METHODOLOGY FOR ROCK CONDITION ASSESSMENT AND ROCK CONSTRUCTION DESIGN IN ACCORDANCE WITH THE OBSERVATIONAL METHOD

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SUMMARY

The construction of the tunnels through the Hallandsås ridge in Sweden is still going on. Difficult rock conditions, a lot of water and problems with lowering of the ground water level in rock and soil have made it a difficult task. Another large project, Citybanan, has just started in Stockholm. The question in both cases is: Are decisions on location of tunnels and selection of construction methods based on assessments of rock, soil and water conditions and can severe rock conditions be communicated between geologists and engineers in a way that gives a realistic risk assessment? The intention of this paper is to introduce an early version of a methodology for assessment of rock conditions and for rock construction design based on geological and hydrogeological information. Valuable information is often available (e.g. in geological maps and data bases) but has to be translated and communicated to those constructing in rock.

To present the methodology we use basic data from the Geological Survey of Sweden (SGU) describing the Hallandsås area. Three main parts are included: a rock condition assessment matrix; principle descriptions of expected soil conditions and; estimates of tunnel inflow. The rock condition assessment matrix is based on the different kinds of rock identified using geological maps, possible rock contacts and degree and geometry of fracturing of the rock. The methodology identifies and confirms the difficult rock conditions, the vulnerability of soils, large tunnel inflows, and the risks related to a lowering of the ground water level. The methodology would allow an early assessment of the “most probable” and the “most unfavorable conceivable deviations from these conditions”, which is in agreement with the Observational method [1]. The observational method is expected to be an important part of future rock construction work. Similar data are available for most areas in Sweden and an analysis of them in a framework of this type will give the stakeholders a basis for a realistic design and layout assessment.

INTRODUCTION

A translation of geological information to straightforward engineering information is not trivial. Rock classification systems like the RMR [2] and Q [3] systems are attempts to condense geological information and present it in a way that engineers can digest. Efforts have been made to tie the classifications to case data bases to give direct construction guidelines. The results are however not encouraging and in reality the classification systems as they are used seem to be a part of the problem rather than the solution [4]. One additional issue is that in tunnel construction the information on what lies ahead of the tunnel front is never complete and adjustments on reinforcements and grouting to rock conditions have to be made regularly. This approach is formalized in the Observational method according to Eurocode 7 [5] where the rules for how the design is reviewed are based on observations during construction to arrive at an acceptable behavior of the system.

The intention of this paper is to introduce an early version of a methodology for assessment of rock conditions and for rock construction design based on geological and hydrogeological information. Focus in this case will be on grouting and this is an initial step towards a framework for interpretation, description and communication of rock conditions (both probable and unfavorable). Descriptions of rock, soil and water conditions are of importance and valuable information is often available (e.g. in geological maps and data bases) but has to be translated and communicated to those constructing in rock. In this paper, early estimates of tunnel inflow are made, estimates that should be updated and revised based on e.g. borehole investigations. A further description on the topic is found in the paper *The use of proxy parameters in pre-investigation, design and construction of tunnels with application to grouting* [6].

SUGGESTED METHODOLOGY

For grouting purposes, three parts are included in the suggested methodology:

- A rock condition assessment matrix
- Principle descriptions of expected soil conditions
- Estimates of tunnel inflow

To present the methodology we use basic data from the Geological Survey of Sweden (SGU) describing the Hallandsås area. Descriptions of the fracture system and a suggested rock condition assessment matrix are of great importance and therefore an introduction will be given here. Expected soil conditions and; Estimates of tunnel inflow will be presented under the heading Case study: Hallandsås.

Description of fracture systems

Description of the waterbearing fracture system forms a basis for grouting design. Table 1 presents descriptions of fracture systems (all fractures and waterbearing fractures), important parameters and examples of investigation methods. For grouting design, strike, dip and frequency of conductive fractures are valuable input data. For detailed grouting fan design, the transmissivity distribution (ability of individual fractures to transmit water) and the depth of tunnel are also needed. In a similar way one could suggest that strike, dip and fracture frequency of all fractures are of importance for geomechanical issues. An important difference here is that filled fractures that are not waterbearing or groutable may still risk deformation. Properties of different groups (sets) of fractures should be described. Stereoplots, Figure 1, are useful for this task.

