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Is it watertight? Observations and comments related to grouting of rock mass

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Abstract

In Sweden, a permit under the Environmental Code is not required if it is obvious that neither public nor private interests are harmed by the impact of water activities on water conditions. For large infrastructure projects however, a permit is typically required, and this keynote aims at highlighting the importance of an increased integration between hydrogeology, technical feasibility of grouting, and environmental impact assessment.

Observations and reflections on four relevant issues are presented. First, the degree of difficulty in pre-excavation grouting is visualised and discussed based on values of required hydraulic conductivity and required sealing efficiency.

The second topic relates to the impact, effects, and consequences; essential components of an environmental impact assessment. For instance, the question is asked: Are there any consequences if the required hydraulic conductivity is assumed to be too low?

Thirdly, the imminent need to further investigate and link technical design and feasibility to measured reductions in hydraulic conductivity is pinpointed. Finally, a few observations will be presented related to general nature, pattern, and properties of rock (and soil) and the importance of an adaptation of the grouting design to hydrogeological conditions. With that, highlighting the need of additional knowledge and understanding as an input for analysing and modelling the impact on water conditions.

The findings suggest that project risks, as well as risks for private and public interests, can be reduced if additional focus is given to the above. When highlighting these four issues we are better equipped to identify what sealing measures are necessary and sustainable, from an environmental perspective and hence reduce the risk of a project ending up in a very difficult task related to grouting and sealing of shafts and tunnels.

Keywords

Environmental permit, hydrogeology, grouting, technical feasibility, environmental impact assessment

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1 Introduction

In Sweden, a permit under the Environmental Code is not required if it is obvious that neither public nor private interests are harmed by the impact of water activities on water conditions (Riksdagen 1998). For large infrastructure projects however, a permit is typically required, and an environmental impact assessment is performed to investigate the impact, effect and consequence of the water activities.

As an example, Fig. 1 shows sketches of drawdown around a circular shaft in rock (red) and in soil (blue). The impact would be the shaft itself and the effect would be the change that occurs in the environment, such as a drawdown or settlement. The consequence would be the significance of this change, for example harm to buildings, a well, or species in need of protection (Naturvårdsverket 2024).

In this paper observations and reflections on four relevant issues related to grouting of rock mass are presented. First, focus is on the degree of difficulty in pre-excavation grouting. Can this be visualised to help in transdisciplinary communication? Further, if the hydraulic conductivity of a grouted zone is set too low in a model, how would this influence our assessment of effect and consequence? Both questions relate to early descriptions and models. Models that should be validated based on investigations and measured data and where measured data may also influence the modification of grouting design.

All the above can be illustrated using Fig. 1 that shows the hydraulic conductivity of rock before grouting, K_0, and following grouting, K_g. As a simplification, the greater the reduction, the greater the degree of difficulty in pre-excavation grouting. This will be further investigated and visualised in section 2.1. An assessment of the degree of difficulty in pre-excavation grouting was based on Stille (2015).

In addition to the above, Fig. 1 also includes a graph representing drawdown with no grouting, left, and a graph representing a smaller drawdown due to a grouted zone with reduced hydraulic conductivity, right. If the hydraulic conductivity in a model is set too low, there will be a limited drawdown and a risk that potential effects and consequences will not be identified, see section 2.2. Further, if this hydraulic conductivity cannot be achieved in practice, there is a risk that protective measures may not be in place or that they are not at all prepared for. This also highlights the importance of investigating the hydraulic conductivity during a grouting performance, to either confirm that what was expected was achieved, or allow for a modification of design if not, see section 2.3.

General nature, pattern and (hydraulic) properties of rock are key for design and adaptation of grouting. If the most water-bearing features intersecting the vertical shaft in Fig. 1 were horizontal, vertical boreholes would intersect these water-bearing features. A horizontal tunnel and sub-horizontal grouting boreholes would risk not being as successful in a geology with this fracture pattern. This is highlighted in section 2.4. Finally, groundwater levels and inflow are key observations related to grouting, both parameters are shown in Fig. 1. Parameters that are of importance for the follow up of an environmental permit, and that should be used as guidance for all groundwater related tunnelling works.

