Grouting Techniques for Deep Subsea Sewage Tunnels in Hong Kong

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ABSTRACT

Harbour Area Treatment Scheme Stage 2A (HATS 2A) in Hong Kong includes the construction of a deep seated sewage conveyance system with thirteen vertical shafts. The total tunnel length amounts to 20 km at about 70 m and 160 m below sea level. The tunnel alignment runs mainly below urban areas founded on reclaimed land with long sections being located subsea. The hydrostatic groundwater pressure increases the risk of ground settlement and potentially large groundwater ingress into the tunnels during construction. Hence, preventing ground settlement in urban areas by adequate ground water ingress control is one of the key priorities of the HATS 2A construction stage.

The targeted levels of residual groundwater ingress during construction are stringent, ranging from 5 to 30 L/min and 100 m of tunnel under urban areas in general, and 2.5 L/min and 100 m for the most critical section. In order to satisfy such a demand for “watertight” tunnelling, it is required to execute grouting in front of the excavation face. Pre-Excavation Grouting (PEG) is based on an empirical, observational design approach and the use of modern grouting materials, like Microfine Cement (MC) and Colloidal Silica (CS). Appropriate high-pressure grouting equipment is very important. The selected MC grout is non-bleeding with low viscosity combined with early set and high final strength. Where MC cannot penetrate even at high grouting pressure, CS will permeate the ground almost like water. High rock conductivity contrast is dealt with by using dual stop criteria and additional grouting stages as needed. This grouting method limits the grout material consumption, while still achieving sufficient grout penetration and distribution. Moreover, a decisive reason for choosing the drill and blast tunnelling method is the excellent access to the tunnel face and the fully mechanised drilling equipment available for the required extensive drilling of probe holes and grout holes.

This paper presents the background of this notable project in HK and the unique and special grouting techniques to be applied for rock tunnels in order to control the groundwater ingress.

1. INTRODUCTION

1.1. Project background

The Hong Kong Government initiated the Harbour Area Treatment Scheme (HATS), formerly known as the Strategic Sewage Disposal Scheme, 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 meet acceptable standards.

The HATS 2A project includes the construction of 20 km deep seated tunnels and thirteen vertical shafts. The three contracts for the construction of SCS tunnels and shafts commenced in July 2009, and the works are anticipated to be completed in early 2015. The project layout plan is shown in Figure 1.

The tunnel 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, preventing ground settlement in urban areas by limiting the groundwater ingress is one of the key priorities for HATS 2A.

This paper describes the PEG works in the drill and blast tunnels of HATS 2A. Tunnel excavation and grouting works are in progress at the time of writing.

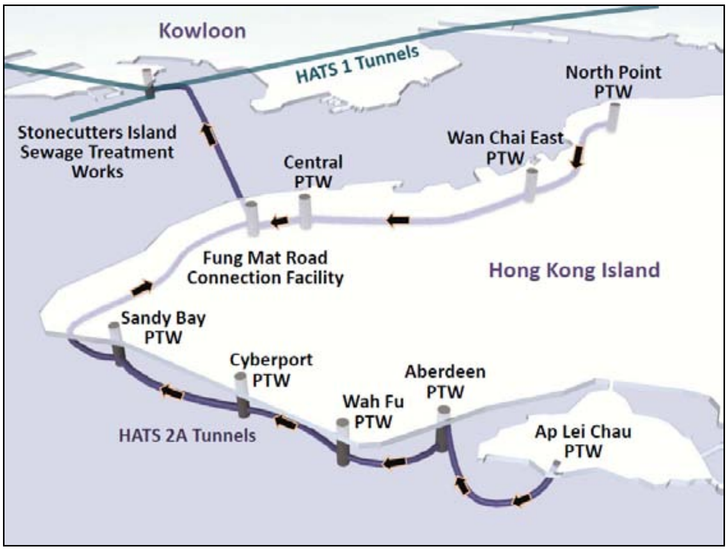

Figure 1 HATS 2A project layout plan

1.2. *Contract requirement on groundwater ingress control*

The experience gained during construction of HATS Stage 1 demonstrated clearly the serious consequences of poorly controlled groundwater ingress during tunnel construction. Therefore, the HATS 2A project has been designed with emphasis on adequate groundwater control as an integral part of the tunnelling process.

