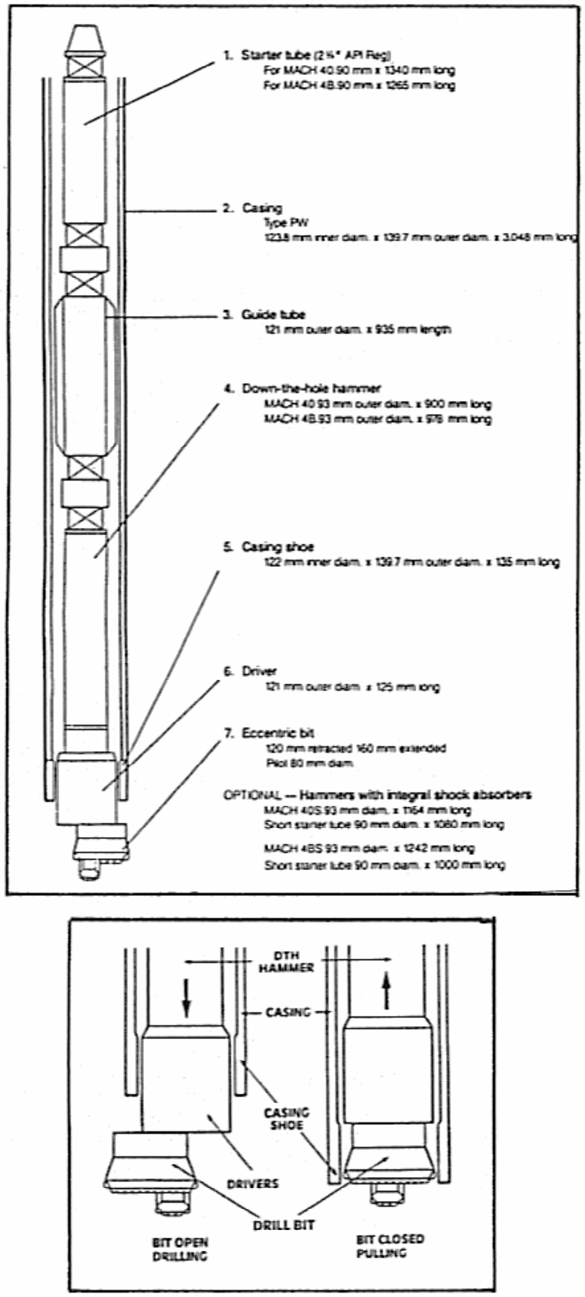


Figure 6 Comparison of a) Top Hammer (above), and b) Down-the-Hole ODEX Systems (right), and data on System Sizes (Atlas Copco)



	Sim-Cas 3	*Sim-Cas 4*	*Sim-Cas 5*	*Sim-Cas 6*
Casing O.D.	114mm	140mm	167mm	194mm
Casing I.D.	101.6mm	125.5mm	149.2mm	178mm
Maximum drill-through dia.	98mm	120mm	146mm	172mm
Halco down-the-hole hammer types	Mach 30B	Mach 4B/40B	Mach 5V/50V	Mach 6V/60V

Figure 7 Details of Sim Cas System (Halco)

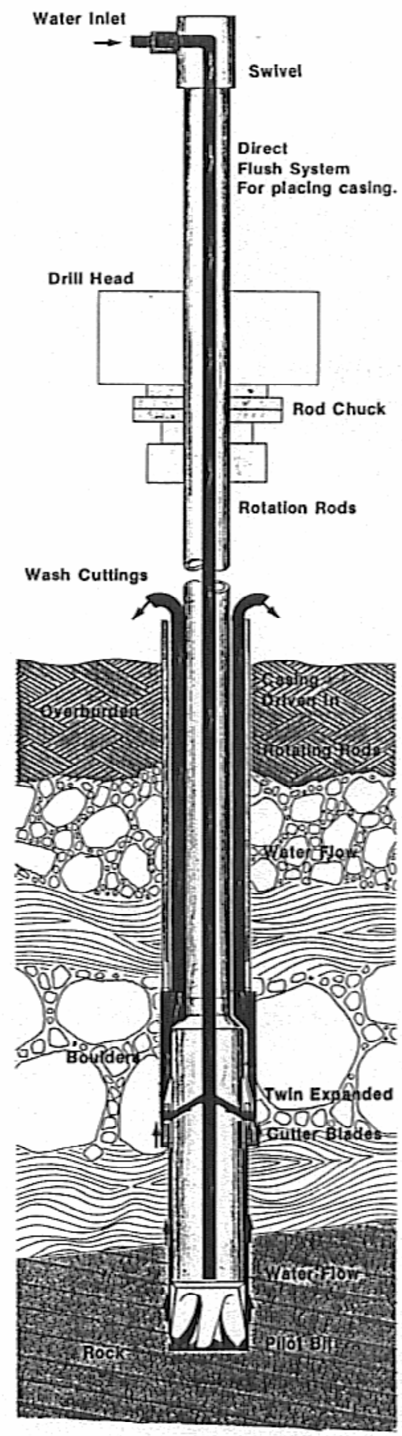


Figure 8 Operating Principle of Casing Underreamer System (Acker)

As shown in Figure 8 the underreaming is not conducted by the eccentric bit system of ODEX, but by activating outwards cutting blades above the pilot bit. These are opened by reaction to the penetration of the bit. Thus if the overburden is soft, resistance is low, the blades remain retracted and the casing advances in the simple duplex manner.

However, when hard layers are encountered the blades open and cut the clearance necessary for the advancement of the casing. At final depth, thrust is removed from the drill string, the underreamer blades fell in, and the string can be extracted. The system permits either subsequent or concurrent advancement of the casing, relative to the rods. Two sizes (Table 4) are available, designed for

Sizes	NW Casing	HW Casing
Pilot Hole or Bit Diameter	73.0 mm	95.2 mm
Underreamed Hole Dia (Max)	92.0 mm	117.4 mm
Pin Connection	"NW" Rod	"HW" Rod
Pilot Bit Connection Box	"NW" Rod	$2\frac{3}{8}$ API
Feed Pressure to Operate	29.1kg/sq cm	65.8kg/sq cm
Optional Feed Pressure	14.0kg/sq cm	32.4kg/sq cm

Assembly Description	Size NW *Part No Weight*	Size HW *Part No Weight*
Underreamer (less Pilot Bit)	21145 12.2kg	21144 18.5kg
Optional Underreamed Hole Dia's	To 111.1 mm	To 152.4 mm

Table 4 Specifications for Casing Underreaming System (Acker Drill)

heavy duty applications and the installation of NW or HW flush jointed drill casing. Diamond type cutter blades are available for replacing the twin carbide insert blades when drilling extremely hard material. Diamond pilot bits are also commonly used to replace roller, rock or drag type pilot bits commonly used for drilling average overburden materials.

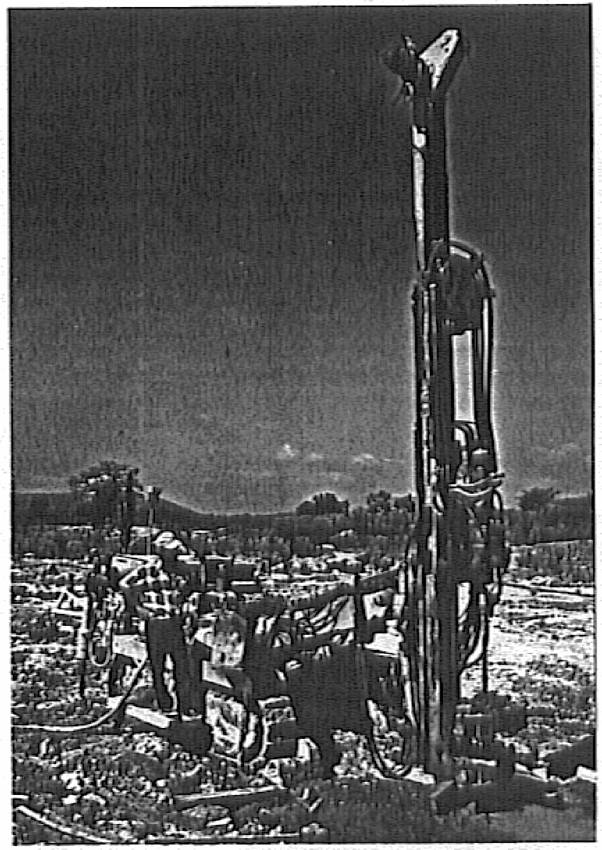
The Underreamer is operated at speeds normally used for rock roller bits or drag bits. The thrust required for the 117.4mm underreamer is about 4 000N and for the 92.0mm is about 2 000N. The water requirements are similar to those for normal rotary drilling. The system is capable of penetrating boulders, rock debris, timbers and steel.

2.2.6. "Double Head" Duplex Drilling

This rotary duplex method is claimed to be especially quiet, to ensure minimal ground disturbance, and consistent cost effective penetration to over 80m in even the most difficult ground conditions. It is distinguished from conventional rotary duplex by the fact that the rods, and casings, are simultaneously rotated but in opposite senses. The inner drill string, with Right Hand rotation carries either a down-the-hole hammer (air or water activated) in hard conditions, or some form of rotary bit in soft ground. Typical rotary requirements are 2,500Nm torque at 40-60rpm.

The casing, with Left Hand rotation, terminates in a substantial crown which cuts a slightly oversized hole, thus reducing casing/ground resistance. Rotational speeds are lower than in conventional duplex drilling, (15-30rpm) to the advantage of the torque availability (to 8,000Nm). However, the benefits of the counter rotation are that the combined action of the casing and rod cutting is enhanced, and the prospect of flush debris blockages in the casing/rod annulus is minimized due to its dynamic boundaries. (Water flush typically 40-601/min at 15 bars). In addition, the counter rotation helps to offset natural tendencies for holes to deviate and, in conjunction with the stiff, thick walled casing used (Table 2) holes of exceptional straightness (say within 1 in 100) can be routinely provided.

This system is driven by special "Double Heads" with both Klemm and Krupp (Table 5)being prime examples. These heads can be mounted happily on relatively small and mobile rack rigs of sufficient hydraulic output (Photo 1). A particular



Photograph 1 Typical medium-sized diesel hydraulic drill rig. (Casagrande)

feature is the ability of moving axially the upper rotator (turning the rods) about 30cm relative to the casing rotator. This affords the driller extra scope in selecting the relative advancement of rod bit and casing shoe in response to ground conditions. The lower rotator can also work in High Gear (say 30rpm, low torque range) or Low Gear (say 15rpm, twice torque previously available). In addition the upper rotator can be replaced with a rotary percussive head and the down-the-hole hammer omitted, as noted in Table 5. As with other percussive duplex variants, a retrievable underreamer can be used to precut the soil to a diameter just larger than the casing shoe.

Double head duplex is common on European sites with particularly difficult ground but restricted access. It was also used under similar conditions recently at the Hines Auditorium in Boston (Bruce, 1988) whilst its use is growing- with the increasing popularity of diesel hydraulic track rigs- on both coasts of the United States. In Canada a project has recently been completed underground in N. Ontario where the 133mm casing has been drilled, straight, to 60m depth through loose mine backfill comprising boulders of up to $500N/mm^2$ compressive strength, in headroom of 4m.

2.2.7. Auger Drilling

Auger drilling is a long established method of drilling cohesive soils with the minimum of hard inclusions, and features the rotation of what is basically a screw into the ground. The continuous flight auger may be in one part (as used in bored piling works) or in connecting sections, in, for example, anchor minipile, or grout hole applications.

The basic method uses a solid stem (or core) to excavate the hole, which, when the auger is

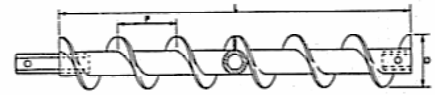
OPERATING METHOD	OUTER CASING INNER ROD		OPTION A Rotated * Rotated *	OPTION B Rotated * Percussed/Rotated *
Service weight including base plate		kg	630	700
Oil flow rate (front/rear rotary mechanism		max. l/min	160/170	160
Oil flow rate (percussive mech. for inner string)		max. l/min	-	-/85
Operating pressure (front/ rear rotary/percussion mech.)		max. bar	210/260/-	210/170/170
Torque (front/rear rotary mechanism)		max. Nm	8000/4000	8000/4000
Number of revolutions* (front/rear rotary mechanism)		max. rpm	110/145	110/110
Number of blows		max. min^{-1}	-	-/1800
Connection thread outer/inner drill strings			to be specified	to be specified
Hole diameter		mm	100-300	100-300
Flushing medium			air/water	air/water

* Clockwise or counterclockwise, but inner and outer drill strings always counter rotating.