Table 1 *Description of fracture systems (all fractures and waterbearing), important parameters and examples of investigation methods. Descriptions of the waterbearing fracture system form a basis for grouting design.*

Fracture system	Important parameters	Investigation methods
Geology – All fractures Discrete fracture network (DFN)	Strike / Dip Fracture frequency	Fracture mapping Fracture mapping
Hydrogeology – Waterbearing fractures Hydro-DFN Grouting design process – performance of grouting	Strike / Dip Frequency conductive fractures Transmissivity distribution Depth of tunnel	Fracture mapping e.g. Water Pressure Tests or detailed measurements of inflow.

Figure 1 presents examples of data from the access tunnel at Äspö Hard Rock Laboratory using stereoplots [7]. A) includes all fractures, B) waterbearing fractures and C) fractures filled with grout. Further, Figure 2 presents a conceptual scheme of waterbearing fracture systems (or permeability structures) where the rock mass is subdivided into *Host rock* and *Fault zones* [8,9]. Figure 1B (waterbearing fractures) has one main conductive fracture set (most fractures vertical having a similar direction) and would result in a two-dimensional (2D) flow described as Type I in Figure 2.

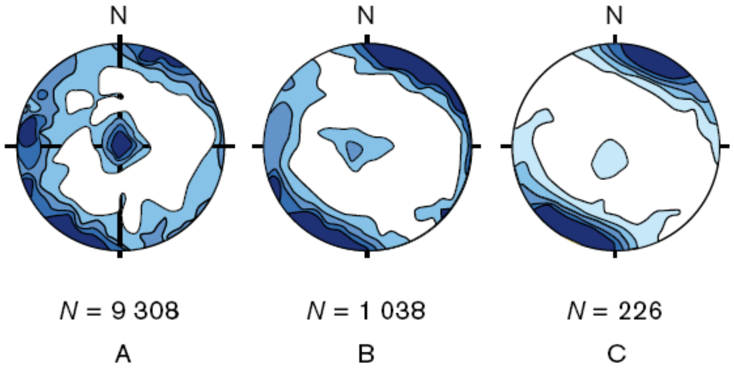


Figure 1 *Stereoplots of A) all fractures; B) waterbearing fractures and; C) fractures filled with grout. Data from the access tunnel at Äspö Hard Rock Laboratory [7]. The waterbearing fractures B) should be used to describe the waterbearing fracture system, see Figure 2.*

From a hydro-mechanical perspective, re-distribution of stresses in the vicinity of a tunnel only or re-distribution in combination with an increased fluid pressure due to grouting could result in deformation of fractures. Using the identified type of fracture system based on stereoplots, e.g. Type I (Figure 2) and *in-situ* and induced stresses due to tunnelling, an assessement of geomechanical or hydro-mechanical effects could be made. For a geomechanical description and at an early stage when the main waterbearing fracture sets are still to be identifed, one could suggest including all main fracture sets. Since grouting will be used as an example in this paper the following will describe the waterbearing fracture system (Figures 2 and 3).

Rock condition assessment matrix: presentation

The rock condition assessment matrix, Figure 3, is based on identified kinds of rock (from geological maps), rock contacts and degree and geometry of fracturing of the rock. The rock includes *Host rock* (protolith) and *Fault zones* [8,9], see Figure 2. Figure 3 consists of *Rock 1* and *Rock 2* (e.g. Gneiss and Amphibolite). The percentage (surface/volume) of each rock identified should be included to indicate the most probable one. For dikes and sills the expected frequency along the future tunnel stretch is important.

The *Rock* may have different *Types of waterbearing fracture systems* consisting of different number of fracture sets (here one: *I*, resulting in 2D flow or; two or more perpendicular sets: *II*, resulting in 3D flow). A fracture zone within the host rock may have an increased fracture frequency (*Iz* or *IIz*). For *Fault zones* (right hand side of Figure 2), shearing has occurred resulting in a tight fault *Core* of varying thickness. Among the *Fault zones*, Localized conduits are described as Type I (2D flow) fault systems. Distributed conduits and Combined conduit-barriers are both characterised by 3D flow (Type II, at least at a local scale).

