THE MPSP GROUTING SYSTEM:
A NEW APPLICATION FOR RAISE BORING

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THE M.P.S.P. GROUTING SYSTEM: A NEW APPLICATION FOR RAISE BORING

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1. INTRODUCTION

One of the decade's few advances in the methodology of rock grouting is the Multiple Packer Sleeved Pipe System (MPSP)*. MPSP overcomes the problems posed to efficient treatment in the face of collapsing, voided or highly variable ground conditions. The method has been used with distinction to form grout curtains in association with several high dams in Asia and Europe, while it can also be used to improve the mechanical properties of masses when used in 'consolidation' grouting applications (Bruce and Gallavresi, 1988).

Most recently, it has been adopted in an entirely different environment—to stabilize highly variable weakly cemented rock fill, approximately 800 m underground in an operational copper mine in northern Ontario. This particular case history is not only of interest and relevance to the underground mining community, but it also provides a clear demonstration of the workings of the method in general.

2. THE MPSP METHOD

2.1 Background

The fissure grouting of rock masses is typically conducted by some type of stage grouting procedure (Figure 1). In "downstage grouting," grout holes are advanced by drilling a certain length, usually 3-5 m, grouting it, and then repeating the process after the grout has set, until final depth is reached. The packer may be kept at the top of the hole, or moved successively downwards to the top of each new stage in turn. In "upstage grouting," the hole is drilled to full depth in one pass and injected progressively in successive stages from the bottom upwards through a down-the-hole packer. Houlsby (1982) also describes "circuit grouting, downstage," which is not dissimilar to downstage without packer. This system has proponents in the U.S.A. (e.g. Burwell, 1958) although Ewart (1985) views the method's effectiveness "with some skepticism," being concerned about hydraulic fracturing "somewhere

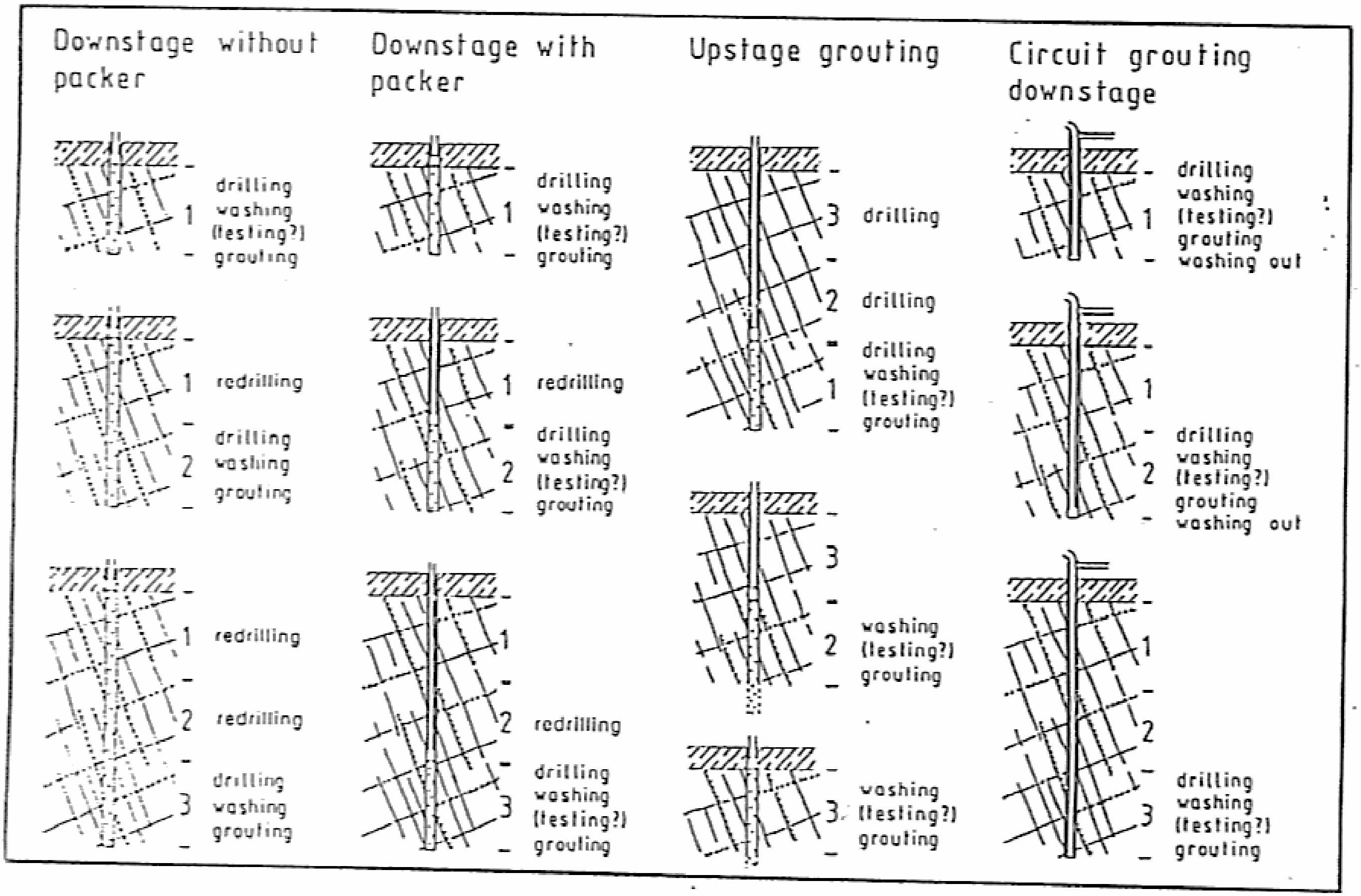

Figure 1. Conventional stage grouting methods for rock mass fissures (Ewart, 1985, after Houlsby, 1982).

