Getting it Tight at Great Depth
A Tunnel Sealing Project at Åspö HRL, Sweden

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1 Background

The Swedish Nuclear Fuel and Waste Management Co (SKB) faces a major project, to construct a safe repository for spent nuclear fuel. The repository concept is the so called KBS-3 concept which means that the spent fuel will be deposited at a depth of 400-700 m in a crystalline rock mass, see Fig.1.

The project falls under the Nuclear Activities Act. To claim that the concept is feasible, SKB must demonstrate, among other things, that sealing of the fractures in the rock mass can be accomplished at large depths [1]. The sealing is planned to be carried out by grouting and is needed in order to construct and operate the repository facility. Even though the grouting has no direct barrier or long term safety function it is obvious that the nuclear character of the project raises demands on transparent, comprehensive and systematic processes.

Swedish bedrock is to a major extent composed of hard crystalline rock, favorable for rock construction. The fact that the rock mass cannot be readily described by a number of distinct parameters has meant that rock grouting has been carried out almost exclusively on an empirical basis. To meet the requirements for the repository and to further complement the empirical base with theoretical understanding, SKB in 1993 initiated a series of research and development projects concerned with rock characterization for grouting, grouting materials, grouting predictions and grouting design. A number of projects is still under way.

Figure 1 The KBS-3 concept, vertical alternative. Deposition tunnels are excavated in crystalline rock mass and deposition holes drilled in the tunnel floors. The spent nuclear fuel is encapsulated in tight load bearing canisters surrounded by a buffer of swelling bentonite clay and deposited in the deposition holes. The buffer prevents ground water flow and protects the canister. The tunnels required to deposit the canisters are backfilled.
Progress in the area of grouting has also been made thanks to studies financed by other organizations, and a number of references are available, see e.g. [2]. The result is a grouting design methodology that is theoretically supported. The methodology or parts thereof have been applied in a number of experiments and projects [3]. The tunnel sealing project at Äspö HRL (Hard Rock Laboratory) takes the new understanding and methodology down to 450 m depth for the construction and sealing of an 80 m long tunnel.

2 Premises and purpose

The goals set up for the project are related to the requirements that will apply to the construction of the final repository facility. Project goals were:
- To show that silica sol is an appropriate grout at the planned repository depth.
- To show that it is possible to achieve a rock mass tightness corresponding to a maximum inflow of 1 litre/minute per 60 m tunnel using grouts applicable for the final repository.

Another goal was to confirm that increased tightness will result both from ordinary grouting fans drilled outside the tunnel contour and with grouting holes drilled only within the tunnel contour, respectively. It was also important to gain further understanding and execution experience and to identify further requirements on grouts and equipment.

The strict inflow requirement relates to the preliminary restriction on a deposition tunnel. As it was obvious early in the studies that very fine fractures needed to be sealed it was also clear that cement based grouts would not suffice, as cement cannot penetrate very fine fractures [4]. Furthermore, another restriction is that no material producing a leachate with pH above 11 may be used. Ordinary cement based grouts produce a leachate with pH of around 12-13. Consequently SKB has carried out studies on alternative grouting materials. A special low pH cement based grout has been developed and comprehensive studies have been carried out on colloidal silica (silica sol). The work has been carried out in cooperation with Posiva and Numo [5].

The properties of the grouts were a vital premise for the design. The cement based grout consisted of ordinary grouting cement with superplasticizer and a large addition of silica fume to lower the pH. The grout can be described as “thick and sticky” with a high shear resistance but still a high flowability. The size of the cement grains (d$_{50}$) is 16 µm and the penetration limit is around 100 µm in hydraulic aperture. In cases where tests indicated hydraulic openings of 150 µm or more, the cement-based grout should be used. Silica sol is a fairly new agent for grouting. It consists of nano-sized particles of silica SiO$_2$ in water. When mixed with a salt solution (NaCl) the viscosity of the water-like fluid increases; it starts to gel. Gelling time is regulated by adjusting the amount of salt added, making it possible to control the spread.