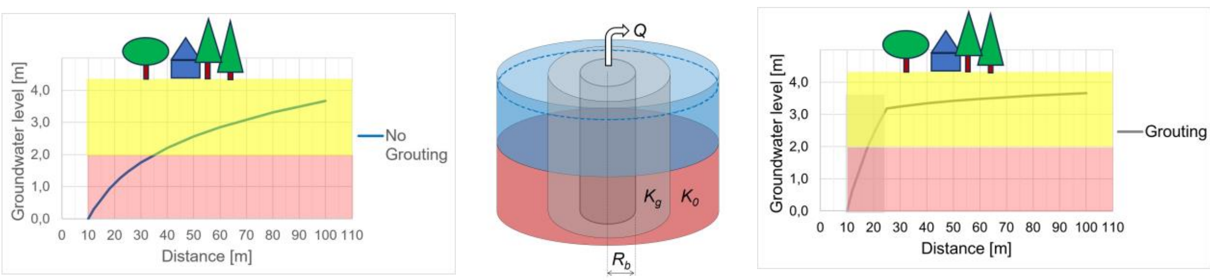


Fig. 1 Sketches of groundwater levels and drawdown around a circular shaft in rock (red) and in soil (blue). The left graph shows a situation with no grouting, hydraulic conductivity, K_0, and the right graph shows a situation with a grouted zone, K_g.

2 Observations and reflections - Four relevant issues

2.1 Degree of difficulty in pre-excavation grouting

The starting point for assessing and visualising the degree of difficulty in pre-excavation grouting was an integration of data from the map viewer Hydraulic conductivity in rock from the Geological Survey of Sweden (SGU 2024) and a table describing the difficulty of pre-excavation grouting (Stille 2015), see Table 1. The map viewer shows calculated hydraulic conductivity (log10K) for a subset of rock-drilled wells in SGU's Well Archive. The map is assumed to represent hydraulic conductivity in rock within 100 m of the ground surface, except for the very top part of the bedrock.

Central input for the table is the required hydraulic conductivity, K_g, and the required sealing efficiency. The required sealing efficiency can be estimated based on the below:

$$\text{Required sealing efficiency} = 1 - K_g/K_0 \tag{1}$$

Where K_g Required hydraulic conductivity (grouted rock)
K_0 Initial hydraulic conductivity (ungrouted rock)

These two, in turn, can be used to make a qualitative assessment of the difficulty of pre-excavation grouting from uncomplicated grouting to very difficult grouting, see Table 1.

Table 1 Degree of difficulty in pre-excavation grouting. Modified based on Stille (2015).

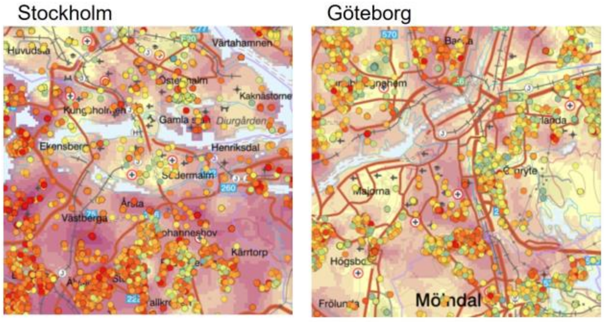
	Required sealing efficiency 1-K_g/K_0		
Required hydraulic conductivity, K_g	< 90%	90-99%	> 99%
> 1.0E-7 m/s	Uncomplicated grouting	Fair grouting	Difficult grouting
1.0E-7 to 1.0E-8 m/s	Fair grouting	Difficult grouting	Very difficult grouting
< 1.0E-8 m/s	Difficult grouting	Very difficult grouting	Very difficult grouting

The novel idea, for visualisation and to help in transdisciplinary communication, was to use Eq. 1 to estimate initial hydraulic conductivities, K_0, given required sealing efficiencies and required hydraulic conductivities. Further, relevant intervals and colours of K_0, were based on the legend of SGU's map viewer Hydraulic conductivity in rock (SGU 2024). Finally, estimated values and related colours were included in a modified version of Table 1, see Fig. 2. The visualisation indicates areas where, for example, difficult or very difficult grouting could be encountered. A qualitative assessment that can be related to actual experiences from pre-excavation grouting of tunnels.

