ROCK ENGINEERING RESEARCH FOUNDATION
STIFTELSEN BERGTEKNISK FORSKNING

THE APPLICABILITY OF GEOELECTRICAL METHODS IN PRE-INVESTIGATION FOR CONSTRUCTION IN ROCK

Geoelektriska metoders tillämpbarhet vid bergbyggnadstekniska förundersökningar

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Förord

Förundersökning är ett måste innan ett bergarbete påbörjas. Förundersökning skall ge mest möjlig information om bergförhållandena och underlag för val av teknik, metod och utrustning för berguttag, förstärkning, tätning mm. Målet är att undersökningar skall ge adekvat information om byggbarhet, kostnad, omgivningspåverkan, inre miljö, beständighet och underhållsbehov. Vanliga metoder är kart och arkivstudier, flygbildstolkning, geofysiska mätningar, provborrningar, strukturkartering, borrhålsundersökningar bergspänningsmätningar och belastningsförsök. Geofysiska undersökningsmetoder utnyttjar variationen i fysikaliska egenskaper som elektrisk ledningsförmåga, elastiske egenskaper, densitet och magnetiska egenskaper för att ge information om bergmassans sammansättning och uppbyggnad.

Refraktionsseismik har länge varit en standard metod för framtagning av information om jorddjupet och bergets sprickighet. SveBeFo rapporten Geofysik för bergbyggare från år 2001 ger en sammanfattning av Geofysiska metoder och dessas utförande.

Berit Ensted Danielsen har i sin doktorsavhandling undersökt tillämpbarheten av Geoelektrik vid bergbyggnadstekniska förundersökningar. Hon visar på Geoelektriska metoders användning och nytta i olika skalor. För ändamålet har Berit utvecklat en metodik för datavärdes analys VOIA (Value of Information Analysis). Det är en kostnad - nytta analys för stöd i val av förundersökningsprogram för aktuell geologisk miljö.

Föreliggande rapport visar på behovet av att undersökningar görs konsekvent och strukturerat uppifrån och ned. Att de startar översiktligt för att bli alltmer detaljerade. Berit framhåller kommunikationens betydelse i projekt och att ny kunskap integreras. ”*Det spelar ingen roll hur många metoder som används om resultaten ignoreras*” .

Stockholm i maj 2011

Mikael Hellsten

Sammanfattning

Byggande i berg är förenat med risker, eftersom kunskap om geologin och markförhållandena är begränsad. Oförutsedda grundförhållanden innebär en stor risk för projektet som kan leda till förseningar och extra kostnader. För att minimera riskerna, måste en optimerad förundersökning genomföras där viktig information samlas för att ligga till grund för bästa möjliga beslut i hela byggprojektet.

I detta projekt utvärderas tillämpbarheten av geoelektriska metoder som ett verktyg för undersökning av bergmassans egenskaper. Användningen av geoelektriska metoder i olika skalor har visat sig ge värdefull information i olika skeden av tunnelbygget. I de geologiska förhållanden vid Hallandsåsen indikerar metoden sprickor, vattenförande berg, vittrat berg och i viss mån förändringar i litologin. Storskalig geoelektrisk undersökning är användbar i konstruktions- och produktionsplaneringsstadiet samt i byggskedet. Geoelektriska metoder kan kombineras med andra geofysiska metoder i borrhålsloggning och tillämpas sent i konstruktions- och produktionsplaneringsstadiet. Dessutom är borrhålsgeofysik viktig för in-situ korrelation och kontroll av storskaliga geoelektriska data.

I ett försök att visa tillämpbarheten av geoelektriska metoder vid bergbyggnadstekniska förundersökningar, har ett koncept för användningen av Datavärdesanalys (Value of Information Analysis or VOIA) utvecklats. VOIA används för att välja det förundersökningsprogram som är mest lämpligt för en specifik geologisk miljö. VOIA bygger på Bayes statistik och kostnads-nyttoanalys och lämpar sig för problem där olika alternativ utvärderas och jämförs. I VOIA jämförs kostnaden för ny information med den minskade risken för att ta ett ekonomiskt ofördelaktigt beslut. Ny information är endast intressant när det kan förändra beslutet och därmed är av värde för beslutsfattaren. Kostnaden för en undersökning eller mätning bör vara mindre än vad besparingen förväntas vara, annars bör undersökningen inte göras. VOIA av geofysiska metoder som används i förundersökningen visade obestridligen att värdet av att utföra geoelektriska och markbaserade magnetiska mätningar innan borrningarna har ett högre värde än endast borrning. Detta resultat gäller endast för denna geologi och är platsspecifik. Den utvecklade konceptet kan hjälpa till att utforma det bästa mätprogrammet för ett specifikt geologisk förhållande där VOIA används för att välja mellan olika geofysiska metoder, t ex geoelektiska metoder, seismiska och magnetiska eller en kombination. Det koncept som utvecklats har potentialen att bli en integrerad del av en förundersökning.

Med en optimerad förundersökning med väl integrerade resultat, minskas osäkerheten i den ingenjörsgeologiska prognosen och risken för att något oförutsett skulle inträffa minskar. Geoelektriska metoder och borrhålsgeofysik bidrar till att minska osäkerheten och bör därför betraktas som en potentiell del av alla förundersökningar samt produktionsskedet.

Nyckelord: Geoelektriska metoder, använd geofysik, förundersökningar, borrhålsgeofysik, Datavärdesanalys.

Abstract

Construction in rock is associated with risks because knowledge of the geology and ground conditions is limited. Unforeseen rock conditions involve a large risk to the project and can in the end entail delays and extra costs. To minimize the risks, an optimized pre-investigation program has to be conducted where essential information is gathered in order to make the best decisions throughout the construction project.

In this report the main focus has been on the applicability of geoelectrical methods as a tool for predicting geological and rock mass conditions. The application of the geoelectrical methods at different scales has been proved to provide useful information at different stages of rock tunnel construction. In the geological setting at the Hallandsås Horst the method can indicate fractured, water bearing rock, weathered rock and to some extent lithology changes in crystalline bedrock. Large scale geoelectrical imaging is useful in the design/production planning stage and in the construction stage. Geoelectrical measurements are performed at a more detailed scale between two horizontal boreholes mainly in the construction stage. At even more detailed scale, geoelectrical methods may be combined with other geophysical methods in borehole logging and be applied late in the design/production planning stage. Additionally, borehole geophysics is important for in situ correlation/verification of the large-scale geoelectrical data.

In an attempt to demonstrate the applicability of geoelectrical imaging in pre-investigations for rock tunnel construction, a framework for Value of Information Analysis (VOIA) has been developed. The VOIA is used for choosing the pre-investigation program best suited for a specific geological environment. VOIA is based on Bayesian statistics and cost-benefit analysis and is suitable for problems where different alternatives are evaluated and compared. In VOIA the cost for new information is compared with the reduced risk for taking an economically unfavourable decision. New information is only interesting when it can change the outcome of the decision and thus is of value for the decision-maker. The cost of an investigation or measurement should be less than what is expected to be saved; otherwise the investigation should not be made. The VOIA of geophysical methods used in pre-investigation showed indisputably that the value of performing geoelectrical imaging and ground based magnetic measurements prior to drillings has a higher value than only drilling. This result is only valid for this particular geological setting and is site specific. Nevertheless the framework can help designing the best measurement program for a specific geological setting if the VOIA is used to decide between different geophysical methods, e.g. geoelectrical imaging, seismic, magnetic or a combination. The framework developed has the potential to become an integral part of any pre-investigation.

With an optimized pre-investigation with well integrated results, the uncertainty in the engineering geological prognosis is reduced and the risk that something unexpected happens is reduced. Geoelectrical imaging and borehole geophysics contributes to reduce the uncertainties and should therefore be considered as a prospective part of all pre-investigations as well as the production stage.

Keywords: Geoelectrical imaging, applied geophysics, pre-investigation, borehole geophysics, Value of Information Analysis (VOIA).

Table of contents

1 Introduction

1.1 Background

Construction in rock is associated with risks as the knowledge of the geology and ground conditions usually is limited. Unforeseen rock conditions involve a large risk to the project and can in the end entail delays and extra costs. To minimize the risks, a profound and optimized pre-investigation has to be conducted where the necessary information is gathered in order to make the best decisions throughout the construction project (Baynes et al., 2005; Ngan-Tillard et al., 2010).

Different geophysical methods are important in these investigations. Geoelectrical imaging is one of the geophysical methods that have proved to be important at a large scale, especially for pre-investigations at the feasibility stage (e.g. Cavinato et al., 2006; Dahlin et al., 1999; Danielsen and Dahlin, 2009; Ganerød et al., 2006; Rønning, 2003; Stanfors, 1987). The method can also be relevant in small scale and used for cross hole tomography studies (e.g. Daily et al., 1995; Daily and Owen, 1991; Danielsen and Dahlin, 2010; Deceuster et al., 2006; Denis et al., 2002; French et al., 2002; Goes and Meekes, 2004; Guérin, 2005; LaBrecque et al., 1996) and as logging tool (e.g. Daniels and Keys, 1990; Ellis and Singer, 2007; Ernstson, 2006; Howard, 1990; ISRM, 1981; Paillet and Ellefsen, 2005; Rasmussen and Bai, 1987; Schepers et al., 2001; Segesman, 1980). However, the authors experience from several unpublished pre-investigation reports from tunnel projects in Sweden is that the method has not been fully recognised as an integrated part of the pre-investigations.

In this report the main focus is on the applicability of the geoelectrical method as a tool for predicting geological and rock mass conditions. By applying the geoelectrical method at different scales and together with other geophysical methods it has proven to give useful information at different stages of rock tunnel construction. For this geoelectrical data measured at the Hallandsås Horst in Southern Sweden are evaluated regarding its ability to resolve different properties of the rock mass.

