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# TUNNEL CONSTRUCTION GUIDELINES
# 05 - GUIDANCE NOTE ON PRE-EXCAVATION GROUTING FOR UNDERGROUND CONSTRUCTION IN HARD ROCK – PRINCIPLES & DESIGN ELEMENTS

## 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 ingress control measures installed as part of the final lining (typically polymer sheet membrane), mostly will become effective far too late to prevent surface settlement and damage.

This guideline describes the principles and design 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.

## EXECUTION OF PEG

The aim of PEG is to seal off joints and fissures in the rock mass by placing grout screens along the tunnel or cavern, to 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 the screen also has to cover the invert since this is even more important than sealing off the upper part. The reason is that residual leakage in the invert is more difficult to observe as well as presenting problems for drilling for post grouting.

Modern PEG requires the use of stable micro cement grout with low viscosity, mostly used with fixed water-cement ratio. This grouting approach employs dual stop criteria. Each hole is either stopped at maximum pressure or on maximum quantity, thus preventing unnecessary spread of grout. In comparison, traditional technology uses bleeding, high water-cement ratio (by weight) 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 borehole wall. Modern hard rock fissure grouting utilizes normal grout permeation, but is furthermore greatly helped by pressure-widening of existing fissures, thus improving grout penetration, compaction and sealing effect.

The details of design and execution of PEG are highly dependent on the ground conditions. Therefore, adequate ground investigation is required to support good understanding of ground characteristics for the planning and tendering stage. Short-section Lugeon tests at different levels will be very useful.

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 to implement preferably the drill and blast method in projects with extensive PEG.

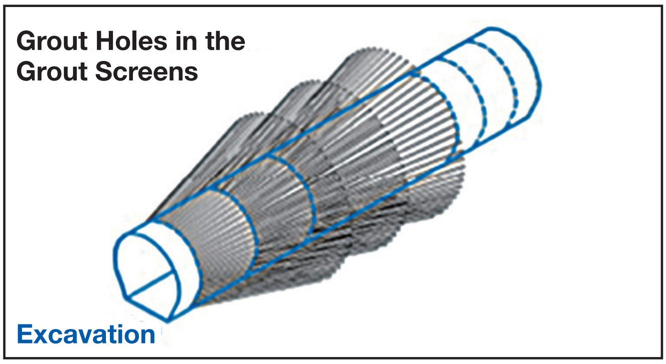


Figure 1: Typical systematic grout screens with overlap along an excavation

## REASONS TO USE PEG

During 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. Some important reasons include:

- 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.
- The risk of major water inrush, or of unexpectedly running into extremely poor ground, can be virtually

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

eliminated (due to systematic probe drilling ahead of the face being an integral part of PEG). Without PEG, the excavation may hit lots of water which would have to be sealed by post-grouting. Post grouting is time consuming and expensive and far less effective than PEG. Difficult cases can be close to impossible to successfully solve by post grouting.

- 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 collapse in the face area.
- Risk of pollution from tunnels transporting sewage, or other hazardous materials, can be avoided or limited. Ground treated by PEG 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. Such lining offers a substantial savings potential in construction cost and time which is the main reason for the increased interest and use. Sprayed concrete linings are difficult to install with satisfactory quality under very wet (running water) conditions and ground water ingress control by PEG can solve this problem.
- Using 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.

## PRINCEPLES OF PEG

The design process for PEG is empirical, and involves observational design-feedback during execution as described below:

- Once the water ingress limits are defined, the project data and all available information about rock conditions and hydrogeology must be analyzed with a view to those limits. 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 achieve as closely as possible the required maximum residual ingress into the excavated tunnel.
- During excavation the resulting actual ingress can and must be measured. This allows a quantitative and accurate comparison between targeted maximum water ingress and the actual result after excavation. If the result is satisfactory, the work will continue without changes, and only continuing verification of results by ingress measurements will be required.
- If the measured rate of water ingress in a newly excavated section is too high, this information will be used to decide on two action steps. 1) What steps to take to improve tightness of the failed section of tunnel and 2) How to modify the «design» to ensure satisfactory results in tunnel sections not yet excavated. The post grouting works in the failed section may have to be executed in stages, until satisfactory ingress values can be measured.

