High Pressure Grouting for Groundwater Ingress Control in Rock Tunnels and Caverns

K.F. Garshol & J.K.W. Tam
AECOM Asia Co. Ltd., Hong Kong

H.K.M. Chau & K.C.K. Lau
Drainage Services Department, Hong Kong

ABSTRACT

In underground hard rock construction, ground treatment is normally limited to installation of support to provide stable ground and safe working conditions. In addition, groundwater ingress control is often necessary to prevent surface settlement and damage, or environmental impact to vegetation and groundwater resources. Worldwide there are many projects that demonstrate the potentially serious consequences of inadequate groundwater ingress control during underground construction. Therefore, for many projects it is necessary to implement groundwater control as an integral part of the underground construction process.

Pre-Excavation Grouting (PEG) offers effective restriction of groundwater ingress in advance of the excavation. PEG ground treatment can provide "dry" underground openings and as a side effect also improved ground stability. Modern PEG includes high-pressure injection of non-bleeding stable grout with low viscosity and mostly fixed water-cement ratio. Furthermore, suitable Microfine Cement and Colloidal Silica injected through proven grouting equipment have to be ensured. The maximum grouting pressure should be in the range 50 to 100 bar.

1 INTRODUCTION

In underground hard rock construction, ground treatment is normally limited to installation of support to provide stable ground and safe working conditions. In addition, groundwater ingress control is often necessary to prevent surface settlement and damage, or environmental impact to vegetation and groundwater resources. Worldwide there are many examples of serious consequences of inadequate groundwater ingress control during underground construction. Therefore, for many projects it is necessary to implement groundwater control as an integral part of the underground construction process. It should be noted that the ingress control measures installed as part of the final lining (typically sheet membrane), mostly will become effective far too late to prevent surface settlement and damage.

This paper describes the most important elements of high-pressure Pre-Excavation Grouting (PEG) necessary for the purpose of achieving targeted maximum residual groundwater ingress into tunnels and caverns in hard rock. Examples from relevant projects in Hong Kong and elsewhere are presented.

1.1 Reasons for the increased use of high pressure grouting

In the past 20 years, high-pressure grouting (PEG) ahead of the face in tunnels or caverns has become an important technique in modern underground construction. Garshol (2007a) provided some reasons for this:

- Limits on permitted ground water drainage into underground space are now frequently imposed by the authorities for environmental protection reasons or to avoid settlement above the underground space. Settlement may cause damage to infrastructure like buildings, roads, drainage pipes, supply lines, cables and ducts.
- The risk of major water inrush, or of unexpectedly running into extremely poor ground, can be virtually eliminated (due to systematic probe drilling ahead of the face being an integral part of PEG). It should be noted that if the excavation hits lots of water this would have to be sealed by post-grouting. This

process is not only time consuming and expensive, but is also far less effective than PEG. In difficult situations it can be close to impossible to successfully solve the problem.

- Poor and unstable ground ahead of the face can be substantially improved and stabilized before exposing it by excavation. This improves the face area stable stand-up-time, thus reducing the risk of uncontrolled collapse.
- Risk of pollution from tunnels transporting sewage, or other hazardous materials, can be avoided or limited. Ground treated by pre-injection becomes less permeable and such hazardous materials cannot freely egress from the tunnel.
- Sprayed concrete linings are increasingly being installed as the final and permanent lining in tunnels. The savings potential in construction cost and time is substantial, this being the main reasons for the increased interest and use. Such linings are difficult to install with satisfactory quality under wet (running water) conditions and ground water ingress control by pre-grouting can solve the problem.
- With modern drilling jumbos even very hard rock can be penetrated at a rate of 2.5 to 3.0 m/min. Therefore, the cost of probe drilling to guard against sudden catastrophic water inflows is now much lower than it used to be. A number of projects have experienced such catastrophic cases, typically being stopped for months and probe holes offer an inexpensive insurance.

2 PEG METHOD FOR UNDERGROUND CONSTRUCTION

PEG offers effective restriction of groundwater ingress in advance of the excavation resulting in "dry" underground openings and as a side effect also improved ground stability. For this to work out as planned the project must use the latest grouting technology and avoid shortcuts. This includes high-pressure injection of non-bleeding stable grout with low viscosity and mostly fixed water-cement ratio. Furthermore, suitable Microfine Cement (MC) and Colloidal Silica (CS) must be used. Proven grouting equipment is equally important. Two main properties that define a suitable MC are early set and high final strength. High pressure injection means that existing cracks and joints in the rock mass will dilate and allow grout penetration where MC would otherwise not permeate. Maximum grouting pressure from 50 to 100 bar is normal.