The results of the geophysical measurements usually have to be processed and evaluated by a geophysicist. The geophysicist knows the sensitivity and resolution of the methods. Thus the decision maker does not always have appropriate understanding of the advantages and limitations of the various geophysical methods. On the other hand the geophysicist does not always have detailed understanding of what the decision maker requires; e.g. at what scale information is needed. One task for the decision maker and the geophysicist is to find a common language. Value of information analysis (VOIA) might be an approach for communicating with the decision makers.

VOIA can help to create a rational design strategy for investigation programmes. The method is based on Bayesian statistics and cost-benefit analysis and is suitable for problems where different alternatives are evaluated and compared, e.g. the design of an investigation programme when the number of measurements or investigations needs to be determined. In VOIA the value of new information, from measurements for example, is assessed by estimating the uncertainties in the present information compared to the expected reduction in uncertainty following collection of new information. The cost and the time it takes to obtain better information must be compared to what can be saved by modifying the investigation programme. New information is only interesting when it can change the outcome of the decision and thus is of value for the decision maker. The cost of an investigation or making a measurement should be less than what is expected to be saved; otherwise the investigation should not be made (Bedford and Cooke, 2001; Freeze et al., 1992).

One of the central tasks is to evaluate how good different geophysical methods are at detecting problematic rock conditions in otherwise good rock. Because such estimation can be biased (based on experience, affiliation etc.), our approach is to ask geophysical experts to judge this in order to get a more objective result. The experts will be presented with a number of simulations of tentative rock volumes and the estimate should be based on those. The expert's opinion is then the foundation for the probability used in the VOIA. It is also important to remember that the estimate is only valid for a specific geological setting. In the framework developed in this thesis a hypothetical example is used, but it is inspired by the construction of the Hallberg tunnel in Sweden.

1.2 Aim and objectives

The overall aim with this project is to investigate the applicability of geoelectrical methods in pre-investigation for hard rock tunnel construction. This is achieved by evaluation of geoelectrical methods in different scales, case studies, theoretical studies and development of a framework for VOIA. A secondary purpose is to demonstrate the importance of planning and execution of a pre-investigation program with geophysics, including geoelectrical methods, to engineers and decision makers.

The work is presented in Danielsen (2010) as a Ph.D. thesis and six papers are a part of the thesis:

Paper 1 Danielsen, B.E., Arver, H., Karlsson, T. and Dahlin, T. (2008) Geoelectrical and IP imaging used for pre-investigation at a tunnel project. *Conference proceeding. 14th Meeting Environmental and Engineering Geophysics, Krakow, Poland, 15-17 September 2008*, *P44, 4p.*

Paper 2 Danielsen, B.E. and Dahlin, T. (2010) Numerical modelling of resolution and sensitivity of ERT in horizontal boreholes. *Journal of Applied Geophysics*. 70: 245-254

Paper 3 Danielsen, B.E. (2010) Borehole geophysics provides detailed information in pre-investigation for rock tunnel construction. Submitted for publication to *Canadian Geotechnical Journal.*

Paper 4 Danielsen, B.E. and Madsen, H.B. (2010) Geophysical logging as a tool for identifying initial weathering in crystalline rocks. Accepted for publication in *Near Surface Geophysics (with revisions).*

Paper 5 Danielsen, B.E. and Dahlin, T. (2009) Comparison of geoelectrical imaging and tunnel documentation at the Hallandsås Tunnel, Sweden. *Engineering Geology. 107: 118-129*

Paper 6 Danielsen, B.E., Norberg, T. and Rosén, L. Framework for Value of Information Analysis applied to geophysical methods used for pre-investigation. *Manuscript.*

The specific objectives have been fulfilled by:

- Giving examples on how pre-investigation was done in three tunnel projects and what the outcome was for the projects (Chapter 2).
- Creating a flow chart for pre-investigation (Chapter 3).
- Demonstrating the applicability of the geoelectrical method in different scales (Chapter 5).
- Developing a framework for VOIA for geophysical methods prior to drillings (Chapter 6).
- Assessing the possibilities, strengths and weaknesses of the geoelectrical imaging and the application of VOIA (Chapter 7).

Chapter 4 presents the applied geophysical methods. Chapter 6 presents the theory behind VOIA. Chapter 8 summarises the conclusions of the work and chapter 9 presents some recommendations for the future work within this research area.

1.3 Limitations

Attempting to apply general rules to geological problems always involves limitations. The true complex geology can never be fully explained by a model. Even though some general remarks about the flow scheme in a pre-investigation is given in chapter 3 the main focus in this project is on the applicability of geoelectrical methods used in different scales in pre-investigation for hard rock tunnel construction. It is also important to stress that there exist several other useful geophysical methods to consider when planning a pre-investigation and that the information from the geophysical methods only is a part of the compilation of an engineering geological prognosis.

For the application of VOIA there are several limitations. The framework developed is a simplification of reality where e.g. only two different rock classes are considered. Additionally is the framework only tested on one tunnel project and it is important to remember that a VOIA is site specific. Even though a large effort was put into finding the correct economic key numbers some assumptions had to be made concerning the additional cost due to unexpected events during tunnel construction.

1.4 Description of the papers

The first large scale geoelectrical imaging measurements were carried out at the Hallandsås Horst in 1998 (Fig. 2.6) and chapter 5.2-5.5 can be considered as natural successors following the top-down approach in a pre-investigation (Fig. 1.1). In chapter

5.6 the geoelectrical imaging data measured during pre-investigation is evaluated for the use in the construction stage. A VOIA should ideally be made prior to additional measurements in order to evaluate if it is worthwhile to make them. Thus there should be a VOIA prior to each of the chapters 5.2-5.5. However, the VOIA in chapter 6 is a framework developed to help decide if it is worthwhile to perform the measurements in chapter 5.2.

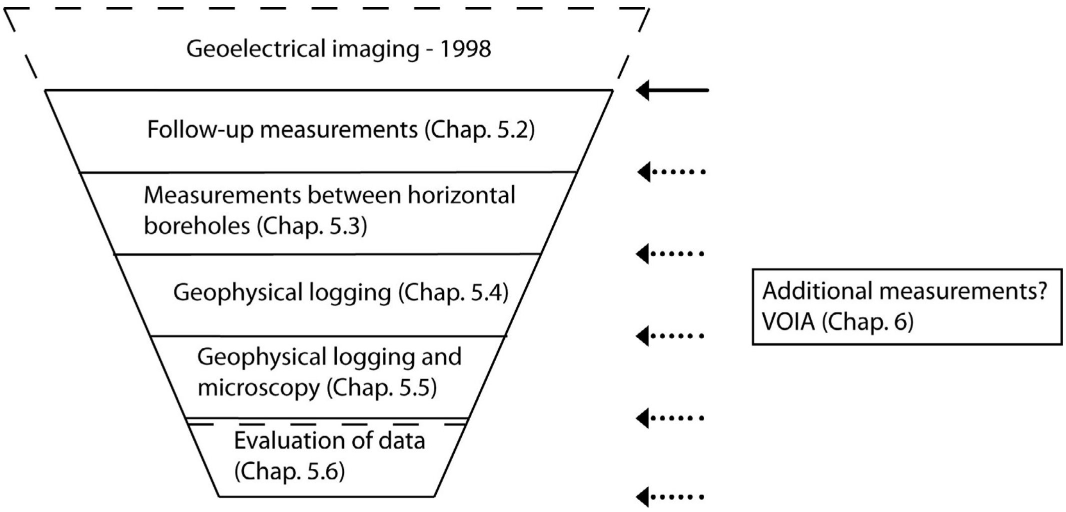

Figure 1.1. The flow in the results presented in this report.

Chapter 5.2, paper 1: Geoelectrical and IP imaging used for pre-investigation at a tunnel project

In this extended abstract geoelectrical and IP imaging are combined with ground based magnetic measurement to compile a geological model of 900 metre of the Hallandsås Tunnel, Southern Sweden. IP proved to be useful at locating dolerites and resistivity was useful for the general distribution of fractures. Magnetic measurements are a good supplement to pinpoint the exact position of the dolerite. Based on the general geologic information, resistivity and IP measurements, recommendations can be given on where to drill in order to improve the geological model.

Chapter 5.3, paper 2: Numerical modelling of resolution and sensitivity of ERT in horizontal boreholes

In this paper resistivity is measured in horizontal boreholes to obtain information about the rock volume between the boreholes. This is an attempt to identify a suitable methodology for an effective measuring routine for this type of geophysical measurements under actual construction site conditions. Prior to any measurements numerical modelling was done to evaluate the resolution of different electrode arrays, the sensitivity towards inaccurate borehole geometry and the influence of water in the boreholes.

Chapter 5.4, paper 3: Borehole geophysics provides detailed information in pre-investigation for rock tunnel construction

Focus in this paper is how borehole geophysical logging can provide high resolution and detailed information about the lithology change, fractures and weathering of crystalline bedrock. In two core drilled and one percussion drilled boreholes at the Hallandsås Horst, Southern Sweden, geophysical logging with gamma, caliper and short/long normal resistivity was performed. The results suggest that logging should be done in non-cored boreholes as a cheaper alternative to core drilled holes.

Chapter 5.5, paper 4: Geophysical logging as a tool for identifying initial weathering in crystalline rocks

The scope of this paper is to show how even low degrees of weathering of rocks affects the geophysical log response, by means of thin section microscopy, point counting and logging. This was done on gneisses and amphibolites from two drill cores done in connection with the construction of the Hallandsås Tunnel, Southern Sweden. The resistivity logs can detect even low grades of weathering of amphibolites which can be important for the mechanical properties of the rock.

