Chapter 31

PRE-EXCAVATION GROUTING DESIGN GUIDELINES FOR HARD ROCK EXCAVATIONS

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ABSTRACT

Groundwater inflows during construction pose one of the greatest risks to the successful completion of tunnel projects. Inflows can result in safety concerns, difficulty in mining and ground support, impact sensitive environmental habitats, create surface settlement and increase costs. Adequately planned pre-excavation grouting programs benefit both the Owner and Contractor in reducing risks and controlling project costs and potential schedule delays. This paper outlines strategic guidelines for assessment of site conditions for pre-excavation grouting hard rock tunnels. It also describes the design of pre-excavation grouting programs with respect to project requirements.

UNDERSTANDING RISK

Groundwater inflows into tunnel excavations must be evaluated relative to tolerable risk. Any tunnel constructed below the water table is exposed to some level of risk associated with water inflows. The magnitude of this risk is highly variable and dependent upon the site conditions, impacts of inflows on third parties and the means and methods undertaken to construct the tunnel. Understanding the magnitude of these risks and developing appropriate measures to mitigate these risks is one of the keys to successful construction of a tunnel. Repeatedly, tunnel projects encountering high groundwater inflows have suffered severe cost overruns, schedule delays, and environmental impacts when the consequences of these risks were not fully recognized and there was no contractual mechanism to mitigate these groundwater inflows. This paper discusses pre-excavation grouting, which is one of several measures that could be considered to mitigate risks associated with groundwater inflows. Other mitigation measures, which are integral to the design of the project, should be evaluated in addition to pre-excavation grouting. The applications for performing pre-excavation grouting in this paper pertain primarily to fractured rock.

Table 1. Summary of impacts due to groundwater inflows and tunnel construction

Impacts To Tunnel Construction and Service Performance	Impacts To Area Surrounding Tunnel
Impediment to Tunnel Excavation	Groundwater Depletion
Impediment to Placement and Quality of the Final Lining	Ground Surface Subsidence Impacting Surface Structures
Decrease in Rock Mass Stability Around the Tunnel	Subsurface Settlement Impacting Buried Structures
Hazardous Groundwater Inflow Conditions—Including Contaminated Groundwater, Hazardous Dissolved Gases, Elevated Water Temperatures	Habitat Impacts Due To Groundwater Head Loss and Depletion
Increase In Water Treatment and Water Handling Costs	Groundwater Mitigation Costs
Excessive Infiltration That Violates Tunnel Service Criteria	Groundwater Contamination

Any method of groundwater control in a tunneling operation, including pre-excavation grouting executed from within the tunnel, will negatively impact the progress of the tunnel compared to a tunnel that is excavated in dry conditions. However, a poorly conceived pre-excavation grouting can have devastating effects on project costs and the schedule. The guidelines described in this paper are intended to assist in developing pre-excavation grouting operations are more cost effective and efficient. Very intensive pre-excavation grouting efforts can achieve more effective control of inflows, but with a penalty of higher costs and greater schedule delays. Likewise, the implementation of less intensive pre-excavation grouting efforts may decrease the time spent on this operation, but there is risk of excessive inflows. Therefore, a balanced approach to pre-excavation grouting is needed so that the grouting program has a high probability of reducing the groundwater inflows to values that can be managed by the tunneling operation while limiting costs of schedule delays to acceptable levels.

HYDROGEOLOGIC ASSESSMENTS

The potential for groundwater inflows into hard rock tunnel excavations and the nature of impact upon both the tunnel construction and upon the surrounding area must be sufficiently understood before an effective pre-excavation grouting program can be developed. The impact of groundwater inflows into a tunnel can be divided into two distinct categories (summarized in Table 1). The first category directly impacts the tunnel construction and its service life. The second category, impacts the area surrounding the tunnel.

Estimating groundwater inflows into rock tunnels is far from an exact science. Several authors have investigated this issue including Goodman et al. (1965) and Heuer (1995). There are also several numerical models, which can be used to estimate potential inflows. In general, the uncertainty with groundwater inflow estimates greatly increases with increasing hydrostatic head and complexity in the geological conditions.

