The stabilization of loose backfill by drilling and grouting techniques

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ABSTRACT: Recent work at Kidd Creek Mine, Timmins, Ontario, has focused attention on the difficulties of drilling and grouting loose backfill underground. This treatment had to be undertaken to ensure the security of a subsequent raise bore operation, and also to provide stability to other volumes of fill adjacent to blasting operations. The various methods of drilling and grouting in such difficult conditions are reviewed generically. Special consideration is given to the physical and practical restraints of working underground. The paper concludes with a brief description of the work executed at Kidd Creek, in which the application of the various principles of selection and methodology are clearly illustrated.

1. BACKGROUND

When operating in sound, competent rock masses, drilling and grouting operations are a matter of routine for experienced personnel. This is equally true whether these operations are being conducted on the surface, such as for dam foundation grouting, or underground such as for sealing troublesome aquifers. A further aid to success is the fact that the organization responsible for the design and supervision of such works has usually a long history of involvement in the "local conditions" so that even when the methods specified and/or employed, may no longer be modern or even the most apposite, they are still adequate for the solution sought. This paradigm, however, can be taken to ludicrous extremes, and one only has to look at aspects of current U.S. rock grouting practice - dictated by specifications generated over 50 years ago - to understand why, in that field at least, foreign practice is years advanced both technically and contractually.

The drilling and efficient grouting of poor rock and soil, in contrast, is usually a stimulating challenge to innovative and progressive specialists, but invariably also a disheartening conundrum to traditionalist functionaries. The quality of backfill varies from mine to mine for a variety of well known reasons. At its best, it reacts to subsequent attempts to drill, or otherwise bore or tunnel through it, as a competent cemented rock mass requiring little or no supplemental support. At its worst, it is either unconsolidated rockfill or it gives a fair impersonation of a very poorly cemented till or conglomerate. Such fills need considerable extra attention to permit safe, efficient and economic mining operations to proceed. At this stage, the knowledge and experience of the "soft ground" driller and grouter are necessary.

The development of deeper mine levels often involves some form of excavation activity in filled stopes, pillars or previously abandoned shafts. Such an example is the recent activity at Kidd Creek Mines, Timmins, Ontario (Bruce and Croxall, 1989) where an ongoing expansion required vertical raise bores, 630 mm in diameter, to be drilled 60 m down through previously backfilled areas. Conventional "open hole" drilling and grouting operations were defeated by the instability of the backfill, as a result of its extremely variable degree of cementation. A unique grout treatment scheme was enacted to stabilize the ground to permit the raise boring to progress.

This paper later summarizes the work conducted on this project, but first it provides a review of the options available to the ground treatment engineer. This review provides the background to the selection of the drilling and grouting method actually adopted, with great success.

2. DRILLING AND GROUTING COMPETENT ROCK

It is fair to say that the debate continues (Deere, 1982) on the "best" way to drill competent rock formations to permit the grouting of fissures. Generically there are two types of drilling methods, the details of which are well known in the industry:

a) rotary percussive drilling
   - by top hammer (drifter)
   - by down-the-hole hammer

b) rotary drilling
   - high speed, low torque (e.g. coring)
   - low speed, high torque (e.g. tricone)

Traditionalists in North America still tend towards the use of rotary drilling though the insistence for core recovery is being relaxed. Elsewhere in the world, if the rock permits, rotary percussive is favored, being several times faster and more economic than pure rotary drilling. Current opinion is that the nature of the flush is the more significant determinant of the "groutability" of the fissures intersected by the boreholes: water is preferred over air. Even here, however, the examples are increasing of the permitted use of air (in conjunction with down-the-hole hammers) for grout hole drilling. Overall, and especially in the mining industry, it seems that the major determinant of drilling method is the equipment already available underground, be it for exploration, blast hole drilling, or rock bolting.

The grouting of such rock masses has been described at length by several authors, but most recently and elegantly by Houlsby (1990) and Weaver (1991). Each of these excellent books has an extensive bibliography, and is far superior to certain recent, parochial texts which have emanated from Europe.