In the example presented in Fig. 2, a required hydraulic conductivity, K_g, of < 1.0E-8 m/s was assumed and intervals of the initial hydraulic conductivity of rock, K_0, were estimated for the required sealing efficiencies < 90%, 90-99% and > 99%. The intervals of K_0 were then indicated using the same colours as for the SGU´s map viewer.

Fig. 2 also includes a compilation of maps from Stockholm, Göteborg, Varberg and Hallandsås originating from the same map viewer. Areas with a burgundy colour, K_0 < 1.0E-7 m/s (log*K* -7.0), would indicate difficult grouting. Areas with a green colour, K_0 > 1.0E-6 m/s (log*K* -6.0), would indicate very difficult grouting,

Based on Fig. 2 a first conclusion is that if assuming a required hydraulic conductivity < 1.0E-8 m/s, the degree of difficulty will be either difficult or very difficult. A relevant question would be, is this necessary?



	Required sealing efficiency, 1-K_g/K_0		
Required hydraulic conductivity, K_g	**< 90%**	**90-99%**	**> 99%**
> 1,0E-07 m/s	Uncomplicated grouting	Fair grouting	Difficult grouting
1,0E-7 to 1E-8 m/s	Fair grouting	Difficult grouting	Very difficult grouting
< 1,0E-08 m/s	Difficult grouting K_0 < 1,0E-07 -7,75 -7,5 -7,25	Very difficult grouting -7,0 -6,75 -6,5 -6,25 -6,0	Very difficult grouting K_0 > 1,0E-06 -5,75 -5,5 -5,25

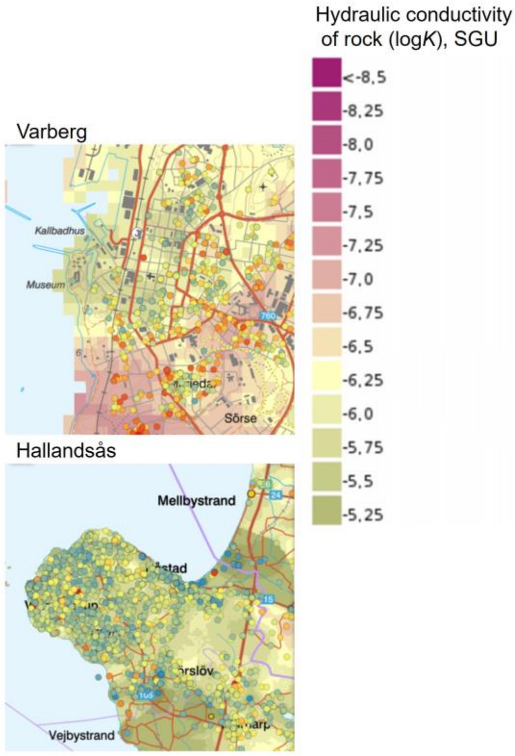


Fig. 2 Degree of difficulty in pre-excavation grouting. An assessment of difficulty assuming a required hydraulic conductivity, $K_g < 1{\cdot}10^{-8}$ m/s. Green, yellow and light red colours based on SGU (2024), indicate very difficult grouting. Table modified based on Stille (2015).

2.2 Impact, effect and consequence – if the hydraulic conductivity is set too low

The second topic relates to the impact, effects, and consequences that are essential components of an environmental impact assessment and evaluation of necessity. For instance, the question is asked: Are there any consequences if the required hydraulic conductivity is assumed being too low?

2.2.1 Observation 1 Tunnel in a rural area

At an early stage of a tunnel project, it was concluded based on a groundwater model that a lake above a section of the tunnel would not be affected by the tunnel work. On closer inspection, this was likely to be because the hydraulic conductivity of the grouted zone around the tunnel had been set to a low value. A value that would not necessarily be easy to achieve in practice, since pre-excavation grouting was the proposed technical measure. In addition, the hydraulic boundary conditions were formulated in a way that made a drawdown less likely.