Where MC cannot penetrate sufficiently to satisfy very strict residual ingress limits, CS offers an excellent supplement. Even though CS is a suspension of particles, it behaves practically as a true liquid and will permeate the ground almost like water. The volcanic tuff in Hong Kong has typically more closely spaced joint sets than the granitic rock and CS injection is often required following MC injection. High rock conductivity contrast is dealt with by using MC first and CS next and by dual stop criteria. The dual stop criteria approach limits the grout material consumption and prevents unnecessary spread, while still achieving sufficient grout penetration and distribution. High-pressure grouting requires careful consideration of safety. Besides proper dimensioning of couplings and pressure lines, the packers or standpipes installed in the grout holes must be secured against blow-out.

The aim of PEG is to seal off joints and fissures in the rock mass by providing grout screens along the tunnel or cavern, which can stop or reduce water ingress during excavation. Figure 1 shows a typical illustration of systematic grout screens with overlap around an underground space. Note that of course the screen is also covering the invert.

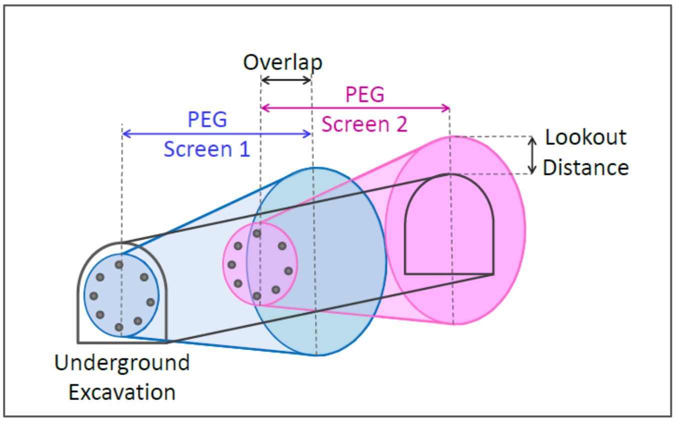

Figure 1 Typical systematic grout screens with overlap around an underground space

3 SPECIAL ISSUES OF PEG

3.1 Use of stable grout

Cement grout can only permeate into cracks and joints by applied pump pressure. If the grout is not pressure stable, the water in the grout will easily be squeezed out of the grout, leaving a dry plug behind and further grout penetration will stop. This process is particularly negative when the grout reaches narrow joints and channels in the ground.

Cement grout with high bleed has also typically very poor pressure stability and this is one reason why stable grouts perform better. However, pressure stability needs to be checked by measuring the pressure filtration coefficient (K_{pf}) according to the American Petroleum Institute recommended Practice 13. Good pressure stability would give $K_{pf} < 0.1$.

3.2 Maximum grout pumping pressure

The maximum allowed injection pressure is commonly discussed from two different viewpoints:

- The low-pressure approach where the focus is on not creating damage in the rock structure around the tunnel or anywhere in the surroundings of the project. It is normally linked to the use of cement and Bentonite and very high w/c-ratio (typically > 3.0). This requires grout-to-refusal technique to counteract the negative effects of the unstable and bleeding grout by squeezing out surplus water.
- The high-pressure approach where the focus is on getting the job done efficiently both regarding time, economy and quality of result. It is typically executed with stable, non-bleeding grout and individual boreholes are stopped either on specified maximum pressure or a maximum quantity, whichever is reached first. By limiting quantity per hole the potential lifting force created by pressurized grout is also limited and any damage is typically not done.

Grouting in real life is executed to control ground water flow and/or to improve stability of the rock formation before excavating into it. Both these motives for grouting exist because of cracks, joints, channels, low friction joint materials, clay, crushed shear zone material etc. and sometimes pretty high hydrostatic ground water head (e.g. > 20 bar). It should be quite easy to agree that the purpose of pre-injection in such cases can only be satisfied if the grout can be placed into those openings and discontinuities by the use of sufficient pumping pressure.

The maximum pressure specified for pumping of the grout is normally given as a net value in addition to the local hydrostatic head. However, when starting injection on a hole, there has normally been a lot of drainage from the drilling process before any packers can be installed, so the practical GW head will mostly be substantially lower than the original virgin ground water head.

The maximum injection pressure has to be evaluated on a running basis and especially it has to be checked against local conditions in the tunnel. Very poor rock conditions in the face area, high hydrostatic water head and existing backflow will be indicators that maximum pressure must be limited, even if the rock cover is hundreds of meters. Otherwise, 50 to 100 bar works very well.

