APPROACH FOR EARLY ENGINEERING GEOLOGICAL PROGNOSIS ADAPTED TO ROCK GROUTING DESIGN

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Summary

Planning of suitable water-mitigating measures, such as grouting, can be valuable for feasibility studies of underground construction projects. However, grouting design work becomes more difficult if hydraulic properties of the rock mass are insufficiently investigated and the geological information presented in the engineering geological prognoses mainly focus on stability-related parameters. The purpose of this study has been to demonstrate how geological information useful for grouting design can be compiled in engineering geological prognoses during early phases of tunnel projects. Attention is also given to relating geological settings to grouting design classes during the construction phase. The suggested approach was exemplified for the Hallandsås project, Sweden, using low-cost geological information available during the original feasibility study of the project. The prognosis included a conceptualisation of the hydraulic behaviour of the rock mass at the project site, with hydraulic domains representing the flow regimes found in different geological units. The need for sealing measures along the tunnel alignment was expressed with inflow estimates based on data from the SGU Wells archive. This combination of qualitative and quantitative estimates indicated grouting design prerequisites for both favourable and unfavourable scenarios, which could be useful for grouting design classification during construction. The hydraulic domains facilitate the understanding of the relation between geology and grouting design, which is essential for tunnel construction work.

1 Introduction

Design and implementation of water-mitigating measures to reduce groundwater inflow is recognised as a key aspect in the successful construction of tunnels. A number of water-mitigating measures can be implemented to reduce the inflow to acceptable levels, although pre-excavation grouting in conjunction with construction is considered the most cost-effective means of water control in tunnels constructed in fractured, hard rock (Dalmalm, 2004). The design of grouting measures involves making appropriate choices of grout material and grouting technique based on knowledge of the hydraulic properties of the rock mass (Gustafson, 2012). Grouting design thus requires engineering geological information and conceptualisations that can differ from other design applications in tunnel construction and this should be reflected in the characterisation and classification of the geological settings.

Geological information of relevance for grouting should be collected, interpreted and communicated clearly in the engineering geological prognoses developed for each project. There are, however, uncertainties and inadequacies in geological prognoses that affect grouting design negatively. For instance, grouting design work becomes more difficult to conduct if geological prognoses mainly focus on stability-related parameters, such as those described in rock mass classifications systems. Another issue is the scarcity of project-specific geological information in early phases, which could lead to grouting designs being copied between tunnel projects without acknowledging that each project has its own key issues (Palmström and Stille, 2010; Gustafson, 2012).

The general quality of the engineering geological prognoses can be improved if the information relates to the engineering application and to project requirements (Palmström and Stille, 2010).The work presented in this paper suggests an approach for identifying and organising geological information relevant for grouting design in engineering geological prognoses. The focus is on establishing prognoses in early project phases, although suggestions for relating geological settings to grouting design classes during construction is also made. The approach for early engineering geological prognoses for grouting design has been exemplified using the Hallandsås project. The case study demonstrates how a relevant geological structuring can be made.

2 Approach for early engineering geological prognoses

Early engineering geological prognoses for grouting design should preferably provide an estimate of the need for water-mitigating measures, the magnitude of the sealing required and present the geological prerequisites for the implementation. The suggested approach is therefore to conceptualise the hydraulic behaviour of the rock mass at the project site and carry out inflow predictions which can be compared to the expected inflow requirement. The conceptualisation of the hydraulic behaviour should be based on an understanding of the geological and tectonic history at the site, current ground conditions, and influencing mechanical, chemical and hydrological processes. The various hydraulic flow regimes found in different geological units along the tunnel alignment may be defined as hydraulic domains, which is a terminology used by the Swedish Nuclear Fuel and Waste Management Co (SKB) for grouping geological units with similar hydraulic properties, see e.g. Rhén et al. (2003). The hydraulic domains have been further developed and put into the context of grouting design in this work.

