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# Grouting design based on characterization of the fractured rock

## Presentation and demonstration of a methodology

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December 2008

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*Keywords:* Grouting, Rock, Fractures, Characterization, Design methodology, Field experiments

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

# Preface

Grouting of rock fractures in crystalline bedrock to reduce inflow to rock openings has been an active research field in Sweden during the last decades. The research is partly financed by SKB that wishes to present a method that allows for controlled sealing and well-predicted results, which can be taken into use for the construction of the final repository for spent nuclear fuel. The research has been carried out mainly at Chalmers University and The Royal Institute of Technology and it is now possible to approach the design and execution of grouting works in a theoretically funded manner. Designing a grouting work involves to select grout and to establish fan geometry and pumping pressure etc, whereas the basic premise – the rock mass – is given, but to a large extent unknown. To create a description of the rock mass upon which the design can rest, has thus been a vital part of the task.

Today we see a shift in common rail and road tunnel projects from mainly empirically to theoretically funded designs of grouting works, as the new understanding from the research is spread and applied. In these projects the theories put forward are examined under field conditions and feedback is given to verify and further develop the understanding. The new understanding and field experience is presented in various articles and publications.

This report presents the features of a methodology comprising the developed understanding and brief introductions to projects where the full methodology or parts of it have been used. It is compiled based on previously published material. The main aim of the report is to summarise and present the concept of the methodology and to serve as a key to the important references that describe the theoretical development and its application to tunnel construction.

Stockholm, December 2008

Ann Emmelin

# Summary


The design methodology presented in this document is based on an approach that considers the individual fractures. The observations and analyses made during production enable the design to adapt to the encountered conditions. The document is based on previously published material and overview flow charts are used to show the different steps.

Parts of or the full methodology has been applied for a number of tunneling experiments and projects. SKB projects in the Äspö tunnel include a pillar experiment and pre-grouting of a 70 meter long tunnel (TASQ). Further, for Hallandsås railway tunnel (Skåne south Sweden), a field pre-grouting experiment and design and post-grouting of a section of 133 meters have been made. For the Nygård railway tunnel (north of Göteborg, Sweden), design and grouting of a section of 86 meters (pre-grouting) and 60 meters (post-grouting) have been performed. Finally, grouting work at the Törnskog tunnel (Stockholm, Sweden) included design and grouting along a 100 meter long section of one of the two tunnel tubes.

Of importance to consider when doing a design and evaluating the result are:

- The identification of the extent of the grouting needed based on inflow requirements and estimates of tunnel inflow before grouting.
- The selection of grout and performance of grouting materials including penetration ability and length. The penetration length is important for the fan geometry design.
- The ungrouted compared to the grouted and excavated rock mass conditions: estimates of tunnel inflow and (if available) measured inflows after grouting and excavation. Identify if possible explanations for deviations.

For the Hallandsås, Nygård and Törnskog tunnel sections, the use of a Pareto distribution and the estimate of tunnel inflow identified a need for sealing small aperture fractures (< 50 – 100 μm) to meet the inflow requirements. The tunneling projects show that using the hydraulic aperture as a basis for selection of grout is a good approach. All the projects have been successful in terms of decrease in inflow. Either based on the change in median values of inflow to grouting and control boreholes or as in the case of the post-grouting at Hallandsås where the measured inflow to the tunnel decreased. Investigations on how to improve the tunnel inflow prognosis is an ongoing project. To further increase the understanding for how geology, hydrogeology and geomechanics influence the result during both pre- and post-grouting, can give still more chances to improve the result.

# Sammanfattning


Den designmetod som presenteras i denna rapport är baserad på ett tillvägagångssätt som tar hänsyn till de enskilda sprickorna. De observationer och analyser som görs under tunneldrivningen innebär att designen kan anpassas till rådande förhållanden. Rapporten är sammanställd baserat på tidigare publicerat material och översiktliga flödesscheman används för att visa de olika stegen.

Delar av eller hela designmetoden har tillämpats för ett antal tunnelexperiment och projekt. SKB:s projekt i Äspötunneln inkluderar ett experiment i en pelare och förinjektering av en 70 meter lång tunnel (TASQ). Vidare har ett fältexperiment med förinjektering och design samt efterinjektering av en 133 meter lång sektion genomförts i tunneln genom Hallandås. För Nygårdstunneln norr om Göteborg har design och utförande av både förinjektering (86 meter) och efterinjektering (60 meter) gjorts. Avslutningsvis ingår design och förinjektering av en 100 meter lång sektion för ett av de två tunnelrören i Törnskogstunneln, Stockholm.

Vid design och utvärdering av resultat är det viktigt att:

- Identifiera omfattningen av injekteringsarbetet baserat på krav på inflöde och skattat inflöde före injektering.
- Välja injekteringsmedel baserat på medlets egenskaper vilket inkluderar att bedöma såväl dess förmåga att komma in i sprickorna som den resulterande inträngningslängden. Inträngningslängden är viktig för att bestämma skärmgeometri.
- Beakta förhållandena i det oinjekterade och det injekterade berget (efter berguttag): skattning av tunnelinflöde och (om tillgängligt) det uppmätta inflödet efter injektering och tunneldrivning. Om möjligt identifiera orsaker till skillnader.

För sektionerna i Hallandsås-, Nygård och Törnskogstunneln, identifierade en analys där en Pareto-fördelning används och en skattning av tunnelinflöde görs, ett behov att täta sprickor med liten vidd (< 50 – 100 μm) för att nå kravet på max tillåtet inflöde. Resultaten från projekten visar att det är ett bra angreppssätt att använda den hydrauliska vidden som underlag för val av injekteringsmedel. Projekten har även varit lyckade med hänsyn till att de minskat inflödet. Detta antingen baserat på minskningar i medianvärden för inflöde i injekterings- och kontrollhål eller som i fallet med efterinjekteringen på Hallandsås där det uppmätta inflödet till tunneln minskade. Studier av hur inflödesprognoser kan förbättras pågår. Att öka förståelsen för hur geologi, hydrogeologi och geomekanik påverkar resultatet under både för- och efterinjektering kan ge ytterligare möjligheter till förbättringar.