In the HATS 2A contract, PEG is required for ground stabilisation and groundwater exclusion. The injected grout shall stem groundwater ingress to the limits specified in the contract. The cost of grout materials and drilling of probe- grout- and control holes is paid based on measured actual quantities and unit prices. In principle, this is a “Risk Sharing” approach between the client and the contractor.

The target levels of residual groundwater ingress during construction are stringent, ranging from 5 to 30 L/min and 100 m of tunnel under urban areas in general, and 2.5 L/min and 100 m for the most critical location. Tunnel sections with lower risk of settlement, like the crossing of Victoria Harbour, have an ingress limit of 50 L/min and 100 m of tunnel. 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 will be executed as needed.

1.3. *Influence of Site Geology*

The three main geological units recognised along the tunnel alignments are as follows.

- Kowloon granite comprises generally medium grained biotite granite. This granitic bedrock contains about 10% by volume of pegmatite veins, dyke rock intrusions and metamorphosed tuff xenoliths as well as quartz and calcite veins

- Mount Davis Formation consisting of predominantly volcanic coarse ash crystal tuff with subordinate fine ash tuff and metasedimentary rocks.
- Ap Lei Chau Formation consisting of predominantly volcanic fine ash vitric tuff with eutaxitic layers, coarse ash tuff, thin lava and epiclastic layers.

In general, granitic bedrock has fewer effective joint sets than the volcanic rocks. The tunnel alignments are anticipated to intersect several major faults and some of the excavated sections have already encountered fault zones. These fault zones may act as conduits for preferential groundwater flow which could result in groundwater draw down at a large distance from the tunnels. The implications are that the major fault zones and associated features constitute areas of particularly high risk with regard to the potential for and consequences of inadequately controlled groundwater inflow into the tunnels.

2. PRINCIPLE OF PEG

The design process for PEG is based on an empirical, iterative observational design-feedback approach as described below:

- Once the ingress requirements are defined, the project data and all available information about rock conditions and hydrogeology must be analyzed with a view to those requirements. This often includes indicative calculations of potential ground water ingress under different typical situations. Based on empirical data (previous PEG project experience) a complete PEG method statement can be compiled. However, irrespective of how elaborate this method statement (or «design») is and whatever tools and calculations are employed to produce it, it will not be more than a prognosis for the future work. This prognosis will express in detail how to execute the PEG to aim for the required residual ingress into the excavated tunnel.
- During excavation the resulting actual ingress can be measured. This means that a quantitative comparison between targeted water ingress and the actual result can accurately pinpoint if the situation is satisfactory or not. If the results are satisfactory, the work will continue without changes, and only continuing verification of results by ingress measurements will be required.
- If the measured water ingress rate is too high, this information will be used to decide on what steps to take to improve tightness of the measured section of tunnel and how to modify the «design» to ensure satisfactory results in similar sections not yet excavated. The improvement works may have to be executed in stages, until satisfactory ingress values can be measured and typically this means local post-grouting.

PEG at HATS 2A uses the latest grouting technology with injection of stable grout with low viscosity and mostly fixed water-cement ratio. This grouting approach employs dual stop criteria based on pressure or quantity per hole, thus preventing unnecessary spread of grout. In comparison, traditional technology uses bleeding, high water-cement ratio grout with lots of water that is “pumped to refusal” thus giving unnecessary spread of grout. When pressure finally increases the grout cannot penetrate the finer joints because of the filter cake created over the openings along the bore hole wall.

It is also important to select a tunnelling method that provides good access to the tunnel face and allows the use of fully mechanised drilling equipment for the extensive bore hole drilling that is required. This is the main reason for adopting drill and blast tunnelling in the HATS 2A project.

The tunnels of HATS2A being deep seated and underneath long sections of settlement sensitive built-up reclaimed land, PEG execution to strict targeted residual inflow limits is the only practical problem solution. The executed hard rock fissure grouting by normal grout permeation is greatly helped by pressure-widening of existing fissures, thus improving the grout penetration and sealing effect.

3. PEG METHOD IN HATS 2A

3.1. Types of grouting works

The main types of grouting works executed in this project are as follows:

- Grout curtain works behind pipe pile cofferdams to control groundwater inflow when sinking shafts through soil or fill materials.
- Contact grouting to prevent groundwater inflow through the interface between diaphragm walls and bedrock.
- Rock fissure grouting to prevent groundwater inflow into the rock parts of tunnels and shafts, executed as pre-excavation grouting (PEG) and behind the tunnel face as post grouting.

This paper discusses the PEG method for sealing joints and fissures in the rock mass. PEG in rock requires the use of modern cementitious and mineral grouting materials and appropriate high-pressure grouting equipment.