Only in the field of grouting materials have significant advances been made in the practice of competent rock mass treatment. Again this is a subject with a rich literature but two publications (Naudts, 1989, and AFTES, 1991) and one recent conference (ASCE, 1992) provide outstanding guidance, especially in the field of microfine cement grouts (e.g. DePaoli et al, 1992a, 1992b). Again, however, particularly in the mining industry, a somewhat unadventurous approach to grout material selection is often enforced. This is understandable where there are extreme practical, operational, or economic restraints. Where this approach is enforced through ignorance or "custom" it is often the source of major, ongoing problems and extremely disillusioned owners (Naudts, 1991).

3. DRILLING AND GROUTING INCOMPETENT ROCK AND SOIL-LIKE MATERIALS

In certain conditions the ground 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 (Bruce, 1989a, 1989b). However, it is possible to condense these into six major categories, as summarized in Table 1.

Only contemporary "production" methods are reviewed, so that systems synonymous with excessive cost (e.g. diamond coring) or very limited geological capacity (e.g. vibratory) are excluded.

Concentrating on the specific problems of drilling through deep Canadian backfill, typically comprising very hard "aggregate" and very weak "binder", in the prevalent access/headroom conditions found underground, the following categories are normally eliminated on technical/cost effectiveness grounds:

(1) drive drilling (lancing)
(2) rotary duplex
(6) auger drilling

This normally leaves, therefore, as potential options:

(3) rotary percussive concentric duplex
(4) rotary percussive eccentric duplex
(5) "double head" duplex

Regarding ground treatment methods, the most effective and reliable method of grouting incompetent, collapsing or voided rock (like) masses is the relatively new MPSP Method (Bruce and Gallavresi, 1988).

The installation sequence of the Multiple Packer Sleeved Pipe system is shown in Figure 1. The borehole diameter is typically 100-150 mm and the sleeved pipe diameter 50-75 mm. The fabric packer bags and the rubber sleeves are spaced to suit the particular site requirements. This was the system adopted at Kidd Creek and it is described in more detail below.

Regarding the grouting of soil-like materials, the industry is in a far more dynamic situation than is the rock grouting fraternity. It is benefitting from the technological advantages made by chemists, physicists, and geotechnical engi-

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

Table 1. Summary of overburden drilling methods(After Bruce, 1989b)

neers on the one hand, and is being prompted by the increasingly severe demands made by structural, mining and environmental engineers on the others.

The basic categories of soft ground treatment do, however, remain relatively well defined:

A. Hydrofracture 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

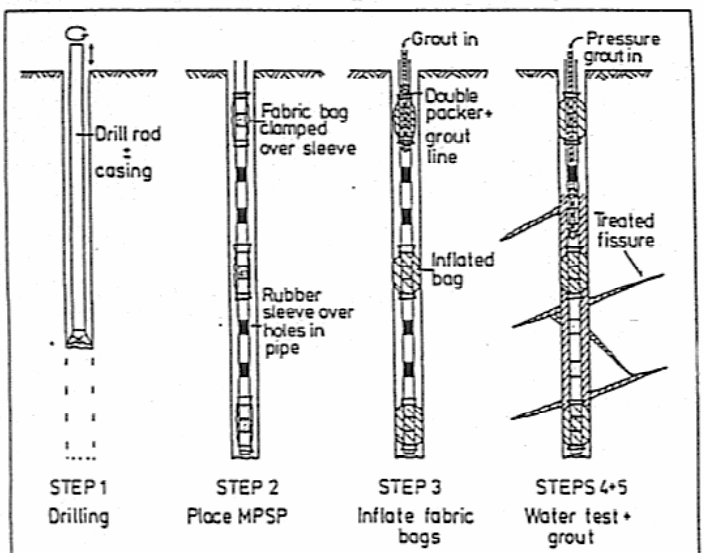


Figure 1. MPSP installation sequence (Bruce and Gallavresi, 1988)

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. In California, certain specialty contractors are promoting this technique under the name "Confrac" (i.e. controlled fracture). Fibers in the grout are claimed to impart significant tensile strength to the grout lenses formed.

B. Compaction grouting. - This is a specialized "uniquely American" process that has been used since the early 1950's 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 on shallow foundations. (Warner, 1982).