As a first step, the maximum potential groundwater inflows along the tunnel alignment should be determined prior to consideration of the effects of any groundwater inflow mitigation procedures. The second step should be to identify and quantify the impacts associated with the maximum potential groundwater inflows. The third step is to determine, if possible, the maximum *allowable* groundwater inflow, that will reduce the impacts to acceptable levels. The maximum allowable inflow should be established as the uppermost limit of inflow that can be tolerated into the tunnel during or after construction. The difference between the maximum potential groundwater inflow and maximum allowable inflow is the amount by which the groundwater inflow must be reduced and this forms the basis to develop the means to reduce water inflows into the tunnel and the magnitude of the effort required. In this paper it is assumed that pre-excavation grouting methods have been selected for controlling groundwater inflows into the tunnel, although other methods are often used in combination with pre-excavation grouting.

ESTABLISHING DESIGN CRITERIA

Allowable Tunnel Inflows

The main design criteria needed for pre-excavation grouting is the maximum allowable inflow into the tunnel. Depending upon project conditions, allowable groundwater inflows will be a combination of two types of inflow; initial or flush inflows and sustained steady-state inflows. The differences between initial and sustained inflows depend upon the site hydrogeology; hydrostatic head; length of exposed, unlined tunnel; and effectiveness of lining in limiting inflows. The time taken for initial inflows to diminish to steady-state levels can vary from a matter of minutes to years. Given this potential variability it is usually prudent to use initial inflows as the basis for estimating the magnitude of inflow for untreated ground in most tunnels.

Probe Hole Inflow Criteria

Another key criteria is the probe hole inflow level that will trigger a grouting cycle. The groundwater inflow measured in the probe holes are used to estimate the potential groundwater inflows into the tunnel section being probed. This groundwater inflow potential is highly dependent upon the site conditions, in particular the nature of the rock mass fractures, hydrostatic head, the number of open probe holes and other boundary conditions within the tunnel. Attempts have been made to assign factors to probe hole inflows to predict subsequent tunnel inflows for untreated ground. The probe hole inflows and associated factors are often used to establish inflow levels at which pre-excavation grouting is initiated. Because of the variability of the geologic and groundwater conditions, it is often desirable to vary the probe hole inflow criteria that triggers grouting based upon the measured flow into the tunnel from either the treated (if grouted) or untreated (if grouting is not triggered) lengths of tunnel probed. Experience has shown that for moderately sized excavations up to about 7 meters in diameter, probe hole factors that should be applied to a single probe hole generally varies between about 3 and 5. However, probe hole factors have been measured between 1 and 12 under hydrostatic head conditions varying from 50 to 150 meters in highly variable granitic rocks. In these particular cases, the higher values are considered to be due to inadequate interception of all the potential inflows to the tunnel by the single probe hole drilled.

In some ground conditions, under increasing hydrostatic head conditions, the potential for ground disturbance, increased water storage, piping effects, and erosion of joints, there is a potential for large, unpredictable groundwater inflows. Therefore, under these conditions, probe hole factors must be used with caution. The use of multiple probe holes will modify the probe hole factor applied and will also lessen the

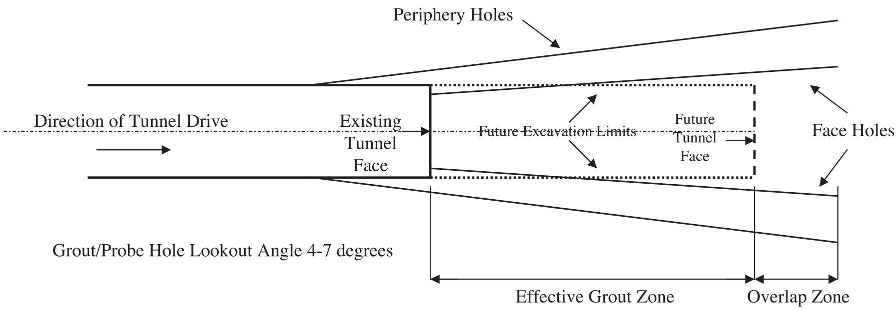

Figure 1. Typical probe and grout hole patterns in plan view

risk of intercepting water in the tunnel excavation that has not been intercepted by, or accounted for in the predicted tunnel inflow.

As a starting point, an assumed probe hole factor can be used to estimate the amount of initial inflow into the tunnel. However, monitoring of inflows from both treated and untreated tunnel sections should be performed and the probe hole inflow that triggers grouting adjusted accordingly to be compatible with the targeted allowable inflows into the tunnel.

ESTABLISHING MINIMUM PARAMETERS

Based upon the understanding of the range of hydrogeologic conditions and the targeted allowable groundwater inflow into the tunnel, an estimate of the grouting material and equipment requirements can be established.