2.2.2 Observation 2 Tunnel in an urban area

Expected inflow to a future tunnel through an urban area was set to a low value. This inflow was used as input when applying for a permit. The inflow could not be reached, and a possible reason was that the required hydraulic conductivity, K_g, had been set too low and that this could not be achieved in practice. Probably, a different choice of method, for example a lining, would have been needed *if* necessary to counteract harmful impact of water activities on water conditions.

The above are two examples indicating that there might be a gap between the required hydraulic conductivity that is assumed when modelling, what is possible to achieve in practice with the suggested method, and what is necessary to counteract harmful impact.

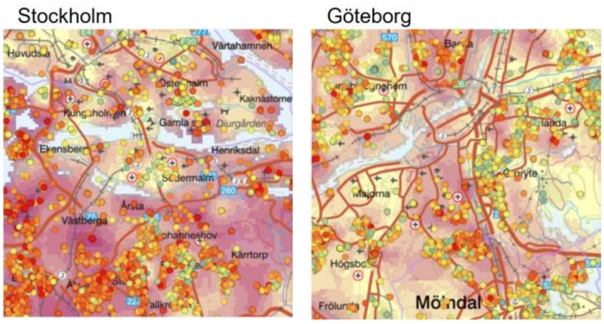
2.3 Technical design and measured reduction in hydraulic conductivity

Thirdly, the imminent need to further investigate and link technical design and feasibility to measured reductions in hydraulic conductivity is pinpointed. Instead of suggesting a too low value of the grouted zone, what about investigating what can be achieved and if that is sufficient to counteract harmful impact?

The example that will be presented here relates to a curtain grouting along a limestone quarry, Västra brottet, in Slite, Gotland, Sweden. Grouting was performed using a cement-based grout, and the stepwise procedure of the curtain grouting included drilling boreholes with an internal distance of 10 m. This was followed by water loss measurements and then boreholes were grouted. In the next step, new boreholes were drilled in between the previous ones resulting in a borehole distance of 5 m. For these boreholes, water loss measurements were also performed.

When evaluating the specific capacity, *Q/dh*, based on the water loss measurements, the boreholes of the first group had a median specific capacity of 9E-6 m^2/s and the boreholes in between hade a median specific capacity of 6E-6 m^2/s. Having a borehole section length of 30 m this would result in hydraulic conductivities, here represented by *Q/dh/L* m/s, of 3E-7 m/s and 2E-7 m/s respectively.

The data above was used to further develop the example presented in Fig. 2. This is shown in Fig. 3 where a map of Västra brottet, Slite, is included in the lower right, a map showing log*K*-values of approximately -6 to -6.5. This agrees with the measured median hydraulic conductivity before grouting of 3E-7 m/s (log*K* -6.5). Further, performing the same calculations as presented in section 2.1 would result in a sealing efficiency of approximately 30%, 1- (2E-7/3E-7), when using the measured hydraulic conductivity following grouting of 2E-7m/s. Based on Fig. 3 this would correspond to a sealing efficiency < 90%, a hydraulic conductivity > 1E-7 m/s and an uncomplicated grouting. A grouting performance and a result that was judged to mitigate the effect on the groundwater body, this being the main purpose of the activity.



	Required sealing efficiency, 1-K_g/K_0		
Required hydraulic conductivity, K_g	**< 90%**	90-99%	> 99%
> 1,0E-07 m/s	Uncomplicated grouting -6,5	Fair grouting	Difficult grouting
1,0E-7 to 1E-8 m/s	Fair grouting	Difficult grouting	Very difficult grouting
< 1,0E-08 m/s	Difficult grouting K_0 < 1,0E-07 -7,75 -7,5 -7,25	Very difficult grouting -7,0 -6,75 -6,5 -6,25 -6,0	Very difficult grouting K_0 > 1,0E-06 -5,75 -5,5 -5,25