In the KBS-3 concept the rock mass is a barrier for the migration of nuclides and should be kept as intact as possible. This implies that the amount and spread of grout should be limited, and that holes in the remaining rock mass should be avoided. Thus it was decided to set up and test the concept of a grouting fan with holes within the tunnel contour only. Since fans within the contour was a new concept, the tests were to start with ordinary exterior fans.

An additional goal was to show that post-grouting can increase the water tightness in a previously excavated section. Post-grouting has been carried out, but the results are still under evaluation. Hence, post-grouting is not further discussed in this paper.

To maintain control and transparency an implicit premise was that the newly developed design methodology should be used. Besides showing the fulfillment of sealing requirements, it was important to document the actual conditions under which results were achieved. Since the sealing result still was important, the design was conservative. This meant that the grouting and control measures undertaken were extensive and that optimization was not part of the project.
The following premises were set up to find a suitable location at Åspö for the experiment. No major fracture zones should be present; the tunnel should pass through the main part of the fractures at a 70-90 degrees angle; there should be at least two open fractures per meter; the hydraulic width of the fractures should vary between 10 and 300 µm; and the water pressure 25 m into the rock should be at least 3.5 MPa.

Possible sites at Åspö HRL were evaluated based on available information. The selected candidate site was situated at 450 m depth where it was possible to drive the tunnel almost perpendicular to the major rock stress, meaning that the main part of the open fractures would be met at a 90 degrees angle. Three core holes were drilled along the planned tunnel extension. Hydraulic tests confirmed that the fracturing was suitable with inflow peaks around 40 liters per minute, see Fig. 2, and that the pressure was high enough. The tunnel was given the name TASS.

3 Project outline

The field test was originally designed to be composed of seven pre-grouting fans. The need for flexibility during execution of the project was however emphasized, i.e. adaptation to the encountered rock conditions, results and experiences. The outcome was six grouting fans, see Fig. 2. The grouting consisted of the following stages:
1. Fan 1. A short fan with boreholes outside the contour. Equipment and grouts were tested.
2. Fans 2 and 3. 20-25 m long fans with boreholes outside the tunnel contour.
3. Fan 4, 5 and 6. 20 m long fans with boreholes within the tunnel contour. Based on results and experiences from fan 4 the design was adjusted for fans 5 and 6.
4. Hydraulic tests from tunnel face holes gave low inflows and further excavation was stopped.

Figure 2 The TASS tunnel and inflows from pre-investigations. Above: The project consisted of 6 fans. Red lines indicate weirs to measure the inflow. Below: Inflow in the three core drilled holes measured as natural inflow between packers in 3 m sections. Two holes (green and red) were positioned within the planned tunnel contour, one (blue) at a distance of 1.0 m from the tunnel wall. The section given relates to the deepest positioned packer.
Design of the grouting operations is based on the prognosis from the site selection. It specifies the geometry of the fan, distance between grouting holes, grouting pressure and grout. Controls and conditions for the adjustments of the design to the actual rock mass conditions and achieved results are included. The uncertainties that give cause for an iterative approach exist both in the rock mass variations and in the models that simplify the grout spread and the inflow to the grouted tunnel. The approach which is presented in Table 1 resembles the observational method. Conditions for a stringent application of the method are stated in Eurocode 7 [6].

<table>
<thead>
<tr>
<th>When</th>
<th>Requirement</th>
<th>Observation</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before grouting</td>
<td>Inflow and fracture characteristics to comply with the prognosis used as basis for the basic design</td>
<td>Fracture and hydraulic data from fan and control holes.</td>
<td>In case of compliance, variable values to be selected according to specified conditions. In case of non compliance, special adaptation of the design</td>
</tr>
<tr>
<td>During grouting</td>
<td>Grout flow at designed grout pressure to comply with the flow predicted in the design.</td>
<td>Logged pressure, volume and flow. Occurrence of grout flowing back into the tunnel.</td>
<td>In case of non compliance, adaptation of the grouting measures, primarily by adjusting the variable parameters.</td>
</tr>
<tr>
<td>After grouting, before excavation</td>
<td>Tightness of the grouted rock mass to comply with the designed tightness.</td>
<td>Inflow into control holes.</td>
<td>In case of non compliance, another grouting round, extent based on results from the previous round.</td>
</tr>
<tr>
<td>After excavation</td>
<td>Actual inflow lower than the requirement.</td>
<td>Inflow measured in weirs.</td>
<td>Post-grouting.</td>
</tr>
</tbody>
</table>