Although compaction grouting does have 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

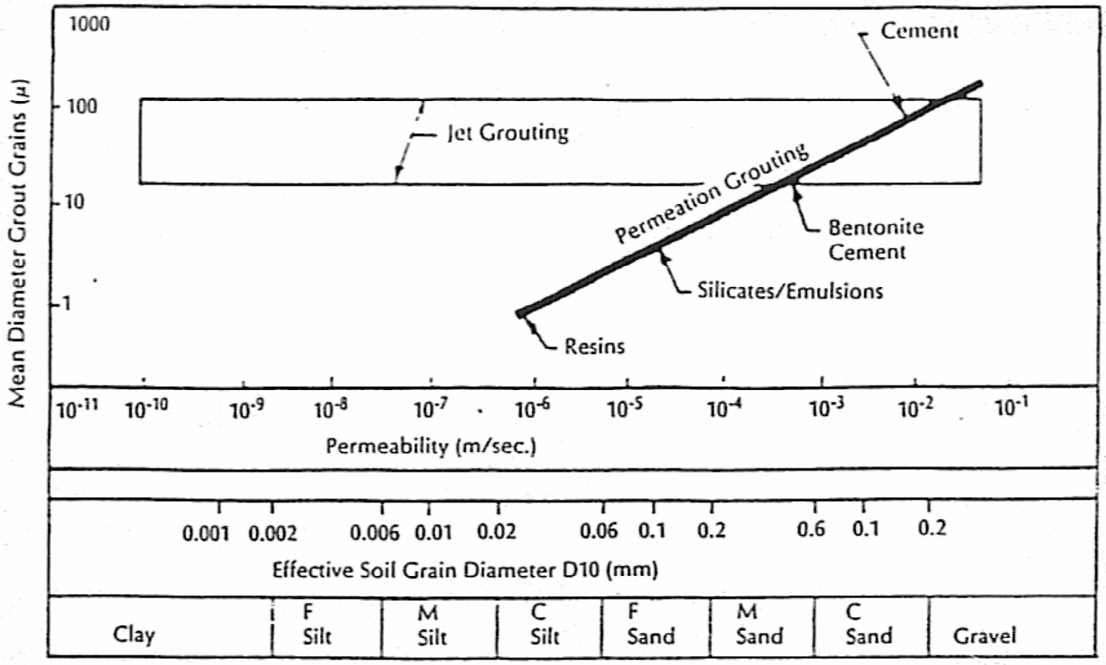


Figure 2. Groutability of soils (Coomber, 1985)

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. Recent papers dealing with more novel applications include these by 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. Warner (1992) provides a fundamental review of mix design and rheology considerations.

C. Permeation grouting. - In certain ways, the techniques involved in permeation grouting are the oldest and best researched. The intent of permeation 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 2). Excellent reviews of the 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 which are described in Bruce (1989a). The most common in North American practice are

- injection through the drill rods or casings during their withdrawal;
- injection via the tube à manchette (sleeved pipe) system, described by various authors including Bruce (1982).

D. Replacement grouting. - Replacement, or jet, grouting is the youngest major category of ground treatment. According to Miki and Nakanishi (1984), 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 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.

Jet grouting can be executed in soils with a wide range of granulometries and permeabilities. Indeed, any limitations with regard to its applicability are imposed by other soil parameters (e.g. the shear strength of cohesive soils or the density of granular depsoits).

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 3 depicts one particular type in which the soil is jetted by an upper nozzle ejecting water at up to 60 N/mm^2 inside an envelope of compressed air at up to 1.2 N/mm^2. The debris are 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 Management (SSSMAN) system provides total (and verifiable) excavation of the soil prior to grouting or concreting. Clearly, each system has its own cost implications. Overall very few examples of jet grouting holes deeper than 45m 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. 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.

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 goverment 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).

The ASCE New Orleans Conference (1992) provides the most up to date exposé of the theory and practice of this - and all the other ground treatment - methods.

4. TREATMENT OF BACKFILL - KIDD CREEK MINES

Hard won experience proved that in order to vertically raise bore safely and economically through 60m of variable backfill some form of ground treatment had to be performed in advance (Bruce and Kord, 1991).