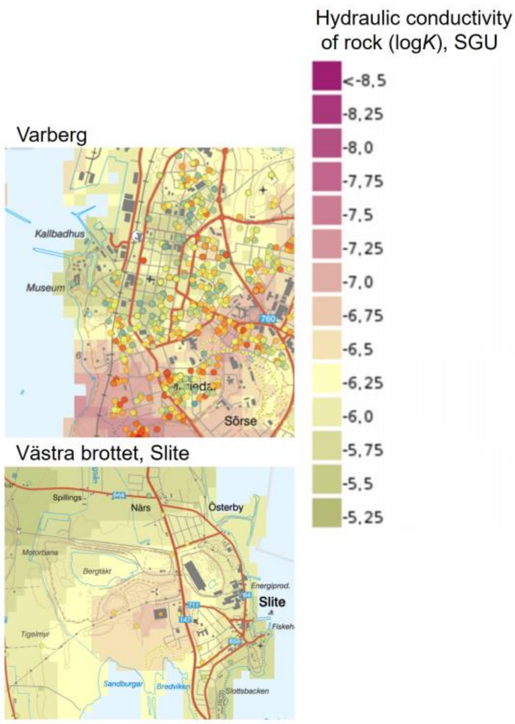


Fig. 3 Degree of difficulty in pre-excavation grouting. Adding an assessment of difficulty for Västra brottet, Slite, with a required (measured) hydraulic conductivity of 2E-7, i.e. K_g > 1E-7 m/s, a sealing efficiency of 30% (1- 2E-7/ 3E-7), and an uncomplicated grouting. Table based on Fig. 2, that was modified based on Stille (2015).

2.4 General nature, pattern and properties of rock and adaptation of grouting design

In previous sections the required hydraulic conductivity, K_g, plays a key role. As illustrated in Fig. 3 a required hydraulic conductivity < 1E-8 m/s can be expected to be difficult or very difficult to achieve with pre-excavation grouting. For a very difficult or an uncomplicated grouting, what can be achieved will always depend on how well the grouting design is adapted to general nature, pattern and properties of rock and soil.

Below, a few observations are presented pointing at the importance of an adaptation of the grouting design to hydrogeological conditions and with that, highlighting the need of additional knowledge and understanding as an input for design and for analysing and modelling the impact on water conditions.

2.4.1 Fracture and grouting hole orientation – are the most water bearing features intersected?

The general nature, pattern, and properties of the bedrock shown in the photograph in Fig. 4 could be condensed into a crystalline host rock with large sub-horizontal fractures where the horizontal hydraulic conductivity exceeds the vertical. Data originates from the Varberg tunnel project.

Knowing this, would intersecting these water-bearing sub-horizontal features be important? Most people would say yes, intersecting the most water-bearing features would be a very good idea. The importance of fracture and grouting hole orientation is exemplified in Fig. 4. The upper part of Fig. 4 indicated by a) shows the results from water loss measurements for the first and second grouting rounds of a grouting experiment, see Fransson (2023). The experiment was performed using vertical boreholes drilled in the specific rock volume where the photo shown in Fig. 4b was later taken.

In Fig. 4a, green boreholes mean that an estimated hydraulic aperture was smaller than 90 µm, orange and red mean that it was larger. Going from orange or red to green meant a reduction in hydraulic conductivity following the first grouting round, this could be seen for all boreholes but one.

The hydraulic apertures were estimated using data from water loss measurements and the cubic law (Witherspoon et al. 1980). Estimates were made assuming that all flow occurred in one fracture and that flow divided by change in head, Q/dh, was equal to the transmissivity of the fracture, T.

What can be observed in Fig. 4a, is that all the vertical boreholes show orange values before the first grouting round. This is reasonable given the large sub-horizontal fractures where the hole orientation is very well adapted to the fracture orientation.

This can be compared to Fig. 4c showing the first and second grouting round of the first grouting fan. This grouting fan was drilled when excavating the service tunnel that is also visible in the photo. Grouting of this tunnel was performed using a traditional grouting fan with sub-horizontal boreholes, see Fransson (2024). Here as well, green boreholes mean that an estimated hydraulic aperture was smaller than 90 µm, orange and red mean that it was larger. In addition to the boreholes around the tunnel, four boreholes were added in the tunnel front to investigate anisotropy. Two boreholes were drilled along the tunnel with a downward direction and aimed at identifying horizontal water-bearing features. Two horizontal boreholes with a direction towards the right were drilled to identify vertical water-bearing features.