Chapter 5.6, paper 5: Comparison of geoelectrical imaging and tunnel documentation at the Hallandsås Tunnel, Sweden

In this work the electrical imaging is evaluated with regards to the method's applicability. The evaluation is done qualitatively by comparing the electrical imaging with tunnel documentation from a tunnel in Southern Sweden. By evaluating the result continuously when constructing the tunnel, a more detailed geological prognosis can be compiled and used in continuing work with the tunnel. The parameters used for the comparison are lithology, Q, RQD, weathering and water leakage. The result was that virtually every change in electrical resistivity image coincides with a change in rock conditions. The general trend was that high resistivity corresponded with good quality gneiss whereas low resistivity corresponds to poor quality rock e.g., high weathering, low RQD, low Q and/or several lithological contacts. The intermediate resistivity is often amphibolites or rock with water bearing fractures. The results were supported by in-situ resistivity measurements inside the tunnel and resistivity logging in a core drilling.

Chapter 6, paper 6: Framework for VOIA applied to geophysical methods used for pre-investigation

VOIA is a cost-benefit analysis of different decision alternatives. In this framework decisions have to be made about how to proceed with pre-investigations for the construction of a rock tunnel. It has to be decided if geophysics should be done prior to drillings. The value of information gained by doing geophysics as part of the pre-investigation is estimated.

2 Case studies

The quality of a pre-investigation and how the information is integrated in the decisions can have huge importance for the outcome of a construction project. In the following three examples of how the pre-investigations in different tunnel projects have been performed and what the consequences were for the projects will be given. The examples are from different geological settings and conditions and therefore cannot be compared directly. The projects are described only briefly and should be seen as an appetizer and explanation to why this report is built up as it is.

2.1 Pungwe water tunnel, Zimbabwe

In the late 1990's a water tunnel in the Pungwe-Mutare Water Supply Project in the eastern Zimbabwe was constructed by Skanska. The purpose was to lead water from the Pungwe river, which runs through the Nyanga National Park, to the city of Mutare (Fig. 2.1).

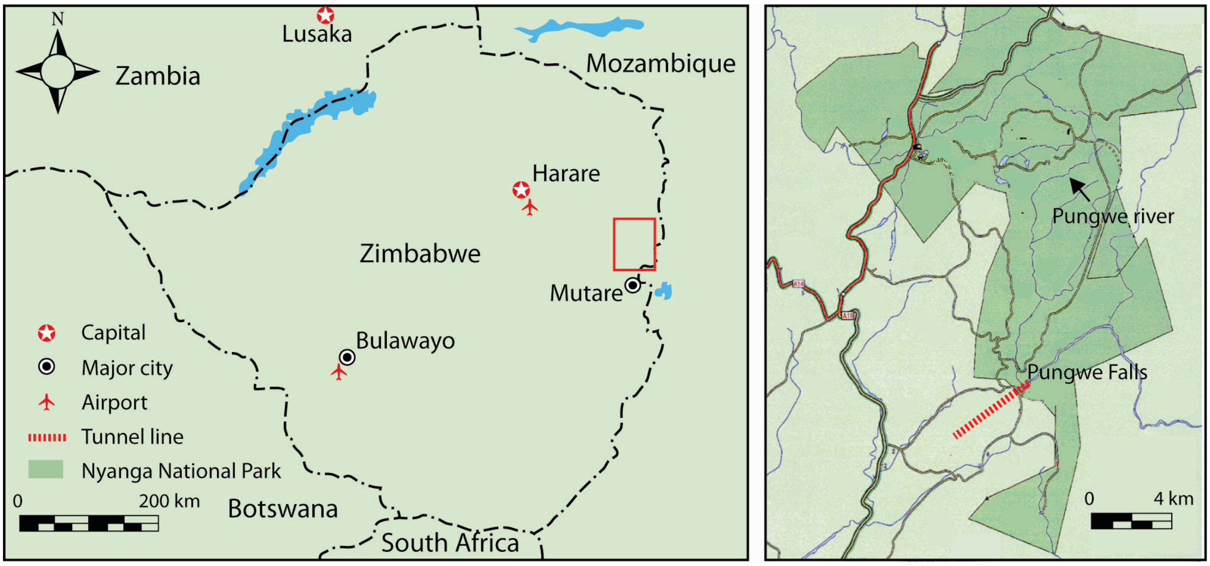

Figure 2.1. Map to the left shows Zimbabwe with the position of the Nyanga National Park (red square) and the city of Mutare. The map to the right shows the approximate tunnel line, with the intake in the north-eastern end. Maps are modified from Henriksson (1996) and mappery.com (2010).

The water is transported through a 4 km long tunnel and 96 km pipeline. For 1 km the tunnel runs though the Nyanga National Park with high environmental responsibilities as a consequence. A minimum of environmental disturbance was required and thus no test drillings were allowed in the national park at this time (Henriksson, 1996). The tunnel with a diameter of 4 metre is constructed in granitic and gneissic rock with fracture zones and deep weathering. Additionally, the terrain is rough and no road access to the tunnel line exists (Dahlin, 1998). Older test drilling results were available and in 1973 the Geological Survey of Zimbabwe performed a preliminary geological report which included these 7 core drillings (Fig. 2.2). The drill holes were distributed along the tunnel line as it was intended at that time. In several of the core drillings fractured and highly weathered rock was encountered above tunnel level but at 60 m relevant to the proposed tunnel the rock is fresh and unfractured. However at the intake there are several dolerite dykes with vertical jointing. Thus the recommendation was to do a more thorough pre-investigation at the water intake area (Kirkpatrick, 1973). When the pre-investigation was resumed in 1997 a 950 metre long CVES profile was performed along the tunnel line (Dahlin, 1998), see figure 2.2.

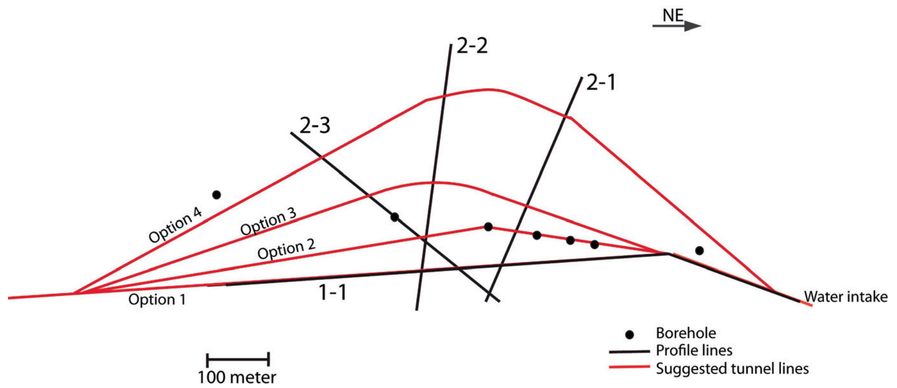

Figure 2.2. Sketch of the Pungwe tunnel, profile line 1-1, 2-1, 2-2 and 2-3 (black lines) and suggested tunnel lines (red lines).The boreholes from 1973 are marked with black dots.

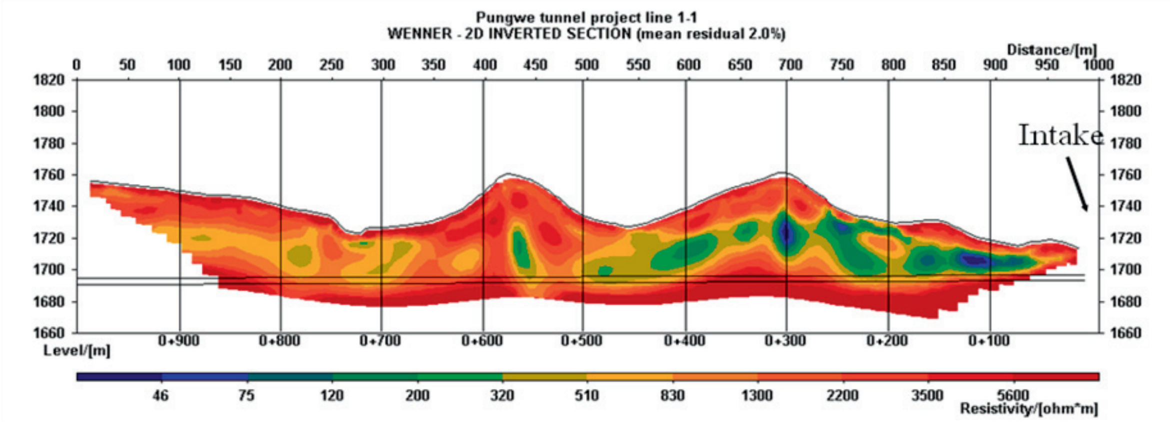

Figure 2.3. 2D resistivity model based on the CVES data from profile line 1-1. The two horizontal parallel lines mark the position of the planned tunnel. From Dahlin (1998).

The CVES data showed that the resistivity was a few hundred Ωm at tunnel level (Fig. 2.3) which indicated very poor rock quality with fractured rock and deep weathered zones. A horizontal borehole from the intake point confirmed the poor rock quality. This would create large problems for the tunnel construction and make it difficult to match the demands for minimal environmental disturbance. Thus additional CVES profiles were measured perpendicular to the planned tunnel line (Fig. 2.2). The three profiles (Fig. 2.4) showed that in the northern part of the line the resistivity was higher than 3500 Ωm and therefore was considered as rock with few fractures and without deep weathering. Due to the detected weathering the tunnel line was moved from option 1 to option 4 (Fig. 2.2), avoiding extra construction time and costs. If the tunnel had followed the original planned line it would have been difficult for Skanska to accomplish the high environmental demands (Dahlin, 1998).