Table 5 Specification for Double Head Drill, with either rotary or rotary percussive option for inner drill string (Krupp).

	Continuous Flight Diameter (D) Auger Series '125' mm (in)	'200' mm (in)	'250' mm (in)	'350' mm (in)	'400' mm (in)	Hole dia (Bit cutting dia.) mm (in)
	115 (4½)	- -	- -	- -	- -	130 (5)
	140 (5½)	140 (5½)	- -	- -	- -	155 (6)
	160 (6¼)	160 (6¼)	- -	- -	- -	180 (7)
	- -	205 (8)	205 (8)	- -	- -	230 (9)
	- -	255 (10)	255 (10)	- -	- -	280 (11)
	- -	305 (12)	305 (12)	305 (12)	305 (12)	340 (13½)
	- -	- -	355 (14)	355 (14)	355 (14)	395 (15½)
	- -	- -	405 (16)	405 (16)	405 (16)	460 (18)
	- -	- -	- -	460 (18)	460 (18)	510 (20)
	- -	- -	- -	510 (20)	510 (20)	570 (22½)
	- -	- -	- -	560 (22)	560 (22)	620 (24½)
	- -	- -	- -	610 (24)	610 (24)	690 (27)
	- -	- -	- -	- -	660 (26)	740 (29)
	- -	- -	- -	- -	710 (28)	800 (31½)
	- -	- -	- -	- -	760 (30)	850 (33½)
Hexagon Coupling Nominal size across flats	1⅝"	1⅝" or 1⅞"	1⅞" or 2"	2⅞"	2⅞"	

Note: Auger and hole diameters have been rounded to nearest ¼".



Standard lengths (L) 1.0, 1.5, and 3 m (3.3, 5 and 10 ft); other lengths and auger diameters readily available

Hollow Stem Augers

Min i/d centre tube mm	(in)	o/d H.S. Auger Flight mm	(in)	o/d Auger Bit mm	(in)
60	(2⅜)	145	(5¾)	160	(6¼)
100	(4)	215	(8½)	240	(9½)
130	(5)	255	(10)	280	(11)
150	(6)	305	(12)	340	(13½)

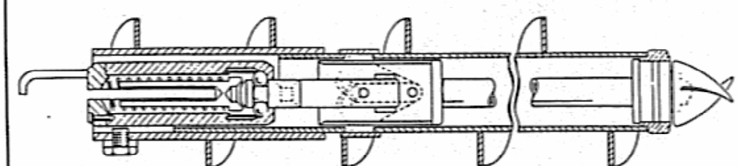


Figure 9 Standard Sizes of Continuous Flight, and Hollow Stem Augers (Hands England)

Hole dia. (mm)	Stem o.d. (mm)	Stem i.d. (mm)
140	76.1	50
155	88.9	64
170	101.6	72
190	108.0	82
230	114.3	88

Table 6 Standard Hollow Stem Auger sizes (Hutte)

withdrawn will remain open only due to the natural competence of the ground, and the absence of ground water pressures. As noted earlier, such "open hole" methods are not the subject of this discussion. Much recent development has focused on hollow stem augers, which permit water, and/or grout to be pumped to the bottom of the hole, allow placing of anchor bars or grout tubes, or enable drilling on into underlying strata for soil sampling or rock socketing. Generally, however, as emphasized by the range of standard sizes Figure 9) and the capacities of typical rotary head models, the whole concept of augering is still related to the larger diameter fields of cast in situ piles, prebored pile holes and sand drains. Common base machines are excavators, piling frames and crawler mounted cranes.

To reduce power requirements and allow adequate clearance for the flights, auger bits (or cutting heads) cut a hole 10-12 percent larger than the auger diameter. The pitch of the flights is 60-80 percent of the outside diameter of the auger to reduce the tendency of the cuttings to roll back down the hole. The leading auger section (0.2-0.5m), and fitted with the appropriate bit or drive shoe, is often armoured to reduce wear on following flights. Expanding auger bits are available for use with continuous flight augers for boring inside casing. The auger bit has an outside diameter equal to the continuous flight auger, but expanding wings increase the cutting diameter to the outside diameter of the casing. During drilling the auger is positioned so that the wings are just below the lower edge of the casing which may then be advanced as cutting proceeds. Reversing the rotation causes the wings to fold back, enabling the auger and bit to be withdrawn without disturbing the casing.

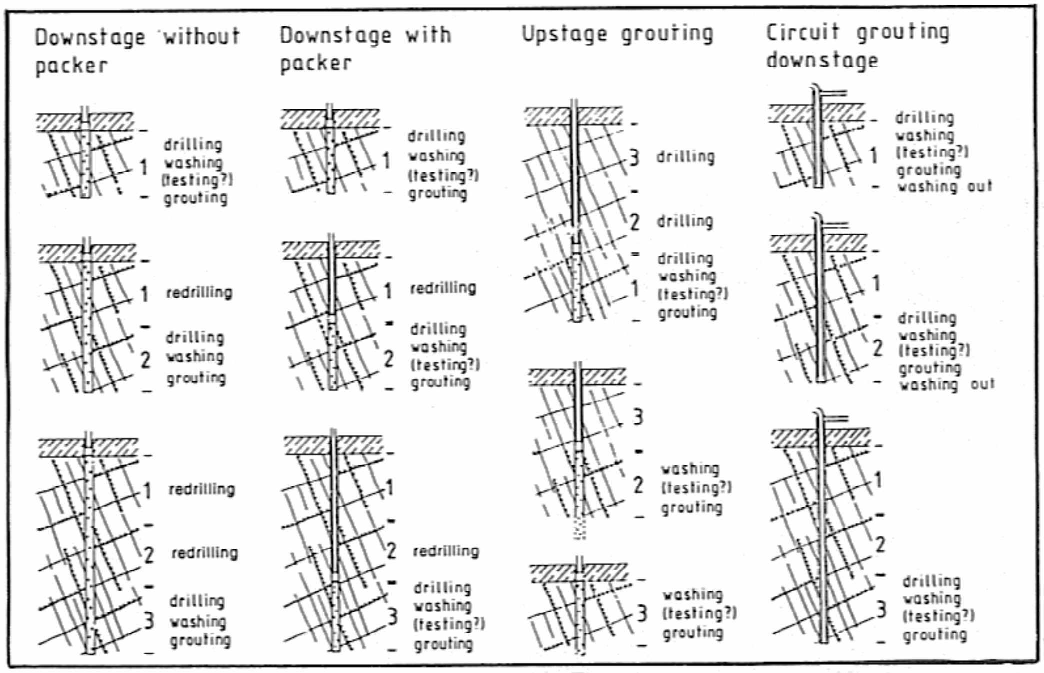
For applications within our field of interest, Table 6 shows typical sizes for hollow stem auger systems.

3. METHODS OF GROUTING

It will be recalled that the scope of this paper is restricted to geotechnical activities. Grouting applications in other fields e.g., duct grouting, (Hope and Ip, 1988) prepacked aggregate injection(Littlejohn, 1984) offshore works (Littlejohn 1981), sewer sealing (eg. Waring, 1989, Johnson, 1989), or mining (White, 1989), are not addressed. In addition, methodologies with restricted, though locally invaluable, applications much as hot bitumen grouting (Lukajic, et al., 1985, Kreikemans, 1989) are also left to other presenters. The technique of Deep Soil Mixing (Suzuki, 1982) is also not considered within the boundaries of the review.

3.1. Rock

The standard methods of fissure grouting rock masses have long been used and so are generally well known. Depending on geological and economic factors, treatment is conducted from the top of hole down, or from the bottom up. In the former method, packers may be left at the top of each hole, or at the top of each descending stage (Figure 10). A most readable synopsis of all aspects of such grouting for dams was presented by



	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.

Figure 10 Conventional Stage Grouting Methods for Rock Fissure Grouting (Ewart, 1985, after Houlsby, 1982)

Houlsby, (1982), and a survey of cement grout design was compiled by Littlejohn, (1982). The book by Ewart, (1985) provides details principally of German dams, whilst Houlsby will publish a book within the next year which will most probably constitute the definitive work on rock fissure grouting for many years following. Bruce, (1982) and Bruce and George, (1983) summarized British practice.

Much of rock grouting methodology is traditional, with changes occurring largely in equipment, materials and instrumentation, as described below. However, there is a major new development- the MPSP System- which has enormous potential in grouting very difficult rock conditions such as collapsing or karstic rock masses, (Bruce and Gallavresi, 1988). As shown in Figure 11, the drill hole is first drilled (and

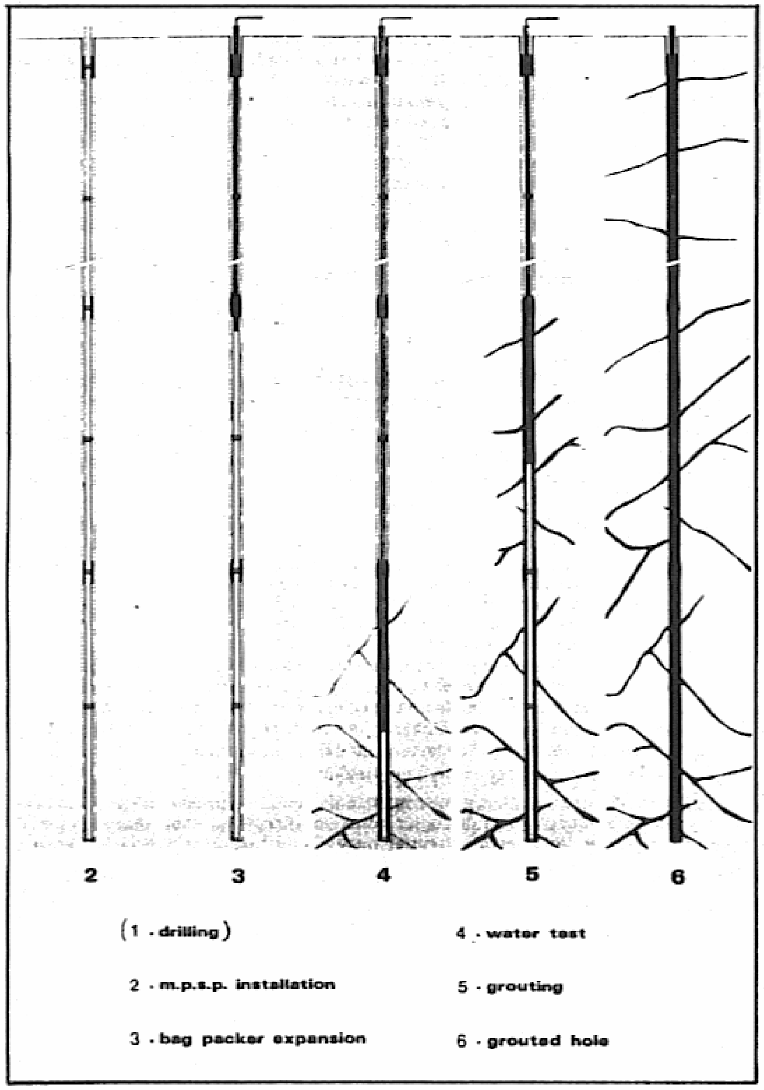
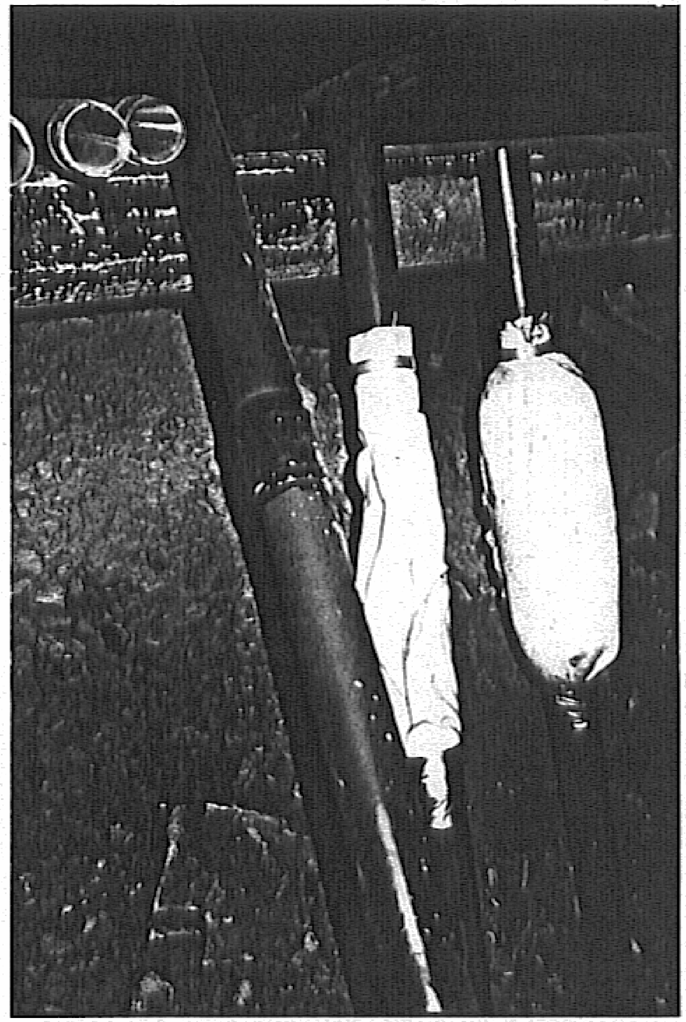