For these boreholes as well, going from orange or red to green meant a reduction in hydraulic conductivity following the first grouting round. There was a reduction, but the pattern was different. Boreholes in the roof and floor indicated a reduction, but other boreholes were green both before and after the first grouting round. This as well would agree with a crystalline host rock with large sub-horizontal fractures where the horizontal hydraulic conductivity exceeded the vertical.

Commonly, the borehole distance within a grouting fan is much smaller than the distance between grouting fans along a tunnel. If assuming a distance between grouting fans of 20 m and looking at the photo, the sub-horizontal fractures would, potentially, be intersected every 20 meters. If the penetration length in this fracture would be less than 10 m, there would be no theoretical overlap and there would be an inflow between fans along the tunnel. To do better, the rock must not be described as isotropic, with the same hydraulic properties in all directions, there is a need to focus first on what is most water-bearing.

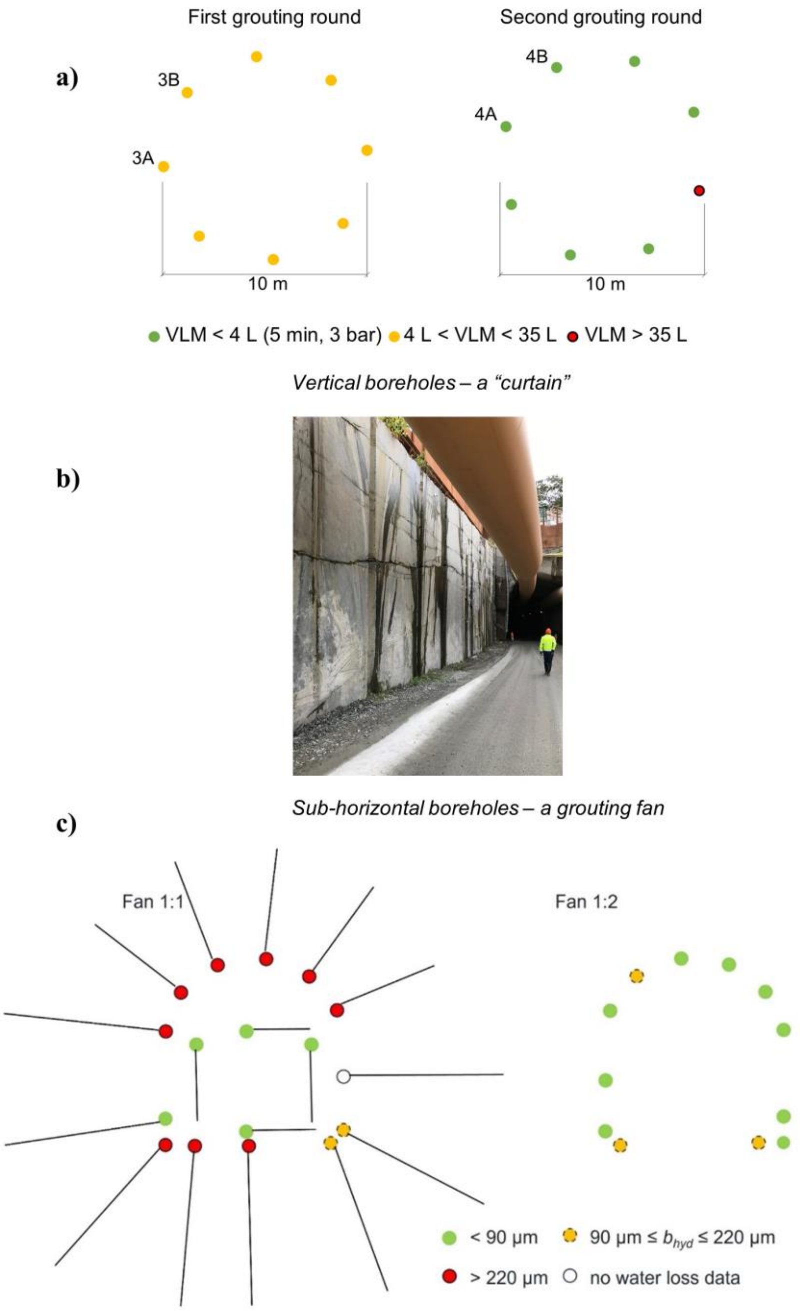


Fig. 4 Fracture and grouting borehole orientation – a) vertical boreholes, a "curtain", b) horizontal fractures (photo) and c) sub-horizontal boreholes, a grouting fan. Data from the Varberg tunnel project. Modified based on Fransson (2023) and Fransson (2024).