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*The MPSP method was devised by the Rodio Group of Companies, who control the rights to its use. Nicholson Construction Company is the licensee in North America.

in the upper stages." Houlsby (1982) also describes it as "difficult, prone to blockages and very expensive." The major advantages and disadvantages of the two basic approaches—upstage and downstage—are summarized in Table 1. Their technical or financial balance on any particular site should logically dictate the final choice of method, but it would seem that tradition and bias often prove at least as decisive.

However, there are often conditions in which neither stage grouting method can be relied upon to provide an effective and reliable treatment. For example, in downstage schemes, the presence of very fissured, granular or fragmented rock (e.g. "sugary limestone") may result in caving of the stage after drilling, and before grouting can be executed. Thus in the worst case only the uppermost part of that stage will be treated, and the lower section will remain ungrouted and most probably cause similar problems during later redrilling operations. Likewise, the presence of such strata, voids and/or soft infill zones will prevent upstage grouting being practical: packers will be very difficult to "seat" efficiently, and may permit grout to bypass upwards, leading to ineffective treatment or trapped packers.

Such geological conditions reflect more typically the problems associated with soil grouting, for which the standard "high tech" approach is the tube à manchette (sleeved pipe), shown in Figure 2. A fundamental feature of the tube à manchette operation is the necessity to rupture the "sleeve" grout, thus permitting egress of grout into the surrounding soil. However, in all but the softest rocks, the lateral restraint afforded by a rock mass is sufficient to prevent the sleeves opening (to allow the flow of grout into surrounding fissures). In addition, the nature of the system—involving the use of a stable cement-bentonite sleeve grout—essentially plugs off, for a short but critical distance, those fissures which are intersected by the borehole, thus further circumscribing the possible effectiveness of the system. In this regard, the finely fissured soft shales very successfully treated at Grimwith Dam, Yorkshire (Bruce, 1982) could well be regarded as an upper limit for rock mass quality in terms of effective tube à manchette grouting.

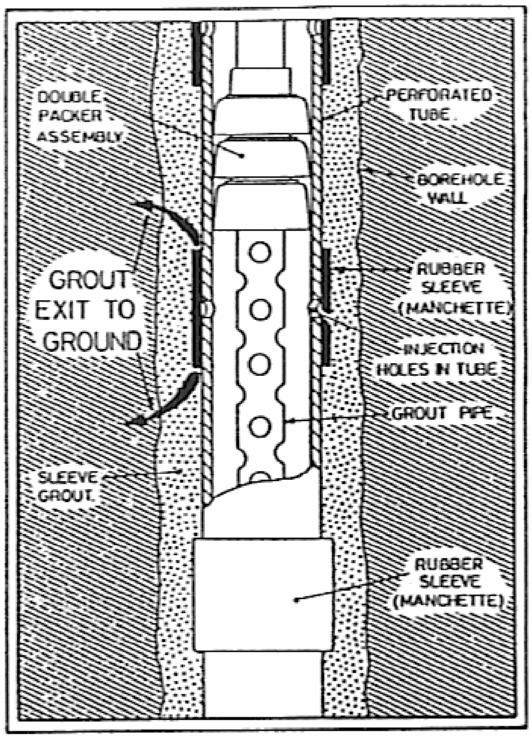


Figure 2. Operating principle of the tube à manchette (sleeved pipe) system.

	DOWNSTAGE	UPSTAGE
ADVANTAGES	1. Ground is consolidated from top down, aiding hole stability and packer seating and allowing successively higher pressures to be used with depth without fear of surface leakage.	1. Drilling in one pass.
	2. Depth of the hole need not be predetermined: grout take analyses may dictate changes from foreseen, and shortening or lengthening of the hole can be easily accommodated.	2. Grouting in one repetitive operation without significant delays.
	3. Stage length can be adapted to conditions as encountered to allow "special" treatment.	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.	1. Grouted depth predetermined.
	2. Relatively wasteful of materials and so generally restricted to cement-based grouts.	2. Hole may collapse before packer introduced or after grouting starts, leading to stuck packers and incomplete treatment.
	3. May lead to significant hole deviation.	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. Collapsing strata will prevent effective grouting of entire stage, unless circuit grouting method can be deployed.	4. Artesian conditions may pose problems.
	5. Weathered and/or highly variable strata problematical.	5. Weathered and/or highly variable strata problematical.
	6. Packer may be difficult to seat in such conditions.	

Table 1. Major advantages and disadvantages of downstage and upstage grouting of rock masses