Drilling Operations

Probe/Grout Hole Location and Orientation. The location that has the primary risk of water inflows into the tunnel is the periphery of the tunnel. Thus, after probe hole flows indicate that grouting is necessary, the goal is to create a zone of lower permeability ground, around and just outside the tunnel periphery, that can withstand the hydrostatic pressure or gradient acting across it. Ideally, the grout holes should be oriented parallel to the tunnel to form a continuous zone of grouted ground around the entire tunnel perimeter. However, given the geometry of the excavation, the ability to collar the holes outside the zone to be excavated is not normally a viable option. A practical compromise is to collar the holes as close as possible to the edge of the excavation as possible and orientate the holes a few degrees (3–7 degrees) away from the tunnel centerline. It is usually convenient to use the probe holes as a grout hole should grouting become necessary, therefore placement of probe holes and subsequently grout holes should be within the zone that is to be established as a low permeability zone. Typical probe/grout hole patterns, shown originating in the periphery and in the face, are shown in Figure 1.

Placement of the grout holes within the cross-section of the tunnel can lead to a plug of grouted material mainly inside that portion of the tunnel that will subsequently be excavated so that the remaining zone of grouted ground around the excavated tunnel could be thin or inadequately treated. Under these conditions, the potential for breaching the thin zone of grouted ground leading to increased inflows becomes an increasing risk as hydrostatic heads and gradients increase. Grouting of the tunnel

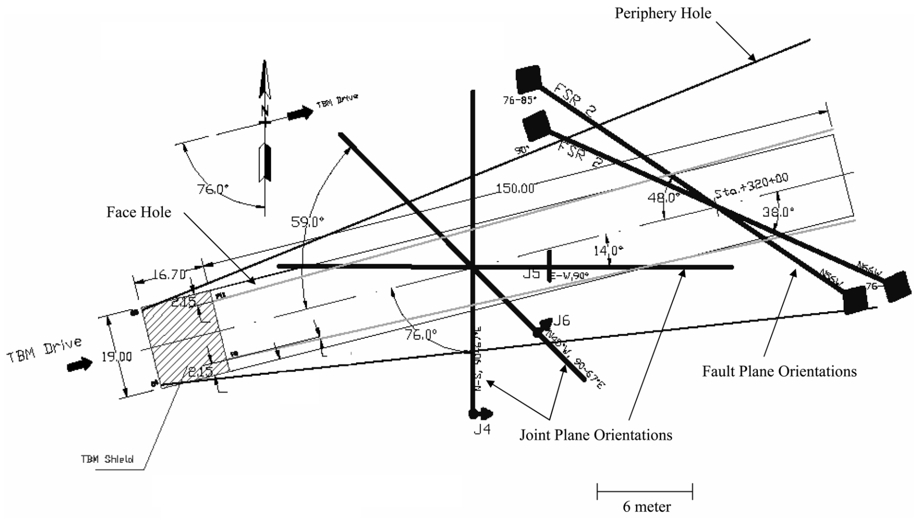

Figure 2. Discontinuity orientation relative to probe/grout holes

cross-section may provide benefits where face stability is a concern or where inflows through the face may be significant and impact tunnel operations.

Selection of probe and grout hole orientations should be optimized to cross as many of the rock fractures as possible. Holes should be orientated to intercept rock fractures of greatest potential of impact to the tunnel and at angles which are near normal as possible to the feature's strike and dip. Fracture orientation information can be obtained from the existing geologic exploration data prior to excavation and supplemented with up to date tunnel mapping. Figure 2 shows an example of available probe and grout hole orientations relative to anticipated rock joint and fault orientations.

Grout Hole Lengths. Maximum hole lengths that can be effectively grouted depends upon the type of ground being grouted (including the number and range of hydraulic conductivities in the zones or fractures to be grouted), the grout hole spacing, and their location relative to the tunnel, the grout pressure that can be applied and the capacity of the grouting equipment and the set or gel time of the grout. Typically, with the appropriate equipment and grout hole patterns, distributed, moderate inflows can be treated to achieve a reasonable reduction in inflow by grouting holes in a single stage with a hole length of about 20 to 40 meters. The effectiveness of grouting holes that are longer than this is questionable due to inadequate penetration in the potentially wide range of conditions encountered within such a long hole.