# Contents

# 1 Introduction

The aim of the document is to present a methodology for a grouting design based on characterization of the fractured rock. It is compiled based on previously published material. The methodology is generally applicable, but the document is written with the Swedish final repository for spent nuclear fuel in mind. The characterization is based on an approach that considers the individual fractures. The methodology is demonstrated using results and conclusions from scientific papers and reports from tunneling experiments and projects.

The observations and analyses made during production that enables the design to adapt to the encountered conditions are of vital importance to meet the requirements. For the different project stages: planning; detailed design; and final design /Emmelin et al. 2007/, hydrogeological investigations are undertaken stepwise, resulting in a successive updating of the rock description and subsequent updating and detailing of the grouting design. The grouting design may also be adapted during execution based on the result of checks defined in control programmes. The aim of control programs are to take care of the uncertainties inherent in data and models, and to finally confirm that the measures undertaken have resulted in the desired result.

The basis for the document is flow charts including the different phases: before grouting; during grouting; after grouting before excavation and; after excavation. The different parts (boxes) of the flow charts are used as a structure for both the document and how to perform the work. For the phases performed in the field, observations and control measures are included.

Important references in the document describe the theoretical development and based on these, brief comments on characterization of rock, selection of grouting materials and penetration of grout are given. Further, estimates of tunnel inflow and a design window related to the risk of jacking, back-flow and erosion are important components of the methodology. The design window is used to compile and present the results and indicate an area of satisfactory solutions.

# 2 Design methodology: Flow charts

This section describes the different steps included in the analysis using flow charts. The main principles including references are described here and examples from tunnelling experiments and projects are presented in Section 3. In /Emmelin et al. 2007/ the stages planning, detailed design and final design are included. The planning stage examines typical and extreme situations to prove feasibility whereas the detailed design has to cover all situations to prepare for actual execution. Output from the detailed design should include grouting drawings, method descriptions and control programs that includes criteria for the action to be undertaken in the next step. For different parts of the repository, the geometry, inflow requirements, fracture distributions and depth will differ and there will therefore be a need for different grouting classes. The grouting classes will describe the grouting design for that situation and the controls that has to be carried out in order to get a basis to confirm or change class.

## 2.1 Planning stage: Preliminary and detailed design

### 2.1.1 Overview of design procedure

Figure 1 presents an overview flow chart for design based on data from investigation boreholes.

The different steps are used to estimate inflow to a tunnel and to identify grouting needs. Of central importance is to relate this estimate of tunnel inflow to the requirements set for the specific part of the repository. The main aims are to identify the sizes of the fracture apertures and especially the smallest fracture aperture that has to be sealed to meet the inflow requirements and what grouting materials are needed to do this. Further, the penetration of grout is important for the grouting fan design. A number of measures can be taken to increase the probability of successful sealing e.g. checking jacking, back-flow and erosion, see Section 2.1.5. A grouting fan design that results in an estimate of inflow to the tunnel that fulfils the inflow requirements is accepted.

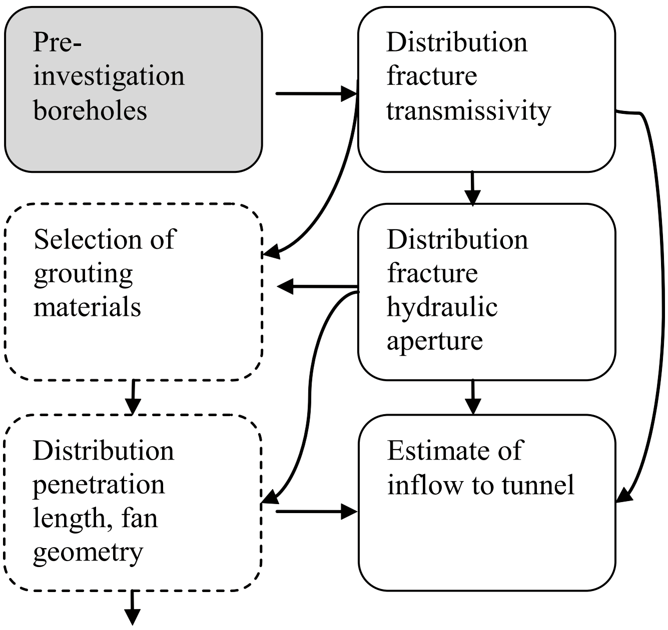


***Figure 1.*** *Overview flow chart for design based on data from investigation boreholes. Grey box: field work; white boxes: analyses (dashed lines: measures can be taken to increase the probability of successful sealing, see Section 2.1.5) A grouting fan design that results in an estimate of inflow to the tunnel that fulfils the inflow requirements is accepted. Resulting output is grouting drawings etc. see central box in Figure 3. From e.g. /Gustafson et al. 2004, Butrón et al. 2008/ and /Fransson and Gustafson 2008/.*

The detailed design result will normally include a few different grouting fans appropriate for different geohydrological conditions that are predicted based on the pre-investigations; i.e. different grouting classes are defined. The control program, which is part of the detailed design result, will specify how it is checked during construction that the conditions are as predicted and thus that the fan design is valid for that location. It is also specified what type of action should be undertaken if the observed parameter values do not fall within the acceptable limits. This approach is in line with the Observational method described in the Eurocode, the standard for geotechnical design, SS-EN 1997-1, where it is suggested as a method to handle design situations where the design has to be based on uncertain data and models.

Table 1 describes what predictions should be checked with the control program and what the requirements are. This is followed by type of observation (criteria) that decides what action that has to be taken.

### 2.1.2 Pre-investigations and estimates of transmissivity, aperture and inflow to tunnel

The characterization is based on an approach that considers the individual fractures. This is important since factors such as:

- the flow of water and grout,
- the ability of the grout to enter a fracture,
- the penetration length of the grout,
- the risk for turbulent flow and erosion,
- the geomechanical behavior of the fracture.

are all linked to the properties of individual fractures. /Fransson 2002/ and /Gustafson and Fransson 2005/ describe a method for estimation of transmissivity- and hydraulic aperture distributions based on the transmissivity and fracture frequency of sections along cored boreholes. A Pareto distribution is fitted to the estimated transmissivities, see examples in Figure 2. A Pareto distribution is a distribution that is suitable to describe data consisting of few large values and numerous small, that has shown to describe fracture aperture distributions well.