2.1 Hydraulic domains

The hydraulic domains represent geological units (e.g. rock types) with similar engineering characteristics in terms of hydraulic properties. A further subdivision of geological units is possible, as well as the merging of several geological units into one hydraulic domain if the hydraulic properties do not vary significantly. The hydraulic domain division can start with a distinction between host rock (*Hydraulic Rock Domains, HRD*) and deformation zones (*Hydraulic Conductor Domains, HCD*). The basis for this subdivision is that deformation zones often display a complex structure and geometry that include a higher degree of alteration and increased fracturing compared to the surrounding rock. This cause deformation zones to have mechanical and hydraulic properties that differ significantly from those of the surrounding rock masses, generally in terms of lower mechanical strength and higher permeability (Andersson et al., 2000). They can therefore act as a negative boundary (barrier) or as a positive boundary (conduit) depending on their composition and thus influence the flow pattern near a tunnel. A conceptual scheme which describes the permeability structure of host rock and deformation zones separately has been presented by Fransson and Hernqvist (2010), shown in Figure 1.

The information needed to develop hydraulic domains includes various geological factors that influence the hydrogeological conditions at the site. These factors include parameters that describe the geometrical characteristics of the water-conducting fracture system, as well as influencing mechanical, chemical and hydrological processes. The geological and tectonic history of the area is also considered useful as it may reveal complex and difficult geological settings that are not obvious from investigations and observations.

A compilation of geological parameters that can be relevant to consider in early engineering geological prognoses is presented in Table 1. All parameters are not of equal importance in every project and it may be possible to remove some parameters from further consideration whereas other factors need to be added. Information about certain parameters may also be missing during early phases and will need to be considered in later project phases when more information becomes available. The geological information should also be representative of the tunnel depth and consider the range of expected ground conditions, both 'good' and 'poor'.

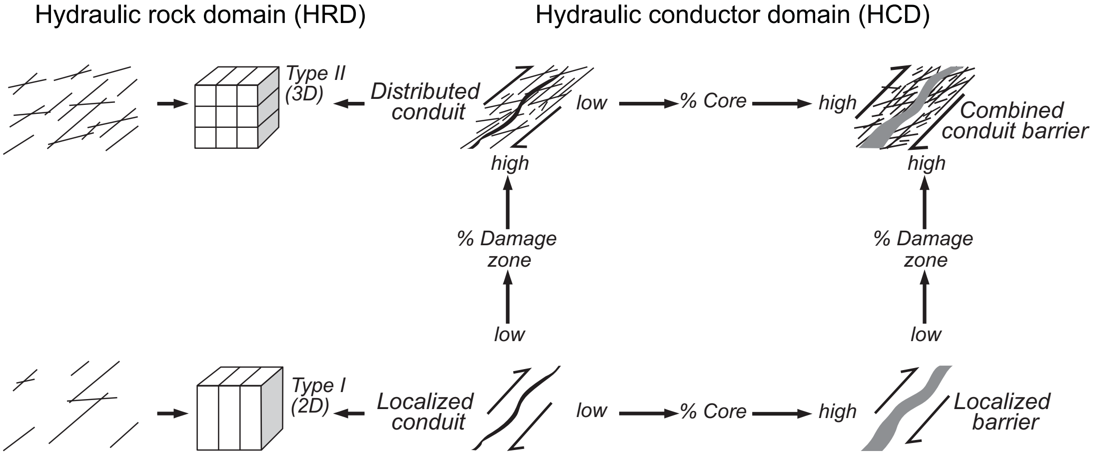


Figure 1 *Conceptual scheme for permeability structures in fault zones (HCD) by Caine et al. (1996) expanded with host rock fracture networks (HRD) by Fransson and Hernqvist (2010). The barrier-conduit structure of the fault zone is based on the development of the fault core (low-permeability barrier) and the damage zone (intensely fractured conduit). The sparsely connected fracture network (Type I) has typically a flow pattern associated with anisotropy, flow restrictions and 2D-flow. The well-connected fracture network (Type II) has a large number of interconnections and 3D-flow usually dominates (Fransson and Hernqvist, 2010).*

***Table 1** Geological parameters considered relevant for grouting and comments on their influence on grouting design and water inflows.*