If a large inflow is encountered in a probe or grout hole, indicating that a significant feature has been encountered, then the hole should be advanced 1 to 2 meters past the feature and this reduced length of hole grouted. This will increase the effectiveness of treating larger water bearing features. Maximum hole length is also dictated by the spread or orientation of the holes as they move away from the tunnel excavation. As the holes diverge away from the tunnel periphery, the holes are too far apart and there is a greater potential for windows of ungrouted ground in between the holes. In addition, wander or deviation of long holes can become excessive, potentially increasing both the hole spacing further and the probability of leaving areas of ground that are ungrouted. Typically grout holes spacing should not be more than one tunnel radius from the future tunnel periphery.

Grout Materials and Mix Designs

Both grout materials and mix designs should maximize the permeation of the rock mass and result in a durable grout with setting/gelling characteristics that are compatible with the sequence of work. Particularly with the advent of ultrafine cements, the required grout penetration can generally be achieved with the use of cementitious grouts.

Grout Materials

The majority of rock mass grouting has relied upon Ordinary Portland Cements (OPC). Typically, Type III cements (high early strength) are the most commonly used. Type III cements have a finer grind and smaller particle size (typically D_{90} = 50–75 microns) compared to Type I/II cements (typically D_{90} = 100 microns). However, over the last two decades, various ultrafine cement grouts with significantly smaller particle sized grouts, (typically D_{90} = 8–10 microns), have been used increasingly in tunnel grouting because of the ability of achieving higher penetration of the water bearing rock fractures. Since ultrafine cement grouts offer superior penetration compared with OPC grouts, the time required to perform the pre-excavation grouting can often be reduced. This is due to a variety of factors, including the need for fewer grout holes, the ability to inject grouts with high solids contents at high rates, and the capacity to penetrate a wider range of fracture sizes than OPC grouts. Discussion of the performance and characteristics of these cements can be found in more detail in Houlsby (1990) and Henn et al. (2001). The choice of the various, available cements will be largely dictated by their availability and the economics to which the project may be subject. In some instances, it may be both viable and more economic to use a combination of different cements to treat the various features that may be encountered. Large water bearing features, typically above 200 lpm, can be grouted with Type III cements, while smaller flows are treated with ultrafine cements.

Admixtures should be used with all types of cement to provide the desired properties. Depending upon the application, admixtures are typically used to properly disperse the cement particles, reduce or increase grout viscosity, accelerate grout set, reduce grout bleed and improve grout stability and durability. Detailed discussion of admixtures meeting these criteria is beyond the scope of this paper. However, it should be noted that care and experience must be taken in the proper use of admixtures. Improper application can result in inappropriate grout properties for the particular application, leading to inadequate reduction in water inflows. Thorough testing of proposed admixtures is recommended to demonstrate compatibility of multiple additives and the ability to meet the requirements of the grout mix designs. Admixtures should not be used as a substitute for poor mix designs or poor mixing equipment. Typically, a limited number of admixtures are necessary on any individual job site.

Grout Mix Designs

A fundamental understanding of the performance characteristics of grout is necessary to design grout mixes for specific applications. Grout mix designs should be tailored to the type of cement selected, most commonly Type III and ultrafine cements, the conditions which the grout is mixed and delivered and the conditions presented by the rock mass. Simplicity is a key ingredient to reliability of the grout performance.

Table 2. Standard quality control tests for grout mixes

Equipment	Parameter	Description/Remarks
Marsh Funnel	Apparent Viscosity	Measured in accordance with API recommended practice 13B-1. Measures consistency and performance of admixtures. Easily performed in the field.
Bariod Mud Balance	Specific Gravity	Measured in accordance with API recommended practice 13B-1. Allows determination of equivalent water cement ratios. Easily performed in the field.
Vicat Needle	Initial and Final Set Times	Modified ASTM C191. Measures hardening of the grout. Typically performed in the laboratory.
Shear Vane/ Penetrometer	Initial and Final Gelation/Cohesion	Two methods of measurement. Measures cohesion which relates to initial and final gelation. Typically measured cohesion of 100 Pa for initial gelation and 1000 Pa for final gelation.
250-ml glass graduated cylinder	Bleed	ASTM C940 Measures separation of cement and water in a mix over time. Significant indicator of grout stability.

Prior to beginning any pre-excavation grouting, test batches should be run using various cements and admixtures to find the best mix which fits the project needs. Water bearing features in the rock mass can vary between two extremes, fine rock fractures to large open cavities. In anticipation of these conditions, grout mixes must be designed to be compatible with the encountered conditions. Where maximum penetration in fine features is needed, fine cement particles, stable grout mixes and low viscosity (high mobility) is desirable. For large water bearing features, high viscosity (low mobility), bulk fillers, resistance to washout or erosion and rapid setting characteristics are desirable. Testing of grout mixes is desirable for most large projects.