The hydraulic aperture, $b$, is estimated using the cubic law:

$$T = \frac{\rho g b^3}{12\mu} \approx \frac{Q}{dh} \qquad (1)$$

In /Fransson 1999/, it is shown that the specific capacity, $Q/dh$, can be used as an estimate of the transmissivity, $T$, for hydraulic tests of short duration. In Equation 1, $Q$, is the flow, $dh$, is the change in hydraulic head, $\rho$ and $\mu$ are the density and viscosity of the fluid and $g$ the acceleration due to gravity. Using the hydraulic aperture distribution and assuming that fractures with a hydraulic aperture exceeding a certain width can be sealed, an inflow to the grouted tunnel can be estimated:

**Table 1 The actual behaviour is checked against the predicted behaviour before, after and during grouting /modified from Emmelin et al. 2007/.**

| When | Prediction to be checked | Requirement | Observation, criteria | Action |
|---|---|---|---|---|
| Before grouting (BG) | Ground behaviour: Ungrouted rock mass conditions | Current values within limits for the predicted class | Water loss, natural inflow in grouting holes | Assessment or change of grouting class |
| During grouting (DG) | System behaviour: The performance of the grout in the rock fractures | Specification on pressure, flow, volume | Logged pressure, flow and volume, observations of e.g. backflow | Adjust grouting measures within class |
| After grouting, before excavation (AG) | System behaviour: The tightness of the tunnel to be excavated | Tightness in grouted zone | Water loss, natural inflow in control holes | Another pre-grouting |
| After excavation (AE) | System behaviour: The inflow to the excavated tunnel | Inflow to tunnel section | Inflow in weir | Post-grouting, lining |

$$q_{gr} = \frac{2\pi T_{tot} H / L}{\ln(2H/r_t) + (T_{tot}/T_{gr} - 1)\cdot \ln(1 + t/r_t) + \xi} \qquad (2)$$

Included in the equation are the total transmissivity along the borehole, $T_{tot}$, the residual transmissivity for fractures not sealed, $T_{gr}$, the depth, $H$, the radius and length of tunnel, $r_t$ and $L$, the thickness of the grouted zone, $t$, and the skin factor, $\xi$ /see e.g. Fransson and Gustafson, 2006, Funehag and Gustafson, 2008b, Hernqvist et al. 2008a/. The estimated inflow is related to the requirement on a maximum total inflow after grouting. Based on the estimated inflow to the tunnel and the inflow requirement set, it is decided what interval of hydraulic apertures that has to be sealed. The remaining, not sealed fractures add up to the transmissivity following grouting, $T_{gr}$.

### 2.1.3 Selection of grouting material

In general the grouting materials are described as either Bingham- or Newtonian fluids. A cement-based grout is a Bingham fluid and the cement particles have a significant influence on the rheological behaviour /e.g. Håkansson 1993/ and the ability of the grout to enter the fractures /e.g. Eriksson et al. 2000/. Concerning the penetrability of grout, the type of grout should be chosen so that it is likely that it will enter the fractures. For small aperture fractures a grout such as silica sol is more likely to give a good result than a cement-based grout. The rheological properties of grout (viscosity and yield stress) should be investigated when selecting the grout for the grouting design (Figure 1) and checked when performing the grouting in the field (Figure 3). Being aware that the rheological properties of grout can change is important.

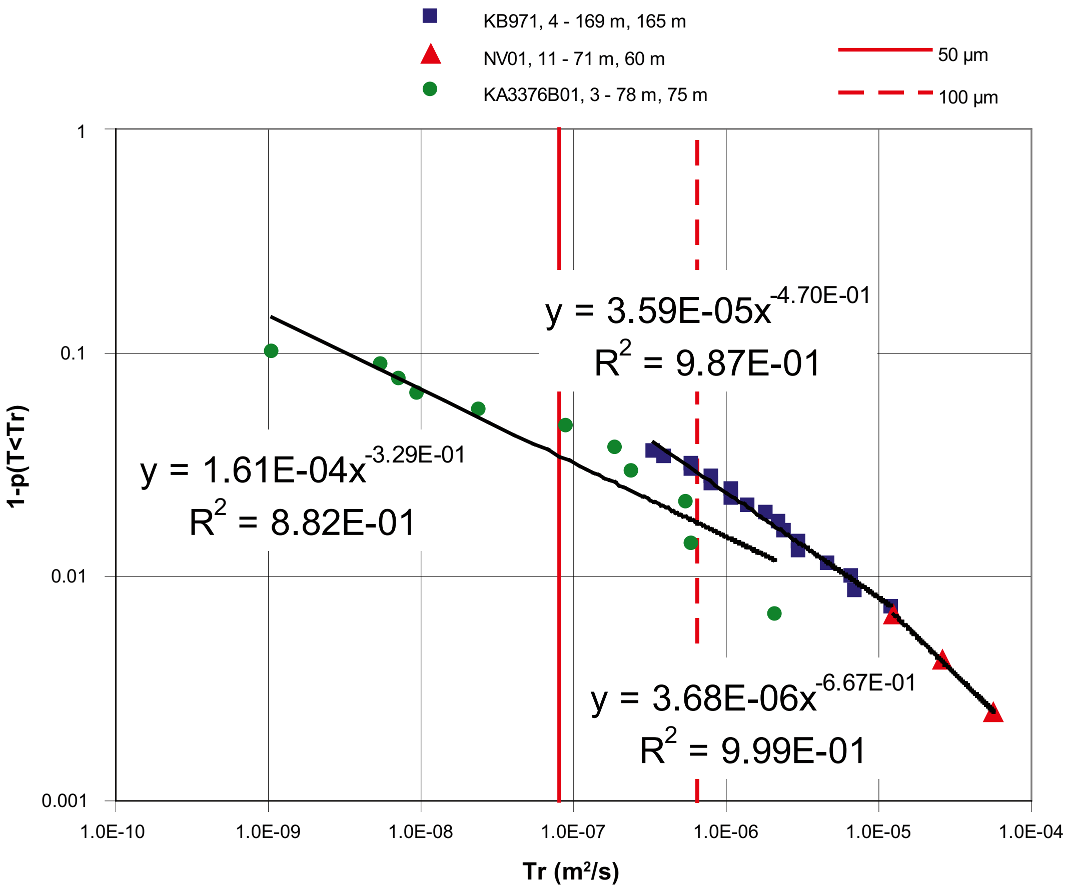


***Figure 2.*** *Examples of Pareto distributions fitted to the estimated transmissivities for individual fractures, $T_r$ (x-axis), where r is the rank ($T_1$, the largest and $T_2$, the second largest transmissivity etc). On the y-axis is shown the probability that the transmissivity exceeds a specified transmissivity, $T_r$. Based on data from the cored boreholes KB971 (Törnskog tunnel), NV01 (Hallandsås tunnel) and KA3376B01 (TASQ tunnel, Äspö Hard Rock Laboratory) /from Fransson and Gustafson 2006/.*