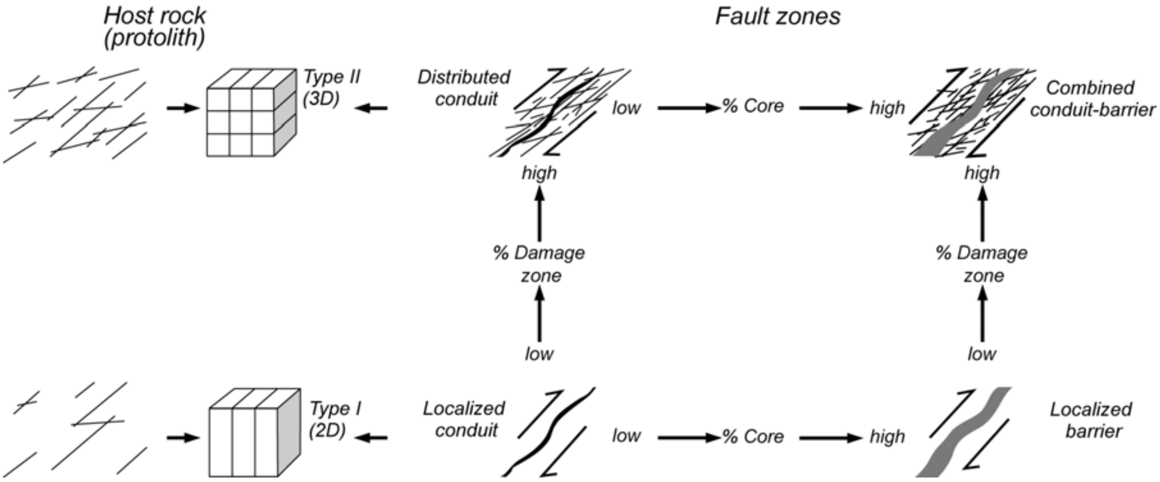


Figure 2 *Conceptual scheme of waterbearing fracture systems or permeability structures [8]. Right hand side of figure modified after [9]. Both the Host rock and the Fault zones are described as Type I (2D flow) or Type II (3D flow) waterbearing fracture systems.*

Rock		**Rock 1 (rock)**			**Rock 2 (rock/dike/sill)**		
	Type of fracture system (water)	***I***	***II***	***Core*** *(tight)*	***I***	***II***	***Core*** *(tight)*
Rock 1 % Surface/ volume	***I***	*I / Iz / fz*	*z / fz*	*fz*	*c / z / fz*	*c / z / fz*	*fz*
	II	▒	*II / IIz / fz*	*fz**	*c / z / fz*	*c / z / fz*	*fz**
	Core *(tight)*	░	▒	*Tight*	*c / z / fz*	*c / z / fz*	*fz*
Rock 2 % Surface/ volume (Frequency)	***I***	░	▒	░	*I / Iz / fz*	*c / fz*	*fz*
	II	▒	▒	▒	▒	*II / IIz / fz*	*fz**
	Core *(tight)*	░	▒	▓	░	▒	*Tight*

I: One set, 2D flow; II: Two (or more) sets, 3D flow; Core: tight; z: zone; c: contact; fz: fault zone; fz: Combined conduit-barrier. Black line: probable.*

Figure 3 *Rock condition assessment matrix: Waterbearing fracture systems and grouting. Example: Row with black line identifies the most probable kind of rock, expected contacts and types of fracture system; Column should indicate corresponding groups of design and performance.*

The *diagonal and upper right corner* of the rock condition assessment matrix, Figure 3, include the different kinds of rock identified, possible contacts and possible waterbearing fracture systems. *Types I/Iz/fz* are shown in the lower left corner of Figure 2, where *I* represents host rock with one main waterbearing fracture set, *Iz* describes a fracture zone due to a higher fracture frequency and *fz* is a fault zone subjected to shearing (Localized conduit). *Types II/IIz/fz* are shown in the upper left corner with two or more perpendicular and waterbearing fracture sets (including the Distributed conduit). In the upper right corner of Figure 2, *fz** is shown (Combined conduit-barrier). As presented in the rock condition assessment matrix, a Combined conduit-barrier consists of a *Type II* waterbearing fracture system and *Core (tight)*.