3.2. Grouting design

Effectiveness of PEG works is controlled by the parameters of the grouting design, including grout hole pattern, overlap length, the selection of grout materials, grout pressure and stop criteria. In the HATS 2A project, the grout holes are typically located around the tunnel circumference and through the tunnel face. Multi-stage grouting is likely to be required when targeting low residual inflow or in fractured ground with high conductivity contrast and water ingress. The typical details of the grout hole pattern are as shown in Figure 2 and as given below:

- Center to center spacing of 1 m to 1.5 m at collaring of bore holes.
- Number of grout holes depends on the grouting stage, tunnel size and targeted ingress limit.
- Grout hole length of 15 m to 25 m.
- Lookout distance at the end of the hole of 3 to 5 m from the theoretical tunnel surface.
- The overlap distance between subsequent grout fans is 5 m or more. In extremely poor ground up to 10 m may be required.

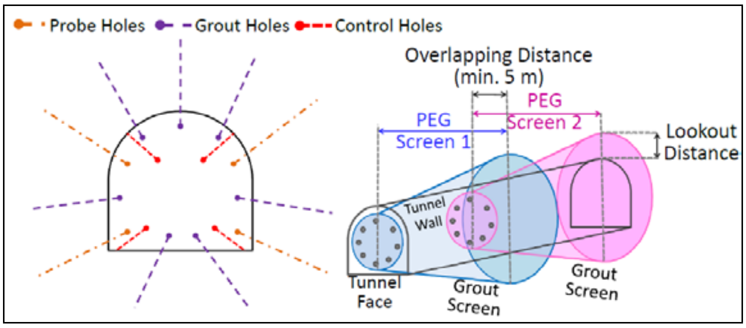

Figure 2 Typical details of the grout hole pattern and ideal layout of grout screens

Microfine cement is the primary grouting material, supplemented by colloidal silica where the cement cannot penetrate and further sealing off is required. Quick foaming polyurethane has 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. Adding accelerator at the packer when grouting with micro cement is also highly efficient for solving such problems.

High rock conductivity contrast is one of the main problems of rock grouting. The 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 given result. 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

- Microfine cement grouting on a single hole will be stopped if a pressure of 30 to 60 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, at flow rate of less than 5 L/min.
- Colloidal silica grouting on a single hole will be stopped if a pressure of 30 to 60 bar is reached, or if grout take reaches 40 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, at flow rate of less than 3 L/min.
- Note that all holes grouted by CS should have the grout pump operating for more than 50% of the gel time of the grout being used.

3.3. Probing and grouting sequence

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 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.

However, for tunnel sections requiring very low target residual inflow (less than 15 L/min and 100 m of tunnel), systematic grouting is being employed. This means that the water ingress results from measurements in the probe holes are not used to decide about PEG or not. Grouting will be performed anyway and ingress from probe holes is for the record and for selection of grouting materials.

A simplified flowchart covering the grouting procedure is shown in Figure 3, and the basic steps include the following:

- Probe holes are to be drilled first to obtain geological advance information and water inflow results to decide about performing PEG or not. In the case of systematic grouting, the probe holes provide information for selection of grouting materials. When selecting whether to grout with micro cement or colloidal silica, the decision should be made per individual hole.
- Drill the grout holes according to the drill plan.
- Install the disposable packers into the holes at typically 3 m depth.
- Grout all probe and grout holes. Holes within the grouting fan to be treated by cement must be grouted first. Then the rest of the fan will be executed with CS. Monitor and record the grout flow rate, volume and pressure.
- Drill control holes that are slightly shorter than the grout holes and measure water inflow from the holes. This is to check the water ingress within and performance of the executed grout fan.
- Decide about performing an additional round of grouting or progressing the excavation.