Figure 11 Installation Sequence for MPSP System



Photograph 2 MPSP grout pipe (3" dia.) showing (left to right) rubber sleeve, uninflated fabric bag, inflated fabric bag.

cased) to full depth. The rods are withdrawn. A plastic pipe is then inserted into the casing. The pipe has sleeved ports at regular distances along it, say every 2 m. These ports are identical to those used in the more familiar tube a` manchette (sleeved pipe) system. Every third sleeve is in turn surrounded by an external fabric bag, clamped either side of the port (Photograph 2). The drill casing is withdrawn. By means of a double packer, each bag is then inflated with cement grout, retaining the pipe in the hole, and isolating the rock mass into successive vertical stages. These can then be grouted through the intermediate ports. Clearly this system ensures that grout can be introduced at every level in the ground, whereas with conventional systems, hole collapse prior to grouting, or the presence of major voids would result in inefficient treatment full depth. Several major applications have been recorded in dams around the world in the last eight years or so, and the first North American application has just been successfully completed in a mine in Northern Ontario.

As a footnote to rock grouting methodology, it should be noted that attitudes towards permeability testing have been much influenced by the publication in 1976 of Houlsby's work on the Modified Lugeon Test. As demonstrated in Bruce and Millmore, (1983) his proposals are not only theoretically sound, but imminently practical, and compatible with good site practice and feasibility.

3.3. Soil

Methods used in soil grouting are in a far more dynamic situation than those for rock grouting. They are benefiting directly from the technological advances made by chemists, physicists and geotechnical engineers on the one hand, and are prompted by the increasingly severe demands made by structural engineers, environmentalists and property developers on the other. Many of the new developments in soil grouting have been associated with tunnelling in urban areas, principally for subway or sewer projects. In most cases, such developments have been designed as an aid to tunnelling contractors in order to speed progress, improve safety and minimize associated settlements. Such has been the progress that grouting is now established not only as a final remedial option when "conventional" techniques have failed, but as the "design tool, as it should be from the onset." (Clough, 1981).

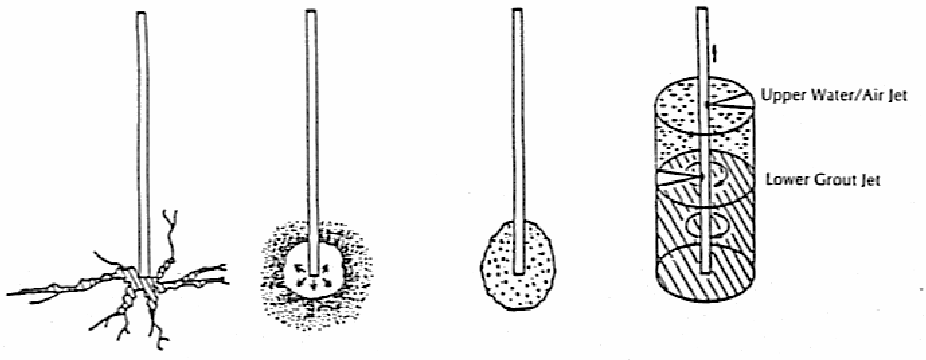


Figure 12 Basic Categories of Soil Grouting

Overviews of ground treatment conventionally identify four basic categories of soil grouting (Figure 12)

1. Hydrofracture
2. Compaction
3. Permeation
4. Replacement

3.2.1. Hydrofracture Grouting

In hydrofracture (or claquage) grouting, the ground is deliberately split by injecting stable but fluid cement-based grouts at high pressures (for example, up to 4 N/mm^2). The lenses and sheets of grout so formed increase total stress, fill unconnected voids, possibly consolidating the soil under injection pressure, and conceptually constitute mainly horizontal impermeable barriers. However, it is typically very difficult to control, and the potential danger of damaging adjacent structures by the use of high pressures often proves prohibitive. It is not common to find this technique alone deliberately exploited outside the French grouting industry, although some hydrofracture phenomena accompany most permeation grouting contracts either accidentally or in conjunction. Tornaghi et al.(1988) note that hydrofracture naturally occurs with conventional cement-based grouts in soils with a permeability of less than 10^{-1} cm/sec.

3.2.2. Compaction Grouting

This is a specialized "Uniquely American" process that has been used since the early 1950's (Baker et al., 1983) and remains very popular in that country. Very stiff soil cement mortar is injected at high pressures (up to 3.5 N/mm^2) at discrete locations to compress and increase the density of soft, loose or disturbed soil. Unlike the case of hydrofracture grouting, the grout forms a very dense and coherent bulb that does not extend far from the point of injection. Near-surface injections result in the lifting of the ground surface (the technique of slab jacking as described, for example, by Bruce and Joyce, 1983) and, indeed, the earlier applications were used exclusively for leveling slabs and light buildings on shallow foundations, (ASCE, 1977, Warner, 1982). Prior to the Bolton Hill Tunnel project, compaction grouting had been used in the Baltimore subway project to remediate settlement problems caused by subway tunnel construction- but only after the tunnel had been completed and settlement of overlying buildings had occurred. However, the Bolton Hill project marked a fundamental change in philosophy, in that compaction grouting was introduced during the excavation of the tunnel at locations just above the crown. In this way, major surface settlements were controlled before they could affect the surface.

Although compaction grouting of course has practical and technical limitations, its popularity continues to grow, in no small way due to its very active and professional promotion in the technical press and at geotechnical seminars by specialty contractors. However, its potential application should be most carefully reviewed when dealing with tall structures or buildings that can tolerate only the smallest differential movements. Under such conditions, it is imperative to attack the cause of the settlements at the source, and prevent them from migrating away from the excavation. Permeation or replacement grouting may then be necessary. Good case histories and guidelines abound (eg. Baker, 1985). Recent papers dealing with more novel applications include these Salley et al.,(1987) referring to liquefaction control measures at Pinopolis West Dam,S.C., and by Welsh, (1988) for combatting sinkhole damage in karstic limestone topographies.

3.2.3. Permeation Grouting

In certain ways, the techniques involved in permeation grouting are the oldest and best researched. Its history may be traced back to 1802 and the efforts of Charles Berigny to repair the Dieppe harbor sea lock that had been damaged by slump and washout. It would appear that grouting was first attempted in the U.S. during the construction of the New Croton Dam, in New York, although the first major application followed around 1910, during shaft sinking and tunnelling for the Catskill Aqueduct, also in New York. The intent of the method is to introduce grout into soil pores without any essential change in the original soil volume and structure. The properties of the soil, and principally the geometry of the pores, are clearly the major determinants of the method of grouting and the materials that may be used (Figure 13). Excellent reviews of the

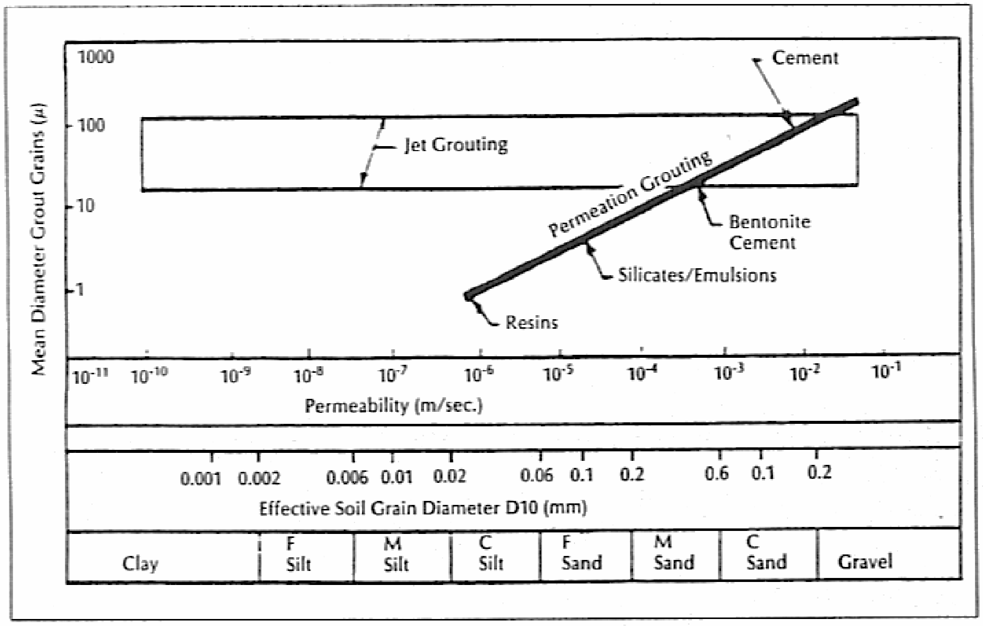


Figure 13 Groutability of Soils in Relation to Grout and Soil Properties (After Coomber, 1985)

subject are provided by the FHWA, (1976), Cambefort, (1977), Karol, (1983), and Littlejohn, (1985).

Permeation grouting of soils may be accomplished by a number of systems, and major groups may be classified as follows.

3.2.3.1. End of Casing Injection

When the ground is suspected as being very open and there is no recognized need for sophisticated multiphase or multi material injections in any one hole, then the simplest group of methods may be grouped as "end of casing". In essence, the casings are installed to the final depth, and grouting conducted through them, via a top hole grouting cap, as the casings are slowly withdrawn. All the forms of drilling outlined in Section 2 can be used for this purpose. Typical examples would range from drive drilling (for shallow grouting of railway enbankments) through percussive duplex (for deeper consolidation, as in mine shafts) to rotary duplex (for grouting of anchors or minipiles). In addition, grouting through the drill rods again during withdrawal, is often conducted for hole stabilization for watertightness, prior to redrilling. Compaction grouting is generally conducted by this method also.

3.2.3.2. Tube a` Manchette

It is generally recognized in Europe and North America that the most controlled method of overburden permeation is the tube a` manchette (or sleeved tube) system (Figure 14). Essentially it permits multiphase injections of various materials with a great degree of control over the grouting variables (Bruce, 1982). The method does however depend for its successful performance on the efficient and economic installation of the plastic or steel grouting tubes. In general, some form of duplex method is used to penetrate to the required depth. The inner rods are withdrawn, the casing topped up with bentonite-cement "sleeve" grout, the sealed grouting pipe inserted, and the drill casing withdrawn. Recently, increasing use has also been made of hollow stem augers for this purpose, and in coarse cohesionless soils, rotary methods with bentonite flush are common. Clearly, the casing must have sufficient bore to permit its extraction without damaging the delicate tube or its rubber sleeves. However, too large a bore will give an unacceptably large annulus of sleeve grout, making a subsequent opening of the sleeves a question of very high initial rupture pressures. Usually an annulus of 20-30mm is sought.