A trial was first conducted in crosscut 735 on the 790 meter level. In addition to proving the system, equipment and materials, this test also permitted the grouted zone to be explored by subsequent down-drilling of the 250mm diameter pilot hole, and upreaming of the 630 mm reamed hole.

The second test site was located at the same level, but at the 660 crosscut - 75 metres to the north. This test incorporated modifications based on the first test, but also demonstrated the competence of the grouted fill with respect to up-drilling of the pilot, and down-reaming of the final bore - a far more severe test of the concept.

The properties of the fill varied somewhat within and between the two stopes. However, the fill was generally highly variable in composition and competence, with a bulk unconfined compressive strength of about 50 bar. The strength of the aggregate itself was over 3,000 bar.

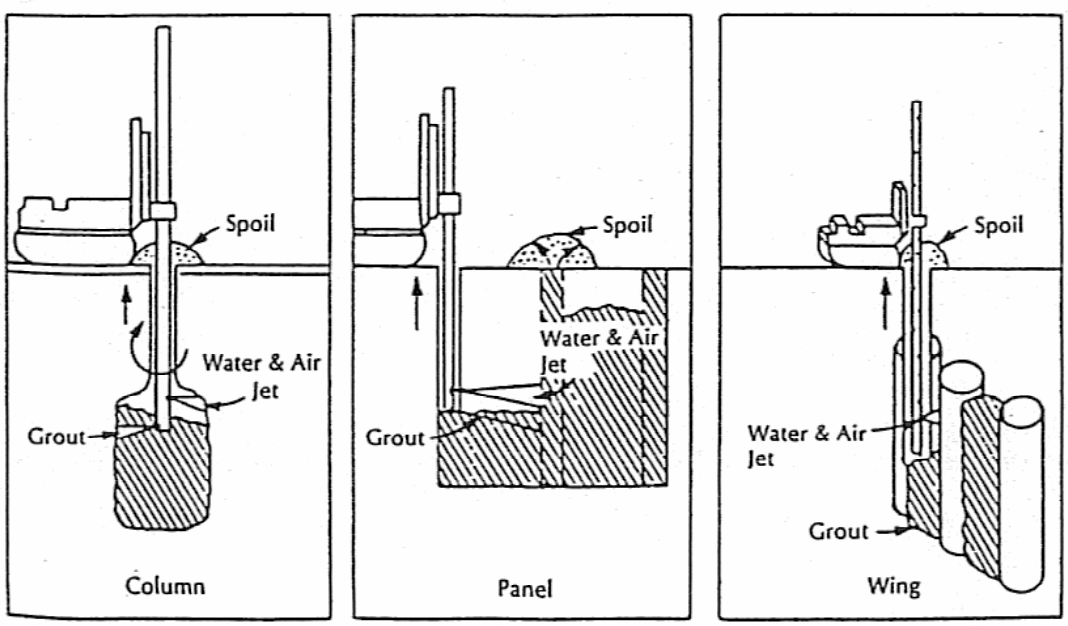


Figure 3. Jet grouting options using a three-fluid system (Coomber, 1985)

The unstable fill demanded the use of a contemporary steel casing during the drilling of the grout holes to prevent their collapse. Given the space restrictions, and these very difficult, aggressive drilling conditions, the double head duplex method (Catetory 5) proved the most promising and cost effective method. The Krupp Doublehead was mounted on a specially adapted short mast Krupp DHR80 diesel hydraulic trackrig. Compaction and hydrofracture grouting were ruled out immediately, while the backfill certainly did not behave like a competent rock mass. Jet grouting likewise would have been defeated by the site and geotechnical conditions and in any case would have been inappropriate to the purpose of cementing such a mass together. The choice of grouting principle was therefore clear: permeation of the existing voids.

The easiest method of permeation grouting in such ground conditions is simply to pump grout through the casing as it is slowly extracted. However, another method was necessary here since:

- The highest degree of control over the grout placement procedure was required;
- Having to use 1-meter-long steel casing would severely interrupt the grouting operation, possibly leading to blockages in the lines, or worse, accidental cementing of the drill casing in the hole.