3.3 Accelerators for MC or CS injection

There are situations where accelerated setting can be necessary. This will typically be in post-grouting cases for backflow cut-off, but also in pre-injection, backflow may happen through the face. If for any reason the grout is pumped into running water, or pressure or channel sizes are extreme, accelerated grout may become necessary. A non-return valve is needed for use with a dosage pump when adding accelerator to cement grout through a separate hose connected at the packer. When pumping accelerated CS, 2-component pumping should be considered rather than working with batches. Furthermore, 2-component PU can be used to block concentrated water leakage at the face.

3.4 Use of packers for high pressure injection

When a hole has been drilled into the rock formation for the purpose of injecting grout at high pressure, a tight connection (seal) between the pumping hose and the borehole is needed. The normal way of achieving this is to insert a packer and two typical types of packers include:

- Re-usable mechanical packers available in different standard lengths (pipe and expander assembly), typically from 1.0 m to 5.0 m in steps of 0.5 m. For very deep packer placements, it is normal to use connectors to join standard pipe lengths of e.g. 3.0 m length. At the outer end of the packer pipe it is normal to fit a ball valve or similar. When injection is completed, the ball valve can be closed and the pump hose disconnected. The valve must remain closed with the packer in place until the grout has set sufficiently to keep the ground water pressure without backflow. The packer may then be removed and cleaned for re-use in a different hole. If removed too late, packers will need to be discarded due to set cement.
- Disposable packers have the same working principle as the re-usable packers, but they are constructed so that when expanded, the expansion is automatically locked in place to allow removal of the inner- and outer pipes used to place the packer and expand it. The packer itself has a one-way valve to keep pressurized grout in place without backflow when releasing the pump pressure and removing the insertion pipes. It is possible to keep the non-return valve open to be able to detect connections from other boreholes being injected or to measure bore hole water ingress.

3.5 Use of standpipe or bag-packer techniques in unstable ground

In poor ground condition, packer placement can be very difficult and borehole stability may also be a problem. When fractured ground conditions are combined with high water ingress at high hydrostatic head, the combination may lead to loss of face stability and progressive collapse. In such cases, shallow packer placement must be avoided, because high water pressure will attack very close to the face conveyed through the drilled probe- or injection hole. Installation of standpipe or bag-packer may be adopted to mitigate such problems:

- Standpipes (Figure 2) are installed by drilling with an over-size drill bit of e.g. 76 mm diameter to a depth of say 3 to 4 m and inserting a steel pipe of suitable diameter (i.d. > 55 mm, o.d. < 66 mm) into this hole. The pipe must be grouted in place using a high quality shrinkage compensated cement grout. This is easy to do by placing a packer close to the inner end of the pipe and by pumping the grout into the annular space between pipe and rock, until it appears at the borehole collar.
- Bag-packer (Figure 3) is a quick and efficient alternative technique when grouting of the normal standpipe is difficult because of ground water encountered in the drilled oversize hole.

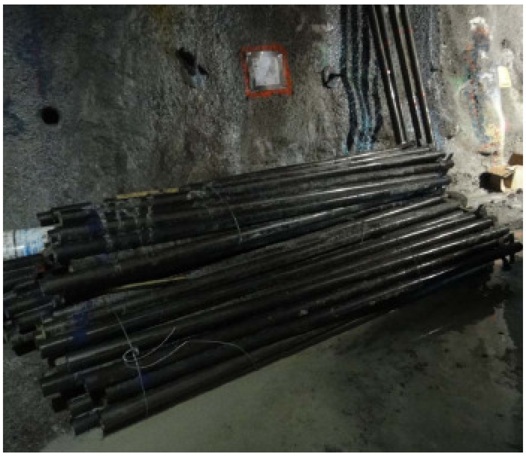

Figure 2 Standpipe

Figure 3 Bag-packer

4 EXAMPLES FROM RELEVANT PROJECTS

4.1 Harbour Area Treatment Scheme Stage 2A (HATS 2A), Hong Kong

The HATS 2A Project includes construction of 20 km deep seated tunnels and thirteen vertical shafts. The tunnel alignment runs at about 70 m and 160 m below sea level and mainly underneath urban areas with long sections located subsea. The HATS 2A tunnels with long sections located underneath settlement sensitive built-up reclaimed land, requires strict residual inflow limits. To achieve this, PEG is the only practical solution to the problem. The hard rock fissure grouting is executed by normal grout permeation, but is also greatly enhanced by pressure-widening of existing fissures. This use of high grouting pressure (up to 80 bar) greatly improves the grout penetration and sealing effect.

MC is the primary grouting material, supplemented by CS where the cement cannot penetrate and further sealing off is required. Standpipe technique and quick foaming polyurethane have been used to block running water through cracks and joints in the face and to avoid backflow of grout materials in locally highly fractured rock. Accelerator added at the packer when grouting with MC or CS, is also highly efficient for solving such problems.