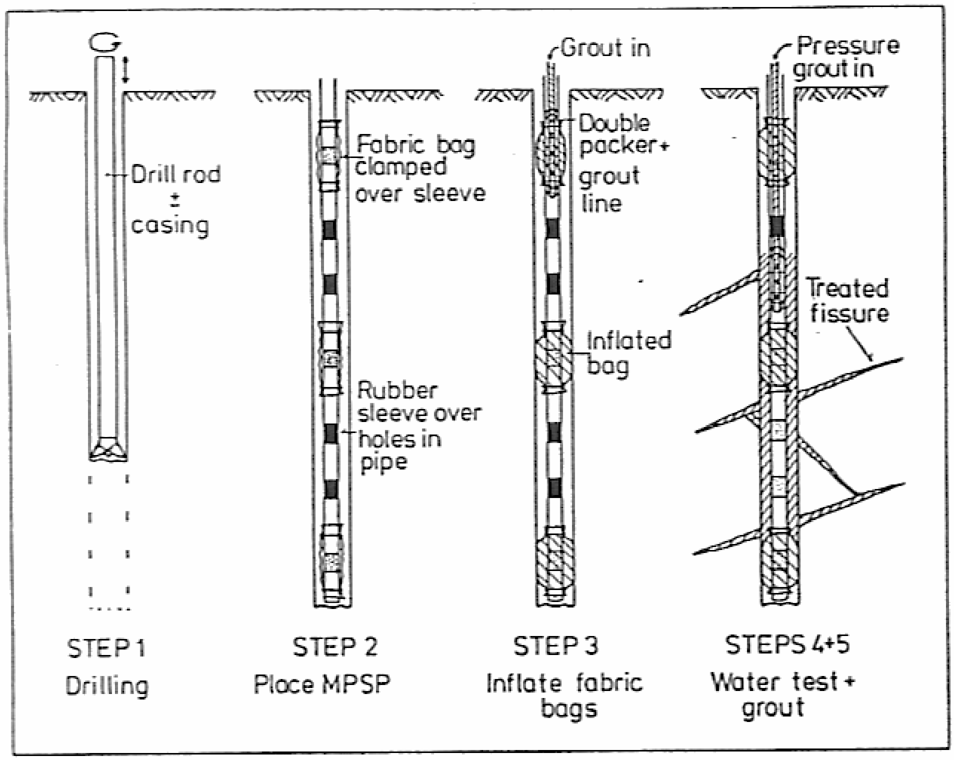


Figure 3. Installation sequence of MPSP system.

It was against this background of providing high-quality treatment of ground which would otherwise frustrate the effectiveness of these conventional methods, that Rodio developed the MPSP system.

2.2 Installation and Operation

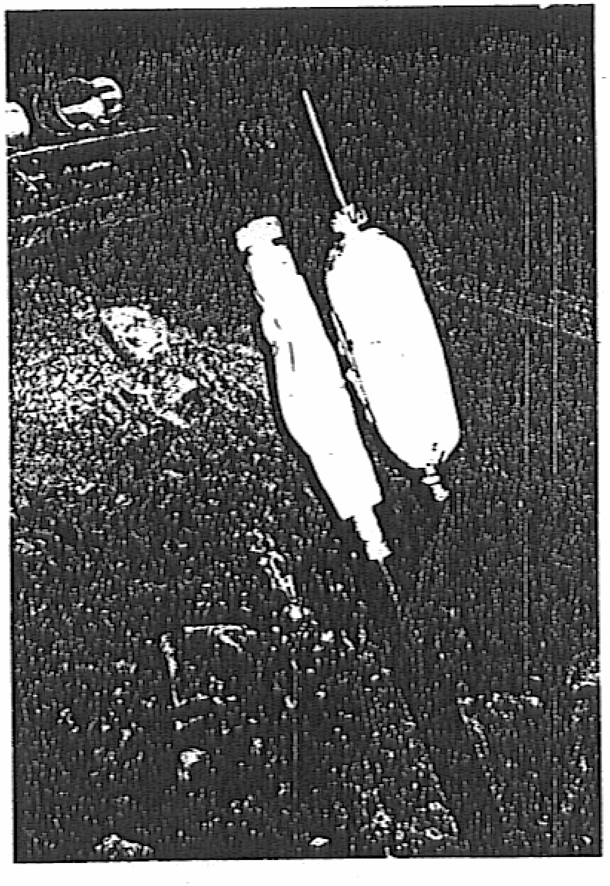
MPSP owes much to the principle of the tube à manchette system, in that grouting of the surrounding rock is effected through the ports of a plastic or steel grout tube placed in a predrilled hole. However, unlike tube à manchette, no sleeve or annulus grout is used. Instead, the grouting tube is retained and centralized in each borehole by collars—fabric bags inflated in situ with cement grout. These collars are positioned along the length of each grout pipe, either at regular intervals (say 3 to 6 m) to isolate standard "stages", or at intermediate or closer centers to ensure intensive treatment of special or particular zones. The system permits the use of all grout types, depending on the characteristics of the rock mass and the purpose of the ground treatment.

The typical construction sequence is as follows (Figure 3):

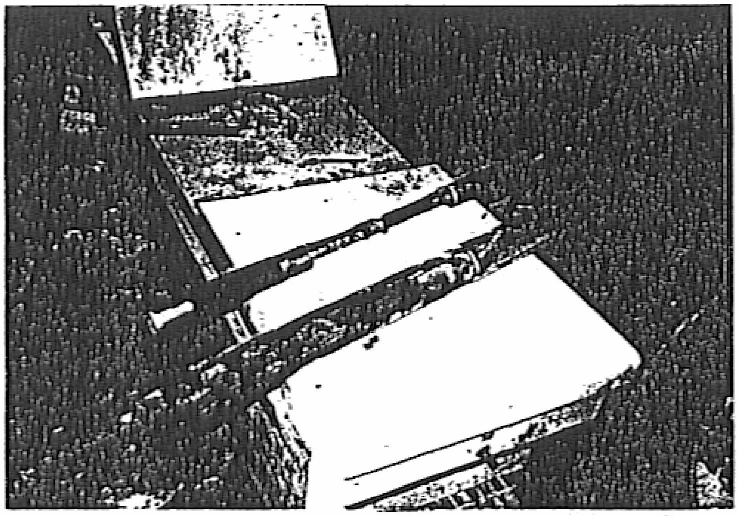
Step 1 - The borehole is drilled by fastest available method (usually rotary percussive) with water flush to full depth. Temporary casing may be necessary to full depth also, as dictated by the degree of instability of the rock mass. Typically borehole diameters are 100-150 mm.