As a minimum for small projects a mud balance (to confirm grout density) and Marsh Funnel (determine flow properties) are necessary. For larger projects and more variable ground conditions, a broader selection of materials and grout mix designs will be necessary. Additional laboratory tests which should be considered include shear vane (measure gelation times), bleed and vicat needle (measure initial and final set times). These various tests are summarized in Table 2.

For most rock mass grouting applications using cement, a plasticizer is typically used to lower the viscosity of cement based grouts. Some ultrafine grouts have a protracted set time, up to 24 hours, particularly when using thinner mixes at cold temperatures. When using these thinner mixes consideration should be given to using an accelerator when nearing completion of a grout hole to ensure the most recently placed grout has set to allow mining to quickly resume. Placement of large quantities of weak grouts should be avoided. Typically for OPC cements, the maximum water cements ratios should not exceed 3:1 and for ultrafine cements not exceed 2:1 both by weight. Weak grout subjected to high hydraulic gradients may be extruded from fractures because of a lack of sufficient hardening, as they are more easily erode out of joints if water flows are present. More detailed information regarding grout mix performance characteristics, admixtures, and testing can be found in Houlsby (1990), Chuaqui, et al. (2003) and Weaver (1991).

Grouting Pressures

For hard rock excavations, it is typically desirable to inject grout at the highest grout pressure that can be used without damaging the rock and resulting in loss of grout to the tunnel face. Under these conditions, the ability to effectively place grout in the water bearing features is severely impacted. Damage to the rock mass occurs when hydraulic fracturing develops new fractures. Hydraulic fracturing typically occurs in brittle rock when the tensile strength and confining stress have been exceeded. It is often recognized as a rapid increase in grout take sometimes accompanied by a pressure loss. This can result in the development of new fractures into which the grout may preferentially flow, potentially resulting in loss of control of the pre-excavation grouting process and the placement of potentially large volumes of grout in locations where it is not needed. The development of new fractures makes treatment of the rock mass much more difficult and unreliable. In rock which is not as brittle, hydraulic jacking will commonly occur when the in situ stress is exceeded. This can be desirable in that discontinuities are dilated resulting in easier placement of the grout. Hydraulic jacking, or the opening of existing fractures in the rock mass, may be beneficial in treating the rock mass, however, care must be exercised to ensure that the zone of treated rock does not extend too far from the tunnel. In either case, eruption of grout at the face may occur, indicating that the grout pressure is too high and has found a path of least resistance towards the face. Occurrences of leakage to the face greatly diminish the ability to adequately permeate and treat the rock mass. This will negatively impact the performance of the pre-excavation grouting operation in meeting its design criteria. Selection of grout pressures are normally based upon the amount of ground cover, and rock mass quality. Typically in moderate rock mass quality, grout pressure should begin at about 0.25 to 0.5 bars per meter of ground cover. More competent and stronger rock may allow higher grout pressures to be applied.

A simple test can be performed to determine if the applied pressure for grouting are excessive. A steady-state, three step water pressure test can be applied in the initial grout hole. A typical test would involve injection of water for 5 minutes at half the maximum anticipated grout pumping pressure and record the take of water (step 1). Step 2 would repeat the water injection test but perform the test at the maximum anticipated grout pressure for 5 minutes and record the take of water. Step 3 repeats step 1 using half the maximum anticipated grout pumping pressure as previously used. A significant increase in take in the third step and non-linear increase between the first and second steps would indicate hydraulic fracturing likely occurred. A mild increase in take during the third step compared to the first could indicate that hydraulic jacking and/or washout of infillings in the rock joints may have occurred. The test also indicates the relative hydraulic conductivity of the rock mass under varied injection pressures and can be used to select the initial grout mix.

Performance Monitoring

The primary role of performance monitoring is to determine whether or not the design criteria is being met and if not to determine the modifications required to the grouting means and methods to effect the necessary improvements. To accomplish this, more than just water inflows should be measured. The primary means of ensuring adequate treatment of the ground is to make sure that a sufficient amount of cement (not necessarily grout) has been placed in the rock mass, in the appropriate locations and under the right circumstances. Performance monitoring is necessary to determine if the ground is being sufficiently treated during the grouting operation and through analysis of the grouting parameters afterwards.

