Groundwater Ingress Control for Deep Subsea Tunnels under Urban Area

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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 proposed tunnel alignment runs mainly below urban areas founded on reclaimed land with long sections being located subsea. The high hydrostatic groundwater head increases the risk of potentially large groundwater ingress into the tunnels during construction which may cause ground settlement and damage on surface. 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.

Modern Pre-Excavation Grouting technology (PEG) has been adopted to control the groundwater ingress during tunnelling. This paper discusses the grouting techniques implemented for the rock tunnels of this notable Hong Kong project.

1. PROJECT BACKGROUND

The Hong Kong Government of Special Administrative Region (HKGSAR) 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 acceptable standards.

The HATS 2A project includes the 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 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.

The three contracts for the construction of SCS tunnels and shafts commenced in July/August 2009, and the works are anticipated to be completed in end 2014. The project layout plan is shown in Figure 1. Tunnel excavation and grouting works are in progress at the time of writing.
2. TECHNICAL SPECIFICATION AND GROUNDWATER INGRESS CONTROL

The experience gained from HATS Stage 1 demonstrates clearly the need for appropriate control of groundwater ingress during tunnel construction. Therefore, the HATS 2A Project has been designed with emphasis on adapted and adequate groundwater control as an integral part of the tunnelling process.

2.1. Contract requirement on residual groundwater inflow

In HATS 2A, 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. 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.

The residual inflow limits for individual sections of the tunnel system are aiming at avoiding surface damage caused by settlement. The ingress limits were determined by ground settlement assessments during the detailed design stage. Finite element modelling was used during detailed design to establish these residual ingress limits for tunnels and shafts.
2.2. Selection of construction method

Drill and blast tunnelling was selected for the tunnel sections from North Point to Aberdeen and from Sai Ying Pun to Stonecutters Island. The drill and blast work cycle includes drilling blast holes, charging/blasting, scaling and mucking out, temporary support installation and then PEG (where necessary) before the next blast round.

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.

2.3. Quantity Measurement of PEG works

In the HATS 2A contracts, 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. It should be recognised that any kind of lump sum payment for PEG would be an invitation to contractor gambling when calculating tender price for the project. Such gambling could easily become a liability for all parties and lump sum payment for PEG was not recommended.

3. PEG METHOD IN HATS 2A

The HATS 2A tunnels being deep seated with long sections located underneath settlement sensitive built-up reclaimed land, strict target residual inflow limits have to be enforced. 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. Post grouting is only used as a supplementary measure to treat point leakages if necessary.

The design of PEG is based on an empirical, observational design-feedback approach. 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 uncontrolled 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 borehole wall.

The aim of PEG is to seal off joints and fissures in the rock mass by providing grout screens along the tunnel, which can stop or reduce water ingress during excavation. Figure 2 shows a typical illustration of systematic grout screens with overlap along a tunnel. Note that of course the screen is also covering the tunnel invert.
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.

3.1. 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 partly 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 3 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.
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. Accelerator may be added at the packer when grouting with micro cement, which 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 the required 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.

3.2. 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)
3.3. 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). Photos 1 to 3 show the three main units (including the mixing unit, control unit and injection unit) of the high-pressure grouting equipment.

- 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 and it is normally named a colloidal mixer.
- The agitated holding tank serves as buffer storage for mixed grout and is required also because mixing time in the colloidal mixer must be limited to 4 minutes to avoid heat development. Slowly 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. Of course, all equipment components have to be dimensioned for this pressure to ensure safe operation.
- 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.

Photos of High Pressure Grouting Equipment
4. CONCLUSIONS

The proposed HATS 2A tunnel mainly runs below urban areas founded on reclaimed land. Therefore, the high hydrostatic groundwater head increases the risk of potentially large groundwater ingress into the tunnels during construction and resulting damage from ground settlement. Moreover, taking into consideration the experience from HATS Stage 1, the importance of keeping appropriate groundwater ingress control has been clearly demonstrated.

Modern PEG is a relatively new and not so well known grouting technology. In comparison with traditional grouting approach it offers the advantage of time saving, as well as much improved groundwater exclusion efficiency. 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 conditions and the actually achieved results.

The HATS 2A contract has been planned and developed such that the risks that might be encountered due to unforeseen ground condition can be shared between the client and the contractor. 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.