The two main rock types that have been encountered in the tunnel excavation are volcanic tuff and plutonic granite. In volcanic tuff that typically has more closely spaced joint sets than the granitic rock, CS injection is often required after MC injection. To reduce the effect of high conductivity contrast, the HATS 2A Project has adopted dual stop criteria on pressure or volume. This approach limits the grout material consumption, while still achieving sufficient grout penetration and distribution.

4.2 Holen Hydropower Project, Øyestøl, Norway

At Holen hydropower project, access Øyestøl (52 m^2), the recorded ground water static head was up to 50 bar. Such pressure may cause quite dramatic effects in the tunnel. When drilling into water bearing zones, frequently water, sand and fines would punch through the drill rod all the way back into the drilling machine. Water supply hoses of normal quality on the drilling machine would blow. When withdrawing the drill rod, the water jet out of a 51-mm diameter hole would easily reach 25 m back from the face. The water yield from a contact at 10 m depth would typically be 2 to 3 m^3/min. A measurement made on a 45 mm diameter hole being 4.5 m long gave 4 to 5 m^3/min.

When high pressure ground water is expected, the drill jumbo must be equipped with hydraulic clamps for securing the drill string during coupling and de-coupling of rods. A last resort at extreme pressure, without such equipment, is to drive the drill jumbo from the face, until the drill string is free of the hole. Also, if necessary, when drilling more holes into the zone, drill all holes to almost full depth. Then couple the last one or two rods by moving the drill jumbo to «motor» the rods in and out.

When conditions allow, it is beneficial to drill a number of holes into contact with the water-bearing zone. The pressure will then normally drop somewhat due to drainage, making it easier to place packers in the holes. Such conditions will significantly benefit from fast-set and high strength grout since drilling of new holes too early may cause a rupture and flushing out of the injected material.

To place packers against static head of 50 bar, adaptations on the drill jumbo have to be made. The drill feeder and drill rod guides must allow handling of the packers by the hydraulic system. Even with such a solution, it is quite complicated to enter the borehole, due to the produced water spray and resulting lack of visibility.

4.3 Oset drinking water treatment plant, Oslo, Norway

Oset Drinking Water cleaning plant is situated in Maridalen, Oslo. The Plant is built in hard rock with 2 caverns (100,000 m^3) and a 500 m long tunnel. Total excavation amounts to 140,000 m^3 of rock. The treatment plant is designed for 390,000 m^3 water/day, and will deliver drinking water to about 500,000 people.

The plant is located in syenite rock of good quality. Average Q-value is 40, but also there were weak zones with Q-value < 1. The allowable water ingress was set at 100 L/min for the whole plant. During construction, water ingress was measured at up to 200 L/min in some of the probe holes.

The whole project, tunnel and caverns were systematically pre-injected with MC and supplemented with rapid hardening OPC. For some zones accelerated grout (MC + alkali free accelerator) was used. Length of the injection holes was 21 meters, with a hole spacing between 1.5 – 2 meters. After the injection, 3 rounds of advance were made, making the injection overlap about 6 meters. Injection was carried out with a modern computerized injection rig. The rig had integrated accelerator dosage pump for injection of accelerated grout.

The materials consumption amounted to 1,510 tons of MC, 820 tons OPC and 38 tons of accelerated MC grout used for blocking backflow or limit materials spread. The final result is amazingly good. The total ingress into the whole plant (tunnel and caverns), is only 20 L / min (the requirement being 100 L/min).

5 CONCLUSIONS

High ground water static head, high ground water ingress, project access through shaft or decline, strict limitations on residual water ingress and other possible problem-enhancing features, require that the following set of measures must be considered for dealing with ground water issues:

- Probe drilling ahead of the face on a routine basis must be executed. The amount of pre-grouting must be balanced against the project specific consequences of not achieving the required target ingress rate.
- The reserve pump capacity must be at least 100 % more than the maximum expected water inrush.
- Back-up diesel generators are required to ensure supply of electricity to the dewatering pump system.
- It is a requirement that the grouting equipment has sufficient capacity regarding flow and pressure and the ability to pump particle size up to 5 mm.
- Post grouting is difficult and time consuming and may become impossible.
- Pre grouting, on the other hand, is simple and efficient, provided that a tight face area is maintained. A 5 m tight buffer zone is recommended in sound rock. In weak and poor rock more may be required.
- High static head requires care and special measures. Do not allow high-pressure water too close to the face, particularly in poor ground. It does not help to have 10 m of buffer zone if the packers are placed only 2 m into the borehole and face collapse could result.
- Finally: Keep the face area watertight and never blast the next round if in doubt.

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