		GEOLOGICAL PARAMETERS	INFLUENCE ON GROUTING DESIGN AND WATER INFLOW
GENERAL FACTORS	LARGE-SCALE FACTORS	Rock types, rock contacts, dykes	Controls the geometry of the fracture systems and fracture properties. Dykes and contacts can be associated with variations in fracturing.
		Topography	Provides a geometric framework for water balance calculations and deformation zone identification.
		Rock stresses	Control the opening of fractures and thus the geometry of the water-conducting fracture system. Influence deformability of fractures during grouting.
		Hydraulic conductivity	Enables assessment of water inflows and indicates grouting difficulty.
		Hydraulic head	Affects water inflows and grouting pressures and is needed to assess hydraulic apertures.
		Hydraulic gradient	Influences the risk of backflow and grout erosion during grouting.
		Groundwater recharge	Needed to assess water balance, which affects water inflow and drawdown recovery.
		Groundwater chemistry	Affects grout degradation.
DOMAIN-SPECIFIC FACTORS	HOST ROCK	Hydraulic aperture/transmissivity	Enables assessment of water inflow, grout penetrability and grout spread, which form the basis for grouting design.
		Other fracture properties: open/sealed fractures, fracture roughness, fracture filling/alteration, flow dimension	Affect flow paths and thus grout spread within fractures.
		Fracture system properties: fracture frequency, orientation and number of fracture sets (anisotropy), flow dimension	Affect network connectivity and thus grout spread and water inflow.
	DEF. ZONES	Hydraulic aperture/ transmissivity	Enables assessment of water inflow, grout penetrability and grout spread, which form the basis for grouting design.
		Thickness, orientation	Control the length of intersection with the tunnel and thus grout fan length and grout hole orientations
		Composition: core/damage zone	Affects connectivity and flow anisotropy within and across the zone.

2.2 Inflow estimate

The inflow estimate is a central input to grouting design. Together with inflow requirements it enables an assessment to be made of the required sealing efficiency and the required hydraulic conductivity of the grouted zone, which could indicate the complexity and degree of difficulty of grouting work (Stille, 2012). In early phases when project-specific data is scarce inflow estimates can be based on data from short-duration pumping tests of wells accessed from the SGU Wells archive. Gustafson (2012) proposes an analytical expression (Eq. 1) which is based on Thiem's well equation:

$$q \approx \frac{H}{2R_0} \cdot \left(Q/d\right)_{50} \cdot \ln\left(\frac{R_0}{r_w}\right) \qquad \text{Eq. 1}$$

The leakage is expressed as a summarisation of the drawdown in infinitesimal wells along the length of the tunnel and included in the equation is the undisturbed hydrostatic pressure H above the tunnel, the radius of influence R_0, the median well capacity Q_{50}, the median well depth d_{50}, and the well radius r_w. The inflow estimation expression is based on several simplifying assumptions, such as steady-state flow in a homogenous and isotropic rock aquifer where the radius of influence is estimated to be five times the tunnel depth (see details in Gustafson, 2012). These assumptions lead to an oversimplified description of the hydraulic conditions. It is intended, however, to serve as a quick and rough first approximation that can be compared with the expected inflow requirements.

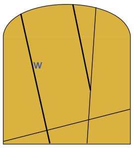
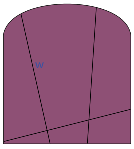
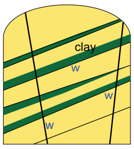
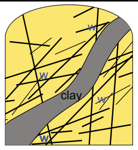
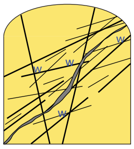
Tunnel inflow estimates can be carried out separately for the various hydraulic domains although separation must be done with caution to ensure each analysed area includes suitable quantities of input data. At later phases, when more information becomes available it is also possible to carry out more advanced analyses of the expected inflow and the fractures that needs to be sealed to satisfy the stated inflow requirement (Hernqvist et al., 2013). Analytical expressions for inflow prognoses can for instance be used to calculate the maximum transmissivity required for the grouted rock mass. The analyses could also be used after grouting, when the transmissivity of the grouted rock can be estimated, to make a prediction of the tunnel inflow. It is, however, important to consider if assumptions associated with the analytical expression and the resulting estimate is reasonable for the geological settings at the site.