*Table 1* The permeability of the rock mass, the grouting and the effect of grouting is checked before, during and after excavation. The table is based on [1], where a first interpretation of the observational method for grouting is presented, and adapted to the project aims.

The design model used is presented in Fig. 3. It considers the individual fractures that need to be sealed and is more comprehensively described in [3]. The starting point was the maximum allowable inflow and data from the pre-investigations (Fig. 3, step 1 and 2). Transmissivities and hydraulic apertures were derived with the assumptions of one major fracture per 3 m section and unconnected fractures. The specific capacity (measured inflow divided by pressure) was used as an estimation of the transmissivity, and the hydraulic apertures were calculated with the cubic law.

*Figure 3* Design model, showing the steps referred to in the text.
Figure 4 Calculated hydraulic apertures fitted to a pareto distribution and presented as a cumulative function. The vertical line indicates the design fracture, i.e. the smallest fracture to be sealed in order to comply with the sealing requirement.

The cubic law states that the transmissivity is proportional to the cube of the hydraulic aperture, see further [7]. Based on section inflows the hydraulic apertures were calculated to range up to 200 µm. Data were fitted to Pareto distributions (Fig.3 step 3 and 4). The pareto distribution is a distribution with few high values and several low values. In Fig. 4 the hydraulic aperture distribution is presented as a cumulative function. The figure shows e.g. that 95 % of the fractures were expected to be smaller than 20 µm. The inflow to the tunnel, if no grouting were to take place, was calculated to around 90 l/min based on the transmissivity distribution (Fig.3 step 5). For the expression used for calculation of inflow to the tunnel, see [7].

Every fracture contributes to the inflow. By deducting the contribution first from the largest fracture and then from the successively smaller fractures, the smallest fracture that needs to be sealed, the “design fracture” (10 µm), was identified (Fig.3 step 6). With fractures to be sealed ranging from 10 to 200 µm it was confirmed that both silica sol and cement were to be used (Fig.3 step 7).

Fracture orientations were studied (Fig.3 step 8) to determine grouting fan geometries with a high probability for the holes to intersect the fractures (Fig.3 step 9). The aim of the grouting is to create a sealed zone around the tunnel. Fans are traditionally drilled from the tunnel front at an angle outwards and forward in the direction of the tunnel and the sealed zone is considered to be equal to the distance between the tunnel contour and the fan bottom, usually around 4-5 m. A common fan length is around 20 m which equals 4 blasting rounds plus a 4 m overlap between fans. With major fractures perpendicular to the tunnel no reason was found to change the geometry for the basic design. In the case of fans within the contour the sealed zone is assessed as the grout spread that takes place within the remaining rock mass in the design fracture.

For both fan types the grout spread in the design fracture is required to set the grouting hole distance. The grout should spread far enough to meet the grout from a neighboring hole. As the fracture is not the shortest distance between holes, a theoretical grout spread overlap is desired. With perpendicular fractures, an overlap of 50% was chosen. With a hole distance of 2,0 m, the corresponding grout spread was set to 1,5 m.