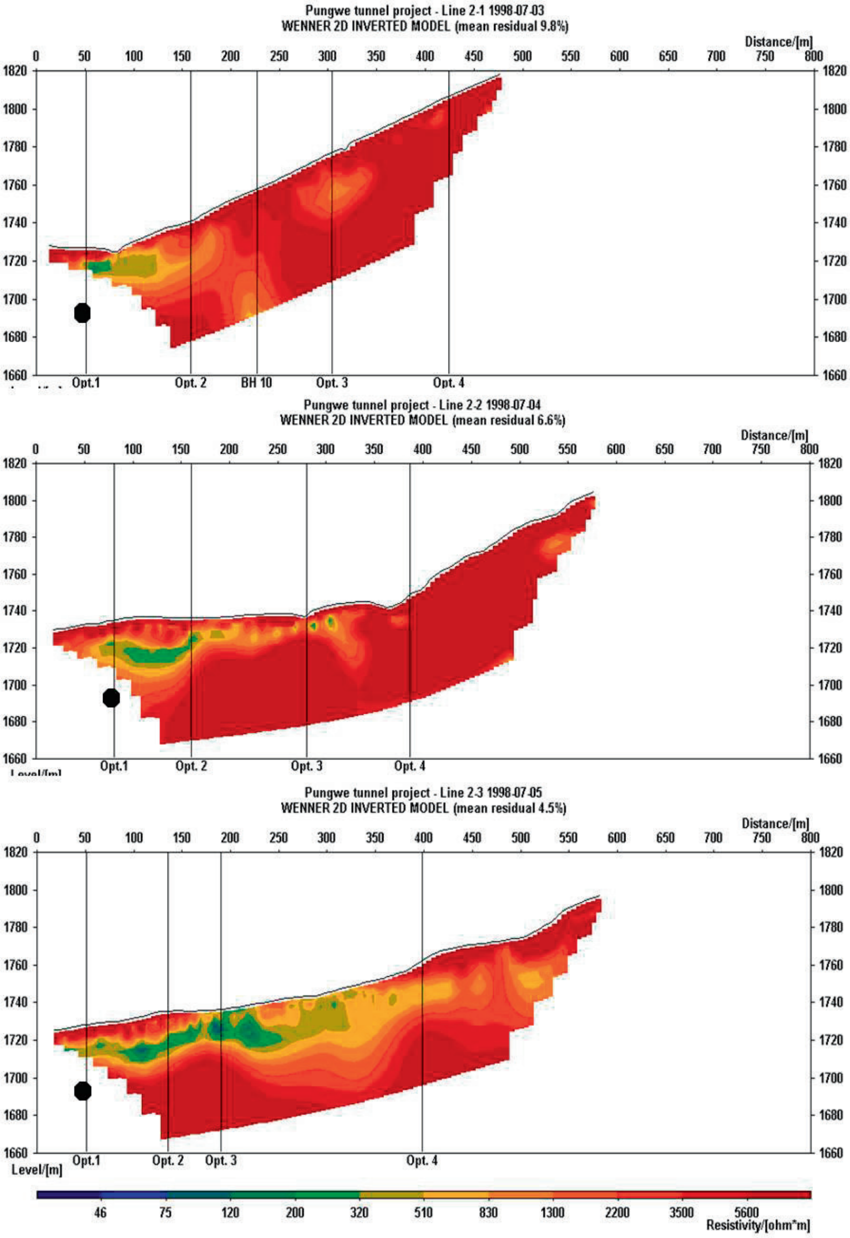

Figure 2.4. The CVES profiles, 2-1, 2-2 and 2-3. The four vertical lines mark the four different tunnel options, where the original option 1 is marked with a black dot. From Dahlin (1998).

2.2 Hallandsås railway tunnel, Sweden

The railway tunnel through the Hallandsås Horst is a well-known project in Sweden that from time to time has taken up large space in the media due to extensive delays and budget overruns. It is a 8.6 km long twin track tunnel through the most northern part of the Scanian horsts (see figure 2.5 and chapter 5.1 and 5.2 for more information about the geological setting). When the project started in 1992 the plan was to complete construction in 1996. The new time schedule aims for 2015 with a total budget of 10.5 billion SEK (2008 monetary value) (Trafikverket, 2010).

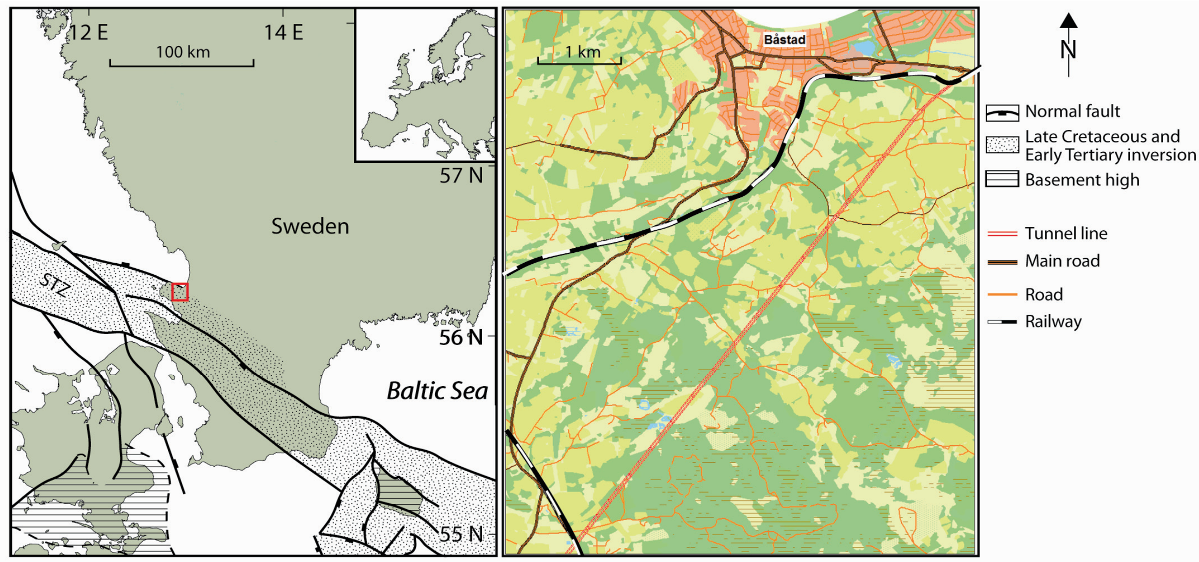

Figure 2.5. Left: Map of Southern Sweden showing the position of the investigation area and the outline of the Tornquist Zone (STZ). Right: The tunnel line. Maps are modified from Graversen (2009), Lantmäteriverket (2001) and Liboriussen et al. (1987).

The Swedish company *Kraftbyggarna* started constructing the tunnel in 1992 using an open tunnel boring machine (TBM). This turned out to be a wrong approach because the TBM was designed for competent hard rock. However the first hundred of metres was weathered rock partly with mechanical properties similar to stiff clay. In 1993 *Kraftbyggarna* began using a drill and blast approach instead. In 1995 *Kraftbyggarna* left the project after constructing 3 km of the tunnel, due to an economic dispute with the project owner, *Banverket* (Swedish Railroad Administration). In 1996 *Skanska* continued the work using drill and blast as excavation method. Skanska made an opening in the central part of the horst so that they could continue the work on four additional adits, giving a total of eight adits. However within the first year problems with high groundwater leakage into the northern part of the eastern tunnel arose. The groundwater level dropped and wells in the vicinity dried out. Several different sealing products were tested; among those the internationally used chemical sealant Rhoca Gil. In 1997 the use of the product was terminated because high water flow prevented the sealant from hardening and as a consequence contaminated the water in the streams with acrylamide. This caused fish to die and cattle to get sick from drinking water from the streams. The work was ceased and did not commence until 2003 when the consortium *Skanska-Vinci* continued the project with a completely new method including a shielded TBM and continuous concrete lining as means to control the water ingress to the tunnel on both short and long term. Then in 2003 a major leakage of grout penetrated the rock mass at Lyabäcken and again fish died. This time the Mölleback rock deformation (MBZ, see figure 2.6) was the reason. When the TBM started drilling in 2005 one third of the tunnels were finished. In August 2010, the East tunnel was successfully completed and in total 69% of the tunnels were complete and it is planned that traffic through the tunnels will commence in 2015 (Trafikverket, 2010).

Table 2.1. A summary of the pre-investigation performed in connection to the Hallandsås Tunnel during the three major investigation intervals (Banverket,1996; Banverket, 2002; VBB VIAK, 1999).

	1989-1990	1994-2000	2001-2002	Comments
Geophysics				
Seismics	10.5 km	3.6 km		
VLF	19.2 km	6.4 km		
DC resistivity, profiling	8.5 km			
DC resistivity, sounding	23 soundings in 17 points			
DC resistivity, CVES		14.25 km	2.8 km	Shorter profiles in the MBZ, SMZ and NMZ
Magnetics	8.5 km			
Slingram	6 km			
Drillings				
Soil-rock penetration	10			
Percussion drilling	25	11		
Core drilling	13	20*	13	* 5 are horizontal from tunnel level and 2 are wire-line core drillings
Hydraulic tests				There exists a large monitoring project where the groundwater level is measured regularly
From percussion drilling	25	11	13*	* Water-loss measurements
Pump test	6	2		
Geophysical logging		2		
Laboratory tests	13			E.g. point load index, mechanical properties, E-module and Poisson's number

During the project it has become obvious that the geological setting is unusually complex by Swedish standards and as a consequence further investigations have been performed on several occasions from 1989–1990, 1994–2000 and 2001–2002 (Tab. 2.1). However, the tunnel project has the reputation that the parties were not prepared for the complex geology. Prior to project start the most extensive pre-investigation was done where several different geophysical methods were used (Tab. 2.1). The Hallandsås Tunnel succeeds another large tunnel project in Scania, the Bolmen tunnel. In the Bolmen Tunnel project different geophysical methods had been of high value (Stanfors, 1987). In one area geophysical data even changed the tunnel line position due to poor rock quality (Backblom and Stanfors, 1986). The successful use of geophysical methods may have been the reason why so many different methods were used at the Hallandsås. The main focus was on the known difficult areas with poor rock quality, which were the northern (NMZ) and southern marginal zones (SMZ), whereas very little focus was on the central parts where good rock quality was expected. Despite the amount of work focussed on SMZ and NMZ, the project managers were taken by surprise by the failure of the first TBM in the poor rock in NMZ. How this happened is not for the author to speculate, but a lesson to be learned. Thus in this case it did not matter how much pre-investigation was done or how many different methods were applied since the information was not fully used and integrated in the decision-making.