The *diagonal and lower left corner (grey)* indicate groups of design and performance and is linked to the upper right corner. The different nuances of grey should be related to the performance e.g. borehole direction (light grey one main fracture set to intersect; medium grey: two main fracture sets and; dark grey: tight and not groutable). Knowing the strike, dip and fracture frequency of main waterbearing fracture sets is a good basis for grouting fan geometry design.

Included in Figure 3 is an example where the *row with black line identifies the most probable kind of rock and expected contacts and types of fracture system*. The geological history (e.g. SGU descriptions) and depth of tunnel are important sources of information to identify what is most probable. This is reviewed during the project and as an example, data presented in Figure 1B could be used to confirm the most probable type of fracture systems, *Types I/Iz/fz*, shown in Figure 3, since mainly one waterbearing fracture set (2D flow) can be identified. The *column with black line would indicate corresponding groups of design and performance*.

CASE STUDY: HALLANDSÅS

Rock condition assessment matrix and geological history

Based on basic data [10,11] describing the area of the Hallandsås tunnel a rock condition assessment matrix is presented, see Figure 4.

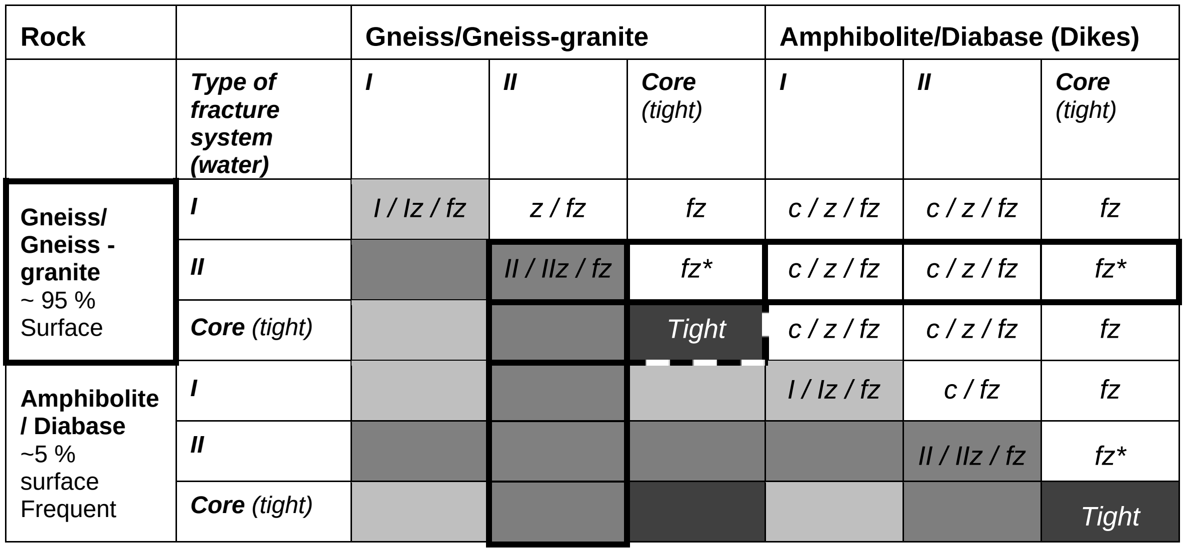
The following kinds of rock are identified:

- <u>Gneiss</u> is the most common rock at the surface (~95%, probable: black line, Figure 4). <u>Gneiss-granite</u> occurs only in few (small) areas.
- <u>Amphibolite and Diabase</u> occur as (rock)/dikes/(sills) (~5%). Several contacts expected –“frequent” (probable: black line).

In this paper, Gneiss/Gneiss-granite and Amphibolite/Diabase are presented in the same rows and columns to obtain a limited size of the matrix.