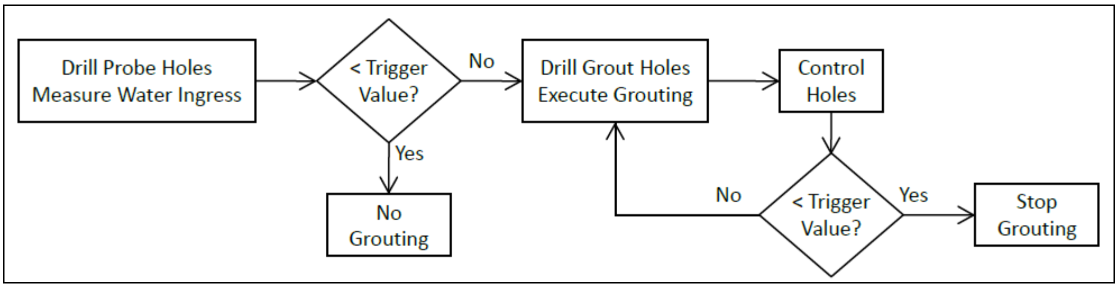

Figure 3 Flowchart of simplified grouting procedure

3.4. *Residual inflow limit*

The residual inflow limits for individual sections of the tunnel system are to avoid surface damage by settlement. The ingress limits were determined by ground settlement assessments during the detailed design stage. Finite element modeling was used during detailed design to establish these residual ingress limits for tunnels and shafts.

In this project, the applied upper limits of targeted residual inflow are 5 – 15 – 30 or 50 L/min per 100 m of tunnel in general, and 2.5 L/min per 100 m for the most critical area.

The control holes executed after a stage of PEG are used to determine the need for further grouting. The water inflow values triggering grouting vary with the local targeted residual inflow limit and can be as low as 0.1 L/min or as high as 5 L/min. The number of control holes is typically 4 to 8 depending on tunnel size and other considerations. The control hole trigger values will be reviewed based on PEG works experience, and they might by modified subject to the ground response and grout fan performance. It should be noted that the control holes trigger values are not the only parameters subject to review when modifications are required to reach the target residual inflow limits. The overall grouting strategy and all execution parameters will be evaluated.

3.5. *Modern grouting materials*

The maximum particle size of the selected microfine cement (MC) is 0.03 mm, or about 1/3 of ordinary Portland cement (OPC). The much smaller particle size enables the MC grout to penetrate into finer fissures. For a given quantity of MC, the total surface area of cement particles is typically double that of the same amount of OPC and this creates a more stable grout (less bleeding). Figure 4 shows the relative particle size of some grouting materials. Note that the colloidal silica (CS) particle shown in the figure would in reality be invisible at the scale of Figure 4.

The particle size of colloidal silica (CS) is 0.016 µm (about 1/6000 of OPC) as supplied by the manufacturer in liquid suspension. This particle size is so small that the suspension behaves as a true liquid. Since the viscosity of the CS grout is only 5 cP, it can penetrate into very fine fissures almost like water. The CS grout will permeate where MC even at high pressure is excluded. The catalyst that is needed to initiate the gel creation is a 10% solution of table salt (NaCl) in water. The gel time can be controlled by varying the dosage of the catalyst, which is also called component B. In this project, CS is being used for relatively low water inflow conditions where the target inflow limit is very stringent, i.e. less than 15 L/min per 100 m.

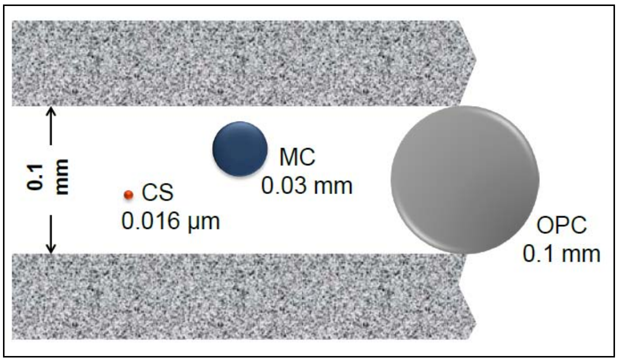

Figure 4 Relative size of grouting materials (CS particle not to scale)

3.6. *Cement grout mix design*

The most important parts of cement mix design considerations are relatively simple. First of all, the cement has to be a micro cement to improve ability to permeate. Secondly, the grout must be non-bleeding in combination with a low viscosity. To achieve this, the properties of the cement must be right and the use of dispersant admixture is needed. The contract specification requires:

- 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, setting time and strength development of the grout cannot require waiting time for next operation while the grout is setting. 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. The specified requirements for grout setting and grout strength are:

- Final setting of grout as measured by Vicat needle between 120 and 150 minutes.
- Minimum compressive strength is 5 MPa after 28 days, but actual strength is typically more than double this value.