For a cement-based grout, a yield stress, $\tau_0$, of the material has to be exceeded for the grout to flow. In addition, flowing water may cause erosion of the grouting material and a large yield stress (governed by the water/solid ratio) increase the possibility for the grout to withstand erosion /Axelsson, 2006/. For the final repository, a preliminary division has been made between materials for grouting of larger fractures (≥ 100 µm) and smaller fractures (≤ 100 µm) see e.g. /Bodén and Sievänen 2005/. Besides a cement-based grout for the larger fractures, a Newtonian fluid such as silica sol is needed since it has the ability to enter and seal small aperture fractures /Funehag and Gustafson 2008a/.

### 2.1.4 Distribution of penetration length and fan geometry

One important effect of the yield stress, $\tau_0$, for a cement-based grout is that it determines the maximum penetration length for the grout /Gustafson and Stille 2005/:

$$I_{\max} = \frac{\Delta p b}{2\tau_0} \tag{3}$$

where $\Delta p$ is the difference between the grouting pressure, $p_g$, and the water pressure, $p_w$. /Gustafson and Stille 2005/ also describe a relative penetration that is related to this maximum penetration length and a function of time. The penetration length of a Newtonian fluid such as silica sol is determined by the difference in pressure, $\Delta p$, and the aperture, $b$, but also the gel induction time, $t_G$, and the viscosity, $\mu_0$. This is described in /Funehag 2007 and Gustafson 2008a/.

The penetration length is important since it is used as a basis to determine fan geometry. Analyses should include controlling that: the penetration length for the smallest fracture is sufficient to theoretically fill this fracture between two boreholes (including an overlap to increase the chance of sealing the fractures) and; the penetration for the largest aperture is acceptable e.g. to avoid a too large grout take. For grouting boreholes drilled with an angle outside the future tunnel contour, the maximum borehole distance and the penetration length are adjusted to obtain a theoretical overlap aiming at sealing the intersected fractures and getting a grouted zone around the tunnel /e.g. Funehag and Gustafson, 2008b/. For boreholes inside the tunnel contour the borehole distance may be small but the thickness of the grouted zone is still important. Several different types of grouting fans can be designed and the inflow along investigation boreholes determines what type of grouting fans to suggest and how they should be placed.

### 2.1.5 Measures to increase the probability of successful sealing

A number of measures concerning the selection of grouting materials and the fan geometry design (dashed lines, Figure 1) can be taken to increase the probability of successful sealing.

Around a tunnel, high water pressure, large hydraulic gradient and redistribution of stresses may result in back-flow of grout, erosion and jacking (deformation). Some theoretical considerations regarding these issues are presented and demonstrated in /Fransson and Gustafson 2006/ and /Fransson and Gustafson 2008/. In these reports, a design window was used to compile and present the results and indicate an area of solutions that are satisfactory, see example in Table 2. The design window considered:

- the risk of jacking and uncontrolled spreading of grout (here assumed to happen when the estimated fluid pressure in the fracture exceeds the stress due to the weight of the overburden, $\rho_b gH \geq p_w + \Delta p/3$, where $\rho_b$ is the density of the rock, $g$, acceleration due to gravity, $H$, depth of tunnel, $p_w$, water pressure and $\Delta p$, the difference between the grouting pressure and the water pressure) and,
- the risk of grout flowing back to the borehole (back-flow) due to too short grouting time or insufficient yield stress of the grout.

The issues above need to be further investigated and verified in the field and the conditions presented should be looked upon as qualitative guidelines and not absolute demands. The design window is a good basis for discussions and revision of grouting design. For the example presented in Table 2, an overpressure (grouting pressure – water pressure) of 0.5 MPa is recommended at a depth of 20 meters. It is also possible to include the estimated penetration length for the different combinations of pressures instead of "OK" in the design window.

**Table 2. The design window is used to compile and present the results and indicate an area of satisfactory solutions.**

| H [m] | $p_w$ [MPa] | Δp [MPa] 0.1 | 0.5 | 1.0 | 2.0 | 3.0 |
|---|---|---|---|---|---|---|
| 0 | 0 | – | – | – | – | – |
| 10 | 0.1 | – | – | – | – | – |
| 20 | 0.2 | – | OK | – | – | – |
| 40 | 0.4 | – | OK | OK | – | – |
| 60 | 0.6 | – | – | OK | OK | – |

## 2.2 Construction and operation – Final design

### 2.2.1 Control of grouting performance in tunnel

The preliminary design will be based on the initial characterization interpreted from the pre-investigations, and thus the design will be valid for these conditions. During performance additional information will be achieved from hydraulic tests and grouting data. The data will be used to confirm or update the characterization. If different, the new data will be evaluated using the principles described in 2.1. The updated characterization together with practical experience gained during execution may result in changes of the design. An overview flow chart for control of the grouting performance in the tunnel is presented in Figure 3. Before grouting (BG), arrow A is followed and based on these data selection of grouting materials and type of grouting fan is made (assessment or change of grouting class). Arrow B indicates the performance of grouting and adjustments are possible based on grouting data. After grouting (AG), analysis of hydraulic testing data of control holes is used to determine if grouting should continue or if the tunnel should be excavated (rhomb). Predictions to be checked, requirements, observation criteria and actions are summarised in Table 1.