Step 2 - The MPSP is installed. Pipe details can be varied with requirements, but a typical choice consists of a steel pipe, 50 mm o.d., with each length screwed and socketted. Each 5 m pipe has three 80 mm long, 4 mm thick rubber sleeves equally spaced along the length, protecting groups of 4 mm diameter holes drilled in the pipe. A concentric polypropylene fabric bag is sealed by clips above and below the uppermost sleeve in each length and is typically 400 to 600 mm long (Photograph 1). For short drill holes, plastic pipes of smaller diameter may be used. The temporary drill casing is then extracted, and any collapsing material simply falls against the outside wall of the MPSP tube.

Step 3 - Starting from the lowermost pipe length, each fabric bag is inflated via a double packer positioned at the sleeved port covered by the bag. A neat cement grout is used at excess pressures of up to 2 bar (29 psi), to ensure intimate contact with the borehole wall. The material of the bag permits seepage of water out of the grout, thus promoting high early strength and no possibility of shrinkage. Clearly



Photograph 1. MPSP pipes showing (left) fabric bag clipped to pipe over a sleeved port and (right) fabric bag after grout inflation through that port.



Photograph 2. Special inflatable double packer, as used inside the MPSP pipe.

the choice of the bag material is crucial to the efficient operation of the system: the fabric must have strength, a certain elasticity, and a carefully prescribed permeability.

Step 4 - Water testing may be conducted if required, through either of the two "free" sleeves per length, again through a double packer. Tests show that a properly seated fabric collar will permit effective "stage" water testing at up to 4 bar (58 psi) excess pressure.

Step 5 - Grouting is executed in standard tube à manchette fashion from bottom up via the double packer (usually of the inflatable type, Photograph 2). The grouting parameters are chosen to respect target volumes (to prevent potentially wasteful long-distance travel of the grout) and/or target pressures (to prevent potentially dangerous structural upheavals).

The following additional points are especially noteworthy regarding the MPSP System. Firstly, it is clear that, if a hole has been grouted once, it generally cannot be regrouted: some of the pressure grout will remain in the annulus outside the tube and so form a strong "sleeve grout" preventing the opening of sleeves in contact unless a very weak mix was used. (The system does, however, allow different stages in the same hole to be treated at different times.) Thus the MPSP system adopts the principles of stage grouting, where "split spacing" methods are used: the intermediate Secondary holes both demonstrate the effectiveness of the Primaries and intensify the treatment by intersecting incompletely grouted zones. Analyses of water test records, grout injection parameters, "reduction ratios" and so on will dictate the need for further intermediate grouting phases.

Secondly, in addition to the technical advantages of the system, there are significant logistical and work scheduling attractions. For example, the drilling and installation work can proceed regularly at well known rates of production, without requiring an integrated effort from the grouting crews (as in downstage grouting). In addition, the "secure" nature of the grout tube prevents the possibility of stuck packers, which is an unpleasant but unavoidable fact of life in upstage grouting in boreholes in most rock types. Grouting progress is therefore also more predictable and smoother, to the operational, technical and financial advantage of all parties concerned.

A third point relates to the straightness of the borehole and thus the integrity and continuity of the ground treatment. The temporary drill casings used in the hole drilling operations (Step 1) are typically thick-walled and robust. They therefore promote hole straightness, whereas the uncased boreholes common in stage grouting in rock, and drilled by relatively flexible small-diameter rods, are known to deviate substantially, especially in cases where fissures and/or softish zones in the rock mass are unfavorably located or oriented. By way of illustration, at Metramo Dam, Italy, the maximum deviation recorded in a test block of 150 holes each 120 m long was 1.5%, with the great majority being less than 1%.

3. CASE HISTORY: KIDD CREEK MINES, TIMMINS, ONTARIO

3.1 Background

As described by Yu and Counter (1983) Kidd Creek Mines, near Timmins, northern Ontario, routinely used consolidated rockfill to fill mined openings underground such as stopes and pillars. The minesite produces 4.5 million tons of copper, zinc, lead and silver ores annually from its No. 1 and No. 2 underground mining operations.

No. 1 Mine was developed with a shaft to a depth of 930 m in 1973 to recover the ore between the floor of the open pit and a depth of 792 m. Stoping widths are normally 18 m, the heights varying from 90-135 m and lengths from 22 to 65 m. Vertical rib pillars between stopes are typically 24 m wide and sill pillars are about 30 m thick. Pillar recovery is implemented after filling the mined stopes with the consolidated backfill. This permits total recovery of the ore with a minimum dilution, while also maintaining safe working conditions.

No. 2 Mine was developed from a second shaft, sunk to a depth of 1530 m in 1978, for the recovery of ore beneath No. 1 Mine.

A total of 2.5 million tons of backfill are required to completely fill the mined-out areas annually. About 80% has been consolidated material, consisting of crushed mine rock—generally less than 150 mm in maximum dimension—mixed with a cementitious binder before being gravity fed into the voids. The balance has been unconsolidated rockfill or sandfill.

As part of the ongoing expansion of the mine, it will be necessary to backfill at greater depths, and to facilitate this operation, vertical holes 630 mm in diameter, drilled through previously backfilled areas, were projected. Typically a Raise Boring machine is used to firstly drill, by rotary methods, a pilot hole 250 mm in diameter. This is then reamed out to full diameter in the raise boring.

However, early tests in the older filled areas where these holes were required showed that the degree of consolidation of the backfill was highly variable, and in some cases almost non-existent. As a result, conventional drilling was exceptionally difficult, and led to massive overbreak in the fill—always a major safety concern underground. Clearly some form of additional ground stabilization was required, and a research program was put in hand.