Considering contacts between rock and types of fracture system [10,11]:

- Gneiss-granite is less fractured than the Gneiss.
- Contacts between Gneiss/Amphibolite: Layers of Amphibolite where movement has occurred has enhanced weathering of rock to larger depths.
- Contacts between Gneiss/Diabase: Diabase orientation NW-SE to WNW-ESE (vertical and widths between decimeters and 50 meters). Contacts commonly dry, waterbearing fractures common in adjacent rock.
- Hallandsås is a horst and deformation has occurred <u>at least</u> at the boundaries. These are expected to be fault zones (Combined conduit-barriers), *fz** (probable: black line). Further, the topography indicates additional fracture or fault zones. General deformation and a well connected fracture network, *II/IIz/fz,* is expected (probable: black line).
- Deep weathering has occurred, resulting in alteration of rock into e.g. caolinite, (larger volumes of altered, tight rock is possible: dashed line).



Rock		**Gneiss/Gneiss-granite**			**Amphibolite/Diabase (Dikes)**		
	Type of fracture system (water)	***I***	***II***	***Core*** *(tight)*	***I***	***II***	***Core*** *(tight)*
Gneiss/ Gneiss - granite ~ 95 % Surface	***I***	*I / Iz / fz*	*z / fz*	*fz*	*c / z / fz*	*c / z / fz*	*fz*
	II		*II / IIz / fz*	*fz**	*c / z / fz*	*c / z / fz*	*fz**
	Core *(tight)*			*Tight*	*c / z / fz*	*c / z / fz*	*fz*
Amphibolite / Diabase ~5 % surface Frequent	***I***				*I / Iz / fz*	*c / fz*	*fz*
	II					*II / IIz / fz*	*fz**
	Core *(tight)*						*Tight*

I: One set, 2D flow; II: Two (or more) sets, 3D flow; Core: tight; z: zone; c: contact; fz: fault zone; fz: Combined conduit-barrier. Black line: probable; Dashed line: possible*

Figure 4 *Rock condition assessment matrix: Waterbearing fracture system and grouting. Example: Row with black line identifies the most probable kind of rock, expected contacts and types of fracture system; Column should indicate corresponding groups of design and performance.*

Based on the above, row with black line identifies the most probable kind of rock, expected contacts and types of fracture system. Column should indicate corresponding groups of design and performance. In this case large contrasts in fracturing, weathering and rock strength can be expected within small distances (e.g. contacts Gneiss/Amphibolite or Gneiss/Diabase). This may cause both grouting- and stability problems. An additional comment is that a contact between fractured Gneiss (Type II) and a less fractured Amphibolite or Diabase (Type I) may act as a barrier even though it is not expected to be as tight as the Combined conduit-barrier.

This is an early prognosis that should be reviewed during a project. At this stage, further investigations are advisable to confirm or revise the rock condition assessment matrix. This should be a basis for planning and decisions regarding e.g. tunnel alignment. Design and performance should be based on and prepared for the identified conditions. During tunnelling when identifying any of the conditions presented, the corresponding design should be selected.

Expected soil conditions: Hallandsås

The main part of the soil cover in Hallandsåsconsists of till, with a thickness generally less than 5-10 m [12]. The groundwater level is located close to the surface. The southern part is dominated by farmland on sandy till with a thickness up to twenty meters. The central part is covered with forest, and occasional fens. In the northern part rock outcrops are frequently occurring. Small occurrences of glaciofluvial deposits are present in valleys on top of the horst. A reduction of the groundwater level, which would be the consequence of drainage into a tunnel, would affect the surficial water in creeks and fens, and the capacity of wells in the area.

Hallandsås is situated in an area with relatively high annual precipitation and the hydrogeological map [13] shows that the tunnel is located in an area of very good groundwater exploitation potential. The map also highlights two major fracture zones, probably with better exploitation potential than the surrounding rock. The horst is likely to contain large amounts of groundwater since it consists of fractured and weathered rock in combination with a high rate of groundwater recharge.

Estimates of tunnel inflow: Hallandsås

The inflow of groundwater into a tunnel can be estimated using data from short duration pumping tests of wells in the area, included in the SGU well archive [14], see the equation below [15]:

$$q \approx \frac{H}{2R_0} \cdot \left(Q/d\right)_{50} \cdot \ln \frac{R_0}{r_w}$$

where H, is the groundwater head, R_0, the radius of influence, Q_{50}, the median well capacity, d_{50}, the median well depth and r_w, the well radius. The groundwater head, H, is estimated to 50 – 140 meters based on topography and tunnel depth, with lower heads in the beginning and in the end of the tunnel. The radius of influence, R_0, is estimated as $5 \cdot H$ [15].