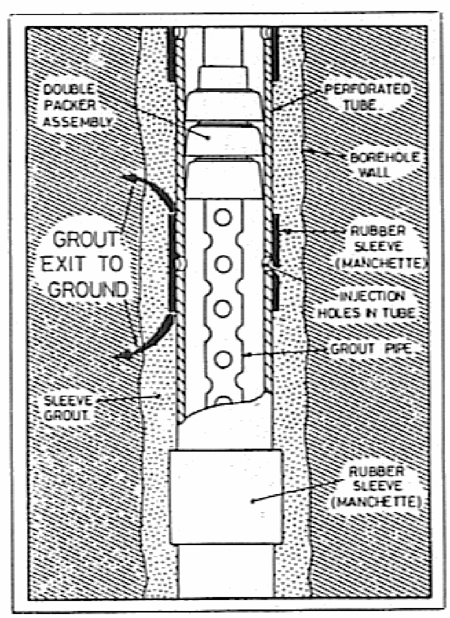


Figure 14 Operating Principle of Tube a` Manchette (Sleeved Pipe) System.

Despite the advances in other forms of soil grouting, permeation by sleeved pipes remains one of the most popular systems worldwide. Major recent applications include tunnels eg (Hong Kong Metro (Bruce and Shirlaw, 1985), Cairo Sewers (Greenwood et al., 1987), Milan Metro (Mongilardi and Tornaghi, 1986), deep excavations (Littlejohn, et al., 1989) and dams (Bell, 1982). In the States many examples can be cited of recent work in New York, (eg. Brand et al., 1988) Pittsburgh, and Baltimore, and ongoing work in the Los Angeles Metro.

Claquage grouting is also conducted through sleeved pipes of this type.

3.2.3.3. Valve Tube System

In many ways similar to the tube a` manchette system in terms of its grouting capabilities, this system, developed by Stabilator of Sweden in the middle 1960's, has one major difference. The steel grouting pipe, equipped with spring loaded grouting ports doubles as the drill casing, and as such has a non-retrievable crown (or ring bit) (Figure 15). The casing is not rotated during driving. Clearly the initial lineal cost of tube installed is high, but this is claimed to be offset by the high rate of installation, in which no time need be spent extracting temporary casing, as in the case of tube a`manchette grouting, for example. Several successful major applications have been recorded throughout the world with a particularly good description provided by Lamberton (1982).

3.2.3.4. Limited Area Grouting (LAG)

In the last 25 years there has been a tremendous growth in tunnelling and deep foundation projects in Japan. This is reflected in the high reputation currently held by the Japanese as soft ground tunnellers, and as developers of novel ground treatment systems, of which LAG is one of the most common (Figure 16 (a)) throughout Southeast Asia.

It features the introduction by small hollow spindle rotary drill rig of a combined rod-casing assembly, followed by the injection of a flash setting (5 secs) grout via one exit port during rotated withdrawal of the string (20rpm at about 2m/min). With respect to Figure 16(b),passage A carries the base component (silicate solution), and passage B the reagent. These are mixed and ejected at the port, which during drilling is kept closed by a spring arrangement. A diameter of treatment of 0.6-1.0m per hole is anticipated.

Typical ground conditions suited to LAG are clays, silts, sands and fine gravels. It is notable that the tube a`manchette system is relatively little used in Japan due to its (i) relative cost and complexity (ii) potential for dilution and dispersion of grout under dynamic ground water conditions, (iii) leaving in of tubes after completion of treatment, and (iv) possibility of water supply contamination due to comparatively large lateral grout travel resulting from high pressures and longish gel times (eg. Tokoro et al., 1982).

Grouted ground strengths of 0.2-0.5N/mm^2 are common, and this system accounts for 20% of the Japanese domestic market but a larger proportion of the work executed by their specialist companies elsewhere in S.E. Asia (e.g. MTR in Hong Kong, MRT in Singapore). The system is protected by at least six patents and one Association.

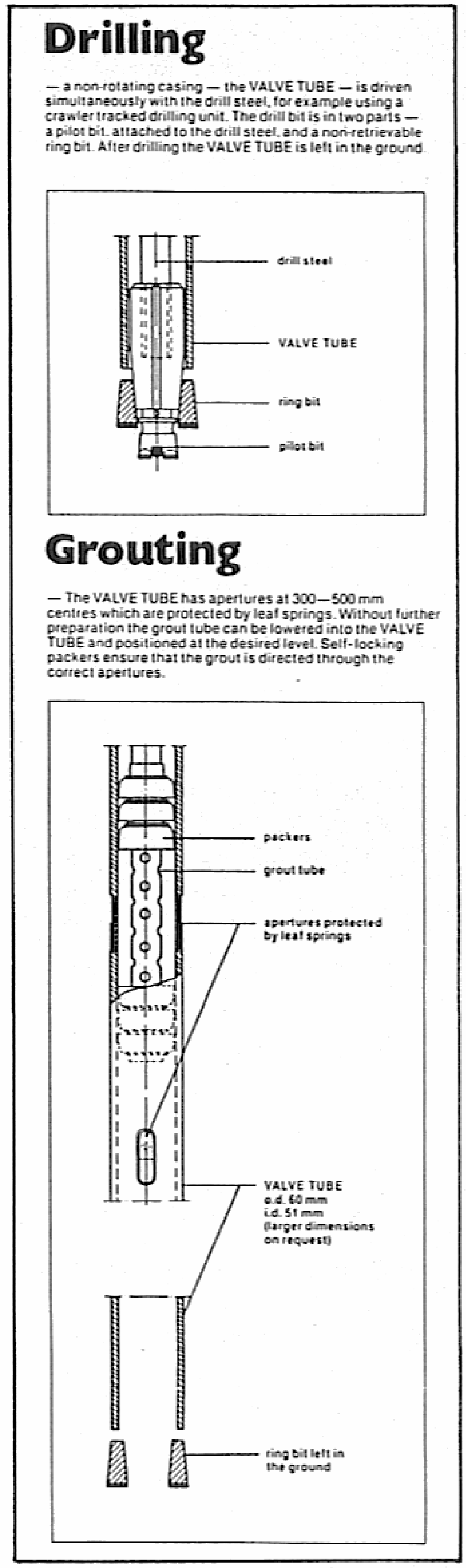


Figure 15 Details of the Valve Tube System (Stabilator)

3.2.3.5. DDS (Double Tube Drilling and Seepage)

The system is in some ways similar to LAG.It features the rotary insertion of fixed rod casing system (42mm o.d.) with water flush. At the terminal depth a small plug is activated by grouting pressure against a retaining springabove the drill bit: this exposes six lateral nozzles through which the fast setting grout (10-30secs) components are ejected. As in LAG the grout consists of a mix of silicate plus reagent,

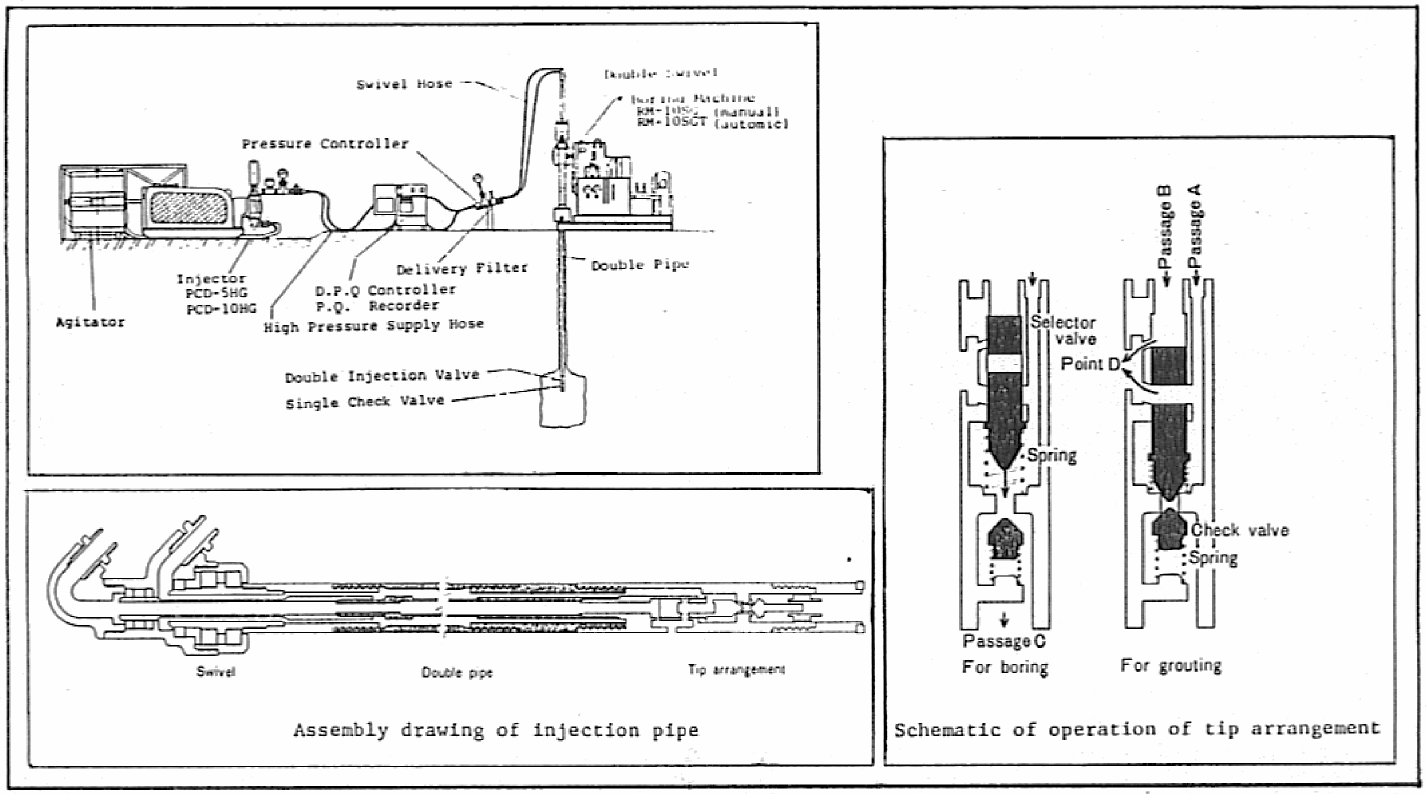


Figure 16 Operating Principle, and Key Components of LAG System (Tokoro et al., 1982)

delivered in seperate passages, with final mixing occurring only at the nozzles. No rotation is required during extraction. Water flush characteristics of 15-251/min at 10 bars give a diameter of influence of up to 1 m. Withdrawal rates of around 15min/m are common, with grouting pressures of up to 1.5 N/mm^2. Presently, about 50% of the Japanese domestic chemical grouting market features this system. Again, small hollow head drilling rigs, (say up to 30HP) are adequate, and their quiet and vibration-free operation makes them very popular in urban or underground grouting works.

It should be noted that there are several other variants of this type, e.g. SGR ("Space Grouting Rocket System"), in Japan, where environmental and geotechnical considerations clearly favor this approach. However, their market share is small, and the other systems described above would appear to be of far wider relevance outside that country.

3.2.4. Replacement Grouting

Replacement, or jet, grouting is the youngest major category of ground treatment. According to Miki and Nakanishi, (1984) and Miki, (1985) the basic concept was propounded in Japan in 1965, but it is generally agreed that it is only within the last 10 years that the various derivatives of jet grouting have approached their full economic and operational potential (Figure 17 and Table 7) to the extent that today it is the fastest growing method of ground treatment worldwide. Its development was fostered by the need to thoroughly treat soils from gravels to clays to random fills in areas where major environmental controls were strongly exercised over the use of chemical (permeation) grouts and allowable ground movements. As indicated in Figure 13, jet grouting can be executed in soils with a wide range of permeabilities. Indeed, any limitations with regard to its applicability are imposed by other soil parameters (eg. the shear strength of cohesive soils or the density of granular deposits).