2.4.2 Geology, grouting pressure, groundwater pressure and tunnel inflow

In this section the focus is on grouting pressure, groundwater pressure and tunnel inflow. Of particular interest is an example where grouting boreholes intersected a deformation zone and where the grouting pressure was potentially too high. A key question to ask is what inflow and groundwater levels are necessary to maintain for technical function and to counteract harmful groundwater impact. It is also important to have and react on observations that may point in an opposite direction.

For this observation, Observation 3, general nature, pattern, and properties could be condensed into a deformation zone in a crystalline host rock. The rock tunnel was shallow and found below a depression in rock in an urban area.

In Fig. 5 groundwater levels in rock, Rock bh B, and soil, Soil bh A, close to the shallow rock tunnel are shown. In the end of January, there was a sudden drop in groundwater levels (a). This coincided with post-excavation grouting of a deformation zone, an increase in measured tunnel inflow and an observed inflow in the vicinity of grouting boreholes.

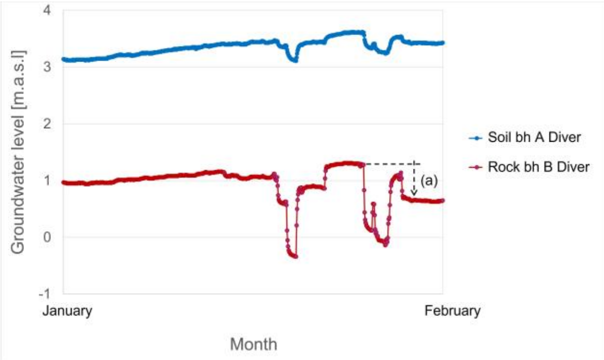


Fig. 5 Observation 3, a shallow rock tunnel intersecting a deformation zone and below a depression in rock. Groundwater levels and hydraulic effect of grouting. Sudden drop of groundwater levels in the end of January (a).

Since the management of groundwater levels and inflow are the main aims of grouting, a follow up focusing on, for example, grout take of boreholes is not sufficient. Further, a feeling that the grouting pressure is just right would not be sufficient either. Following the set of observations above, there is probably a need to make a revision of the grouting performance. Is there a need to lower the grouting pressure and/or modify the borehole geometry to increase the distance between the tunnel wall and the location where the grouting boreholes intersect the deformation zone?

2.4.3 Groundwater pressure – activities inside and outside a tunnel – integration and optimisation

The final observation, Observation 4, has its focus on groundwater levels and the hydraulic effect, i.e. the change in groundwater levels, due to activities inside and outside a tunnel in an urban area. Examples of activities inside a tunnel, besides grouting, could be drilling of boreholes for rock bolts or other installations. Activities outside the tunnel could be infiltration where water is added through boreholes or wells. This observation highlights the importance of integrating and optimising all activities that may influence groundwater levels and tunnel inflow. In Fig. 6 groundwater levels in two boreholes in soil, Soil bh1 and Soil bh 2, close to a rock tunnel are shown from December to April. In the middle of February (a), there was a sudden drop in pressure in borehole Soil bh 2, a drop that went below the level where a pressure transducer was installed. Based on manual measurements in a nearby borehole, Soil bh 1, the drawdown was at least 1.5 m. The sudden drop in pressure coincided with work inside the tunnel, in this case probably drilling of boreholes for installations, or grouting. This can be compared to the drop in pressure of about 0.5 m in early December (b). This drop coincided with the shutdown of an infiltration performed in a borehole in soil close to the tunnel.