3 Case study – the Hallandsås project

The approach suggested in Section 2 was demonstrated with the Hallandsås project to exemplify how a geological domain division can be used in an early grouting prognosis. The geological information used was available at the time of the original feasibility study (1989-1991), including maps of bedrock from the Geological Survey of Sweden, (SGU) (Wikman and Bergström, 1987), well data from SGU Wells archive and construction records from the nearby Bolmen Tunnel project (Stanfors, 1987). A more detailed description of the case study is given in Kvartsberg (2013).

The Hallandsås project is a railway tunnel project currently being run in the province of Skåne in southern Sweden. The project involves the construction of two parallel tunnels, 8.7 km in length, through the Hallandsås horst with rock cover of 100-150 metres along most of the tunnel alignment. The tunnels are excavated through the NW-SE-oriented Hallandsås horst, which was formed as a result of recurring movements and deformations along a tectonic zone called the Tornqvist zone. The rock mass is, to a varying degree, heavily fractured with weathered rock masses reaching down to considerable depths. The bedrock is composed predominantly of Precambrian gneisses as well as layers and dykes of amphibolite. There are also subordinate occurrences of Permian dolerite dykes. These geological settings were conceptualised into five hydraulic domains (see Table 2) according to expected variations in flow properties in the host rock (HRD) and in deformation zones (HCD).

***Table 2** Hydraulic domain division and inflow estimates assessed for the Hallandsås area. There are three hydraulic rock domains, corresponding to various forms of hydraulic behaviour in the host rock, and two hydraulic conductor domains, which separate the deformation zones into barrier-conduit structures and conduit structures. The conductor domains are expected to exist on a larger scale than indicated in this schematic representation. Large-scale factors influencing the grouting design are also presented.*

	HYDRAULIC ROCK DOMAINS			HYDRAULIC CONDUCTOR DOMAINS	
INFLOW ESTIMATE (1 MPa)	120 l/min, 100 m			170 l/min, 100 m	
HYDRAULIC DOMAINS	🟨 Gneissic granite 🟨 Gneiss ▨ Gouge core w Water leakage 🟪 Dolerite 🟩 Amphibolite // Fractures				
	 (I) Homogenous gneiss/gneissic granites	 (II) Dolerite dykes	 (III) Gneiss and amphibolite interlayering	 (IV) Combined conduit-barrier	 (V) Distributed conduits
FLOW CONFIGURATION	3D fracture system, well-connected. Occurrence of localised, highly transmissive conduits	As (I), also increased alteration and fracturing in contacts with surrounding rock, barrier effect	As (I), also weathered amphibolites and clay-filled fractures that create local barrier effects	Complex flow structure: gouge core (barrier) and damage zone (conduit, flow backbone)	2D structure, increased fracture frequency, altered rock, (conduit, flow backbone if continous)
	The host rock is expected to include single fractures that can be highly conductive				
LARGE-SCALE FACTORS	Recurrent contrasts in rock quality, weathered rock masses, conduit-barrier effects, high groundwater pressures (possibly reaching around 1.2 MPa), low confining stresses with increased mobility of rock blocks, structures both parallel and perpendicular to tunnel.				

The division is based on a description of domain-specific factors given in Table 1. Table 2 also present large-scale factors which influence the grouting design in all domains. Together these indicate some general grouting design implications;

- Barrier effects of dykes and amphibolite layers that will influence drawdown patterns and grout penetration,
- High probability of large inflows in the vicinity of dykes and deformation zones,
- Several dominating fracture orientations to adapt grout fan geometries to,
- Well-connected fracture system that needs systematic grouting to avoid redistribution of water between tunnel sections,
- Fracture fillings may hinder grout penetration,
- Low stresses increase risk of rock deformation during grouting,
- High water pressure will act on packers and it increases risk of grout erosion and grout backflow.