### 2.2.2 Before grouting (BG)

The ungrouted rock mass conditions are investigated before grouting. *Drilling and hydraulic testing in grouting boreholes* (see box in Figure 3) are made for assessment or change of grouting class (type of grouting fan). When characterising fractured rock for grouting, hydraulic short duration tests (few minutes) are commonly performed as natural inflow- or as water loss measurements. Here, a natural inflow measurement refers to a test performed by just opening the borehole measuring the natural flow (measuring or assuming a stable pressure). The water loss measurement is performed

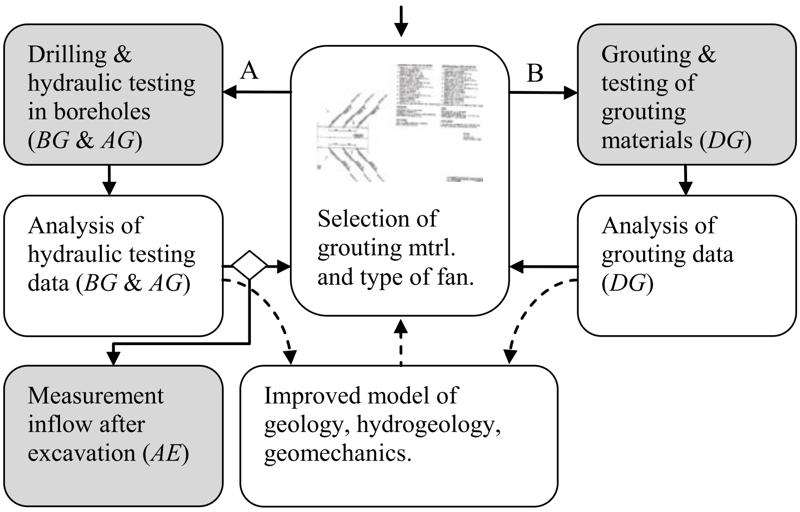


***Figure 3.*** *Overview flow chart for grouting performance in tunnel. Grey boxes: field work; white boxes: analyses. Central box: grouting drawings etc. input from flow chart for design based on data from investigation boreholes (Figure 1) based on Section 2.1. BG: Before grouting; DG: During grouting; AG: After grouting; AE: After excavation, see Table 1 and Sections 2.2.2 – 2.2.5. Modified from /Fransson and Gustafson 2008/.*

by injecting water using a pressure exceeding the pressure measured in the borehole. Hydraulic tests of longer duration (transient tests) are useful since they describe a larger volume of rock indicating conductive features that are not necessarily directly intersected by the grouting boreholes. Data are used to see if the prediction of the ungrouted rock mass conditions can be confirmed and give detail to the description. Otherwise it is used as a basis for revision.

### 2.2.3 During grouting (DG)

The performance of the grout in the rock fractures is checked during *grouting* (see box in Figure 3). The parameters of interest are pressure, flow and volume as a function of time. It is checked that the parameters fall within pre-defined values. Changes in flow can for example indicate deformation and jacking and data can also be used to identify flow dimension /Gustafson and Stille 2005/. Sealing fractures with one dimensional channeled flow is considered more difficult than sealing of fractures with two dimensional (radial) flow due to the lower probability of intersecting the conductive parts of the fractures. *Testing* of previously selected and tested *grouting materials* to verify rheological properties should also be made.

### 2.2.4 After grouting, before excavation (AG)

After grouting, *drilling and hydraulic testing in grouting or control boreholes* are used to describe the grouted rock mass conditions. The analyses of the hydraulic tests are used to determine if grouting should continue or not (rhomb, Figure 3). The result is additional predefined grouting rounds or excavation.

The criteria related to sufficient tightness in the grouted zone is often defined as a limit in inflow or water loss measurement values for all control holes. Figure 4 presents an example showing the successive change in inflow between grouting rounds for a field test in the Hallandsås tunnel. The median inflow was reduced from 2.0 liters/min (Series 1) to 0.2 liters/min (Series 2). The grouting presented in Series 1 and 2 was carried out in an earlier cement grouted rock mass. To estimate the inflow in the rock mass before any grouting was carried out, boreholes were extended into the still ungrouted rockmass and inflow measured (Series 3). The ungrouted rock mass had a median inflow of 70 l/min (Series 3).

### 2.2.5 After excavation (AE)

Following the excavation, the *inflow to the excavated tunnel is measured* using e.g. a weir and a sufficient time gap should be given to allow stable conditions before measurements. If the measured inflow exceeds the requirements, additional sealing is obtained using post-grouting or lining.

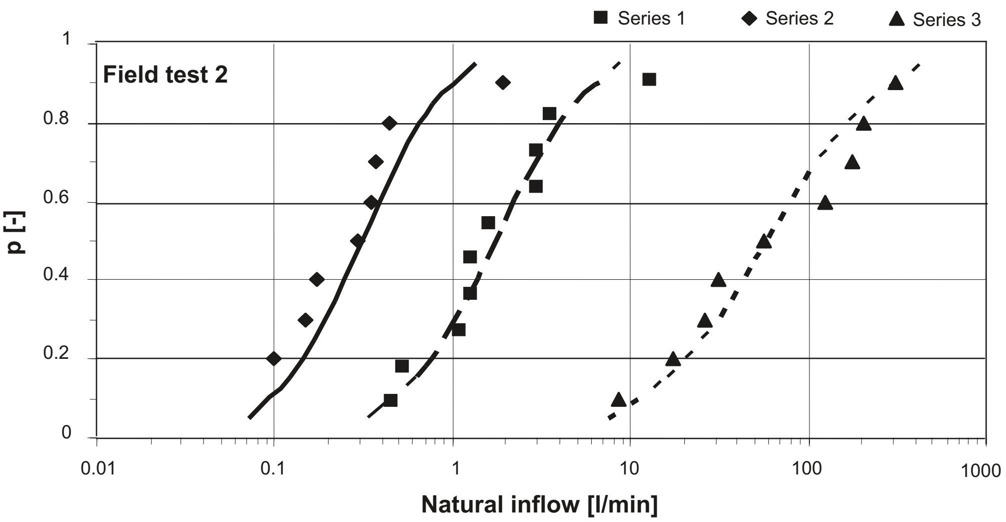


***Figure 4.*** *Measurements of the natural flows into the boreholes, example from the Hallandsås tunnel where the median inflow was reduced from 2.0 liters/min (Series 1) to 0.2 liters/min (Series 2). The ungrouted rock mass had a median inflow of 70 l/min (Series 3). From /Funehag 2007/.*

# 3 Tunneling experiments and projects

Below are presented some tunneling experiments and projects where parts of or the full methodology has been applied. SKB projects in the Äspö tunnel include a pillar experiment and pre-grouting of a 70 meter long tunnel (TASQ). For Hallandsås railway tunnel (Skåne south Sweden), a field experiment (pre-grouting) and design and post-grouting of a section of 133 meters have been made. For the Nygård railway tunnel (north of Göteborg, Sweden), design and grouting of a section of 86 meter (pre-grouting) and 60 meters (post-grouting) have been performed. Grouting work at the Törnskog tunnel (Stockholm, Sweden) included design and grouting along a 100 meter long section of one of the tubes. Included in the descriptions are comments on the parameters included in Figure 1: pre-investigations; distributions of transmissivity and aperture; estimate of inflow to tunnel; selection of grouting materials; penetration length and fan geometry. Important is the verification of predictions and suggestions and the changes and adjustments made during grouting performance.