## GROUTING DESIGN

Effectiveness of PEG execution is controlled by the parameters of the grouting design, including number of probe holes, systematic grouting or not, grout hole pattern and spacing, overlap length, the selection of grout materials and grout properties and grouting stop criteria. Note that the use of high pressure grouting may raise objections for fear of causing damage in the surroundings. This risk is limited by the use of a grout quantity stop, thus limiting the jacking area and total force. Even though damage is highly unlikely when rock cover exceeds say 15 m, situations with low cover and sensitive nearby structures must be handled with special care like reduced stop quantity and stage grouting within long holes.

### Grout Hole Pattern

In most projects, 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, especially in fractured ground with high conductivity contrast and water ingress. Typical details of the grout hole pattern are shown in **Figure 2** and given below:

- Decision on spacing of probe- and control holes must be based on probability and risk analysis. An initial spacing of 4 to 8 m will often work well.
- Grout hole center to center spacing of 1 m to 1.5 m at collaring point is normal and of high importance for the targeted result.
- Number of grout holes (spacing) depends on the grouting stage, tunnel size and targeted ingress limit.
- Grout hole length is dependent on the excavation diameter/span, but 15 m to 25 m is normal.
- Lookout distance at the end of the grout holes of 3 to 5 m from the theoretical tunnel surface.
- Control hole length can be slightly shorter than the grout screen, but must still be long enough to cover the next length of face advance plus safety buffer zone.

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

- Control holes are usually located within the grout screen or even within the excavation profile.
- The overlap between subsequent grout fans should be 5 m or more. In extremely poor ground up to 10 m may be required. A large face area will require more overlap than the face area of a small tunnel.