A total of 105 wells, located within about 500 m of the tunnel stretch, were found in the well archive [14]. The tunnel stretch was subdivided into eight areas (A-H) see Figure 5, depending on the presence of major fracture and fault zones identified by lineaments [16]. The evaluation is divided into five areas of fracture and fault zones and three areas of host rock. The wells from the well archive within each area were used for the inflow estimates according to Table 2.

Table 2 *Estimated inflow to a tunnel for the areas A-H.*

Area	Number of wells [-]	Median capacity [l/h]	Median depth [m]	Estimated inflow [l/(min*100m)]
A	15	3600	138	36
B (llz/fz)	9	5400	128	57
C	13	9000	79	179
D (llz/fz)	6	45060	89	764
E (llz/fz)	2	5400	56	147
F (llz/fz)	3	3000	79	60
G	50	6000	134	69
H (fz)	7	2700	100	39

The inflow estimates of the areas along the tunnel show that inflows between 39 and 764 l/min and 100 meters could be expected. The by far largest value, 764 l/min, 100 m, is found in area D, which is represented by a fracture zone and has several wells located closely to the actual zone. However, the uncertainty of the inflow predictions increases when the number of wells is small, as it is in area E and F. Indicating areas for further investigations is an important part of the work at this stage of a project.

The inflow requirement for the Hallandsås tunnel is 3.5 l/s and 1000 m which would correspond to an inflow of 21 l/min and100 m (two tunnels). Comparing this to the estimated tunnel inflows above, it can be concluded that sealing is an important task.

