PRE-EXCAVATION GROUTING OF UNDERGROUND CONSTRUCTION IN HARD ROCK – SITE PRACTICES

INTRODUCTION

High-pressure Pre-Excavation Grouting (PEG) in hard rock is executed by drilling boreholes of suitable diameter, length and direction into the bedrock, placing packers into the borehole (or using some other means of providing a pressure tight connection to the hole), connecting a grout conveying hose or pipe between a pump and the packer and pumping a prepared grout by overpressure into the cracks and joints of the surrounding rock.

This guideline describes the site practices and some special issues of PEG in hard rock.

OPERATION CYCLE

Figure 1 shows the typical operation cycle of "Drill & Blast" excavation with PEG. The probing activity is typically repeated after every four blasting rounds. The time required to execute one complete grout screen can vary a lot subject to the ground condition, the excavation size and targeted residual inflow rate. The variation range may be in the order of less than one day to more than a week.

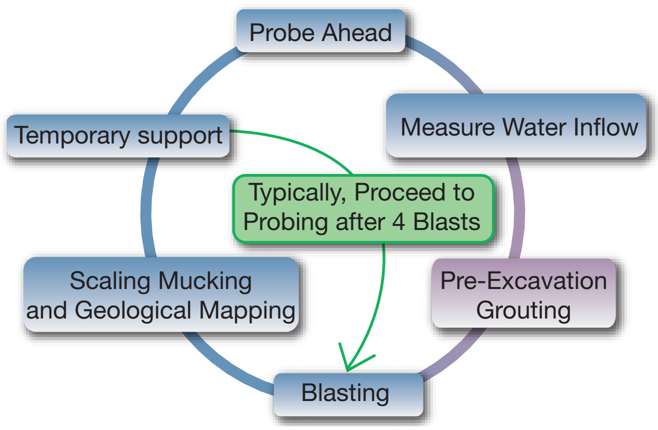

Figure 1: Operation Cycle – Drill & Blast Excavation + PEG

UNDERGROUND CONSTRUCTION - GROUTING IN ROCK

Almost all rock formations are fundamentally different to soil deposits when considering flow of groundwater and any pumped grouting material. What can be achieved and how to execute injection in rock is therefore very different to grouting operations in soil. Most rock materials, in-between discontinuities, are practically impermeable for water and grouts. Leakage and conductivity is therefore linked exclusively to discontinuities and conductive channels within the rock mass. It is vitally important to understand and accept this basic property of rock, to be able to correctly evaluate all aspects of pressure grouting in rock tunneling.

In a rock mass it is evident that the properties of the joints will be of major importance for any grouting program. The variation of joint properties and water conductivity in different types of rock is quite extreme and can easily amount to 4 orders of magnitude along a single 20 m long borehole.

Two fundamentally different situations are typically encountered when grouting in underground excavations, see (**Figure 2**):

- Pre-excavation grouting (PEG), where the boreholes are drilled from the tunnel excavation face into virgin rock in front of the face and grout is pumped in and allowed to set, before advancing the tunnel face through the injected and sealed rock volume. Sometimes, such pre-excavation grouting can be executed from the ground surface, primarily for shallow tunnels with free access to the ground surface area above the tunnel.
- Post-excavation grouting, where the drilling for grout holes and pumping in of the grout material takes place somewhere along the already excavated part of the tunnel. Such locations are mostly selected where unacceptable amounts of water ingress occur after excavation.

It must be emphasized that post-grouting alone cannot achieve any reasonable result, unless extreme cost and time is accepted. Therefore, post-grouting should only be considered a supplementary method to pre-injection.

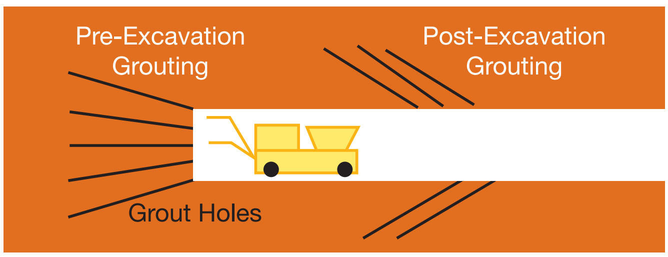

Figure 2: Pre- and Post-Excavation Grouting

(Special thanks to Knut Garshol and Janice Tam for preparation of this guideline)

CEMENTITIOUS GROUTS

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

Practically all grouting can be done by one fixed mix design represented by the grout with lowest possible viscosity (say 32 s) while still satisfying the non-bleeding requirement. The maximum w/c-ratio for this combination is typically about 1.0. To satisfy requirements on short setting time and high strength, this is normally achieved by using 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 even 0.6 may be used. For checking of consistent mix design during grout execution, routine samples can be taken for mud balance density control. If the density of a sample is wrong, this will indicate a mistake in the mix proportions.