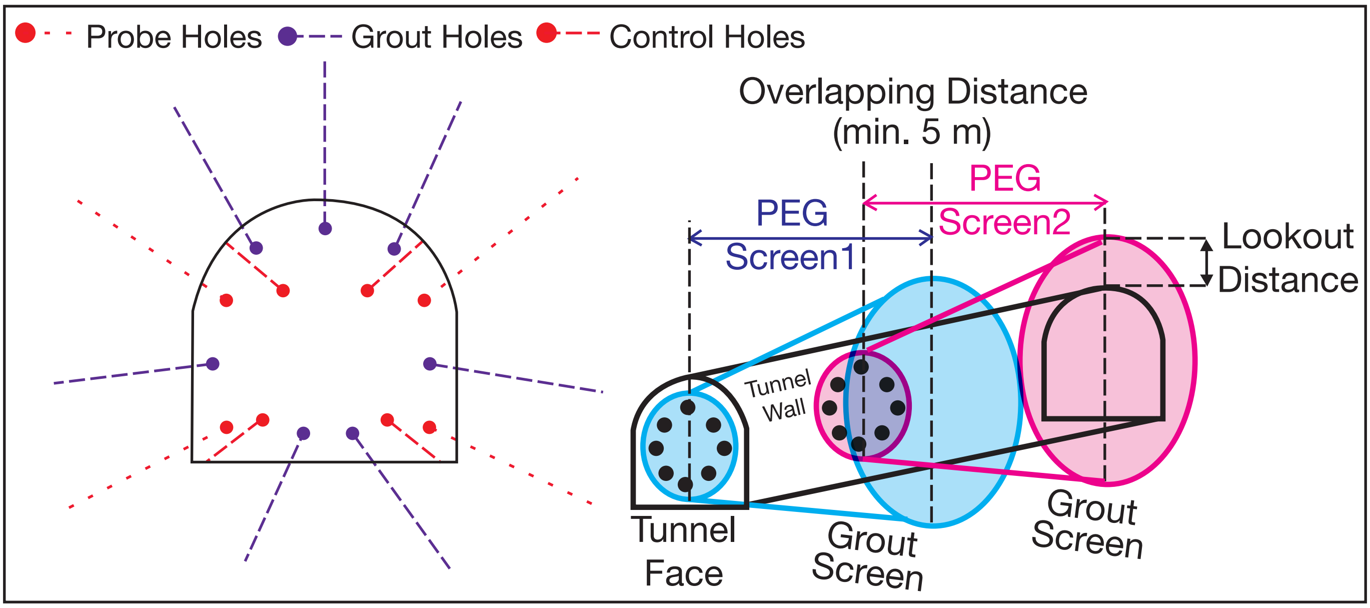


Figure 2: Typical details of the grout hole pattern and layout of grout screens

**Modern Grouting Materials**

*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, 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 typically very poor pressure stability and this is one reason why stable grouts perform better. However, pressure stability needs to be checked separately by measuring the pressure filtration coefficient (Kpf) according to the American Petroleum Institute recommended Practice No 13. Good pressure stability would give Kpf < 0.1.

*Microfine Cement*

A typical microfine cement (MC) has largest particles < 0.03 mm, or about 1/3 of ordinary Portland cement (OPC) particle diameter. 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 3** 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 3**.

*Colloidal Silica*

The particle size of colloidal silica (CS) depends on the product being used but is typically around 0.01 to 0.02 μm (about 1/6000 of OPC) and is supplied by the manufacturer in liquid suspension. This particle size is so small that the suspension for practical purposes behaves like 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 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. CS is best 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 of tunnel.

*Chemical Grouts*

Quick-foaming polyurethane may be used to block running water or grout backflow through cracks and joints in the face. However, polyurethane or other chemical grouts are not suitable as a primary grout material for regular PEG works as described in this document.

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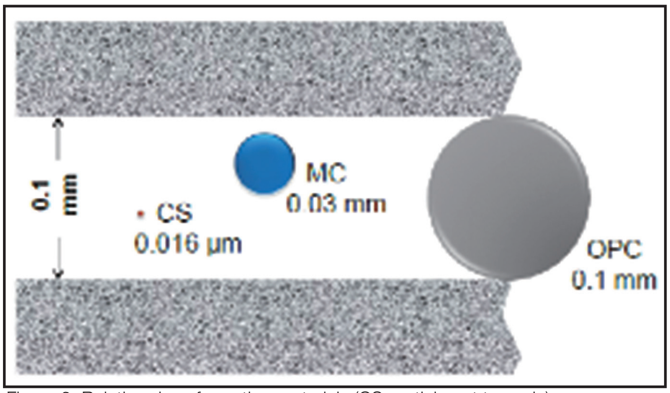

Figure 3: Relative size of grouting materials (CS particle not to scale)

**Dual Stop Criteria**

High 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 material consumption, while still achieving sufficient grout penetration and distribution. A set of typical execution criteria in hard rock could be:

- Microfine cement 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.
- Colloidal silica 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.

**Probing and Grouting Sequence**

For underground construction projects where ground water ingress must be controlled, 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 may 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 (for example, less than 15 L/min and 100 m of tunnel), systematic grouting should be employed. This means that the water ingress results from measurements in the probe holes are not basis for decision. Grouting will be performed anyway and ingress from probe holes may be used for the record and for selection of grouting material for individual holes.

A simplified flowchart covering the grouting procedure is shown in **Figure 4**, 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 packers into the holes at typically 3 m depth. Disposable packers are recommended when rock conditions allow it.
- 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 these holes. This is to check the water ingress within and performance of the executed grout fan.
- Decide if performing an additional round of grouting is required, or continue excavation.