## 3.1 Pillar, section 0/660-0/710, Äspö HRL

The field tests presented in /Fransson 2001, Eriksson 2002/ and /Funehag and Fransson 2006/ were all performed in a pillar at approximately 100 meter depth at Äspö Hard Rock Laboratory. The main rock type was granite and the pillar was described as being between damp and completely dry.

Fixed interval test-length transmissivities and the corresponding number of fractures were used to estimate probabilities of conductive fractures. A good agreement was found when investigating the pillar in further detail. Based on transient hydraulic tests (analyzing pressure and flow as a function of time), the main conductive fracture had an estimated hydraulic aperture of 40 – 50 µm. When comparing this transmissivity to the specific capacity, *Q/dh*, obtained from short duration tests in several boreholes assuming steady state conditions, the median specific capacity was found to be a good estimate of the effective transmissivity. This indicates that several ”local” estimates of specific capacity can be used to describe the more “general” transmissivity of the entire intersected fracture. The same result was found for a laboratory experiment presented in /Fransson 1999/.

Based on the size of the aperture and the limited penetrability expected for cement-based grouts, selecting a grouting material for small aperture grouting would therefore be reasonable. This was both predicted and verified by /Eriksson 2002/ and /Funehag and Fransson 2006/. In these trials the cement-based grout was halted by the limited penetrability whereas the other grouting material (silica sol) had a visually identified penetration length that was in good agreement with the prediction (exact penetration not known but within less than half a meter).

For a gelling silica sol, /Funehag and Gustafson 2008b/, present a laboratory experiment in a pipe comparing measured and calculated penetration lengths. Here as well the agreement is good. The difference is less than tens of centimeters at early times and less than a meter for the final penetration length (approximately 6 meters). The prediction for the penetration of cement grout in the pillar /Eriksson 2002/ was a span of possible results between “zero” grout penetration and around 200 mm. Taking out a 200 mm core around the grouted borehole, part of the fracture contained grout and other parts did not and the result and the prediction were found to agree.

## 3.2 TASQ – tunnel, Äspö HRL (70 m)

/Eriksson et al. 2005/ present grouting of a 70-meter long tunnel at 450 meter depth. The rock mainly consists of medium to large grained granite to granodiorite. Hydrogeological investigations were undertaken stepwise, resulting in a successive updating of the rock description followed by grouting design and prognoses.

Two grouting fans were designed. The final locations of the two grouting fans were as predicted based on a parallel pre-excavation drilled investigation borehole (80 m), see Figure 5. The design had to be revised for one of the grouting fans based on additional information from one pair of

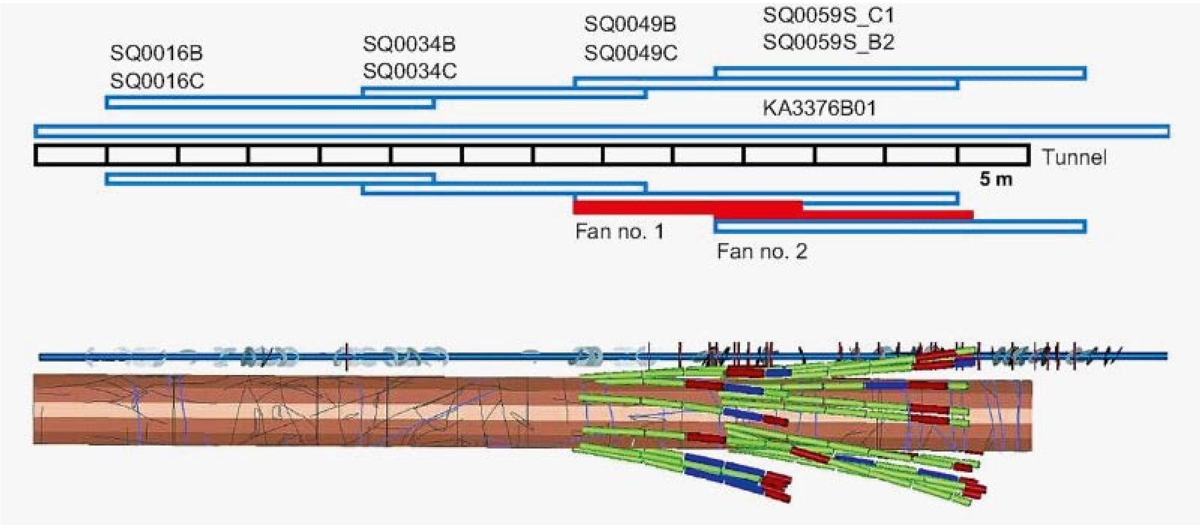


*__Figure 5.__ Compilation of data from boreholes and tunnel mapping for the TASQ-tunnel using SKB's Rock Visualisation System (RVS). Along the parallel "pre-excavation" drilled investigation borehole (80 m) locations of fractures (grey discs) and inflows > 2 L/min (red lines) are shown. The four pairs of boreholes drilled in the tunnel front (≈ 20 - 25 m) are visible in the upper figure. For the two grouting fans (Fan 1 and Fan 2), boreholes having a section (3m) inflow exceeding 2 L/min are included. Green: section inflow < 2 L/min; Blue: > 2 L/min and; Red: largest section inflow /from Emmelin et al. 2004/.*

boreholes drilled in the tunnel front. This was already indicated by hydraulic pressure-time data for the 80 meter borehole. The decrease in inflow for the two grouting fans were 99.9% and 95% based on median values of inflow to grouting and control boreholes. A cement based grout was used and due to the limited penetrability, sealing of fractures no smaller than 50 µm was expected. That fractures of about 50 µm but not below 30 µm had been sealed was later confirmed by /Hernqvist et al. 2008a/. In the Hernqvist study the hydraulic properties and the presence of grout was investigated using four cored boreholes in the tunnel wall. Using Equation 2 and assuming that fractures larger than 50 µm are sealed resulted in an estimated inflow to the tunnel of 20 liters/min. The measured inflow is somewhat uncertain but approximately 5 liters/min. One explanation for the difference is the possible sealing of a larger conductive fracture or fracture zone identified by hydraulic tests and pressure changes in other boreholes at the Äspö HRL /Emmelin et al. 2004/ and /Hernqvist et al. 2008b/. Before grouting, this fracture could have been the main supplier of water to many finer, connected fractures.