The ASCE Geotechnical Engineering Division Committee on Grouting (1980) defined jet grouting as a "technique utilizing a special drill bit with horizontal and vertical high speed water jets to excavate alluvial soils and produce hard impervious columns by pumping grout through the horizontal nozzles that jets and mixes with foundation material as the drill bit is withdrawn." Figure 18 depicts one particular type in which the soil is jetted by an upper nozzle ejecting

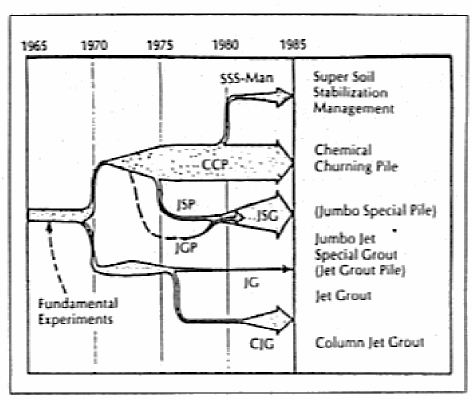


Figure 17 Development of Jet Grouting Methods in Japan (Miki and Nakanishi, 1984)

Original Japanese Name	Principal of Operation	Jetting Pressure (N/mm^2)	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 Stabili-zation Manage-ment (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 tech-nique, but ensures desired performance

Table 7 Major Categories of Jet Grouting Variants

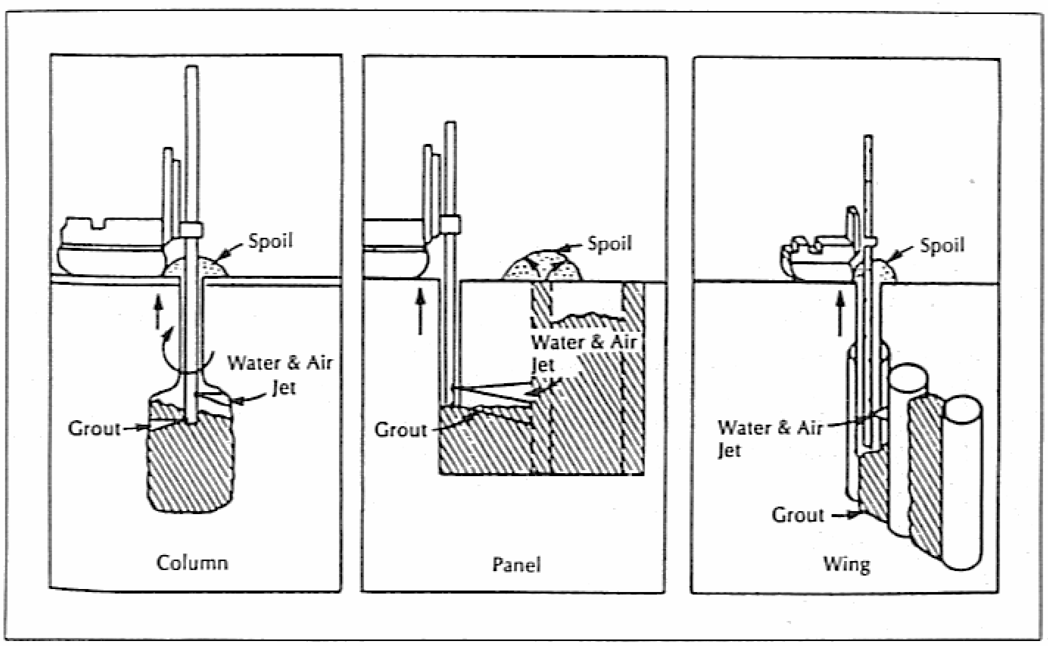


Figure 18 Jet Grouting Options Using the Three-Fluid System (Coomber, 1985)

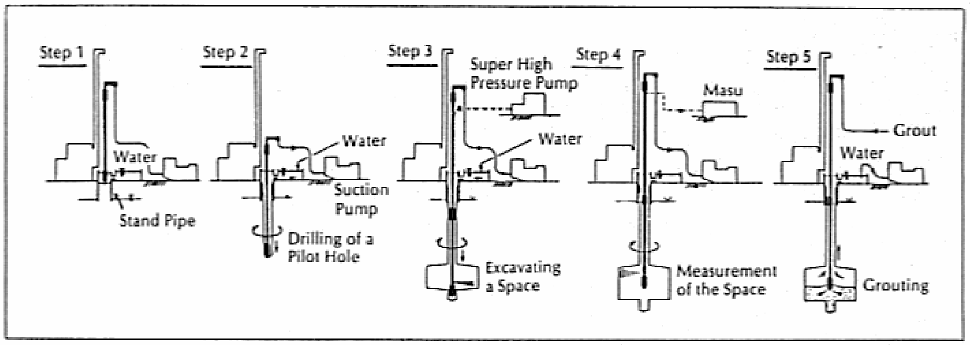


Figure 19 Operating Principle of the SSSMAN Method of Jet Grouting (Miki and Nakanishi, 1984)

water at up to 60 N/mm^2 inside an envelope of compressed air at up to 1.2 N/mm^2. The debris is displaced out of the oversized hole by the simultaneous injection of cement based grout through a lower nozzle (up to 7 or 8 N/mm^2). Other simpler variants utilize grout jetting only to simultaneously erode and inject giving much more of a mix in place action. At the other extreme of complexity, the new Japanese Super Soil Stabilization anagement (SSSMAN) system provides total (and verifiable) excavation of the soil prior to grouting or concreting (Figure 19). Clearly, each system has its own cost implications. Overall very few examples greater than 45m deep have been recorded.

In contrast to the sensitivity and sophistication of some aspects of permeation grouting, the principle of jet grouting stands as a straightforward positive solution, using only cement-based grouts across the whole range of soil types. This opinion is enhanced by the very dramatic photographic evidence from excavated test sections (Photograph 3). However, it must be emphasized that any system that may involve the simultaneous injection of up to three fluids at operating pressures of up to 60 N/mm^2 must be handled with extreme care and only in appropriate applications, circumstances and ground conditions. The credentials, resources and methods of the specialist contractor must, therefore, be reviewed with special care.

The major development trends are heading towards refining operational methods and equipment, trying to obtain a closer understanding of the interaction of ground types and grouting parameters, and in developing monitoring and control systems.

Regarding equipment and methods, a two-fluid jetting system has been successfully developed. In this system, the high pressure jet is concentrated in a compressed air envelope (Figure 20). Thus, the radius of influence of the grout jet is considerably increased, even in saturated conditions. Another major advantage is that it is operationally far simpler than the three-fluid system described above, and much faster and economic.

Regarding design, ASCE, (1987) noted that the fundamental aspects are grout mix, jet nozzle energy and flow rate, and grout pipe rotation and withdrawal rates. Miki and Nakanishi, (1984) reported on data recorded from full scale tests conducted over many years, and they quantified the relationship between method, soil type and resulting column diameters for particular operating parameters. Coomber, (1985) stated that water jet pressure and monitor withdrawal rate are the most significant of these parameters (Figure 21), while similar data were presented in different format by ASCE (Figure 22).

Grout mix constituents and composition can be varied to meet the specific requirements and, for example, the addition of bentonite will reduce the soilcrete permeability. Mix viscosity should be low to promote uniform treatment to the greatest extent, and water/cement ratios (by weight) are rarely less than 1.0. In permeable granular materials, much of the injection water may be expected to be drained out from both soil and grout, whereas in a cohesive soil of low virgin permeability, poor or no drainage is likely. This lack of proper drainage is a principal reason why the strength of the grouted column (depending primarily on the final water/cement ratio) is much lower in clay than in sand and gravel when all other factors are equal.

Regarding quality assurance, recent developments in instrumentation include the Paperjet- a parameter recording system similar to Papero and Paguro described below. Nevertheless,

Photograph 3 Jet grout column formed by three fluid system (Rodinjet3) in alluvial materials excavated after 9 days.

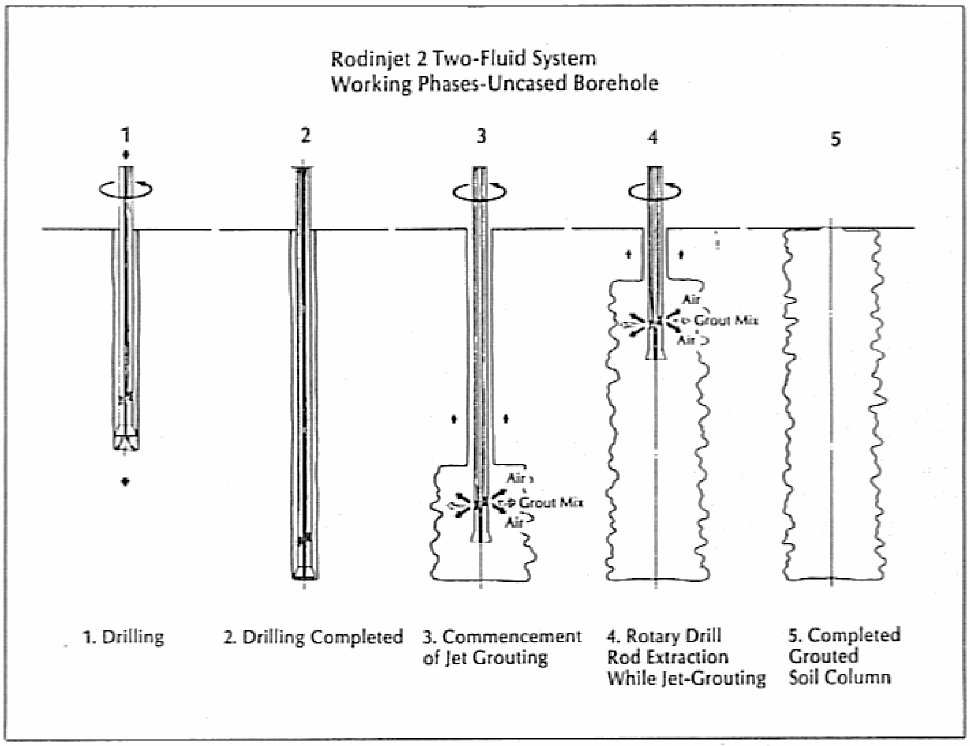


Figure 20 Jet Grouting with Two Fluid System (Rodinjet 2)

it should remain an integral part of every jet grouting program to have a field trial prior to the commencement of production in order to verify and optimize operating parameters. Such trials should include visual inspection of the grouting by excavation wherever practical. A comprehensive example of the planning and execution of such a program is provided by DePaoli et al. (1989), in their description of the stabilization by jet grouting of a highly compressible peaty zone up to 5m thick under a railway embankment near Como, Italy. A range of methods (one-,two- and three-fluids with and without prewashing) and grouting mixes and parameters were systematically assessed prior to the successful treatment of 25,000 m^3 of soil with 1,300 vertical columns each about 2m in diameter. Strengths of up to 7 N/mm^2 were achieved (typically 1 to 2 N/mm^2) with "negligible" compressibility in service.

These remarks on verification and testing apply equally to projects executed with other forms of ground treatment. Experience, often bitter, has underlined the value of such testing, especially when set against the scale of the disruptions that may result "down the line" due to inefficient or inappropriate treatment procedures however well intentioned at the planning stage.

Most jet grouting is conducted to provide circular columns, but panels or membranes can be cut in the ground by omitting rotation during the withdrawal of the tool: the nozzles then act monodirectionally.

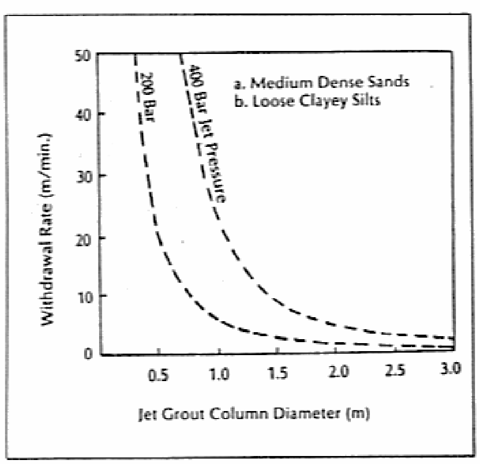


Figure 21 Typical Design Curve for Jet Grouting (Coomber, 1985)

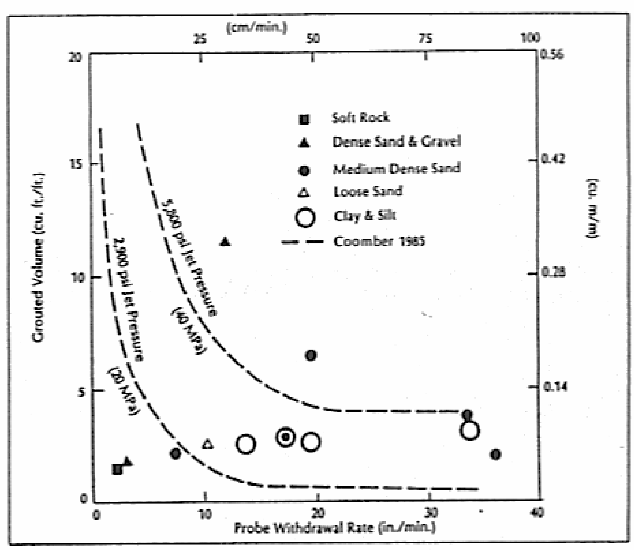


Figure 22 Probe Withdrawal Rate Effects on Jet Grouted Volume (ASCE, 1987)

Applications of jet grouting have been reported throughout Western Europe, the Far East, Soviet Union and South America. Currently, there is a small but growing market in North America, largely under the promotion of certain government agencies and specialist contractors, following a slow and uncertain start (Andromolos and Pettit, 1986). In Canada numerous works have been conducted in the Montreal region, associated with deep excavations, whilst at John Hart Dam BC, jet grouting has been used through an existing dam to create a seismic cutoff (Imrie et al., 1988).
Major applications are:

- Underpinning of existing structures
- Formation of water cutoff walls or diaphragms (to 10^{-6} to 10^{-9} cm/sec)
- Foundation soil consolidation for new structures, embankments and retaining walls
- Soil consolidation for the excavation of shallow tunnels
- Excavation support for open cuts and shafts
- Land slide stabilization

Informative and detailed case histories are provided by Mongilardi and Tornaghi, (1986), Tornaghi and Cippo, (1985), De Paoli et al., (1989), and Tornaghi et al., (1988), whilst a comprehensive overview is given by Welsh, (1989).