The long project history with several pre-investigation campaigns conducted by varying consultants and changing contractors may create difficulties in handling the many different kinds and generations of data. The hydraulic data from the many observation wells are gathered in a database. But other types of geo-data, different raw data and interpreted models, are not gathered in a central database which otherwise would be beneficial to a project of this kind.

Since 2003 the project has learned from history and worked intensively with the engineering geological prognosis and with geological data in general. The geological setting is complex and extremely heterogeneous which demands a large focus on the geological data. A positive tendency in the project is that the geoelectrical imaging profiles (e.g. Fig. 2.6) are used actively in the planning of the use of the TBM and not only applied to the areas containing rock of poor quality but also to the areas with good rock quality.

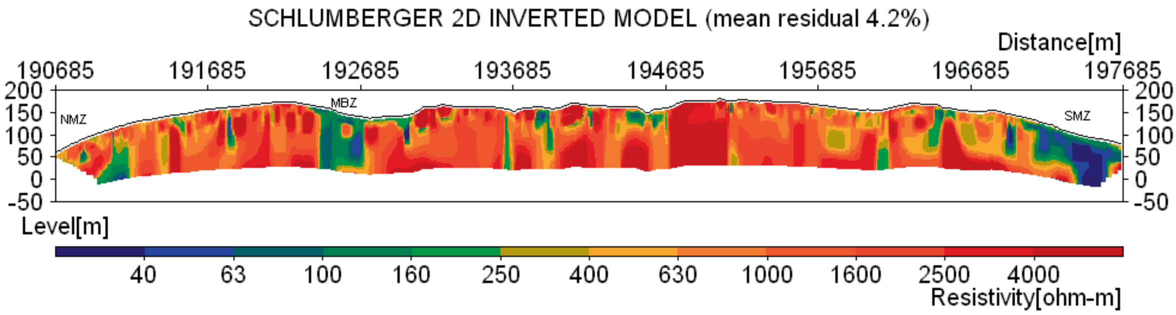

Figure 2.6. The 7 km long geoelectrical imaging (CVES) profile along the tunnel line.

2.3 Citytunneln, Sweden

In Malmö, southern Sweden, a railroad tunnel project called Citytunneln is a good example of how a well planned and integrated pre-investigation can benefit a project. The Citytunneln is a 17 km long railway project of which 6 km is two parallel single track tunnels. The tunnels are drilled beneath the central parts of the city of Malmö, see figure 2.7. The geological setting is not as complex as for the Hallandsås Tunnel, and is mainly a relatively impermeable and homogeneous Bryozoan limestone.

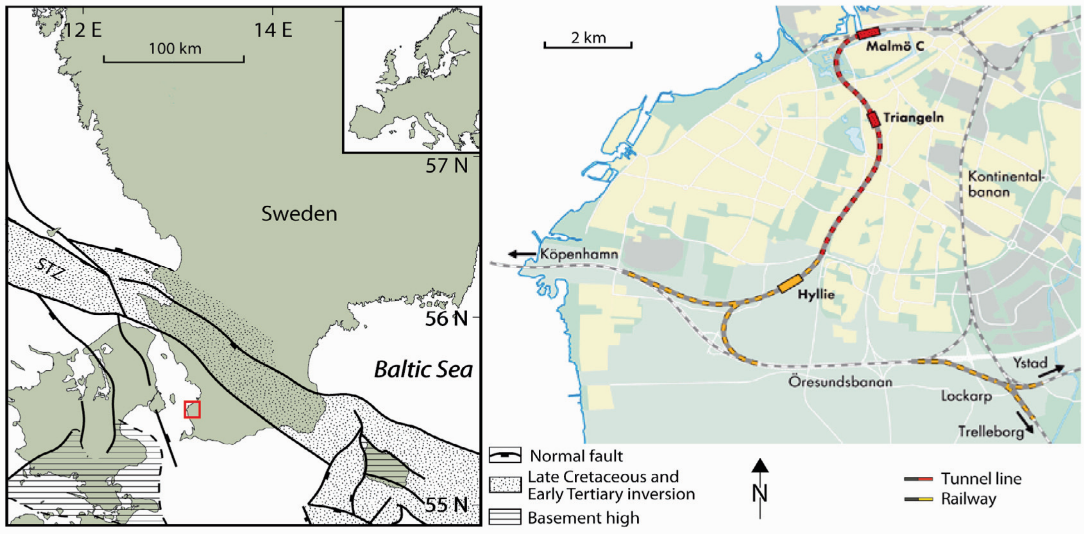

Figure 2.7. Left: Map of Southern Sweden showing the position of the investigation area and the outline of the Tornquist Zone (STZ). Right: The city of Malmö with the tunnel line. Maps are modified from Liboriussen et al. (1987), Graversen (2009) and Citytunnelprojektet (2003).

The project is unique because it is the first major infrastructure project in Sweden where the environmental impact of the project has been tested in the Environmental Court according to the Environmental Code. The Environmental Court have set detailed conditions for e.g. the maximum drawdown and amount of groundwater that may be pumped away and what amount has to be re-injected. On this basis, agreements with contractors had to be made, i.e. choice of working methods and the materials and chemicals used (Citytunnelprojektet, 2003).

The strict environmental demands set by the Environmental Court made it necessary to do an extensive pre-investigation. A summary of the pre-investigation performed in the tunnel part of the project is presented in table 2.2. The first drilling campaign started in 1995 and later several others followed. In the project phase more than 300 drillings were done, and in nearly half of them borehole geophysical logging was performed, providing detailed in situ information about the rock properties (VBB-COWI Joint Venture, 2000a). CPT-soundings, core drillings and percussion drillings were done and rock was sampled for laboratory tests, e.g. mechanical strength and density. Seismic surveys (26 km) provided information of structures and faults in the limestone (VBB-COWI Joint Venture, 2000c). To a small extent surface wave seismic and CVES profiles were tested in a limited area in Lockarp (Wisén and Christiansen, 2005). Pump tests were conducted to make a characterization of the aquifer, e.g. transmissivity and storage coefficient (VBB-COWI Joint Venture, 2000b). All information was gathered in a database and used for an integrated engineering geological prognosis. In addition to data obtained during the project the database also contained more than 9000 boreholes drilled prior to the project, which mainly contributed with stratigrafic information. The database was accessible to all the involved parties (VBB-COWI Joint Venture, 2000c).

Table 2.2. A summary of the pre-investigation performed in connection to the Citytunneln during the project phase (only from the tunnel part) (Based on VBB-COWI Joint Venture, 2000a, b, c*).*

	1995-2000	**Comments**
Geophysics		
Seismics, refraction	11 km	
Seismics, reflection	16 km	
Drillings		
Soil-rock sounding	12	
Percussion drilling	250	
Core drilling	52	
Hydraulic tests		There exists a large monitoring project where the groundwater level is measured regular
Capacity test	107	
Pump test	25	Short and long term
Geophysical logging	138	
Laboratory tests	45	E.g. mechanical properties, E-module and Poisson's number.

The extensive pre-investigation took relatively long time and had a high cost compared to earlier construction projects in Sweden. A possible question is if the pre-investigation was too extensive, but with the high demands from the Environmental Court and a tunnel constructed beneath a city, the ambitions regarding the pre-investigation has to be very high. What can be concluded is that the extensive pre-investigation was a contributing factor to a relatively smooth construction. The tunnel was inaugurated 6 months ahead of schedule with a total cost of 8.565 billion SEK which is 1 billion SEK lower than budgeted (Citytunnelprojektet, 2003).

3 Pre-investigation

A major problem when constructing tunnels is unforeseen rock conditions e.g. water leakage and changes in rock mechanical properties. In a study conducted by Malmtorp and Lundman (2010) it was concluded that uncertainty in the engineering geological prognosis led to delays and raised budgets. To reduce the uncertainty a high-quality engineering geological prognosis is necessary.

The scope of a pre-investigation will essentially be driven by the need to answer questions about the geology, by knowledge of the engineering requirements of the project and appreciation of what level of knowledge is appropriate for satisfactory engineering. The objective of any investigation is maintained by exchange of information between the project owner and consultant. It should be the responsibility of the engineering geologist/geophysicist to determine an appropriate scope for the pre-investigation within a reasonable budget (Baynes, 2003).

Decision makers are in most cases aware of the importance of pre-investigation, but nevertheless the deciding factors are time and money. It takes time to perform, interpret and compile the measured data and time costs money. Looking at a budget for a project it is easy to identify the cost for a thorough pre-investigation. However, what has to be acknowledged is that with a thorough and optimised pre-investigation the uncertainty is reduced and that will in the end save time and money. Unfortunately this is not so easy to quantify and is not an obvious entry in a budget.

3.1 Engineering geological information and prognosis

The aim with the pre-investigations is to prepare an engineering geological prognosis for the construction site which answers a number of key questions. Key questions are the demands for information on engineering geology issues. To be able to investigate and evaluate the relevant aspects of the bedrock, the key questions have to be defined for each individual project before a pre-investigation strategy is identified (Almén et al., 1994; Bergman and Carlsson, 1988). Some key questions could be rock type, weathering/rock cover, rock stress, presence of water and major fault zones (Sturk, 1998).