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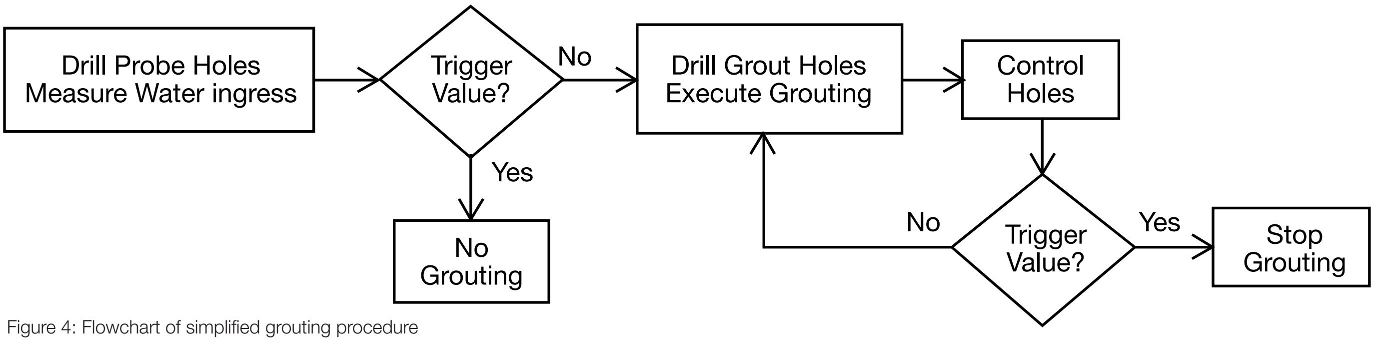


Figure 4: Flowchart of simplified grouting procedure

**Target Residual Inflow Limit & PEG Trigger Values**

The target residual inflow limits for individual sections of the excavation can be determined by ground settlement assessments during the detailed design stage. Numerical modeling can be used to establish these residual ingress limits for tunnels and shafts. The range of upper limits of targeted residual inflow for different projects and situations can be typically 5 to 50 L/min per 100 m of excavated length.

Probe holes before and the control holes executed after each stage of PEG are used to determine the need for (further) grouting. The water inflow values triggering grouting vary with rock conditions and the local targeted residual inflow limit and can be as low as 0.1 L / min or as high as 5 L / minfrom single holes. The control hole trigger values are continuously reviewed and may be modified depending on 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 need to be evaluated.

Generally speaking, the more stringent targeted residual inflow limits will require the lowest PEG trigger values.

## PEG PROJECT REFERENCES

The following list includes references covering projects with application of PEG:

1. Garshol, K.F., 2007. Pre-Excavation Grouting in Tunneling. UGC International, Division of BASF Construction Chemicals (Switzerland) Ltd.
2. Garshol, K. F, 2007. Using Colloidal Silica for Ground Stabilization & Groundwater Control. In: Tunnel Business Magazine. Ohio: Benjamin Media Inc.. pp 34-36
3. Garshol, K. F., Tam, J.K.W., Mui, S.W. B., Chau, H.K.M. & Lau, K.C.K., 2012. Grouting Techniques for Deep Subsea Sewage Tunnels in Hong Kong. In: World Tunnel Congress 2012. Bangkok: Thailand Underground and Tunnelling Group (TUTG), EIT and ITA-AITES.
4. Garshol, K. F., Tam, J.K.W., Mui, S.W. B., Chau, H.K.M. & Lau, K.C.K., 2013. Deep Subsea Rock Tunnels in Hong Kong. In: World Tunnel Congress 2013 Switzerland. Geneva: Swiss Tunnelling Society (STS) and ITA-AITES.

The following selected projects (covered in the above references) adopted PEG during construction, with particularly good results regarding groundwater control.

- Habour Area Treatment Scheme Stage 2A, Hong Kong.
- West Process Propane Cavern, Mongstad, Norway.
- Oset Drinking Water Treatment Plant, Oslo, Norway.

More projects can be found in reference [1].

## SUMMARY

The PEG method is not generally well understood among tunnel engineers and is frequently seen as a nuisance to tunnelling progress rates. However, modern hard rock PEG for tunnels offers substantial time saving, as well as much improved results in terms of groundwater exclusion during tunnel excavation, when comparing with traditional grouting technology. Full benefit requires the use of stable micro cement grout with low viscosity, dual stop pumping criteria and relatively high pumping pressure. It is an empirical, observational design approach, and the method details and grouting criteria must be designed based on experience. Details of the execution will need to be adjusted according to the site conditions and the actual results achieved, compared to targeted residual ingress.

If required, practically dry tunnels may be excavated achieving as little as 5 L/min/100 m of tunnel even at ground water head of more than 15 bar.

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