## 3.3 Hallandsås railway tunnel (test + 133 m section)

For the Hallandsås railway tunnel two different trials will be described here. The first is a field experiment using silica sol at a tunnel front located in section NV 191+780 m, /Funehag and Gustafson 2004/ and /Funehag 2004/. The second is a post-grouting performed along section 190+850 – 190+983 m (133 meters, east tunnel), see /Bergh and Ekström 2007/ and /Fransson and Gustafson 2008/.

The geology mainly consists of gneiss with features of amphibolites. Locally the gneiss has been altered to clay. The depth is approximately 100 meters.

For the field experiment presented in /Funehag and Gustafson 2004/ and /Funehag 2004/ pre-investigations were water loss and inflow measurements and grouting was performed with silica sol to achieve an additional sealing since the tunnel front had already been grouted with cement. Focus was more on investigating the penetration of the silica sol than on actually sealing the section.

A method referred to as split-spacing was used, meaning that after testing and grouting a series of boreholes, a round of new boreholes were drilled in between the previous. The approach allows an evaluation of the sealing effect after each grouting round. The field experiment included two tests with different borehole geometries: (1) a cross with four series of grouting boreholes (approximately 6 meters by 6 meters) and (2) a half traditional grouting fan in the upper part of the tunnel (radius at borehole onset approximately 3.5 meters) with three rounds of boreholes. After grouting the cross, the median inflow of boreholes was reduced from 2.0 liters/min to 0.03 liters/min. The median inflow for the second round of grouting boreholes was close to the median inflow for the first round of grouting boreholes, implying that the penetration of grout in the first round was not sufficient. For the traditional borehole pattern (Field test 2, Figure 4), the median inflow was reduced from 2.0 liters/min to 0.2 liters/min. The ungrouted rock mass had a median inflow of 70 l/min.

The postexcavation design and performance along section 190+850 – 190+983 m (133 meters) followed the flow charts presented in Figure 1 and Figure 3. Instead of data from a cored borehole, the median specific capacities from the pre-grouting and control holes were used as a basis to estimate hydraulic aperture and selection of grout. Following the grouting, complementary analyses using a design window, see Section 2.1.5, were made /Fransson and Gustafson 2008/. What is presented indicates that the postgrouting at Hallandsås has been successful since the measured inflow to the tunnel decreased with 60 – 70%. Comparing the inflow estimated when setting the design and the measured inflow, the measured inflow to the tunnel was larger than estimated. One explanation could be a well connected fracture system where water can easily find another flow path.

The design features boreholes drilled *beyond* the pregrouted zone. This is motivated by the identified risk for erosion of the grout due to the large hydraulic gradients around the tunnel.

## 3.4 Nygård railway tunnel (86 m + 60 m sections)

In the Nygård railway tunnel, both pre-excavation (436+637 – 436+723 m, 86 m) and post-grouting (435+690 – 435+750 m, 60 m) were performed /Butrón et al. 2008, Granberg and Knutsson, 2008/ and /Fransson and Gustafson, 2008/. The main rock types are gneiss and smaller occurrences of amphibolite. The depth is approximately 50 meters.

This work was part of the normal construction of the tunnel but a new design concept was tested. The pre-grouting aimed at drip-sealing of the roof and a general sealing of the tunnel. For this reason silica sol was used for the roof and cement grout for the floor. For the post-grouting, sealing with silica sol was made in selected areas. The design and performance followed the flow charts presented in Figure 1 and Figure 3.

Following the grouting, complementary analyses using a design window, see Section 2.1.5, were made /Fransson and Gustafson, 2008/. Small aperture fractures were expected based on an analysis where data were fitted to a Pareto distribution /Butrón et al. 2008/ and /Gustafson and Fransson 2005/ and for the pre-grouting five fans were made and the estimated hydraulic apertures were between 30 – 100 μm for Fan 1 and 30 – 200 μm for Fan 5. For Fan 1, a flow dimension analysis /see Gustafson and Stille 2005/ mainly identified a one dimensional flow. For Fan 5, several boreholes had a flow dimension larger than 2D. This indicates more open fractures for Fan 5 which was also found when doing a kriging analysis of the transmissivities from the hydraulic tests /Gustafson et al. 2008/.

Looking at the reduction of transmissivity in Fan 1, changes are mainly seen in the roof. This is in line with the ability of silica sol to seal fine aperture fractures.

The post-grouting performed in the roof of the Nygård tunnel seems to have worked well since there is a decrease in inflow of approximately 80% based on a drip mapping /Granberg and Knutsson 2008/. The complementary analyses made, investigating jacking, back-flow and erosion, motivate the design with the grouting boreholes drilled *within* the pregrouted zone.

## 3.5 Törnskog road tunnel (100 m section)

This work was part of the normal construction of the tunnel. Design, execution and evaluation of grouting was made for nine grouting fans along a 100 meter long section of one of the tubes, see /Funehag and Gustafson 2005/ and /Funehag and Gustafson 2008b/. The main rock types in the Törnskog tunnel area are granite and pegmatite. The depth is approximately 20 meters.

The design and performance followed the flow charts presented in Figure 1 and Figure 3. An analysis using a Pareto distribution and an estimate of tunnel inflow showed that fractures as small as 14 μm had to be sealed to reach the inflow requirement of 2 liters/min and 100 meters of tunnel. Silica sol was used and the design worked well and the water inflow was reduced. A mapping of drips in both tubes was made (the second one grouted with cement only). The drips were both larger and more frequent in the tube grouted with cement compared to the one grouted with silica sol. Eight out of nine grouting fans showed a significant sealing effect. When grouting with silica sol it is of vital importance to keep the grouting pressure until the sol has started to gel, or there is a risk for erosion of the grout. This rule was not followed during execution of the ninth fan, which consequently gave a weaker result.