4. CURRENT DEVELOPMENT TRENDS

4.1 Equipment

4.1.1. Drilling

Although the extreme usefulness and effectiveness of air-powered drilling rigs as base machines for rock and overburden drilling have been evident for over three decades, it is clear that in the present drive for "bigger, better, faster, quieter, cheaper", their scope for further development is practically limited. Instead, the potential now lies with hydraulically powered machines, whether activated by diesel or electric power. In addition, the operating principle allows drilling rigs to be created out of a wide range of potential carriers, including excavators, tractors, rough terrain vehicles and trucks. However, regarding purpose-built drilling machines, Table 8 illustrates key features of certain smaller commercially available rigs in popular use today. Given the higher mechanical efficency of hydraulic systems, rigs of this type appear the logical choice provided the initially higher capital outlay can be accommodated.

Another particularly useful development reflecting again the application of higher torques and generally heavier drilling and casing strings is the growing popularity of foot clamps and casing breakers mounted at the mast toe and hydraulically operated. A further aid to good production becoming more widespread is the use of an on board flush pump either hydraulically or electrically operated. These are typically rated at 180 liters per minute at 25 bars or 360 liters per minute at 15 bars.

Especially for jet grouting, anchor or soil nail installation, rigs are being developed with long masts capable of drilling full depth in one stroke. For horizontal drilling underground these masts are mounted on special carriers designed to reduce set up time by virtue of their great range of movements (Photograph 4).

With the developments in base machines, the increasing use of hydraulic top hammers and rotators is logical for grout hole drilling. In purely rotary applications, the Hands England H2 series heads are typical and well proven examples: the FS having a maximum torque of 2,200mN with speeds of 50, 87, or 153rpm and the FD having a maximum torque of 6,300mN at 17, 30, or 53rpm. Likewise, the higher torque options offered by, for example, the Krupp HB series hydraulic top hammers over the last 12 years in comparison to the widely used Atlas Copco BBE air powered models are clear from Table 9. There are, of course, numerous other manufacturers of heads for geotechnical drillings, including Klemm, Wirth, Montabert, Acker, Bohler and Casagrande as probably the most recognizable names. Generally, these high torque hammers require a shank adaptor of 55mm diameter compared with the former standard 38 or 45mm sizes.

Another significant development has been the use of multi-component flushing head arrangements. These permit different casing sizes to be accommodated by changing only one element of the head as opposed to the former alternative of having to replace completely what is a major and expensive drilling consumable. Similarily it is not necessary to scrap the whole device if for example a shank adaptor does break and the rump cannot be extricated from the flushing head.

4.1.2 Grouting

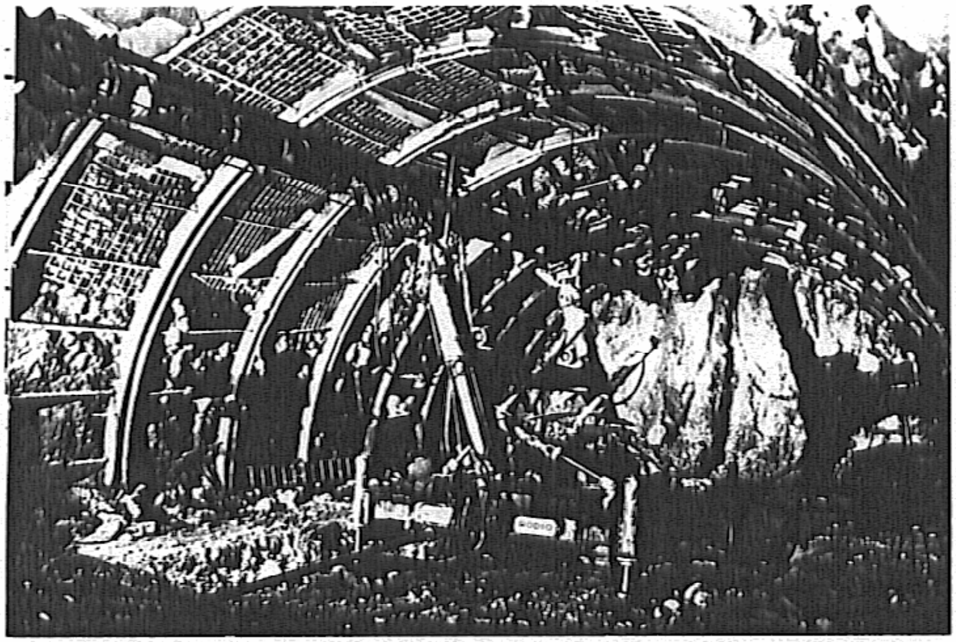
A comprehensive review of grouting equipment was presented by Gourlay and Carson at the New Orleans Conference in 1982. Trends which have continued since then include the following:

MODEL	SIZE & MASS		FEED			POWER	
	Travelling Dimensions (m)	Mass (kg)	Thrust (kg)	Pullup (kg)	Head Travel (m)	Type	Output (HP)
Hands England HERO 30C	4.9 x 2.2 x 1.9	5600	2000	3000	3.5	4Cy Ford	67
Halco 450H	7.1 x 2.2 x 2.2	8500	1100	5270	4.0	5Cy Deutz	70
Casagrande C6	7.0 x 2.1 x 2.3	9000	2700	6000	4.0	6Cy Deutz	} Normal operating maximum 105
Krupp DHR80 A	6.7 x 2.4 x 2.3	7700	2500	4500	4.0	6Cy Deutz	
Atlas Copco ROC601	5.6 x 2.2 x 1.7	4380	2000	2000	3.5	Air powered 600cfm at 7bars	–

Table 8 Summary Details of Some Popular Diesel Hydraulic Drilling Rigs, with Air Powered ROC601 for comparison

MODEL	MASS (kg)	PERCUSSION MECHANISM		ROTATION MECHANISM		ENERGY REQUIREMENTS
		BPM (Nr)	Energy/ Blow (m kg)	RPM (Nr)	Max Torque (Nm)	
AC BBE57	170	1910	23	50-100	350-800	Min 400 cfm air at 7 bars
AC BBE53	250	1950	21	40-50	1085-1220	Min 553 cfm air at 7 bars
Krupp HB101	240	2200	27	0-150	950	Perc. 70-85l/min oil at 150-170 bars Rot. 75l/min at 150 bars
Krupp HB103	270	1800	27	0-40	4000	Perc. 70-851/min at 150-170 bars Rot. 60l/min at 170 bars
Krupp HB105	370	1800	27	40 80	6000 in parallel 3000 in series	Perc. 70-85l/min at 150-170 bars Rot. 120l/min at 150 bars

Table 9 Comparative Data on Rotary Percussive Heads as Manufactured by Atlas Copco (pneumatic) and Krupp (hydraulic)



Photograph 4 Long stroke special drill rig for horizontal drilling. (Rodio)

4.1.2.1. Injection Consumables for Sleeved Pipe Systems

o using more flexible grouting tubes delivered in one piece to the site in order to ease installation, especially from within restricted tunnel access conditions, and in order to reduce the risk of malfunction due to leakage at joints. Alternatively, steel grouting tubes are being used in certain cases, doubling as in situ reinforcement or underpinning for very delicate structures.

o using hydraulically or pneumatically inflated double packers for grouting, thus reducing labor effort, ensuring efficient sealing and permitting any deviated or damaged hole to be "rescued" and still be used for grouting.

4.1.2.2. Mixing and Pumping Equipment

For projects of significant scale, it is more common to find semi automatic grouting "stations", in which the mixer, agitation tanks and pumps are fixed on a frame or in a shipping container. This speeds transportation and set up, reduces space requirements, and facilitates the use of grout parameter recording systems, as described below.

Mixers for high quality grouting works are typically of the high shear colloidal mill or the jet type. There is growing acceptance of piston pumps- the output fluctuations suitably damped- on which the desired refusal pressure or volume can be preset. Recent electro-hydraulic piston pumps can pump at full volume potential to over 90% of their stalling pressure before a reduction in rate of pumping occurs. For jet grouting, pumps, adopted from oil field duties have been developed to provide the pressure/flow characteristics required. In compaction grouting developments are occurring with concrete pumps with up to $9N/mm^2$ output capacity, thus allowing more control over injections being conducted at the 3-5 N/mm^2 range typically used.

For most large projects, materials are held in silos and either screw fed or pumped, under preset electronic control, to the mixers. This greatly enforces quality control and reduces labor requirements. Detailed specifications of grouting equipment are given by Mueller, (1982,1989) and DelVal, (1989).

4.2. Materials

It is well known that one of the main obstacles for grout penetrability through existing fissures or pores is the maximum particle size of the grout components (eg. Karol, 1985). For example the AASHTO Task Force, (1987) notes that cement grouts will only penetrate rock fissures more than three times the largest particle size in the cement. Littlejohn, (1975) advised this limiting fissure width to be 160 microns for usual cements (equivalent to a permeability of 10 Lugeons), but much less for finely ground materials. For soils, Karol, (1960) quoted the Groutability Ratio as follows

$$Gr = \frac{D_{15}\ Soil}{D_{85}\ Grout} > 25 \text{ for permeation}$$

However, other major grout properties also influence their effectiveness, and recently major strides have been made in optimizing those. As background, we should first consider the broad classification of grouts used in permeation. Mongilardi and Tornaghi, (1986) developed the following classification on the basis of rheological performance. The classification is presented in the order of increasing penetrability (and cost):

- particulate suspensions (Binghamian fluids)- cement-based grouts
- colloidal solutions (evolutive Newtonian fluids)- chemical grouts
- pure solutions (non-evolutive Newtonian fluids)- chemical grouts

Suspensions of solids in water are termed unstable when water loss by bleeding is significant. This instability occurs when pure cement grouts are used at high water/cement ratios in fissured rocks, since the water acts largely as a vehicle for cement grains. A suspension is termed stable when bleeding is negligible, as required in general for the treatment of granular

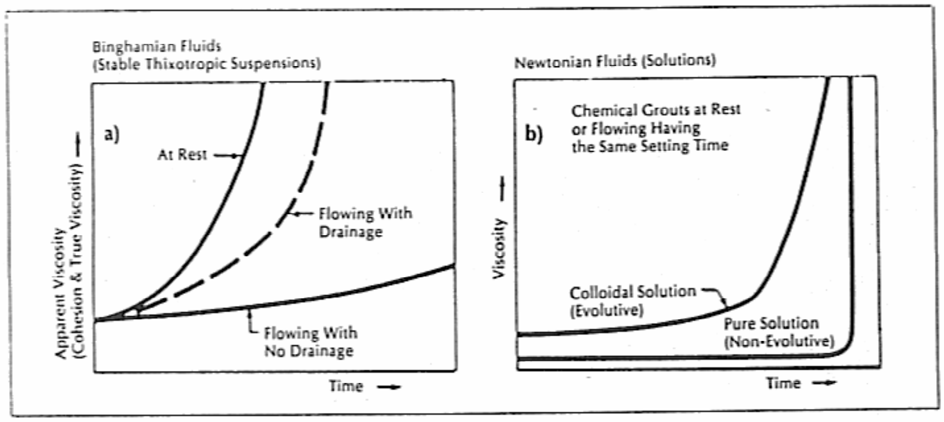


Figure 23 Rheological Behavior of Typical Grouts (Mongilardi and Tornaghi, 1986)

soils (with cement-clay and cement-bentonite mixtures). Stabilized thixotropic grouts have both cohesion (yield value) and plastic viscosity increasing with time at a rate that may be considerably accelerated by drainage under pressure-i.e. "pressure filtration" (Figure 23a). Though the addition of colloidal products can minimize bleeding, filtration must be always considered as an important design factor with respect to penetrability and the final effects of water loss on mechanical properties and volumetric yield. The poor permeation of suspensions in granular soil with a permeability lower than 10^{-1} cm/sec involves the additional or alternative use of chemical solutions in order to minimize hydrofracturing effects. By far the best known colloidal solutions consist of diluted sodium silicate with inorganic or organic reagents (Peruchon, 1989) that produce relatively soft to hard silica gels (0.3-2.0 N/mm^2). The term evolutive means that the viscosity increases before setting at a rate that depends largely on the concentration of reactants (Figure 23b, upper curve).