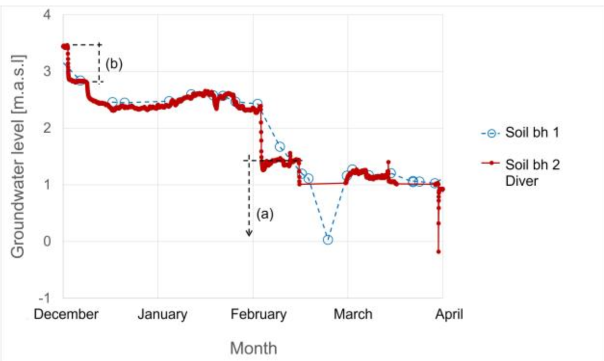


Fig. 6 Observation 4, groundwater levels and hydraulic effect due to activities inside and outside a tunnel. Inside the tunnel, a sudden drop in level in February (a), probably due to drilling of boreholes for installations, or grouting. Outside the tunnel, a shutdown of infiltration in December (b), resulted in a smaller drop.

3 Concluding remarks

The findings in this paper suggest that project risks, as well as risks for private and public interests, can be reduced if additional focus is given to four specific issues. First, the degree of difficulty in pre-excavation grouting was visualised to help in transdisciplinary communication. This included a novel integration of a table describing degree of difficulty (Stille 2015) and SGU's map viewer Hydraulic conductivity in rock (SGU 2024). These early results, that will be further investigated, form a visual and qualitative assessment that can be related to actual site-specific experiences from pre-excavation grouting of tunnels and shafts.

Concerning the second issue, impact, effect and consequence and what happens if hydraulic conductivity around a tunnel in a groundwater model is set too low, it was concluded that there seems to be a gap. A gap or a mismatch between the hydraulic conductivity set around a tunnel in a groundwater model, to investigate impact, effect, and consequence, and what can be achieved with a suggested sealing measure, such as grouting. If the hydraulic conductivity surrounding the tunnel is set too low in the groundwater model, the drawdown will be limited, potential consequences may not be identified, and protective measures may not be prepared for. Watertight? Neither the reasoning nor the future tunnels when we are promising too much.

Thirdly, the need to further investigate and link technical design and feasibility to measured reductions in hydraulic conductivity was pinpointed. Instead of suggesting a too low value of the grouted zone, what about investigating what can be achieved and if that would be sufficient to counteract harmful impact? In the example presented in this paper, a curtain grouting was performed along a limestone quarry, Västra brottet, Slite, Sweden. Based on the result, the sealing efficiency was estimated to 30% with a required (measured) median hydraulic conductivity of 2E-7 m/s and an initial (measured) median hydraulic conductivity of 3E-7 m/s. Based on Fig. 3, a sealing efficiency of 30%, i.e. < 90%, and a hydraulic conductivity following grouting of 2E-7 m/s, i.e. > 1E-7 m/s, would correspond to an uncomplicated grouting. A grouting performance and a result that was judged to mitigate the (hydraulic) effect on the groundwater body, this being the main purpose of the activity.

Finally, general nature, pattern and properties of rock and the adaptation of grouting design was discussed. To do better, the rock must not be described as isotropic, with the same hydraulic properties in all directions, there is a need to focus first on what is most water-bearing.

Considering adaptation, two additional examples were given. The first example had its focus on geology, grouting pressure, groundwater pressure and tunnel inflow. Here, a sudden drop in groundwater level coincided with post-excavation grouting of a deformation zone, an increase in measured tunnel inflow and an observed local inflow. Potentially, the grouting pressure was too high and possibly another borehole orientation could have facilitated the grouting performance. In the second example, a sudden drop in groundwater level, resulting from work performed in the tunnel, seemed to be greater than the increase in groundwater level that was observed based on a shutdown of an infiltration performed in a borehole at a distance from the tunnel. Continuous monitoring of groundwater levels, pore pressure and inflow and an optimisation of where to focus our project efforts, in the tunnel or outside the tunnel for example infiltrating water, should be an important part of the grouting performance. Further, all boreholes that may influence groundwater levels or tunnel inflow should preferably be integrated into an overall grouting strategy.

When highlighting the above we are better equipped to identify what sealing measures are necessary and sustainable from an environmental perspective and hence reduce the risk of a project ending up in a very difficult task related to grouting and sealing of shafts and tunnels.

4 Acknowledgements

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