Deep Subsea Rock Tunnels in Hong Kong


(1) AECOM Asia Co. Ltd., Hong Kong
(2) Drainage Services Department, the Government of the Hong Kong Special Administrative Region

ABSTRACT: Harbour Area Treatment Scheme Stage 2A (HATS 2A) in Hong Kong includes the construction of a deep sewage conveyance system with thirteen vertical shafts. The 20 km long tunnel runs at maximum 160 m below sea level in hard rock, mainly below urban areas with some subsea sections. These conditions give very high risk of ground settlement if groundwater ingress into the tunnels during construction is not sufficiently restricted. HATS 2A has implemented groundwater control by Pre-Excavation Grouting (PEG) as an integral part of the underground construction process. 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, Microfine Cement has been carefully selected for suitability based on its most important properties and Colloidal Silica is a key supplement grout material when the ingress limit is very strict and the ground is difficult to seal off. One important key to successful PEG is maintaining a tight bulkhead between the excavation face and the water logged ground ahead.

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. There are many examples worldwide of serious negative consequences of inadequate groundwater ingress control during underground construction. Therefore, for many underground projects it is necessary to implement groundwater control as an integral part of the construction process. It should be noted that installing ingress control measures as part of the final lining (typically polymer sheet membrane), will mostly become effective far too late to prevent surface settlement and damage.

This paper highlights some important elements and site practices of high-pressure Pre-Excavation Grouting (PEG) necessary for the purpose of achieving targeted maximum residual groundwater ingress into the deep subsea rock tunnels in Hong Kong.

2 Project background

The Government of Hong Kong Special Administrative Region (HKSAR) initiated the Harbour Area Treatment Scheme (HATS) in the late eighties, for the collection and treatment of sewage from the main urban areas on both sides of Victoria Harbour. The HATS Sewage Conveyance System (SCS) is a key element in the effort to improve the water quality of Hong Kong’s inshore marine waters to acceptable standards.

The HATS 2A Project includes the construction of 20 km long, 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 depth of the tunnels could lead to large groundwater ingress during construction. Hence, limiting the groundwater ingress to prevent damaging ground settlement in urban areas is one of the key priorities for HATS 2A.
The two contracts for the construction of SCS tunnels and shafts commenced in Mid-2009, and the works are anticipated to be completed at the end of 2014. The project layout plan is shown in Figure 1. Tunnel excavation and grouting works are in progress at the time of writing.

Figure 1. HATS 2A Project Layout Plan

3 Groundwater inflow limits in HATS 2A

The HATS 2A Project has been designed with emphasis on adapted and adequate groundwater control as an integral part of the tunnelling process. The target levels of residual groundwater ingress during construction are stringent, ranging from 5 to 30 L/min/100 m of tunnel under urban areas in general, and 2.5 L/min/100 m for the most critical location. Tunnel sections with lower risk of settlement, like the crossing underneath Victoria Harbour, have an ingress limit of 50 L/min/100 m of tunnel.

The residual inflow limits for individual sections of the tunnel system are aiming at avoiding surface damage caused by settlement. In order to satisfy this demand for “watertight” tunnelling, it is required to execute systematic probe drilling in front of the excavation face and PEG has to be executed as needed. Moreover, drill and blast tunnelling was selected for the tunnel sections from North Point to Aberdeen and from Sai Ying Pun to Stonecutters Island. The main reason for adopting drill and blast tunnelling is that it provides good access to the tunnel face and allows the use of fully mechanised drilling equipment for the extensive drilling of bore holes that is required. Additionally, multi-hole grouting equipment can be brought all the way up to the tunnel face which improves the efficiency and quality of grouting work.

4 High pressure PEG for the deep subsea rock tunnels of HATS 2A

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. The use of high grouting pressure (up to 100 bar) greatly improves the grout penetration and sealing-off effect.
Microfine Cement (MC) is the primary grouting material, supplemented by Colloidal Silica (CS) where the cement cannot penetrate and further sealing off is still required. Standpipes have been used to prevent backflow of water and grout through cracks and joints in the face when working in particularly fractured rock. Accelerator added at the packer, 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. The volcanic tuff has typically more closely spaced joint sets than the granitic rock, so 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.