The geological and tectonic history of the Hallandsås area revealed several of the large-scale factors, such as formation and reactivation of multiple fracture and fault systems, weathering processes and low stress regimes. Ground conditions identified as unfavourable for grouting included high groundwater pressures at tunnel depth, high-permeability zones, rock deformability and combinations of material-filled and open fractures. The heterogeneous and contrasting geological conditions imply also that grouting requirements can vary significantly within quite short tunnel sections, which makes predictions less reliable.

The estimation of tunnel inflows (Table 2) was carried out using flow log data from water wells located within two kilometres of the tunnel alignment. The wells were assigned to one of the two main types of hydraulic domains, HRD or HCD. The allocation was based on the positions of the wells in relation to deformation zones identified as lineaments and fracture zones on the structural geological map. Consequently, if a well emplacement coincided with a marked deformation zone, it was assigned to the hydraulic conductor domain. Otherwise it was assigned to the hydraulic rock domain. The estimated median tunnel inflow based on well data greatly exceeded the levels normally permitted in Swedish rock tunnel projects, both in host rock and deformation zones, thus indicating a need for extensive water-mitigation measures.

4 Hydraulic domains in grouting design classification

The subdivision of the rock mass into hydraulic domains can be useful during the construction phase when grouting design options are adapted to varying geological settings and requirements encountered during tunnel construction. Water-mitigating measures applied in Swedish tunnel projects should according to the Swedish Transport Administration (STA, 2011) be represented and described using different classes. These classes can express variations in the required hydraulic conductivity of the sealed zone – *sealing classes* – or different grouting designs to be implemented in response to variations in the hydraulic properties during excavation – *design classes* (Emmelin et al., 2007).

The sealing classes put focus on adapting the design to varying requirements along the tunnel alignment (e.g. permissible inflow or nearby structures) whereas design classes present designs adjusted to reach sufficient sealing in the observed hydraulic properties. Schematic illustrations of a sealing class and a design class are shown in Figure 2. There can also be a combination of the two types of class division, meaning that grouting work is adjusted to both variations in requirements and variations in the encountered geological conditions.

The classification of grouting design in some Swedish tunnel projects has been studied: the Törnskog Tunnel, the Namntall Tunnel, the Norra Länken Tunnel Project, the City Link Tunnel Project and the TASS Tunnel at Äspö Hard Rock Laboratory. Some of these projects expressed varying geological settings with Lugeon values or evaluated hydraulic apertures. Others stated more generally that grouting design needs to be adapted in areas with 'low hydraulic head', 'highly transmissive features', 'fracture zones' or other 'deviating conditions'. However, these conditions were generally poorly defined in terms of how they were expected to behave hydraulically, how frequent and for how long stretches they were expected to occur, and how the grouting design is to be modified when encountering them. Such information gaps could make cost estimates uncertain and consequently increase the risk of misclassification (i.e. choices of inappropriate designs) and unexpected amounts of re-grouting.