3.2 Operational Restraints and System Development

The grouting test was to be conducted through 60 m of fill, from the 2600' level, at cross cut 735 (Figure 4). The headroom at the test site was about 4 m, while access to the working location restricted maximum equipment widths and heights to about 2.5 m. The fill was known to be highly variable in composition and competence, with a bulk Unconfined Compressive Strength (U.C.S.) of around 50 bar (700 psi), although the strength of the andesite aggregate itself was over 3000 bar (42,000 psi). The following decisions were made:

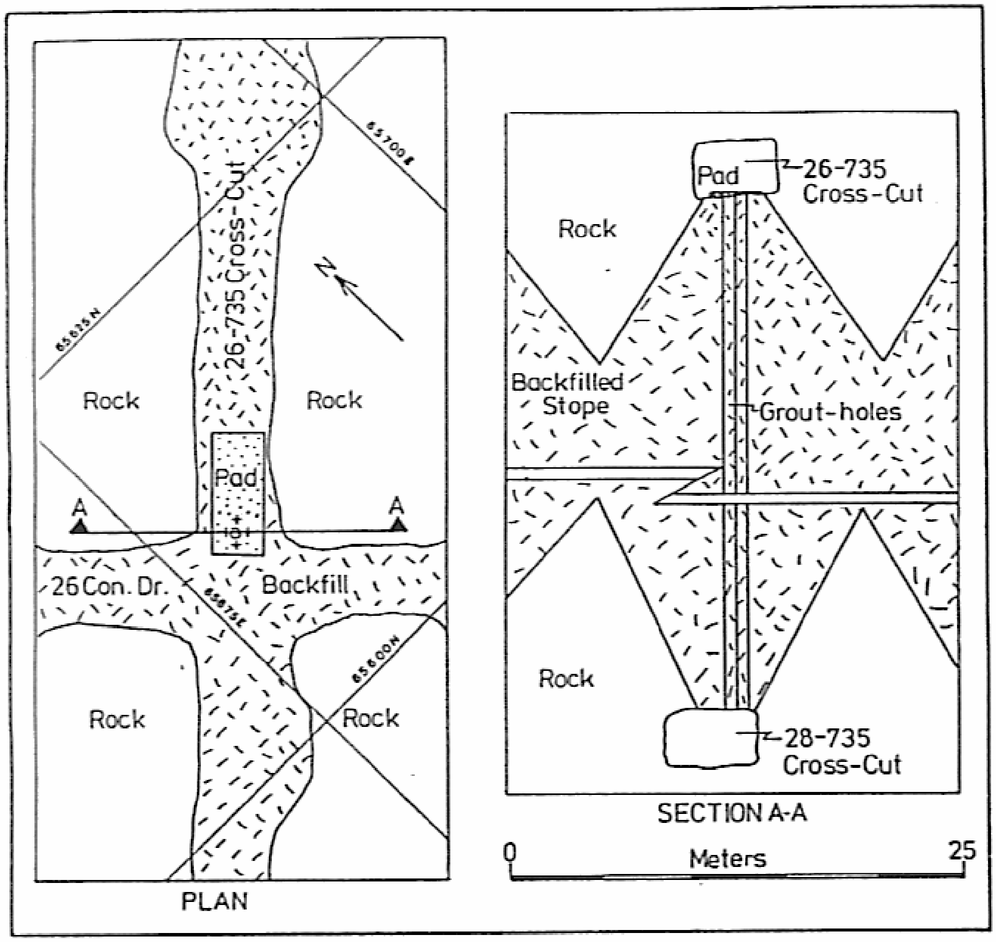


Figure 4. Plan and section of grout holes.

Drilling of grout holes. The unstable ground demanded the use of a continuous contemporary steel casing, full length. This could be advanced only by some form of duplex method (Bruce, 1989), but this would require considerable power to reach full depth in such difficult conditions. Given the restrictions placed on drill size (and so, in a general way, on drill power), the Krupp Double Head drilling system was used. This was mounted on a Krupp DHR 80 diesel hydraulic track rig, with special short mast (Photograph 3). The lower part of the double head rotates the outer casing slowly (but to the benefit of high torque) in one direction, while the upper part simultaneously rotates the inner drill rod (with drill bit and hammer) in the opposite direction. The cutting action of the system is thus enhanced, even though each component—i.e. outer casing and inner rod—is rotating relatively slowly. The system also discourages drill hole deviation as a result of this contra-rotation in association with the use of the tough thick-walled casing (11 mm). The dynamic boundaries of the annulus between rods and casing also help prevent blockages by drilling debris being returned to the surface.

Grouting method. The easiest method of grouting such conditions is to simply pump grout through the casing as it is slowly extracted. However, another method was necessary here, since 1) the highest degree of control over the grouting procedure was required and 2) having to use 1 m long casing lengths would severely interrupt such grouting operations, possibly leading to blockages in the lines, or worse, accidental cementing of the casing string in the hole. A grouting method independent of the drill casing was therefore necessary, and the MPSP system appeared to be ideally suited to the role. This was the first use of the system in North America.

Grouting concept. A pattern of grout holes was arranged around the position of the subsequent raise bore (Figure 5). Grouting was intended to stabilize the ground in this vicinity to permit the raise bore to proceed quickly and safely. A cement-based grout was considered most appropriate, bearing in mind 1) the materials available in the Mine, 2) the suspected nature of the fill, and 3) the intended purpose of the grout in situ.

It was also decided to drill and grout the first two holes (1 and 2) as Primaries, before commencing with the other two (3 and 4). In this way, any beneficial effect of the Primary treatment would be noted in the Secondary activities.