The more expensive pure solutions, based on acrylic, phenolic or amino resins, are non-evolutive Newtonian fluids since viscosity may be kept constant until setting within an adjustable period of time (Figure 23b, lower curve). This outstanding property, asociated with a very low viscosity, allows the impregnation of the finest granular soils within the practical and economical limits imposed by the rate of flow and pressure (silty fine sands with a virgin permeability not lower than 10^{-4} cm/sec).

Regarding the particulate suspensions, main obstacles to penetrability are related to:

- the maximum particle size of the solid components in the grout relative to the pore sizes in the soil; and,
- the rate of pressure filtration that may induce rapid clogging even under low pressures.

The first problem is being tackled by introducing very fine grain cements such as MC500 (Portland cement/slag based, Blaine fineness 8000 cm^2/g) and MC100 (slag based, fineness up to 12,000 cm^2/g) in which the average particle size (Figure 24) is of the order of 3 or 4 microns. Such cements also provide high early strengths, low mortar permeability (10^{-9}cm/sec) and so excellent durability at low to moderate water contents. Such properties are, of course, very advantageous in hazardous waste stabilization and containment. These materials require the addition of small quantities of dispersants to minimize grain agglomeration or flocculation during mixing(Karol, 1985). The MC100 material requires the addition of sodium hydroxide solution to provide set times of 3-5 hours. Microfine cements can also be combined with inorganic sodium silicate solution to give 3-5 minutes set time for dynamic water control. Comprehensive background data are presented by Clarke, (1982, 1984, and 1987).

In contrast, the filtration problem has represented the main obstacle in the past, since in conventional "stable" grouts (Type C in Figure 25) a reduction of water loss rate can be obtained only at the cost of increasing viscosity, by an additional content of active colloidal particles such as bentonite. Usual chemical additives (such as fluidifiers, retarders or dispersing agents) reduce viscosity, but the filtration rate remains significant (grout Type C in Figure 25). Recent research, however, has led to the development of an entirely new class of cement-bentonite grouts named Mistra (Type B in Figure 25) that has the following major properties:

- very low filtration rates, being very close to pure bentonite muds even at very low viscosity.
- no bleeding
- low values of yield point and plastic cohesion over an adjustable period of time (up to several hours)

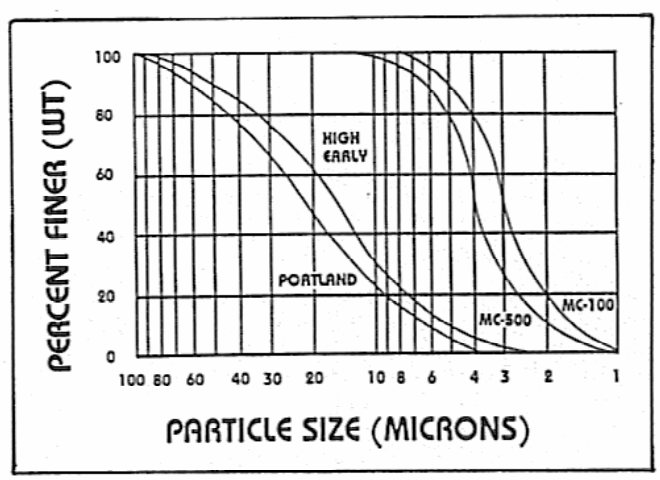


Figure 24 Portland and Microfine Cement Gradation Curves (Clarke, 1987)

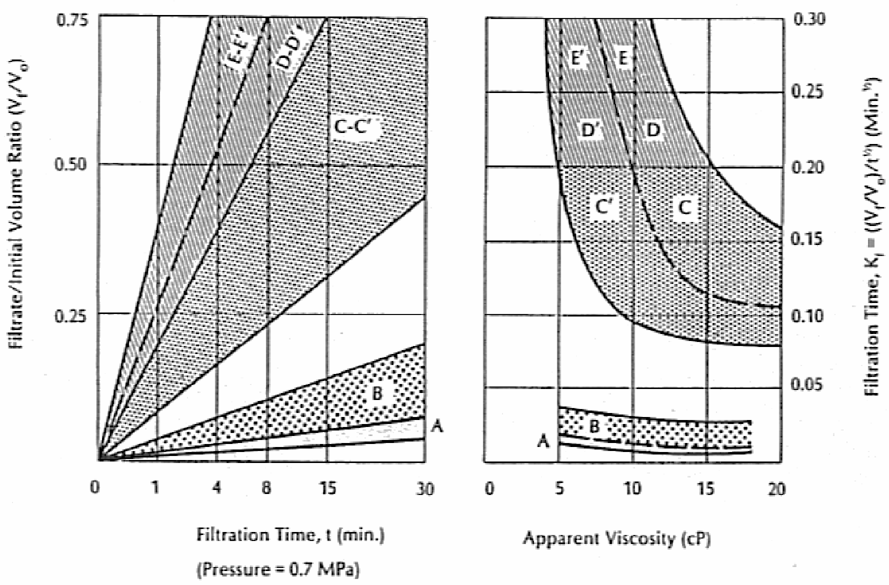


Figure 25 Ranges of Significant Rheological Properties for Various Types of Particulate Suspensions (Tornaghi et al., 1988)

- higher long-term strength and lower permeability in comparison with conventional stable grouts having the same cement content

With respect to composition, the water/cement ratio can vary from 1 to 5, with the overall content of additives ranging from 3 to 6 percent by weight of water, thus providing a wide range of rheological and longterm properties. For example, the Mistra grout being used in Lot 1 PB of the Milan subway has the compostion and properties as listed in Table 10 (Tornaghi et al., 1988).

The practical advantages of this new class of grouts to the tunneling engineer for example can be summarized as follows:

- improved penetrability under a lower pressure in sandy-gravelly soils
- lower water loss, and therefore, a greater volume of voids filled with the same volume of grout
- the possibility to fill all the voids consistent with the size of individual cement particles and therefore to permeate medium-coarse sands with refined products, minimizing any hydrofracturing effects

Chemical grouts based on sodium silicate solutions and inorganic reagents (eg. sodium aluminate or sodium bicarbonate) can produce only soft gels (i.e., an unconfined compressive strength (UCS) of <0.3 N/mm^2) for waterproofing sands, since high dilution is necessary to achieve low viscosity and the appropriate setting time. Most recently, the Japanese have developed the specialized drill and grout systems, such as Limited Area Grouting (LAG) and Double Tube Drilling (DDS) referred to above, that can handle the problems of injecting the stronger flash setting grouts of this type, although these systems are only practical in softer uniform deposits (Tokoro et al., 1982).

The introduction of organic reagents 30 years ago permitted the adjustment of setting time independent of silicate concentration, thus providing "hard to soft" gels depending on the silicate to water ratio. However, in certain areas, including Japan and Germany, such organically based reagents are not environmentally acceptable. Creep effects may be a significant

Composition	Cement/Water Ratio Additives/Water Ratio	0.35 0.04 - 0.05
Bleed Capacity (%)		0 - 2
Marsh Viscosity (sec.)		33 - 37
Rheometer Parameters	Apparent Viscosity (cP) Plastic Viscosity (cP) Yield Strength (Pa)	8 - 12 5 - 8 1.5 - 5
Filter Press Test at 0.7 N/mm²	Filtrate (cm³) after 30' Filtration Rate (mm$^{-1/2}$)	36 - 72 0.016 - 0.032
U.C. Strength (N/mm²) of Grouted Sand after 28 Days		1.2 - 1.8

Table 10 Composition and Characteristics of Mistra Grout, Lot 1B, Passante Ferroviario, Milan, Italy (Tornaghi et al., 1988)

problem for silicate gel stabilized soils if the design involves a high and permanent loading. In addition, questions of permanence and durability under certain conditions may be valid. Syneresis is the major factor in this context, although it is not widely understood that while it is significant in pure gel samples, it tends to become negligible in fine-medium sands (Figure 26).

In light of these problems, potential and real, the newest developments have led to the evolution of a new type of chemical grout (Silacsol) composed of an activated Silica liquor and an inorganic reagent based on calcium. As opposed to commercial alkaline sodium silicates that are aqueous solutions of colloidal silica particles dispersed in soda, the liquor is a true solution of activated silica. The activated dissolved silica when mixed with the reagent, produces calcium hydrosilicates with a crystalline structure that is quite similar to that obtained by the hydration and setting of cement. The resulting product is a complex of permanently stable crystals. Hence, the reaction is not an evolutive gelation as in the case of silica gels which involves the formation of macromolecular aggregates and the possible loss of silicized water (syneresis). On the contrary, it is a direct reaction on a molecular scale. This type of mix, recently developed in France and successfully used in Italy, presents the same groutability range as common silica gels: medium to fine sands can be effectively treated. Even if larger voids or fissures are accidentally created by hydrofracturing, a permanent filling is assured without any subsequent syneresis risk. The activated silica mix has the stability of a cement grout owing to the nature of the resulting products (insoluble crystals of calcium silicate) and to the absence of aggressive by-products, thus safeguarding against pollution.

Other outstanding features relative to silica gels of similar rheological properties are:

- the far lower permeability of 10^{-10} cm/sec for Silacsol, remaining constant over test periods of 15 days at hydraulic gradients of 100, as opposed to 10^{-5} cm/sec for silica gel
- the better creep behavior of treated sands for grouts of similar strength (2 N/mm^2 at a quick strain rate of 0.65 percent per minute): the data in Figure 27 show a much lower long-term deformability at the same stress level and creep rupture at about double the stress level.

As evidence of continuing advances in cement grouting technology in North America, it may be noted that Northwestern University in Illinois has recently won a National Science Foundation Grant for $5 million to become the Center of Science and Technology for "Advanced Cement-Based Materials". It will be associating with the Universities of Illinois (Urbana), Purdue, and Michigan, as well as the National Bureau of Standards. Major research plans are formulated for the following fields: a) chemistry and physics, b) processing science, c)micro structural analysis, d) material properties, and e) fibre reinforcement. An existing study covering some of these aspects is provided by Roy (1987).