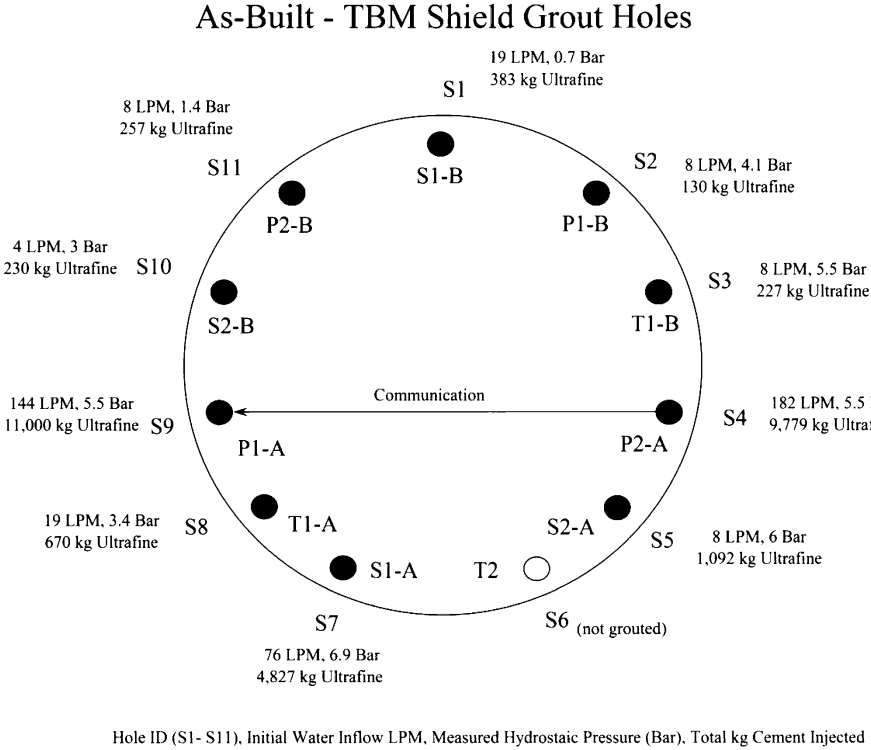

Figure 3.

Monitoring of grout flow rate, total volume and pressure should be performed during grouting by individual or by recording devices on larger jobs developing pressure-flow diagrams. This information is used to determine what quantity of cement has been placed over time and what change in hole permeability is occurring as reflected in the change in grout pressure and grout flow rate. These parameters are used to monitor the targeted amount of cement being placed and whether the grout mix should be changed (usually thickened). It can also indicate if leaks back to the tunnel perimeter or connections to adjacent holes may be occurring or if excessive pressures are causing damage to the rock mass. These parameters should be monitored for each hole.

Each grout hole should have recorded the measured initial inflow and measured hydrostatic pressure (with all other holes closed) and the amount of cement placed in each hole or stage at the completion of grouting. Cross communication should also be noted between holes or within features intercepting the tunnel face or periphery. Figure 3 shows an as-built of a grouting cycle performed through a TBM shield for a 5.8 meter diameter tunnel.

Targeted quantities of cement should be estimated for each hole. Placing excessive quantities of cement negatively impacts the efficiency of the grouting cycle. The key is to place a sufficient quantity of cement in the intended location. Additional holes do a better job of strategically placing the cement and treating the rock mass than excessive pumping from widely spaced holes. Placing excessive quantities of thin grout may not adequately treat the rock mass as discussed above. The target quantity is typically based upon a wide variety of factors and adjusted accordingly. These factors can typically include rock mass permeability, hydrostatic head, hole length, location of the grout hole relative to the tunnel periphery, hole spacing and allowable tunnel inflow. Maximum weight of cement is typically limited for any given water cement ratio or can be limited as a maximum total weight for any given hole. During grouting, if there is no indication in pressure rise and/or decrease in cement take with time as the hole is pumped, then a targeted amount of placed cement would be used before transitioning to the next thicker water/cement grout ratio.

CONCLUSION

Although all of the guidelines described in this paper have been utilized on past projects, difficulties and failures are often encountered when they are ignored. The successes of these projects are the most important justification for using these guidelines. A properly conceived pre-excavation grouting program should be adopted early in a project planning phase and become an integrated component of the design to ensure the project will be successfully completed.

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