The geological prognosis is a preliminary prediction of the relevant aspects of the bedrock and is obtained by evaluating and analysing the geological information available. The geological prognosis should be problem oriented; that is it should structure the available information so physical conditions that may be of (positive or negative) technical or economic significance for the project are highlighted and presented in tangible terms. The prognosis should be dynamic so the results of new investigations become available, followed by further assessments that agree with or modify the original geological prognosis (Bergman and Carlsson, 1988; Stanfors et al., 2001).

How detailed the information in the geological prognosis needs to be depends on the stage of the construction project. The different stages are e.g. the feasibility stage, the design/production planning stage and the construction stage (Sturk, 1998). Each stage needs information at a different scale. In the feasibility stage the scale considered is regional i.e. >>1000 metre depending on the size of the project. For the design and production planning stage the scale of interest has narrowed to a site scale (100─1000 metre). In the construction stage the need for detailed information is greater and the scale can be a block scale (10─100 metre) or a detailed scale (<10 metre) (Almén et al., 1994; Sturk, 1998). In each stage the key questions are related to certain decisions. Examples of key questions and how they could be described in each stage are seen in table 3.1.

Table 3.1. Examples of key questions and how they might be described during each stage. Modified after Almén et al.(1994) and Sturk (1998).

Key question	**Feasibility stage Scale >1000 metre**	**Design/production planning stage Scale 100-1000 metre**	**Construction stage Scale <100 metre**
Rock type	General knowledge. Stop signs?	Rock type distribution. Mechanical parameters for expected rock types.	Location of difficult rock types and boundaries. Stand-up time.
Weathering/ rock cover	Is deep weathering or large cover expected? Rough estimate on depth to fresh rock.	Location of areas with deep weathering or low rock cover. Estimate on depth to fresh rock. Description of geological hazards.	Exact location of areas with weathering, low rock cover and boundaries.
Rock stress	Depth of facility. Location within shields. Tectonic region.	Stress levels in area. Magnitude of stress problem. Description of squeezing and spalling rock. Distribution of problematic areas.	Location of areas with stress problems. Rock stress properties in these areas. Magnitude?
Water	Water expected or not? Rough estimate on need for grouting or sealing. Estimate of pressure levels. Possibility for flowing ground?	Hydraulic parameters of rock mass. Pressures expected. Distribution of values of hydraulic parameters. Estimate on groutability and ways of sealing tunnel.	Location of water bearing structures. Pressures and permeability. Groutablity. Warning bells in current geology?
Major fault zones	Are there zones in the vicinity of the site? One or several?	Number of zones and estimate on location. Estimate on quality and width. Geological hazards.	Location, quality and width of zones. Warning bells in current geology?

The engineering geological information and prognosis have different purposes in the different project stages. The decisions should be based on data acquired by a pre-investigation campaign that has been tailored to the given geological setting. In the feasibility stage the aim is to compile the engineering geological prognosis so it gives a general picture of the geological setting in the area. If the feasibility study concludes that the project should continue, the next step is the design and production planning stage. In this stage the main questions are related to the general design which relates to excavation and support methods, capacities and costs related to these methods. These considerations lead to an estimation of the cost of the project. The key questions are the same as in the previous stage but the demand for detail is greater (Almén et al., 1994; Bergman and Carlsson, 1988; Sturk, 1998). In the construction stage the questions and decisions become more specific. Thus the engineering geological information and prognosis have to be more specific (Sturk, 1998).

In order to make the optimal decisions the key questions and the known geological settings have to be discussed by the geophysicist and the engineers prior to any investigation. In this way proper investigation methods can be applied for each stage. There will always be geological uncertainty connected with construction in rock, but decisions based on a thorough pre-investigation will reduce these uncertainties.

3.2 Flow in pre-investigation

By doing profound pre-investigations construction costs are likely to be reduced because the project parties are better prepared due to more certain rock mass problem identification. Since the pre-investigation itself involves a cost, the goal of exploration planning is to minimize the total cost of the entire construction work inclusive the pre-investigations (Einstein et al., 1978). The primary goal with a pre-investigation is to compile an engineering geological prognosis which is essential in the feasibility stage, design/production planning stage and the construction stage. The pre-investigation should be performed top down, meaning that the investigations should start on large scale and continue into more and more detail so it follows the need for information in the different project stages. The flow diagram in figure 3.2 shows how the pre-investigation preferably should be done. The boundaries between the different stages and scales are rather diffuse and should only be seen as guidelines. Thus the information from the different steps in the flow diagram should be integrated through the whole process.

In the feasibility stage the first step is to do an archive study where all old material is collected and scrutinized. This could be geological maps, topographic maps, drilling reports, airborne geophysics etc. (Danielsen, 2007). It is also important to do a field visit to get an understanding of the study area and the expected geological setting so the pre-investigation program can be tailored and the best suited methods can be chosen. In the design/production planning stage the first step is to use a quick qualitative geophysical method such as ground based magnetics or slingram. In this step it is also appropriate to do earth/rock soundings. The next step is to extend the geophysical survey with quantitative methods that are assumed to be appropriate in sensitive and critical areas, areas where information is scarce and areas where the interpretation is questionable. The large scale geophysics is followed by core drillings and percussion drillings to obtain detailed information about the rock conditions. Thus even small scale (<10 m) is important in the design/production planning stage. Starting with large scale geophysics thus makes it possible to position the boreholes in a more cost efficient way, so as much information is gained as possible. An advantage with e.g. geoelectrical imaging or seismic surveys is that a continuous model of the physical properties in the subsurface is obtained. Boreholes are point information but are essential for making a geological interpretation of the physical model obtained from the geophysical profiling methods. Thus the borehole and the borehole geophysics are valuable for interpretation and calibration of the surface based geophysics. Borehole geophysics is small scale and provides detailed information which should be performed in the final stages of the pre-investigation. The boreholes are not only useful for geophysical logging but can also be used for hydraulic tests and the extracted cores can be used for rock mechanical laboratory tests. A major concern when building rock tunnels is water leakage. Therefore it is an essential part of the pre-investigation to perform hydraulic tests. Several different hydraulic tests are useful depending on purpose and borehole/well conditions (e.g. Butler, 1990; Fetter, 2001; Gustafson, 2009)

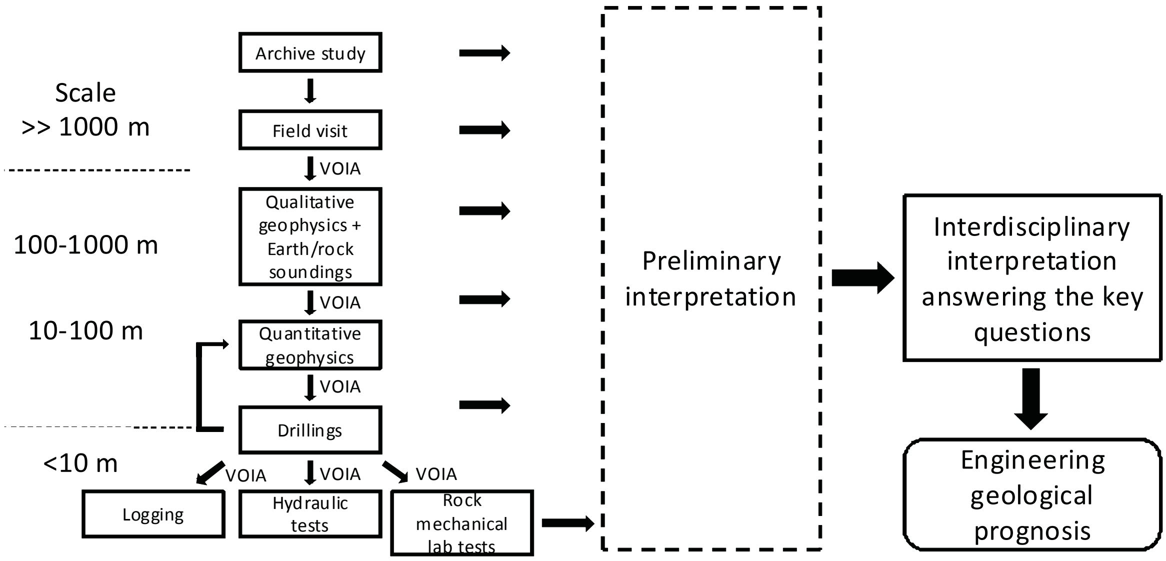

Figure 3.2. A diagram with the optimal flow in a pre-investigation program.

The pre-investigation should be seen as a dynamic process where it is important after each step to make a preliminary interpretation of all information. The framework for VOIA presented in this report should be made prior to additional measurements in order to evaluate the value of more detailed investigations and thereby get a more optimized pre-investigation. When all essential information is gathered an interdisciplinary interpretation answering the key questions should be carried out and based on this the engineering geological prognosis should be established as an aid for making the main decisions.

Through the entire project it is important to integrate all material and not forget the previous investigations. For example in the actual construction stage the geological prognosis, and with this also the geophysical data, can be evaluated against the true conditions, which will provide fundamental references and valuable experience to be used in further interpretation and evaluation. Thus it is essential at all stages to review the geological prognosis and continuously update and modify it when necessary.

In larger projects with several different contracts it is recommended that the reports presenting the results from the pre-investigations be structured in a consistent way. It is of great importance that the natural flow in the pre-investigation is kept in the report presenting the results for the client. Thus the results are presented top-down with large scale information prior to small scale. It is necessary for the client (project owner) to set some requirements and instructions for how the reports should be made.