3.3 Drilling

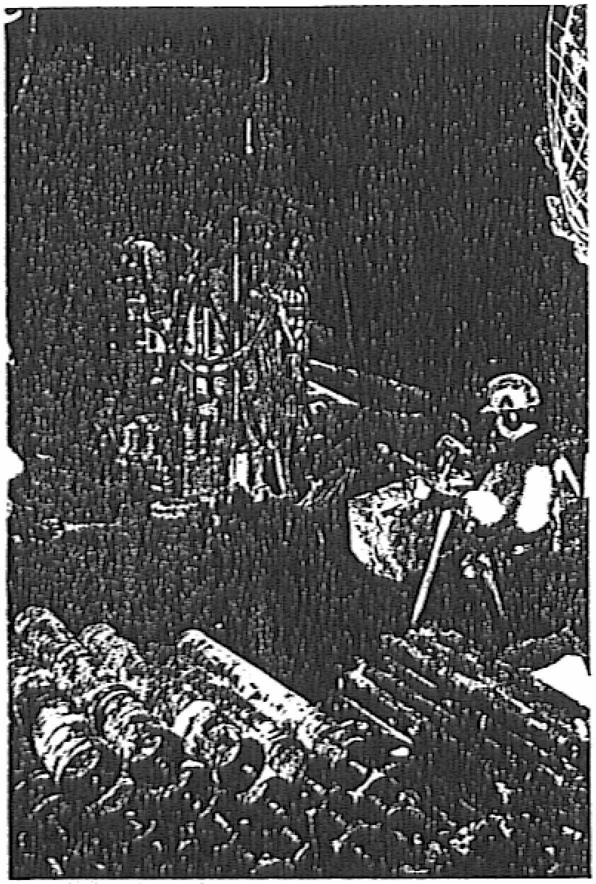
The hole positions were carefully laid out on a specially prepared level concrete pad, 7 x 3 m in plan, cast on the fill and ranging from 100 to 250 mm in thickness. The outer drill casing was 133 mm in diameter, and the inner drill carried a 100 mm down-the-hole hammer.

As is typical in such programs, the drilling of the first hole proved very problematic, and consumed a longer period than foreseen. The drilling confirmed that the fill was generally very loose, and contained frequent very large, very hard rock boulders. However, with adjustments to drilling techniques and hardware, and improvements to air flush characteristics, the holes were drilled with progressively increasing ease.

Penetration times, torque requirements and flush return characteristics were continuously measured, permitting an assessment of gross changes in the fill characteristics every meter. Table 2 summarizes the drill production data, the major points being:

1) the significantly faster drill production after the Primary grouting (i.e. in Holes 1 and 2) and

2) the reduction in "problem zones" in the two later holes.



Photograph 3. Drilling with short-mast Krupp track rig fitted with Krupp double-head drilling system. 1 m long casings and rods stacked foreground.

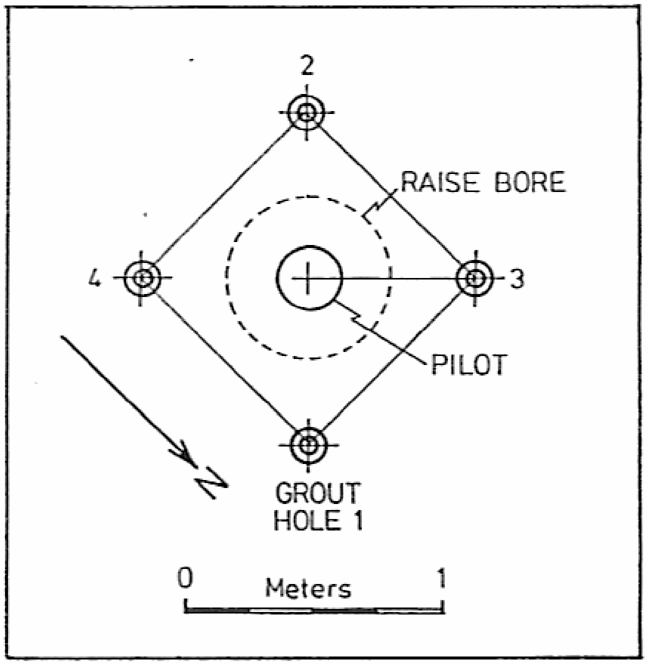


Figure 5. Plan of grout holes and raise bore.

Hole	Drill Days on the Hole	Actual Drilling Times		Penetration Rates (mins/1 m casing)			Depths of Major Obstructions
		On the Hole (mins)	Penetration (mins)	Min.	Max.	Mean	
1	6-1/2	2538	899	3	60	15.2	17, 19, 25, 33, 34, 43 m
2	3-1/4	1115	846	4	50	14.3	11, 12, 35, 36, 37, 38, 45-47 m
3	2-1/4	805	663	4	43	11.2	36, 48, 58 m
4	2-1/4	787	658	5	29	11.2	53 m

Table 2. Drill production analysis

These features can be seen in detail in Figure 6 which compares penetration rates for Holes 1 (Primary) and 4 (Secondary). At the same time, casing torque requirements decreased, while flush characteristics improved in the two later holes: both features indicative of improved ground conditions.

As shown in Figure 4, each of the four holes was designed to "break out" into the drive at the lower 2800' level. This allowed the deviation of the holes to be measured with great accuracy by precise Mine Survey methods (Table 3).

Careful consideration of the drill monitoring data suggested that Hole 2 had "kicked off" the vertical after glancing a large boulder or slab at 45-47 m, while it was probable that over-crowding of the drill system by an overzealous and relatively inexperienced operator caused the deviation of Hole 4. Overall, however, the holes proved remarkably straight, given the extremely onerous drilling conditions, and in all four cases the deviation did not hinder any subsequent operation (e.g. extraction of casings, placing of pipes).

3.4 Placing MPSP Pipes

Plastic pipes in 3 m lengths and 72 mm o.d. were used as the grouting pipes. Each had rubber sleeves at about 1.5 m intervals. Every fourth sleeve was fitted with a 600 mm long fabric bag to therefore provide 6 m stages in the ground. The bags were capable of expansion of up to 190 mm in diameter, and so ensured a good seal with the ground upon inflation.