Assessment of grout spread is presented in [8] and [9, 10]. It is shown that (knowing the pressure and the grout properties) theoretical maximum grout spread is proportional to the hydraulic aperture. Furthermore the relative penetration (to the max penetration) at a certain time is independent of aperture.
In the next step (Fig.3 step 10) combinations of pumping time, pressure and distance between holes were further explored with regard to grout spread in the largest fracture and risk for erosion. The great depth meant that the risk for erosion was considerable. Erosion processes can occur when flowing water carries away the grout; when grout is pressed back into the tunnel “backflow”; or when channels are formed at the grout front during grouting “fingering”. The conditions suggested in [11] to avoid these mechanisms are observed in the project. Considerations include grout yield strength and viscosity, ratio between pumping and groundwater pressure and grout spread when pumping is stopped. The resulting design prescribed a total grouting pressure of 7-9 MPa with gelling times of 19-63 min and grouting times of 15-50 min for silica sol; pressure 10 MPa and grouting time 45 minutes for cement based grout. Fan geometries are shown in Fig 6. The design also included front holes that were grouted before the perimeter holes, in order to lower the pressure gradient and prepare for the next fan. Further design data are found in [12].

The design was concluded (Fig.3 step 11) with conditions for the applicability of the design and for the continued operations, compare Table 1.

5 Control of performance during execution

Of special interest during execution are the inflows in grouting and control holes. Besides giving input to the selection of grouts, pressures and times, they give information which is used to determine the scope of next fan.

Control holes were placed in between two grouted boreholes where a second round of grouting could be of use; between holes that showed large inflows or grout takes, and between hydraulically connected holes. There were always 5 holes evenly spread around the tunnel contour. With these criteria the number of control holes was 5 to 25.

The inflows for the first round of grouting holes are plotted in a probability diagram and fitted to a log-normal distribution. After grouting, inflow data from the control holes are plotted and a new inflow graph created. The difference in median inflow ($\rho=0.5$ on the y-axis) between the rounds signifies the increased tightness of the rock mass. For example, the tunnel face holes for Fan 2, see Fig. 7 have a median inflow prior to grouting of 9 l/min (single black dot). When the inflow was measured in the grouting boreholes in the first round, the inflow had not been significantly reduced (blue). When the boreholes were grouted (first round) with both cement and silica sol, the median inflow measured in control holes (red) was reduced to 0.01 l/min, which indicates a reduction factor of nearly 1000. For the last round (green), no further increase in tightness was achieved.
The inflows from the boreholes before grouting and the inflows in the control holes after grouting. Face holes were used before the ordinary fans in order to decrease the pressure gradients and the risk for erosion. Face hole inflows are here only represented with one black dot corresponding to the median value from four holes.

6 Sealing result and conclusions

The resulting inflows before post-grouting are presented in Table 2. The inflow is smaller than the target except for the first fan within the contour. When the design was changed so as to obtain a theoretically larger extent of the sealed zone, the requirement was met.

Table 2 Target section inflows and inflow in the weirs March 2009 The max allowable inflow 1 liter/minute and 60 meter tunnel is proportionately distributed to the length of the section to obtain the target section inflows.

<table>
<thead>
<tr>
<th>Fan and section</th>
<th>Fan type</th>
<th>Target section inflow [l/min]</th>
<th>Measured inflow [l/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan 2 and 3, 10-34 m</td>
<td>Outside contour</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Fan 4, 34-50 m</td>
<td>Inside contour</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Fan 5 and 6, 50-80 m</td>
<td>Inside contour</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Sum, 10-80 m</td>
<td></td>
<td>1.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

It can be concluded that silica sol works at repository depth for fractures within the hydraulic aperture interval tested (max 150 \(\mu\)m). The gel time for silica sol is important. It is a central parameter in the design and the execution. The test shows that the gel time is controllable, which is a premise for controlled grouting. The cement based grout was found to be readily handled and effective for the larger fractures.

It is possible to achieve very high water tightness even for a deeply situated tunnel. It was possible to reach the target goal with grouting holes drilled only within the tunnel contour when the need for a larger sealed zone was observed. The design work showed that the grouting should be designed to sealing fractures down to 10 \(\mu\)m in order to achieve the target inflow. A robust design, appropriate equipment, a well executed grouting operation and an organization that is suited to the target are a necessity.

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References


[5] A. Bodén, U. Sieväs, Low-pH injection grout for deep repositories - Summary report from a co-operation project between NUMO (Japan), Posiva (Finland) and SKB (Sweden), Report R-05-40, Swedish Nuclear Fuel and Waste Management Company, Stockholm, 2005