4 Applied geophysics in rock tunnel construction

Applied geophysics can contribute to solution of most geotechnical engineering and environmental engineering problems. Geophysical methods measure the contrast in the physical properties of the sub-surface. Thus the condition of the rock mass is presented in a composite form by the geophysical data set. No interpretation is done when raw data are measured, but is mainly done during and after the processing of the data. Most geophysical methods do not directly measure the parameters useful for the project owner, engineer or contractor. For the interpretation of data, background information concerning the geological setting is required because of ambiguity and variability in the physical properties of the rocks. The physical properties are interpreted in terms of geology which in some cases even allows an assessment of the rock mass quality. For some geophysical methods the data output is of direct significance. An example is seismic methods where the p-wave and s-wave velocity are useful mechanical properties and parameters. However, it is often not the physical property itself that is of interest but the spatial change and variation in the property. Different geophysical methods have different advantages and limitations so before they are used in an engineering context the problems to be addressed have to be resolvable by the chosen geophysical method.

Several geophysical methods are suitable for continuous measurements which can give a 2D or even 3D model of the sub-surface. Thus the geophysical methods can be an important part at different stages of a project. The scale at which the measurements are done has to be tailored to match the degree of detail demanded by the actual stage of a project. In the early stages of pre-investigation large scale measurements are important whereas core drillings provide detailed point information and in situ reference data in later stages. Thus the resolution is lower for large scale geophysics than for core drillings but the continuous measurements provide an interpreted physical image of the variation in the physical properties of the rock mass.

Only a short description of the theory behind the geophysical methods used in this report is described in the following chapter, i.e. the geoelectrical method and borehole geophysics (natural gamma, caliper, long/short normal resistivity). Several other geophysical methods are useful in tunnel construction or other types of construction in rock. For more information see Butler (2005), Danielsen (2007), Parasnis (1986), Reynolds (1997), Rønning (2003), Stanfors et al. (2001), Sturk (1998), Takahashi (2004) and Takahashi et al. (2006).

4.1 Geoelectrical imaging

Geoelectrical imaging is one of the geophysical methods that has proved to be important at a large scale, especially for pre-investigations at the feasibility stage (Cavinato et al., 2006; Dahlin et al., 1999; Ganerød et al., 2006; Rønning, 2003; Stanfors, 1987). Geoelectrical imaging at small scale can be done between two or more boreholes, the so called Electrical Resistivity Tomography (ERT). In this study ERT measurements are done in and between boreholes. It can be noted that 2D resistivity imaging based on surface measurements (CVES) is also sometimes referred to as ERT. ERT in vertical boreholes has proven useful for environmental studies (Daily et al., 1995; Daily and Owen, 1991; Deceuster et al., 2006; Denis et al., 2002; French et al., 2002; Goes and Meekes, 2004; Guérin, 2005; LaBrecque et al., 1996). The method has also been demonstrated in boreholes drilled during geotechnical pre-investigation of a tunnelling site to obtain a 2D image of the resistivity close to a tunnel boring machine (TBM) (Denis et al., 2002). Only a brief introduction to the geoelectrical imaging is given here. For more information see e.g. Binley and Kemna, 2005; Parasnis, 1986; Reynolds, 1997; Takahashi, 2004.

Geoelectrical imaging is a relative fast and cost efficient method compared to other profiling methods, e.g. seismic refraction. In order to correctly interpret the data, knowledge of the geological setting e.g. anticipated lithology and groundwater level from geological maps, cores and borehole geophysical measurements etc. is important.

Geoelectrical imaging is used for measuring the spatial variation in the resistivity of the subsurface. The resistivity of the different geological materials differs greatly from about 10^{-6} Ωm in minerals such as graphite to more than 10^{12} Ωm for dry quartzitic rocks, see figure 4.1. Most rock forming minerals are insulators so the resistivity of crystalline rock depends largely on the amount and salinity of water present in fractures and the degree of weathering of the rock. (Binley and Kemna, 2005; Parasnis, 1986).

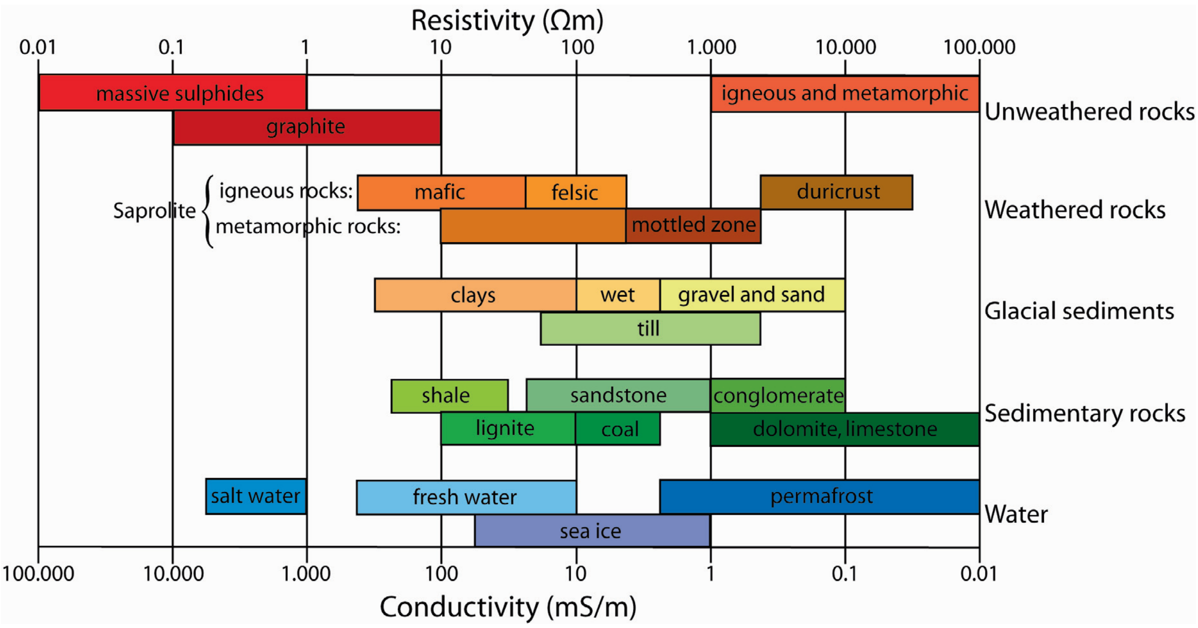

Figure 4.1. Resistivity of different materials measured in Ωm. The reciprocal of resistivity is conductivity which is measured in mS/m. Modified from Palacky (1987).

When electrical resistivity measurements are done, a direct current is transmitted between two electrodes and the potential difference is measured between two other electrodes, see figure 4.2. The measurement results in an apparent resistivity value that depends on the subsurface conditions. The convention today is to perform a large number of four electrode measurements along profiles or over areas to achieve resistivity models as 2D sections or as 3D volumes respectively. This is normally done using multi-electrode systems, i.e. Continuous Vertical Electrical Sounding (CVES). This is a rapid approach for getting information of the spatial distribution of the resistivity in the sub-surface (Dahlin, 1996).

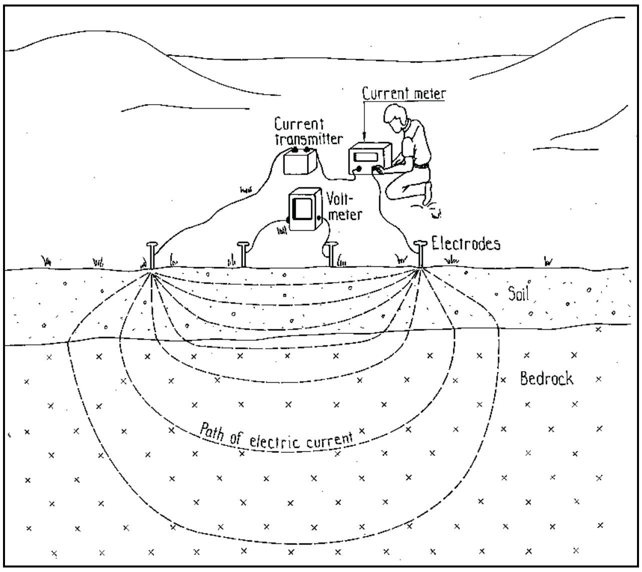

Figure 4.2. Principles of resistivity surveying (modified from Robinson and Coruh, 1988).

For an estimate of the actual resistivity distribution it is necessary to perform inverse modelling on the measured apparent resistivity data (Binley and Kemna, 2005). Techniques for acquisition and interpretation of resistivity data have been developing continuously during the last century.

Generally the depth of investigation of the method increases with increasing electrode distance. As a rule of thumb the penetration depth for the most common arrays is in the range of L/6 to L/4, where L is the distance between two outermost active current electrodes (Loke, 2004). However this is only the case if the sub-surface is a homogenous which is rarely the case. The current will go through the lowest possible total resistance on the path between the two current electrodes. For example a very low resistive layer near the surface would prevent the current from penetrating deeper into the ground. In this case the resolution of the deeper layer will be limited. In contrast, a very high resistivity layer close to the surface would force the current down to a less resistive layer. The depth of investigation thus depends much on the resistivity of the different layers as well as the largest electrode distance.

Usually the resistivity data are measured as 2D profiles while the subsurface is 3D. Assuming a 2D model can in some cases be problematic when it creates so called 3D effects in the resistivity data, especially if the geology changes on a relatively small scale. In order to obtain the best 2D view, the profiles should be perpendicular to the geological structures. With the development in computer power and data acquisition, 3D surveys are becoming more common, and these do provide a more complete image of the sub-surface.

4.2 Borehole geophysics

For obtaining detailed information from borehole geophysics numerous different logging probes exist. Several of the large scale geophysical methods can also be used in boreholes (e.g. geoelectrical imaging) but there are also additional methods available such as optical televiewer or caliper log. For calibration of the models based on large scale geophysics it is important to remember the difference in scale which may not always make it possible to compare large and small scale data.