After placing of the MPSP in each hole, and the extraction of the steel drill casing, the bags were inflated via a Rodio double packer, using carefully controlled volumes of neat cement grout.

3.5 Grouting

In order to reduce the amount of bagged dry materials to be transported and handled underground, the "base" of the cement grout mix was one of the Mine's standard formulations. These grouts are prepared under the highest quality control at the surface, and pumped through miles of 100 or 150 mm diameter steel lines to the point of usage underground.

In this case, the slurry was pumped to a large storage tank, near the special mixer/pump to be used for the trial (Photograph 4). The design of the mix is shown in Table 4. Early tests confirmed that, while it was easily pumpable and had a long setting period, it was too fluid and unstable (i.e. high bleed capacity) to use in this particular application. Thus, dry cement was added to this slurry, in a Colcrete colloidal mixer, in a proportion providing the thickest mix capable of routine mixing and pumping (Table 5).

The grout was then pumped by a Moyno progressive cavity pump through the flexible injection line and inflatable packer (Photograph 5). In each hole, grouting was conducted from the bottom up, successive stages being designated Primary and Secondary and treated in that order to allow an extra degree of data analysis and control. Flow rates and volumes were regulated by manually controlled valves on the grout circulation line system.

Based on estimated grout travels and theoretical ground porosity, each stage was injected with 2000 liters of grout. Early on it became clear that the grout was flowing very freely, with considerable amounts, from the lower stages especially, draining into the opening at the 2800' level up to 4 or 5 m distant from the hole. To try to stop this leakage, and to help localize the effect of the grouting, sodium silicate solution was added from the adjacent hole during grouting. When encountering each other, a very rapid or flash set occurs in the ground, the exact time depending on the composition and relative amounts of each component.

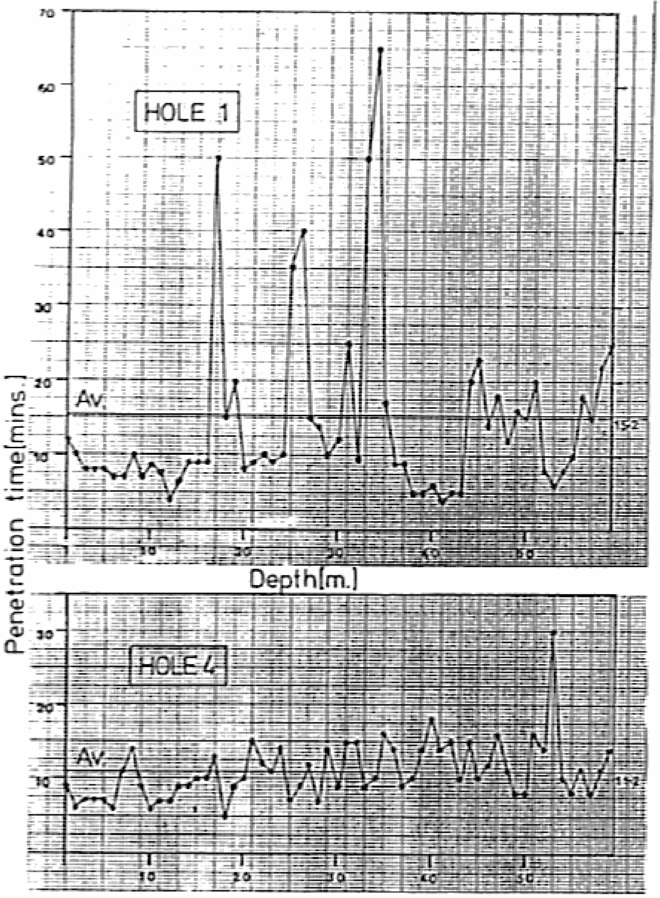
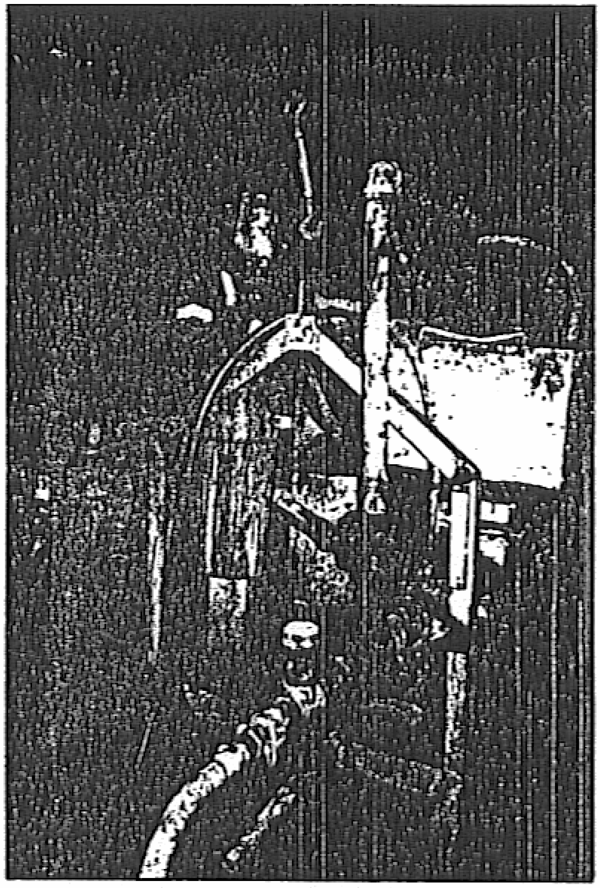


Figure 6. Comparison of drilling penetration rates: Hole 1 (Primary) and Hole 4 (Secondary).