The use of non-bleeding grout is preferred to avoid residual leakage 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.

MAXIMUM PUMPING PRESSURE

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

- The low-pressure approach is focused on avoiding damage to the rock structure around the tunnel and surroundings. This approach is normally linked to the use of mixed ordinary Portland cement and Bentonite and partly very high w/c-ratio (> 3.0). This requires a grout-to-refusal technique to counteract the negative effects of unstable and bleeding grout by squeezing out surplus water by pressure filtration.
- The high-pressure approach is focused on getting the job done efficiently with regard to time, economy and quality. It is typically executed with stable, non-bleeding micro fine cement grout; individual boreholes are stopped either on specified maximum pressure or a maximum quantity, whichever is reached first. By limiting the 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 excavation. Both these motives for grouting exist because of the actual presence of cracks, joints, channels, low friction joint materials, clay, crushed shear zone material and other physical attributes of the discontinuities and possibly 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 pump 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 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.

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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 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 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 (**Figure 3 & 4**) 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.

Figure 3: Disposable Packer & Injection Lances

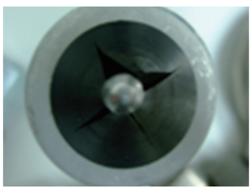

Figure 4: Non Return Valve of Disposable Packer

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 Colloidal Silica (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.

STAND-PIPE OR BAG-PACKER TECHNIQUES IN UNSTABLE GROUND

In poor ground condition, packers tend to leak 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 (before drilling beyond the overlap zone to hit water) may be adopted to mitigate such problems:

- Stand-pipes (**Figure 5**) 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-packer (**Figure 6**) is a quick and efficient alternative technique when grouting of the normal stand-pipe is difficult because of groundwater encountered in the drilled oversize hole.

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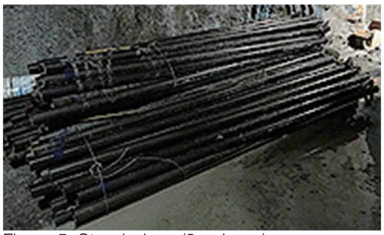

Figure 5: Stand-pipes (3 m Long)

Figure 6: Bag-Packers

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.

HIGH-PRESSURE GROUTING EQUIPMENT

It may be required to tailor make high-pressure grouting equipment to meet specific project requirements. However, the main components of the grouting platform must in any case include batching and mixing units, agitated holding tank for mixed grout, grout pump and preferably a computerized recording and control unit. The equipment could have 3 parallel grouting lines, allowing simultaneous grouting of up to 3 holes (or grouting on 2 holes with one line as back up). Figure 7 shows the simplest possible equipment setup for one grout line with an electronic logging unit.

- In the batching and mixing unit, 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. The unit is 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.
- The grout pump can produce pressure of up to 100 bar, while the normal maximum pressure to be used is typically 60 to 80 bar.
- The electronic data recording device gets its information from a grout flow meter and pressure sensor.

Figure 7: Grouting Equipment for One Grout Line

PLACEMENT OF ROCK BOLTS AFTER PEG

Installation of rock bolts may penetrate the grouted zone and cause point leakage. To seal such leakage after the bolt has been installed is very difficult. Preferably, any bolthole giving water should be grouted before placing the bolt. Generally, shorter bolts or even support without bolts should be considered.

SUMMARY

The purpose of PEG is to seal off joints and fissures in the rock mass against water migration by executing grout screens along the tunnel or cavern. 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. With a tight bulkhead, water and grout will not bypass the packer and run back through the face when pumping grout. A tight bulkhead also allows application of the necessary high pressure grouting that brings the best penetration and sealing-off effect. This is the important reason to use enough overlap between grout screens. If significant water feature is identified in short distance from the face, make sure to maintain the bulkhead and do not take a next blast if there is any doubt.

(Special thanks to Knut Garshol and Janice Tam for preparation of this guideline)