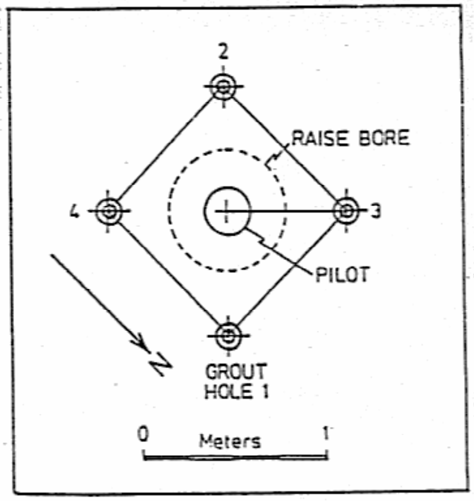
A grouting method independent of the drill casing was therefore necessary. The Multiple Packer Sleeved Pipe (MPSP) system appeared to be ideally suited to the role.

A pattern of four grout holes was arranged around the position of the subsequent bored raise (Figure 4). 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 because of:

- The materials available in the mine;
- The suspected nature of the fill;
- And the intended purpose of the grout in situ.

Hole positions were carefully laid out on a specially prepared level concrete pad, 7 x 3 meters 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 rods carried a 100 mm down-the-hole hammer.

As is typical in such programs, the first hole took longer to drill than planned. Drilling confirmed the fill was very loose, and contained frequent very large, very hard rock boulders. However, with adjustments to drilling techniques and hardware, and improvements in air



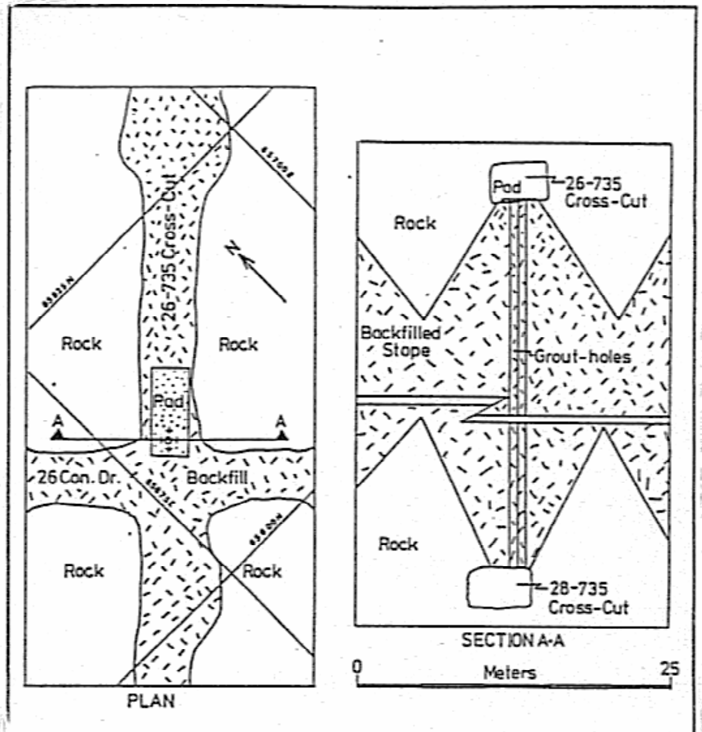


Figure 4. Arrangement of grout holes, first site

flushing, the holes were drilled with progressively increasing ease.

Penetration time, torque and flush return characteristics were measured continuously. From these data, gross changes in the quality of the fill every meter could be assessed.

Holes 1 and 2 were drilled and fully grouted, followed by Holes 3 and 4. Each hole was designed to break through into the drive on the lower, 850 meter level. Excellent linearity and straightness were achieved.

Plastic pipes of 72 mm outside diameter, in 3-meter lengths were used as grouting pipes. Each length of pipe had rubber sleeves at about 1.5 meter intervals, covering groups of holes in the pipes. Every fourth sleeve was fitted with a 600 mm long fabric bag. This provided stage lengths of 6 meters in the holes. The bags were capable of expanding up to 190 mm in diameter, ensuring a good seal with the ground upon inflation.

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

Ash-cement grouts at the Kidd Creek mine are prepared under strict quality-controlled conditions on surface and pumped underground through many kilometers of 100 or 150 mm diameter steel lines. In this case, the slurry was pumped to a large storage tank near a special mixer/pump used in this trial. Early tests confirmed that, while the slurry was easily pumped and had a long setting period, it was too fluid and unstable to use in this particular application. Therefore, dry cement was added to the slurry at the test site in a Colcrete colloidal mixer.