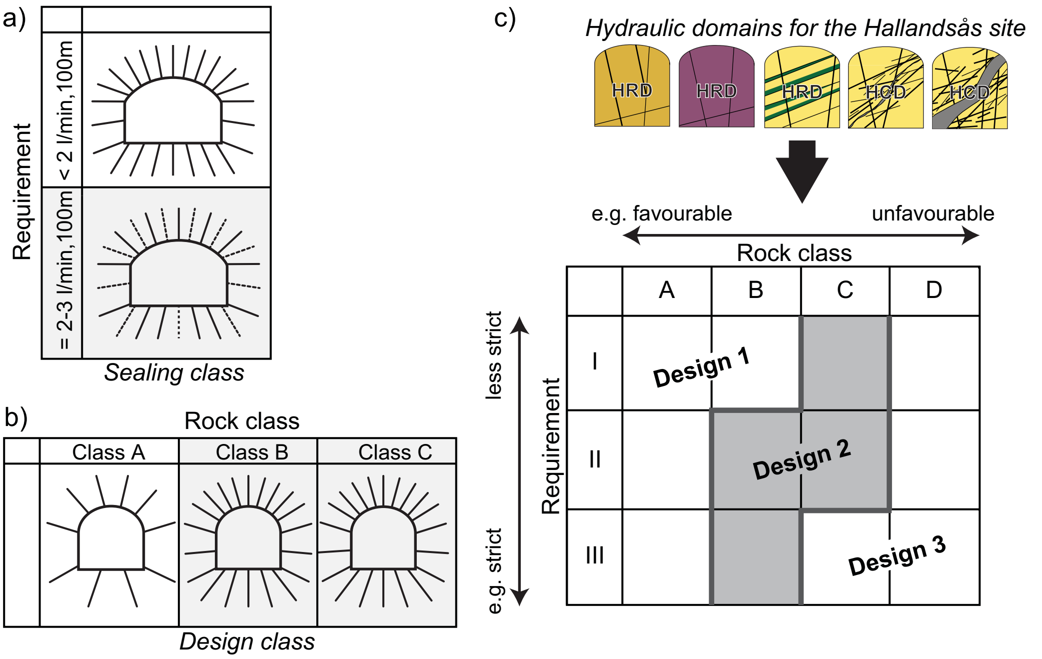


Figure 2 a) *Illustration of a sealing class with designs solely adapted to varying requirements.*
b) *Illustration of design classes adapted to different geological settings.*
c) *Matrix displaying an example of how the relationships between the geological settings (rock class), the project requirements and the stepped, pre-defined designs can be handled (from Gustafson, 2012). The selection of a design depends on the requirement, the layout and the rock class, and different rock classes could require the same design. Hydraulic domains, illustrated with the Hallandsås domains, could correspond to an initial attempt to define various rock classes for grouting design.*

The use of hydraulic domains can facilitate the description of the expected range of geological settings to which grouting design needs to be adapted, see Figure 2. The domains formally define what to expect in terms of hydraulic behaviours, and they enable the preparation of pre-defined grouting classes and contingency measures for both favourable and unfavourable scenarios. The term 'hydraulic domain' also signifies that the focus is on hydraulic properties. This reduces the risk of confusing the geological settings of importance for grouting with the groups of geological settings used in rock support, which are often labelled 'rock classes' (Palmström and Stille 2010).

5 Discussion and conclusions

An engineering geological prognosis developed for grouting design should preferably focus on geological parameters that can increase understanding of the hydraulic properties of the rock mass (Gustafson, 2012). Ideally, identification of grouting design prerequisites, such as potential tunnel inflows, should already have been made in the early project phases based on information available from geological databases and previous construction activities. This facilitates the optimisation of the construction, planning of investigations and reduces the risk of encountering unforeseen ground conditions in later phases.

The suggested approach was demonstrated with the Hallandsås project and it exemplified how geological information can be structured for the early planning of water-mitigating measures. The conceptualisation of the ground conditions was presented with hydraulic domains and inflow estimates separated for host rock and deformation zones. The hydraulic domains describe foreseeable hydraulic behaviour, both favourable and unfavourable, and formed a basis for grouting design recommendations. The early assessment did not provide sufficient quantitative data for finalising site models or establishing detailed grouting designs. Further analyses are advisable to revise and update the hydraulic domains and tunnel inflow estimates. However, the prognosis could outline geological settings that are crucial to the design and identify areas that require further investigation. Published material on tectonic development and experiences from a nearby tunnel were central for the early evaluation of Hallandsås. This emphases the importance of considering the geological and tectonic history and reviewing previous construction activities.

The hydraulic domain divisions could aid the planning of grouting designs which facilitate the understanding of the relation between geology and engineering design. This is essential for all tunnel construction work. Hydraulic domains are also suggested to be used during grouting implementation to provide a structure for establishing grouting design classes adapted to requirements *and* various expected hydraulic behaviours. This follows the requirements stated in Eurocode 7 for rock construction design according to the observational method. Based on the domains it is possible to state how the expected ground conditions will behave hydraulically, where they will occur, and how the grouting design is to be modified when certain conditions are encountered. However, it is important to remember that there will always be uncertainties inherent in the ground conditions and a lack of geological understanding and incorrect interpretations could have a negative effect on engineering analyses. Grouting design should therefore be iterative and conceptualisations should be examined carefully throughout the construction process.

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