4.3. Instrumentation and Monitoring

Throughout the grouting industry the use of computer-aided devices such as monitors over

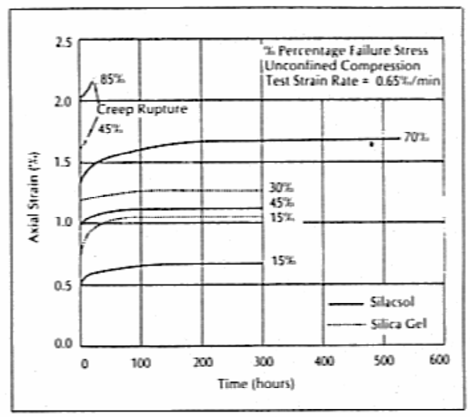


Figure 27 Unconfined Creep Results for Silica Gel and Silacsol Grout (Samples of grouted medium fine sand) (Tornaghi et al., 1988)

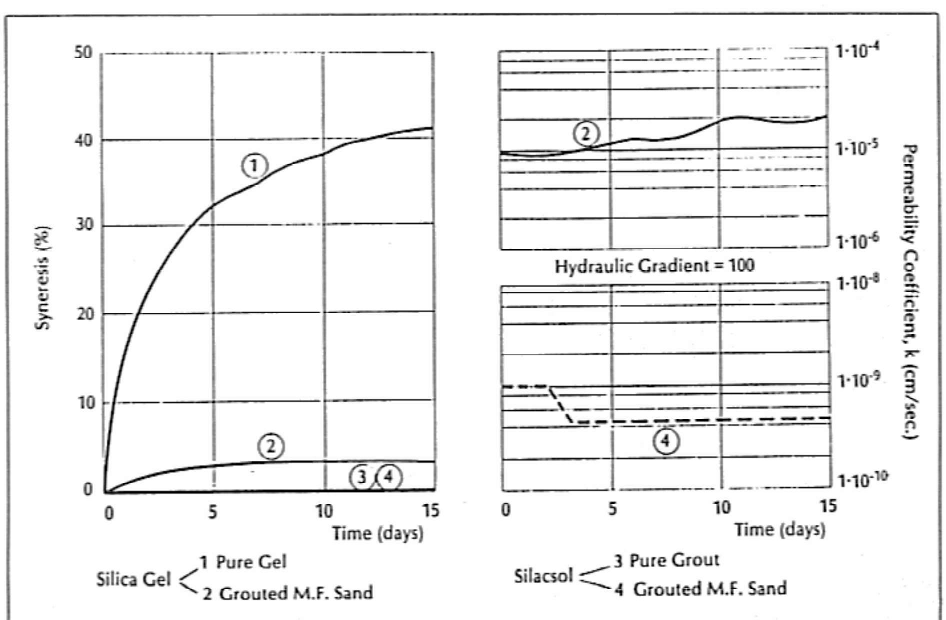


Figure 26 Effect of Time on Syneresis and Permeability of Typical Chemical Grouts (Tornaghi et al., 1988)

grouting operations in the field is increasing. This growth is reflected in several of the papers presented at the ASCE Convention in Denver, CO, in 1985. More recently major developments have been made in the exploitation of instrumentation for soil investigation and grout parameter design. At the same time various methods are being investigated to judge the extent and efficiency of grouting, by cross hole methods. The following sections review progress in each category of instrumentation.

4.3.1. Drilling

Over the past few years the contractors' main concern has been to optimize drilling methods in order to increase output, minimize drilling problems, and reduce costs. However, the need for better knowledge of the ground has not diminished and the precise monitoring of a soil improvement process is still dependent mainly on the accuracy of the preliminary investigations. Although designers are increasing the variety, sophistication and number of the investigation techniques, cost is always a limiting factor. Grouting programs usually involve a large number of holes, and by the early 70's, contractors (in France) conceived the ideas to (1) make use of the grout holes themselves to detect and record the main soil features, and (2) to reduce the cost of site investigations for large projects by using a quick extrapolation method which could be calibrated back to a small number of cored holes, to thus give a continuous image of the ground, whatever the type of soil or rock. An excellent review of the historical development of the system, and its current capabilities is provided by Pfister, (1985). The basic instrumentation is known to different contractors by different names eg. Enpasol, (Soletanche), Papero, (Rodio), but the principles of the newest generation are as follows:

Sensors fitted to the drill continuously record the penetration rate, rotational speed, thrust, torque and flush pressure as each hole is drilled. These data are then combined to give an indication of "drillability", for example, the specific energy. The computer then relates this factor to ground type, and prints out a geological log interpretation (Figure 28 with boundaries at 10 cm intervals). This log thus permits optimization of the grouting parameters, as well as providing initial information for the general contractor. The key to the accuracy of the system is clearly the ability of the computer to relate specific energy to ground type. This process is achieved by conducting statistical analyses of the specific energies recorded at discrete depths, with visual observations from adjacent cores, or subsequent exposures. The latest systems can also allow for site specific hydrological variations, and borehole inclinations in arriving at accurate predictions (Bruce, 1988).

Such data can also be used as a basic element in the design, guidance and control of grouting, and Pfister, (1985) provides a good example from Civauxnuclear power plant in France. The data firstly permitted the virgin state of the rock to be assessed-- a faulted, karstic limestone-- and showed that some areas did not require treatment. The data were then used to demonstrate the effectiveness of each successive phase of the work. On the basis of the primary takes, and the correlations of the Enpasol data with the rock classification, the grouting programs were then automatically printed for each hole of the test area on detailed forms which included the amount of grout to inject per stage.

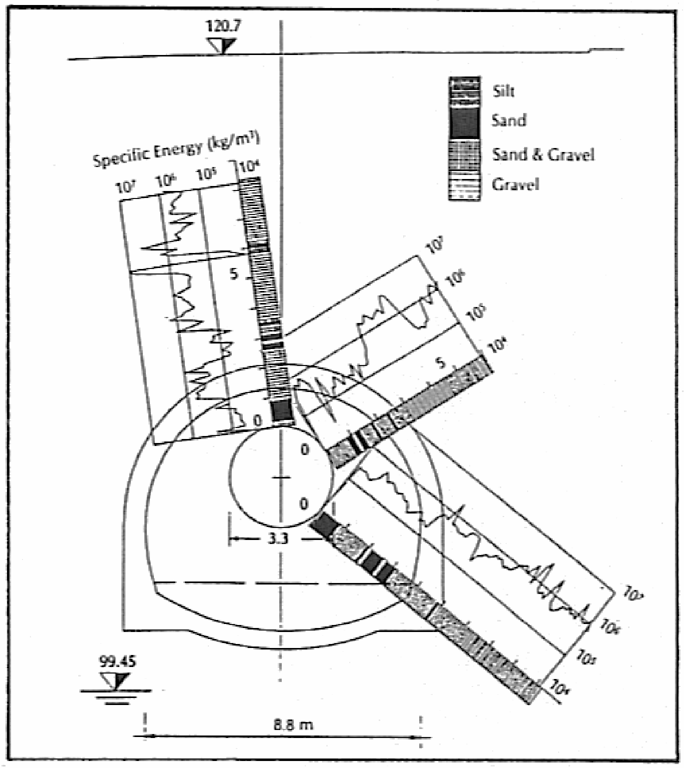


Figure 28 Soil Profiles Derived from the Evaluation of Electronically Recorded Drilling Parameters (PAPERO) in Terms of Specific Energy (Milan Metro)

There is no question that such systems can now be made to work on production sites. However, as the parameter/geology correlation is statistical, and the equipment is sophisticated and costly, only large projects can realistically be considered for such programs.

4.3.2. Grouting

There is a rather greater range in sophistication apparent on instrumentation for grouting parameter recording, and Quality Control. For example, most modular grouting equipment provides a record of pump pressure (on circular or strip charts) and pump volume (by counting pump strokes or by using electromagnetic flow sensors). In addition there is portable equipment for standard site use like the Grout Minder, as supplied by Acker, which can provide strip chart records of flow rate, volume and pressure. This equipment can provide audio/visual warnings if certain preset parameters are exceeded, and has a servomechanism injection pressure.

The most sophisticated type is like the electronic Paguro System, developed by Rodio. This centralized, remote system monitors and displays in real time numerically and graphically the full injection characteristics of each pump. It thereafter gives a print out summary of each sleeve injected (including volume, maximum and average pressures, flow rates and time). Such data then provide the basis for the technical review of the grouting conducted, and the quantities of work executed for payment purposes. The investment in such a level of sophistication is economically viable only in projects of appreciable scale and/or complexity such as the Milan Metro (Fairweather, 1987). The impact on U.S. practice is clear from the Burec "Policy Statements for Grouting", issued in 1984. Section XI notes "...The specifications for Ridgway Dam Stage II construction required strip chart recorders for real time monitoring of grout pressures and flows. A modification....was proposed...under which the real-time data would be processed by microcomputers, stored on disc, and displayed in various formats on the CRT and in hard copy. The same microcomputer graphic system is being used to display grouting records in summary form on profiles along the curtain. The system is in its developmental stage, and the desired format of data presentation is under review. Field personnel are finding the system useful." Further information is provided in the Burec publication as "Cement Grout Flow Behavior in Fractured Rock" (1987), while details of the instrumentation and data processing are provided by Jefferies et al., (1982). An application of this monitoring and processing principle- the Multiple Hole Grouting System (Figure 29)- was described by Mueller, (1982).

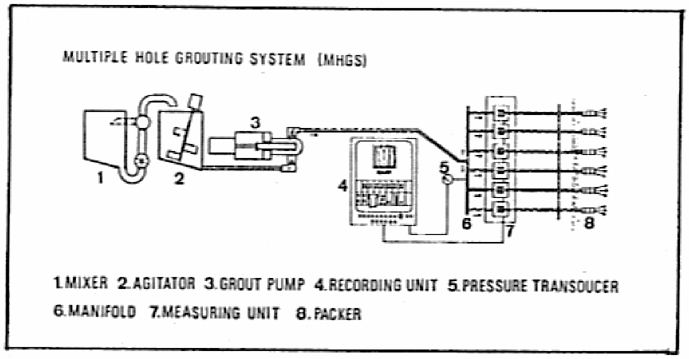


Figure 29 Operating Principle of the Multiple Hole Grouting System (Mueller, 1982)

4.3.3. Grouted Soil

Several methods, in addition to the analysis of drilling and grouting parameters are being developed to track grout location and condition (i.e. for Quality Assurance). An excellent review was provided by Baker, (1982) from which the following information is drawn, while borehole radar and cross hole accoustic monitoring were also described by Huck et al., (1982).

4.3.3.1. Acoustic Emission Monitoring of Injection Pressure (AEM)

AEM may be used to detect stuctural distress in geotechnical materials. In grouting it can detect hydraulic fracturing and therefore aid control of this phenomenon. Indications of fracturing are bursts of microseismic noises heard by the system, denoted by increased acoustic emission count rates. Hydraulic fracturing can reduce grouting cost, but the critical initiation pressure can vary by a factor of several times even in closely spaced holes. AEM thus allows for detection and control. The sensor is placed in an inactive grout pipe at the approximate depth of injection. It can filter out frequencies below 1000hz which includes most construction noise. After testing and calibration, the system is placed so that the grouter can see the recorded output. He can then increase the injection pressure at each injection point until fracture begins, and then decrease the pressure to a comfortable safety margin.

In a very informative paper, Koerneret al., (1985) concluded firmly that as a non destructive testing technique, AEM was a "likely candidate" for application to the problem of detecting and monitoring subsurface flow phenomena.

4.3.3.2. Geophysical Quality Assurance Tools

Baker, (1982) concluded that the most useful geophysical tests for evaluating grouted soils include crosshole seismic profiling and ground probing radar. These are well suited to defining increases in soil modulus, and grout presence, respectively.

Borehole Radar. In the preferred method of transillumination profiling, a transmitter is lowered down one borehole, and a receiver down an adjacent hole, to the same level. They are then raised simultaneously to give a "radar profile" by taking profiles before and after grouting. The effects of the grouting can readily be seen in the comparison of the profiles. This system is best used to determine grout location and an indication of the amount of grout present. Weaver, (1989) suggests that its use should be limited to granular soils as its resolution in cohesive soils is often inadequate.

Cross Hole Acoustic Velocity Cross hole acoustic transmissions are used to measure acoustic velocity and spectra of received signals. Profiles are obtained between two boreholes as in the radar method, except that the signal is mechanical rather than electromagnetic. The system is set to determine if the transmitted spectrum indicates an improved acoustic medium after impregnation with grout. Attenuation of acoustic energy in soil is highly dependent upon the stiffness of the ground. For example, grouted sands are known to increase in low-strain stiffness, and thus show increased velocity. Such surveys demonstrate qualitatively the strength of the grouted zone and relative changes in acoustic velocity are of significance. Baker notes that post grouting velocities may be as high as 2000m/sec- up to ten times that of ungrouted soil- diagnostic of a change from soil to weak rock, and so indicative of a well grouted material. Generally, though, it must be noted that a large number of routine case histories has not yet been amassed, and so cautious use of such systems must currently be exercised.

5. CLOSING REMARKS

Engineers in the grouting industry have always been assailed by the claims that grouting is an art- and a black art at that. On the threshold of the 1990's engineers are now able to refute these accusations, and to their credit, an increasing proportion of them do exactly that. There is no longer a place in our profession for black magicians- although artistry is still to be encouraged- who deliberately obfuscate issues in order to maintain some form of self serving, mystique. Such people have no place in the advancement of our technology and indeed are sooner or later exposed as having fundamentally limited understanding or relevence.

The increasingly onerous demands placed on the grouting industry by the rigours of novel applications, and the harsh reality of economic competitiveness, are being answered by engineers worldwide in an inventive and vigorous manner. Our state of practice, as summarized and referenced in this paper, is irrefutable confirmation.

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