# 4 Conclusions

The design methodology presented in this document is based on an approach that considers the individual fractures. Overview flow charts are used to show the different steps. The observations and analyses made during production enable the design to adapt to the encountered conditions. This section includes general comments and conclusions related to prediction and verification for the grouting in the tunneling projects in Section 3.

Of importance to consider when doing a design and evaluating the result are:

- The identification of the extent of the grouting needed based on inflow requirements and estimates of tunnel inflow before grouting.
- The selection of grout and performance of grouting materials including penetration ability and length. The penetration length is important for the fan geometry design.
- The ungrouted compared to the grouted and excavated rock mass conditions: estimates of tunnel inflow and (if available) measured inflows after grouting and excavation. Identify if possible explanations for deviations.

The inflow requirement is of central importance and the grouting should be designed to fulfill this. For the pillar experiment and the TASQ-tunnel (Äspö HRL), no inflow requirements were set. However, since only a cement-based grout was used in the TASQ-tunnel, sealing of fractures below an aperture of 50 µm was not expected. For the Hallandsås-, Nygård and Törnskog tunnels, the use of a Pareto distribution and the estimate of tunnel inflow identified a need for sealing small aperture fractures (< 50 – 100 µm) to meet the requirements. This should be in agreement with general expectations since Hallandsås has proven to be a difficult case and a drip sealing was the aim of the grouting at the Nygård tunnel.

The tunneling projects also show that using the hydraulic aperture as a basis for selection of grout is a good approach. Particularly the pillar experiment (Äspö HRL) identifies a clear difference between the very limited penetration (penetrability) of the cement-based grout and the larger penetration for silica sol in a hydraulic aperture of 50 µm. In addition, the results from the TASQ-tunnel using a cement-based grout confirms that fractures of about 50 µm but not below 30 µm had been sealed. The expectation when designing the grouting was to seal fractures down to approximately 50 µm. Another example pointing in the same direction is the Nygård tunnel, where all boreholes in Fan 1 /Gustafson et al. 2008/ have estimated hydraulic fracture apertures below 100 µm. The main change in transmissivity is seen in the roof where silica sol was used. Only a minor change was identified in the cement grouted boreholes in the floor of the tunnel. A conclusion drawn from these projects is that fractures with an estimated hydraulic fracture aperture below 50 – 100 µm are not likely to be groutable with a cement-based grout. To improve the result, a grout for fine aperture fractures should be used.

The pillar experiment at Äspö and laboratory work performed at Chalmers and KTH show that the developed theories can be used to estimate penetration length for both a gelling Newtonian fluid such as silica sol and a cement-based grout with Bingham fluid properties. For some of the projects, the penetration length for the smallest fracture to be sealed has been used as a basis to choose maximum borehole distance. Commonly an overlap of grout penetration has been used to increase the possibility of sealing the rock mass.

To investigate the result after grouting, the median specific capacity of the boreholes has been used. Using the median specific capacity to describe the general transmissivity of a fracture is in agreement with the result in /Fransson 2001/ and similar results presented in e.g. /Fransson 1999/ and /Sanchez-Vila et al. 1999/. Based on this, using the median specific capacity is a reasonable way to handle the issue. In all presented tunnel sections the proposed methodology has resulted in a successively decreased median inflow.

In the Hallandsås tunnel, one experiment was set up as a cross and the decrease in inflow was a factor of 100 (the median inflow of boreholes was reduced from 2.0 liters/min to 0.03 liters/min). However, both for the cross and the post-grouting at Hallandsås the median inflow for one round of grouting boreholes was close to the median inflow for the previous round of grouting boreholes indicating that the boreholes were not close enough to enable additional sealing. Explanations could be an insufficient penetration length but also channeled flow that decreases the chance of intersecting the conductive parts of the fractures. The latter was confirmed by studies of the flow dimension. In addition to the penetration length as the basic design criterion, a design window allows other issues to be addressed. Jacking, back flow and erosion were considered in an analysis for the Hallandsås and the Nygård tunnels. In these cases using boreholes drilled *beyond* the pregrouted zone for the Hallandsås tunnel (100 m depth) and *within* the pregrouted zone for the Nygård tunnel (50 m depth) had been suggested. The complementary analyses, investigating jacking, back-flow and erosion motivated the respective grouting fan designs. For future work, to continue to develop the design window approach is important. Already included issues considering e.g. jacking can be further developed and new issues could be added. There is also need for a verified method to set a criterion based on indications from inflow in control holes, to be used during construction, to decide when the achieved tightness is sufficient and the excavation should start.

Among the projects presented, the TASQ-tunnel at Äspö HRL and the post-grouting at Hallandsås have predicted tunnel inflows using the proposed methodology that have been followed up using weirs. For the TASQ-tunnel the predicted inflow based on a Pareto analysis was approximately 20 liters/min. The measured inflow is somewhat uncertain but approximately 5 liters/min. The prognosis overestimated the tunnel inflow. Sealing of a larger conductive fracture or fracture zone being the main supplier of water to many finer, connected fractures can be part of the explanation. For the post-grouting at Hallandsås the analysis was based on data from the pre-grouting fans and here, the prognosis underestimated the tunnel inflow. A well connected fracture system allowing flow to find other flow paths could be one explanation. Investigating how to improve the tunnel inflow prognosis is an ongoing project. To further increase the understanding for how geology, hydrogeology and geomechanics influence the result during both pre- and post-grouting can give still more chances to improve the result.

All the projects have been successful in terms of decrease in inflow. For the TASQ-tunnel pre-grouting, the decrease for the two grouting fans were 99.9% and 95% based on median values of inflow to grouting and control boreholes and for the postexcavation at Hallandås the measured inflow to the tunnel has decreased with 60 – 70%. Also, the post-grouting performed in the roof of the Nygård tunnel seems to have worked well since there is a decreased inflow of approximately 80% based on mapping of the drips /Granberg and Knutsson 2008/. For the Törnskog tunnel, eight out of nine grouting fans showed a significant sealing effect. The result was a general improvement when comparing to the parallel cement grouted tube. For the grouting fan with a weaker result, the design was not followed since pumping did not continue until gelling had started. This shows that a successful grouting is dependent not only on a carefully considered design, but also on a carefully controlled execution.

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