The grout was then pumped by a Moyno progressive cavity pump through the flexible injection line and inflatable packer. In each hole, grouting was conducted from the bottom up. Flow rates and volumes were regulated by valves on the grout circulation line.

Based on estimated grout travel distances and theoretical ground porosity, 2,000 liters of grout were injected in each 6 meter stage. Early on, the grout flowed freely, with a considerable amount, especially from the lower stages, draining into the 850 meter level. Leakage occurred up to 4-5 meters radially from the hole breakthrough location. To stop this leakage, sodium silicate solution was added from the adjacent hole during grouting. When such grout encounters sodium silicate a very rapid or "flash" set occurs - how rapidly depends on the composition and relative amounts of each component.

A total of 76,000 liters of cement grout and 9,000 liters of sodium silicate solution were injected in the four holes. At each phase, there was a slight reduction in flow rate and a slight increase in pumping pressure. This behavior highlighted a degree of progressive "tightening up" in the ground.

Seepage patterns on the 850 meter level suggested the grout was not remaining local to the points of injection and was not filling the voids completely. Instead, it was felt that the grout was passing down through the fill, and thoroughly coating the aggregate en route. When set, the grout was gluing blocks together as opposed to filling the voids between them. A 250 mm diameter pilot hole was then downdrilled at a rate of about 2 meters per hour. Deviation from vertical was measured as 2% upon breakthrough. The raise was then successfully upreamed to a diameter of 630 mm at a rate of 1.5 meters per hour.

A video camera survey was conducted to view the effectiveness of the grouting. Grouting had reduced the porosity quite substantially in places, but elsewhere the fill was still relatively open, though stable. 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.

Because of the more arduous reaming requirements of the second test (i.e., reaming from top to bottom), various changes were made:

- Six peripheral holes were drilled (<u>Figure 5</u>), supplemented by a seventh, central hole.
- The peripheral holes and the bottom of the central hole (hole 7) were grouted with a more viscous, stable cement based grout, incorporating bentonite. The aim was to restrict flow and improve void-filling efficiency. The central hole was grouted with a higher strength, neat cement grout, for additional support.
- The grout station was overhauled to provide higher volumes and pressures and larger diameter grout delivery lines were installed to facilitate faster pumping.

As in the first test, grouting was done in phases: Holes 1, 3, and 5 drilled and grouted, followed by Holes 2, 4, and 6 and finally, central Hole 7.

The raise collar for the second test was positioned in the center of 28-662 stope, about 15 meters from the point where backfill trucks dumped and downslope from the peak of the fill cone. A very high torque was necessary to rotate the drill casing in all holes. The best performance was obtained with the "Lost Crown" system (Bruce, 1989b). This gives an oversized hole (140 mm in diameter) without needing an eccentric drill bit.

Difficulties were encountered in penetrating unconsolidated backfill. These occurred where the original slurry mix design changed to a slurry-to-aggregate ratio of 3.6% from 6.4%. In most holes, the casing had to be withdrawn temporarily and the drill bit replaced.

Holes 2 and 4 were drilled faster and slightly easier. The first attempt at Hole 6 had to be abandoned, possibly because of an artificial obstruction in the fill. Another hole was drilled to replace it.