Hole	Length (m)	Deviation Direction	Distance (cm)	Angular Deviation (%)
1	59.2	East	6	6/5920 = 0.1%
2	59.2	Northeast	125	125/5920 = 2.1%
3	59.4	Southwest	32	130/5960 = 0.5%
4	59.6	West	130	130/5960 = 2.2%
		Overall Average:	$\frac{293}{23,740}$ = 1.2%	

Table 3. Summary of drill hole deviations.



Photograph 4. Mixer pump unit where bagged cement (left) was added to standard Mine slurry (top pipeline, left).

Component	Weight (kg)	S.G.	Yield (liters)
Portland Cement	4272	3.1	1378
PFA	2091	2.7	774
Water	4759	1.0	4759
Mix	11,122		6,911

WSR = 4759/4272 + 2091 = 0.75
Bulk Density = 11122/6911 = 1.61

Table 4. Composition of one "batch" of standard mine mix (Recipe 4).

One Tank of Slurry (60 liters capacity)		+	Added Dry Cement	=	Injected Mix
PC	37 kg	+	30 kg	=	67 kg
PFA	18 kg		-	=	18 kg
Water	41 kg		-	=	41 kg
Total	96 kg	+	30 kg	=	126 kg

For the injected mix
WSR = 0.48
Bulk Density = 1.82
Bleed = 19% (after 2 hours)

Reaction time with equal volume of sodium silicate solution = 50 secs

Cube strength = 12N/mm^2 at 28 days.

Table 5. Composition and properties of injected mix. (Note: The volumes and weights cited are consistent with the batch capacity of the storage and mixing tanks of the grout plant, and reflect site practice.)

By the end of the grouting, over 76,000 liters of cement grout and 9,000 liters of sodium silicate solution had been injected. At each level, there was a slight reduction in rate of flow, and a slight increase in pumping pressure through each successive phase of grouting, highlighting a certain degree of "tightening up" in the ground. Typical grout flow rates were 20-30 liters/min. with pressures of about 15-20 bar (220-290 psi). However, these values reflected less on the properties of the ground than the hydraulic characteristics of the pumping hardware and ancillaries, in which the limiting diameter was 11 mm in the 60 m long flexible grout line.

Consideration of the grouting patterns into the 2800' level led to the conclusion that the grout was not necessarily remaining local to the points of injection and so not filling completely the voids it encountered. Given the very open nature of the fill, and the characteristics of the grout used, this was scarcely surprising. Instead, it was felt that the grout was in general passing down through the fill, and thoroughly coating the aggregate en route. The grout, when set, would therefore be gluing adjacent blocks together, as opposed to completely filling all the voids between them. This was supported, as noted above, by the much improved drilling performance after the grouting of the first two holes.

Grouting was therefore considered complete when all the stages had been grouted once, and preparations were made to commence raise boring.

3.6 Raise Boring

The test raise collar was prepared by bolting the base plates to rebars grouted into the concrete pad. The 250 mm diameter pilot hole was drilled by rotary methods using a Robbins 34-R raise borer. The industrial production rate was about 2 m per hour on the hole.

Photograph 5. Hand pump used to inflate packer attached to flexible groutline placed in MPSP pipe (left foreground).

Deviation from vertical was measured as 2% upon breakthrough. The raise was then successfully upreamed from the 2800' to the 2600' level to a final nominal diameter of 630 mm. The production rate for this operation was approximately 1.5 m per hour.

Thereafter, a television camera survey was conducted to view the effectiveness of the grouting and the condition of the raise wall. Table 6 summarizes the visual record of porosity.

% Total Raise Length	Estimated % Porosity of the Surrounding Fill
48	Less than 15
30	15-30
22	Over 30

Table 6. Visual record of fill around raise bore.

These observations suggest that the grouting had reduced the porosity quite substantially in places, but that elsewhere the fill was still relatively open structured, though stable. This confirmed the "feel" for the gluing action of the grout, obtained during the injection phases. In addition, it was possible that the rigid plastic pipes, at relatively close centers, had contributed an in situ reinforcing effect to the larger fill blocks, helping to "stitch" them together somewhat and so forming a more stable skeleton.

3.7 Further Developments

The success of this first test proved very encouraging, although there were concerns about the void-filling—as opposed to gluing—efficiency of the cement grout. Experiments have therefore been conducted on the grouting materials and a new cementitious mix, with bentonite has been evolved. This grout has thixotropic characteristics, and has minimal bleed on setting. It has a 28-day strength of about 40 bar (580 psi) and is very economic with respect to dry materials. To improve injection progress, changes have been made to the injection hardware, including the upsizing of the grout line bore to 18 mm.

4. FINAL REMARKS

The fill stabilization at Kidd Creek has proved to be an unusual but successful application of the MPSP system. The system is more accustomed to usage in open-air locations to provide grout curtains. However, the special restrictions imposed by working 800 m underground in low headroom situations have not compromised its effectiveness, even when used in its new role of ground strengthening. This success bodes well for the continuing expansion in the popularity of MPSP, not only in the mining industry but in new applications within its traditional base of civil engineering construction.

ACKNOWLEDGEMENTS

The work described herein was an engineering joint venture between the owner, Kidd Creek Division of Falconbridge Ltd., and the contractor, Nicholson Construction Company. The individuals most closely involved in the former party were Jim Croxall, Clay Wittchen, Faramaz Kord, Doug Duke and Peter Corcoran. For the contractor, Dennis Raab, Jim Jones and Ron Triplett merit acknowledgement, while the lead author conceived the solution and directed the site works. Thanks are also due to engineers at Rodio, Milan, Italy and at Krupp, USA.

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