For the HATS 2A Project, continuous probe drilling ahead of the face is required (with minimum overlap of 5 m). If recorded water ingress from the probe holes is larger than the specified trigger level for PEG at the current location, a full round of grout holes (grout hole length of 15 m to 25 m and lookout distance of 3 m to 5 m) must be drilled and grouted. When following this approach, there will occasionally be probe drilling stations that will not trigger PEG, and drill and blast excavation can proceed until next probe drilling station. Figure 2 shows a typical illustration of overlapping grout screens along a tunnel. Note that the screens are also covering the tunnel invert. The following subsections describe some of the site practices of the PEG method in the HATS 2A Project.

![Grout Holes in the Grout Screens](image)

**Figure 2. Typical overlapping grout screens along a tunnel**

### 4.1 Dual Stop Criteria

High rock conductivity contrast is one of the main problems of grouting in rock. Grout takes the path of least resistance, which may lead to overconsumption of grout materials and many stages of grouting may be needed to reach a targeted result. To reduce the effect of high conductivity contrast, dual stop criteria (pressure or volume) are applied, but more than one stage of grouting may still be needed. This approach limits the grout materials consumption, while still achieving sufficient grout penetration and distribution. A set of typical execution criteria adopted in HATS 2A is as follows:

- **MC grouting on a single hole should be stopped if a pressure of 50 to 100 bar is reached, or if grout take reaches 100 L/m of grout hole without reaching maximum pressure first. When stopping on pressure, the pressure must be stable above the pressure stop criterion for more than 15 seconds, ideally at zero flow rate.**

- **CS grouting on a single hole should be stopped if a pressure of 20 to 50 bar is reached, or if grout take reaches 30 L/m of grout hole without reaching maximum pressure first. When stopping on pressure, the pressure must be stable above the pressure stop criterion for 15 seconds, ideally at zero flow rate.**

- **Note that all holes grouted by CS should have the grout pump operating for more than 50% of the gel time of the grout mix being used.**
• If MC and CS is used in the same grouting stage (group of grout holes), always grout the holes that shall take MC first and then the holes for CS afterwards.

4.2 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 $K_{pf} < 0.1$.

In the HATS 2A tunnels, the selected grout must be non-bleeding in combination with low viscosity. The specifications of grout are expressed as follows:

• Bleeding less than 2% measured after 60 minutes.
• Marsh cone viscosity of less than 35 s measured on 1 L of grout (European approach).

Furthermore, working at a tunnel face, fast setting and strength development of the grout should allow continuous work progress. Remember that the cost of time at a tunnel face is very high. A good final strength of grout also helps improving ground stability and there is reduced risk of grout blow-out due to high water pressure. Specification of requirements for grout setting and grout strength could be:

• Final setting of grout as measured by Vicat needle between 120 and 180 minutes.
• Minimum compressive strength of test cubes should be 10 MPa after 28 days, but a good Portland cement should give substantially higher strength.

The use of non-bleeding grout is motivated by avoiding residual leakage channels after grouting. Especially when a grout hole is stopped on quantity, the channels filled will be relatively large and the size of any channels caused by bleeding could convey significant residual leakage.

4.3 Maximum 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. This approach is normally linked to the use of ordinary Portland cement and Bentonite and partly very high w/c-ratio (like > 3.0). This requires grout-to-refusal technique to counteract the negative effects of the unstable and bleeding grout thus squeezing out surplus water by pressure filtration.

• 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 MC 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 groundwater flow and/or to improve stability of the rock formation before excavating into it. Both these motives for grouting exist because of the actual presence of cracks, joints, channels, low friction joint materials, clay, crushed shear zone material etc. and sometimes pretty high hydrostatic groundwater head (e.g. > 15 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 caused by the drilling process before any packers can be installed, so the practical groundwater head will often be substantially lower than the original virgin groundwater 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 of grout 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 and should be used.

4.4 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 that expands against the borehole wall. Two typical types of packers include:

- Re-usable mechanical packers available in different standard lengths (pipe and expander assembly, often called a lance), 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 should be 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 groundwater 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.

4.5 Use of accelerator against backflow conditions

There are situations where highly accelerated setting can be necessary. This will typically be in post-grouting cases for cut-off of grout backflow, but also during pre-injection when backflow may happen through the face. If the grout is pumped into running water, or pressure or channel sizes are extreme, accelerated grout may help controlling grout placement and consumption. A non-return valve is needed for use with a dosage pump for adding the accelerator to the 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 fast foaming PU can be used to block concentrated water leakage at the face.