Practically all grouting is done by one fixed mix design represented by the grout with lowest possible viscosity (typically 32 s) while still satisfying the non-bleeding requirement. The maximum w/c-ratio for this combination is typically 1.0. To satisfy requirements on setting time and strength, this is achieved by using a pure Portland cement, since blended cements are typically much slower and giving lower strength. For special purposes, grout with w/c-ratio of 0.8 and 0.6 may also be used. For checking of consistent mix design during grout execution, routine samples are taken for baroid mud balance density control.

The focus on using a non-bleeding grout is motivated by avoiding that bleeding will create 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 bleeding channels could give significant residual leakage.

3.7. *High-pressure grouting equipment*

The high-pressure grouting equipment has been tailor made to the requirements of this project. The main components of the grouting platform include component batching and mixing unit, agitated holding tank for mixed grout, grout pump and the computerized recording and control unit. The equipment has 3 parallel grouting lines, allowing simultaneous grouting of up to 3 holes (or grouting on 2 holes with one line as back up).

- In the batching and mixing unit, big bag cement is filled into the silo and delivered to the mixer via screw conveyor. The mixer sits on weight cells, allowing the computer to control the weight of cement, and water for each batch. The mixer creates high-shear turbulent circulation to mix cement, water and admixtures, often named a colloidal mixer.
- The agitated holding tank serves as buffer storage of mixed grout and is required also because mixing time in the colloidal mixer must be limited to 4 minutes to avoid heat development. Slow rotating agitation (60 rpm) is created by mixing paddles inside the tank driven by a hydraulic motor.
- The grout pumps can produce pressure of up to 100 bar, while the normal maximum pressure used so far is 60 bar.
- The control unit includes the operator panel, remote controlled crane and man-basket, hydraulic power pack and transformer. The operator panel is linked to the CPU control system and data recording device, which gets its information from grout flow meters and pressure sensors.

Disposable packers are being used to save time and cost. The packer itself has a non-return valve and the insertion pipe can therefore be removed, cleaned and re-used immediately after finishing a grout hole. Accelerator for the MC grout can be added at the packer via Yconnection and a non-return valve. Grout setting time down to a few minutes can be safely utilized without risking blockage of equipment or grouting lines. This technique is very efficient for control of backflow.

4. CHALLENGES ENCOUNTERED DURING GROUTING OPERATION

4.1. Stringent residual inflow limit in difficult ground

Some parts of the tunnel excavation have started within the sections with very tight target residual inflow. Therefore systematic grouting and a small trigger limit in the control holes are required. Moreover, some of these sections are located in fractured tuff within a fault zone, which produces high grout consumption and requires multi-stage grouting. There are cases where the excavation proceeded even though the control hole trigger limit was exceeded, because the face was too fractured to drill any more holes.

In order to resolve this difficulty, the next stage grouting was carried out after a short blast (about 2 m pull length). As an alternative and preferred option, bag-packers or standpipes should have been installed. The water ingress condition and piezometric levels in the surroundings are being closely monitored, and post excavation grouting may need to be executed if required.

4.2. Face grout leakage (backflow)

Due to rock face fracturing, there are a few cases where loss of grout material back through the face (backflow) caused termination of grouting. For such cases, PU grout has been used at shallow depth from the tunnel face to create a tight bulk head for the subsequent grouting by MC or CS. This PU grouting method can be carried out if the face is generally fractured and especially if leaking water is part of the problem. Alternatively, when PEG causes backflow through the face, accelerator should be used in MC grout by dosing at the packer, or by reducing the gel time of CS grout until the backflow gets blocked.

4.3. Hole connections

When connection between grout holes is observed during the grout pumping phase, close the packer that shows the connection and grout the two (or more) holes together. Switch the pumping from one to the other at intervals. The maximum quantity to be grouted into connected holes (if stop on quantity) must be the stop quantity times the number of holes connected.

5. CONCLUSIONS

Modern PEG is a relatively new and not so well known grouting technology that has the advantage of time saving, as well as giving much improved results in terms of groundwater exclusion during tunnel excavation in comparison with the traditional grouting approach. It is an empirical, observational design approach, and the method details and grouting criteria are designed based on experience while actual execution will be modified according to the site condition and the targeted results.

In a team effort between the contractors and supervision, ground water ingress to shafts and tunnels is kept under control at all times using PEG. In view of the potentially serious consequences of ground settlement, PEG is an essential though time-consuming operation that also brings positive side effects. Almost dry tunnels provide good working conditions, increased tunnel advance rate and improved tunnelling safety with substantially reduced risk of rock instability or water inrush crisis situations. This will be of obvious and major benefit to the Project and all parties involved.