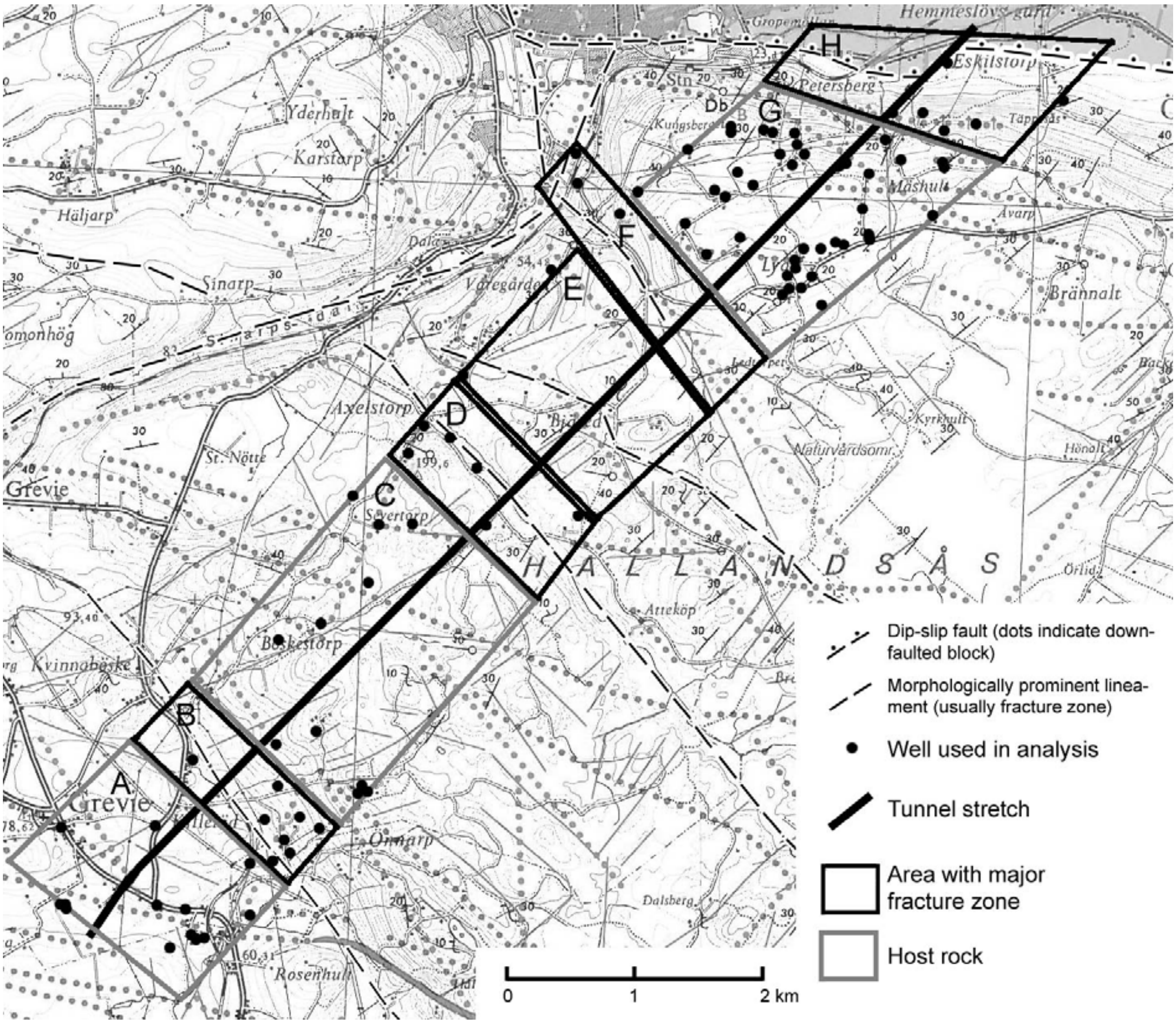


__Figure 5__ The stretch of the Hallandsås tunnels on a tectonic map [16], © Geological Survey of Sweden (SGU). Areas that roughly corresponds to the host rock of the area are marked with grey squares, and areas with major fracture zones are marked with black squares. Wells present in the SGU well archive [14], that are within these squares are marked, and have been used for the inflow estimates.

Comments: Hallandsås

A well connected fracture system with variations in fracturing, weathering and rock strength within small distances is expected. Large estimated tunnel inflows compared to the inflow requirements show that sealing is an important task. Considering the grouting design, two or more fracture sets have to be intersected and a well connected fracture system increases the need for systematic grouting. For fracture zones (*IIz*) and fault zones (*fz*) having an increased fracture frequency more fine- and large aperture fractures will be present increasing the need for different types of grout. Areas that cannot be grouted due to alteration may exist even though contacts with surrounding rock are likely to transmit water, e.g. Combined conduit-barrier, see Figure 2 [8,9]. Principle descriptions of expected soil conditions indicate that creeks, fens and wells risk being influenced by a lowering of the water table in case of too large inflows into the tunnel.

Some of the difficult areas along the tunnel stretch (e.g. E and F, Figure 5) were not identified based on the well archive and an explanation for this is the limited amount of well data. Except for these, the description seems to capture the areas with larger inflow (particularly C and D) that has actually been identified during the project. Areas were information is limited demand increased investigations; otherwise the tunneling project will be subjected to greater risks when constructing the tunnel.

CONCLUSIONS

The methodology identifies and confirms difficulties encountered at the Hallandsås tunnel. This includes the difficult rock conditions, the vulnerability of soils, large tunnel inflows, and the risks related to a lowering of the ground water level. The methodology would allow an early assessment of the “most probable” and the “most unfavorable conceivable deviations from these conditions”, which is in agreement with the Observational method [1].

The example presented is an early prognosis that should be reviewed during a project. At this stage, further investigations are advisable to confirm or revise the rock condition assessment matrix and the tunnel inflow. This should be a basis for planning and decisions regarding e.g. tunnel alignment. Design and performance should be based on and prepared for the identified conditions. During tunnelling when identifying any of the conditions presented in the rock condition assessment matrix, the corresponding design should be selected.

The observational method is expected to be an important part of future rock construction work. Similar data are available for most areas in Sweden and an analysis of them in a framework of this type will give the stakeholders a basis for a realistic design and layout assessment.

ACKNOWLEDGEMENT

Financial support provided by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, Formas, is acknowledged. For a couple of years, we have performed similar investigations in collaboration with third year students at Chalmers. Discussions and thoughts originating from this work are highly appreciated.

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