4.6 Stand-pipe or bag-packer technique in unstable ground

In poor ground condition, packers tend to leak or be bypassed and borehole stability may become 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 even progressive face 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 stand-pipe or bag-packer may be adopted to avoid such problems:

- Stand-pipes (Figure 3) are installed by drilling with an over-size drill bit of e.g. 76 mm diameter to a depth of say 3 to 5 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 grout appears at the borehole collar.
• Bag-packers (Figure 4) are a quick and efficient alternative solution when grouting of the normal stand-pipe is difficult because of groundwater encountered in the drilled oversize hole.

**Figure 3. Stand-pipes (3 m long)**

**Figure 4. Bag-packers**

4.7 **Split-pipe technique in good rock with high groundwater inflow condition**

In good rock condition with high pressure full blast groundwater inflow into boreholes, installation of re-usable or disposable packer may become very difficult. Split-pipe installation may be the appropriate technique to adopt (same principle as a Split-Set bolt). A split-pipe is installed when a hole drilled with the normal drill bit of e.g. 51 mm diameter hits extreme inflow. The split-pipe could be say 4 m long with a cut split from one end running about 2 m long. The pipe outer diameter should be slightly larger than the borehole diameter and the split must allow the pipe to enter the hole when compressing the split. The split-pipe can then be hammered into the hole with no resistance from the water, until it wedges solidly against the borehole walls.

4.8 **Stage-grouting in fractured rocks against backflow conditions**

It may become a challenge to pump grout into rock fissures and channels in a controlled manner and to keep the grout in place when working in fractured rocks. Without a tight bulkhead, water and grout may bypass the packer and run back through the face when pumping grout (i.e. pumping against backflow conditions). In a few cases of the HATS 2A tunnels, stage-grouting with the use of standpipe was implemented in order to achieve the tight bulkhead and the necessary high pressure grouting that brings the best penetration and sealing-off effect. The adopted procedures of stage-grouting are described as follows:
• The 3 m long stand-pipe is inserted into a 3 m long borehole. Cement grouting is carried out to fill the annular space between the stand-pipe and the borehole wall.

• The borehole is then extended to 4 m depth with a smaller drill bit and disposable packer is installed at the end of the stand-pipe. MC grout is pumped until maximum 30 bar pressure with maximum quantity of 1000 L. Accelerator would be added at the packer if backflow is observed during pumping. If no or limited increase in pumping pressure is encountered before about 50% of the maximum quantity, accelerator would be added.

• The borehole is extended to 12 m, placing the disposable packer at the end of the stand-pipe. MC grout is pumped until either 60 bar pressure, or maximum quantity of 2000 L. If the water leakage from the borehole is less than 1 L/min, CS would be pump at 30 bar pressure to maximum quantity of 1000 L. Accelerator needs to be added if backflow is observed during pumping. If no or limited increase in pumping pressure has been encountered until 50% of the maximum quantity, accelerator would be added at the packer.

5 Conclusion
PEG is not a well established or generally accepted method among most tunnel engineers. However, modern PEG compared to traditional "grout to refusal" techniques offers substantial time saving as well as much improved results in terms of groundwater exclusion during tunnel excavation. It requires systematic probe drilling ahead of the face, the use of stable MC grout with low viscosity, dual stop pumping criteria and the use of high stop pressure. PEG execution is based on an empirical, observational design approach, while the practical procedures will be modified according to the site conditions and the actual results achieved as compared to targeted residual ingress. Even within the same rock type, a given grouting approach may produce variable results due to variation in ground conditions. Therefore, it is important to measure the grouting results (residual ingress to the tunnel) and modify the procedures as required.

The purpose of PEG will be to seal off joints and fissures in the rock mass against water migration by executing grout screens along the tunnel. This will stop or reduce water ingress during excavation. The targeted effect requires that the grout mix can be pumped into and kept in the rock fissures and channels in a controlled manner. One important key to successfully placing grout where it is needed is a tight bulkhead between the excavation face and the water logged ground ahead. With a tight bulkhead, water and grout will not bypass the packer and run back through the face during grouting. A tight bulkhead also allows application of the high grouting pressure necessary for best penetration and sealing-off effect. This is the main reason why enough overlap between grout screens is a must. If significant water features are identified in short distance from the face, it is imperative to maintain the tight bulkhead and to not take a next blast until the PEG is finalized and verified.

6 Acknowledgement
The authors gratefully acknowledge the Director of Drainage Services Department, the Government of the Hong Kong Special Administrative Region for permission to publish this paper.

7 Reference