Peripheral and plug grouting in this test was executed with a bentonite-en-

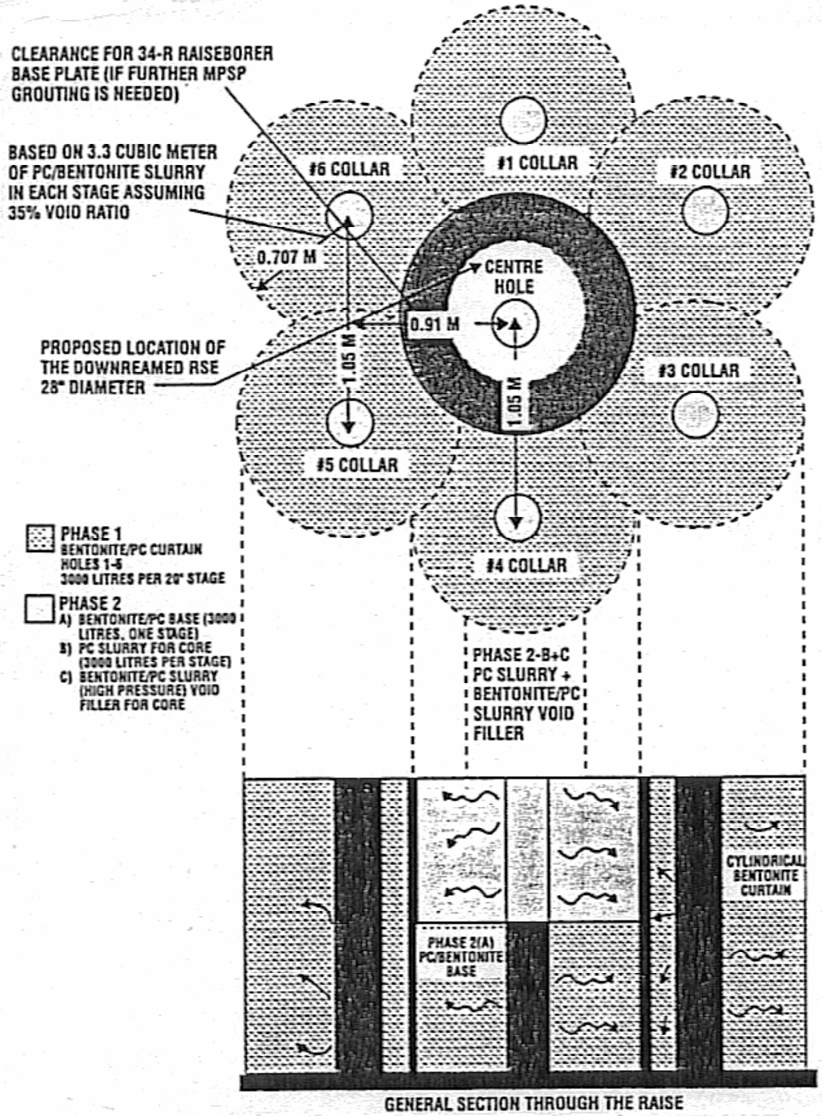


Figure 5. Arrangement of grout holes, second site

riched slurry. Each 100-liter batch of 60% P.D. mine slurry had almost 6 kg of bentonite added at the colloidal mixer. The target volume was 3,000 liters per 6-meter stage. This was achieved at pumping rates of up to 60 liters per minute.

In contrast to the first test, no leakage of grout into the 850-meter level was recorded. This indicated that the bentonite successfully restricted excessive travel. No sodium silicate was therefore necessary.

A total of 160 cu. meters of bentonite-enriched grout was injected into the six perimeter holes. A further 30 cu. meters of higher-strength cement grout was injected into the upper portionof Hole 7.

Again, a Robbins 34R machine was used to drill a 250 mm diameter pilot hole. The rate of penetration was an extremely high 12 meters per hour. During reaming, thrust pressure was maintained the same as for the pilot hole, but rotational speed was decreased to 16 r.p.m. from 40. Penetration rate for reaming averaged 4.2 meters per hour.

A subsequent video survey showed that although some zones of coarse, bonded fill remained, the overall condition of the fill was very stable and well cemented. The average porosity of the grouted fill was estimated at less than 15%. This compares with an estimate of 35% for typical mine backfill.

This improvement relative to the first raise may be due to three factors:

- Location of the raise in the fill cone compared with the first test which was located in the segregation zone;
- An increased intensity of grouting from seven holes instead of four.
- Improved grout mix design.

5. FINAL REMARKS

The subject of ground treatment by drilling and grouting is extremely wide, and touches knowledge and experience from many disciplines. The Kidd Creek case history is a clear example of how the most appropriate drilling and grouting systems can be rationally selected, and responsively improved as on-site experience is gained. It should not be overlooked that both the driling and grouting methods selected were relatively novel, and certainly challenged the paradigms of those originally involved with the problem. This scope for originality and flexibility of response is the keynote of treating difficult ground such as loose backfills.

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