Strictly speaking borehole logging is an alternative or supplement to the analysis of drill cores and cuttings. However, core drillings are often preferred because of the possibility of continuous analysis of the rock formation over a given interval, but economic and technical problems limit the use of cores. Coring takes time, and is therefore expensive. A core drilling is about five times as expensive as a percussion drilling (Swedish prices 2010, without mobilization/demobilization (Bjelm, 2010)). In many soft and friable rocks, e.g. in clay weathered rocks it might only be possible to recover part of the interval cored. Geophysical logging gives in situ measurements which are of great value when there is poor or no core recovery. Cuttings, extracted from e.g. percussion drillings, are one of the largest sources of subsurface sampling. However, the reconstruction of the lithological sequence from cuttings is imprecise due to the problem of exactly associating a depth with any given sample. It also demands skilled personnel to determine the lithology and weathering from the small cutting samples. Although most well logging techniques do not give direct access to the rock samples, they do, however by indirect means, provide continuous, in situ measurements of parameters related to lithology and other rock properties of interest (Ellis and Singer, 2007).

If core recovery is poor, borehole geophysics will help clarify if it is due to e.g. weathering or fractures. It is thus important that borehole geophysical data is stored for later re-interpretations. Cores should also be stored, but the moisture will disappear and new fractures may occur. Normally cuttings from the percussion drilled holes are sampled every metre or every third metre and give a useful overall impression of the variations in the borehole. The moisture will also disappear from the cuttings. The borehole geophysics will on the other hand always show the conditions in the borehole when the data was recorded.

In the following a very brief presentation of the different logging probes used in paper 3 and 4 is given. For more elaborate information the reader is referred to literature (e.g. Daniels and Keys, 1990; Ellis and Singer, 2007; Ernstson, 2006; Howard, 1990; ISRM, 1981; Paillet and Ellefsen, 2005; Rasmussen and Bai,1987; Schepers et al., 2001; Segesman, 1980).

4.2.1 Natural gamma log

Natural gamma logging is a passive logging technique where the natural gamma-ray intensity of the formation along the borehole is measured. The gamma photons are mainly produced by decay of naturally occurring potassium (^{40}K), uranium (^{238}U) and thorium (^{232}Th). For example K-feldspars are radioactive because of the large content of potassium. On the other hand amphiboles and quartz are not radioactive. Thus gneiss is more radioactive than amphibolites (Ernstson, 2006; Nielson et al., 1990). The radioactivity is often measured in count per second (cps).

4.2.2 Caliper log

The three-arm caliper measures variations in borehole diameter with depth. The diameter is determined by three mechanically coupled arms in contact with the borehole walls. The use of a caliper tool to locate fractures requires the fractures to be either open or sufficiently enlarged by drilling, e.g. clay weathered rock can be washed out, to permit a change in borehole diameter to be detected by the tip of the caliper arm (Howard, 1990). The measurements are done when the tool is pulled up the borehole. The caliper probe is equipped with a gamma detector for depth matching. The borehole diameter is given in mm.

4.2.3 Long/Short Normal Resistivity log

The resistivity log is the oldest logging method and was first used in 1927 by the Schlumberger brothers and H. Doll (Ellis and Singer, 2007). The measured physical property is the same as for geoelectrical imaging (Chap. 4.1). There exists several different instrument setups but in this project the short and long normal resistivity logs are used. The probe has a current and two potential electrodes with different intervals of 16” (short) and 64” (long). The distance between current and potential electrodes determines the depth of penetration. The larger the distance between the electrodes, the deeper into the formation the current can penetrate which also depends on the resistivity of the rock. The drawback with the larger penetration depth is that small zones are not detected. Water is necessary in the borehole for the measurements to be performed and they cannot be done in cased boreholes (Parasnis, 1986). The probe is equipped with a gamma probe for depth matching.

5 Geoelectrical methods applied at Hallandsås Horst, Sweden

In the following sections examples are given on the applicability of geoelectrical methods and other geophysical data at different scales (Chap. 5.2–5.4) and for different purposes. The natural flow in pre-investigation is top-down thus the investigation begins with large scale measurements and continues into more and more details. All the data presented in this chapter and in the papers originates from the Hallandsås Horst, Southern Sweden (Fig. 5.1), where a 7 km long geoelectrical imaging profile measured along the tunnel in 1998 gave important information about three large weak zones (Fig. 2.6). However, additional geoelectrical and ground based magnetic measurements were performed within this research project (Chap. 5.2, paper 1) with the purpose of answering some of the key questions (Tab. 3.1) and thus make a more reliable geological model by combining different geophysical methods. This was done in a more detailed scale (10–100 m) than the 1998 measurements. By performing geoelectrical measurements between two horizontal boreholes (Chap. 5.3, paper 2) data at a smaller scale (<10 m) were obtained. However the purpose of this work was mainly to develop a methodology for measuring in horizontal boreholes at an actual construction site. Geophysical borehole logging (Chap. 5.4 and 5.5, paper 3 and 4) uses different geophysical methods for providing information in an even smaller scale (<1 m). The information can be used for calibration of the results from the surface geophysics and increases the reliability of the engineering geological prognosis. In chapter 5.5 the search for an explanation to ambiguous resistivity readings has made it necessary to investigate at even finer detail (mm-scale). During the different stages in a project it is essential to have a dynamic process where the engineering geological prognosis is continuously updated when new information is obtained. Therefore the data measured in 1998 is re-processed and compared with the tunnel documentation (Chap. 5.6, paper 5) in order to learn from the tunnel construction and use that in the following construction work. The experience from the work with the geoelectrical method at the Hallandsås Horst is a natural basis for estimating the probabilities used in the VOIA in chapter 6.

Even though the Hallandsås Tunnel is under construction all data presented in this chapter should be seen as part of a pre-investigation. From a research point of view the advantage with the project is that there exist large amounts of data for correlation. In the following, only the main results from paper 1–5 is shown and discussed, and the reader is referred to the papers for further details.

5.1 Geological setting

The Hallandsås Horst, located in Southern Sweden (Fig. 5.1), is the result of a tectonic activity that has been ongoing since Silurian times. The uplifted blocks have a NW-SE orientation and occur in the Tornquist Zone. This tectonic element stretches all the way to the Black Sea (Wikman and Bergström, 1987). The Hallandsås Horst is 8–10 km wide, 60–80 km long and reaches an elevation of 150–200 metres in the tunnel area.

Crystalline Precambrian rocks and gneisses presumably of intrusive origin compose most of the bedrock, whereas sedimentary rock covers minor areas. Amphibolites of several generations occur where the oldest often are seen as minor layers or schlieren parallel to the layering in the gneisses. The younger amphibolites have distinct contacts and cross cut older structures. These younger dykes are commonly oriented in a NNE-SSW direction (Wikman and Bergström, 1987).

The bedrock is also intruded by a set of younger dolerite dykes with their trend parallel to the Scanian horsts (Wikman and Bergström, 1987). These dolerite dykes are seen as very distinct linear positive anomalies on the aeromagnetic map (Swedish Geological Survey, 1981). On the aeromagnetic maps it is even possible to see a NNE-SSW and NE-SW oriented fracture systems because they disconnect the positive anomalies associated with the dolerite dykes. The dominant fracture system is oriented in NW-SE direction corresponding to the Tornquist Zone. Another distinct fracture system has a NNE-SSW direction and is younger than the NW-SE system. Substantial deep weathering of the bedrock began during Triassic and continued periodically during the Cretaceous and to the present day. This resulted in weathering of bedrock to mainly kaolinite. The weathering is documented in drill cores from the area (Wikman and Bergström, 1987).

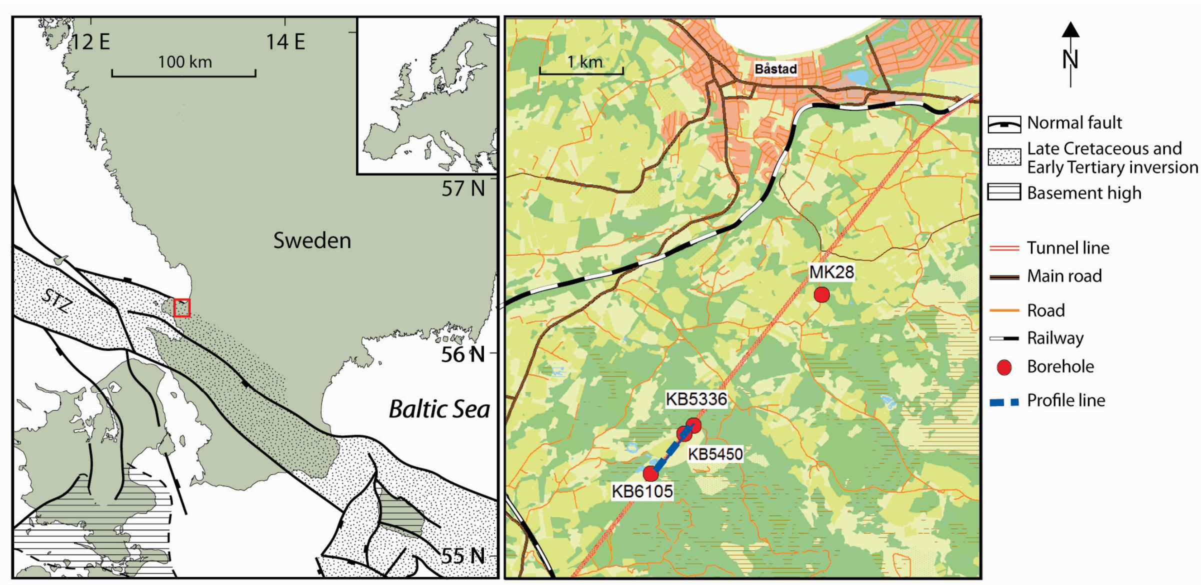

Figure 5.1. Left: Map of Southern Sweden showing the position of the investigated area and the outline of the Tornquist Zone (STZ). Right: Map of northwestern part of the Hallandsås with position of the core drilled holes KB5336, KB5450, KB6105 and the percussion drilled hole MK28. The CVES/IP profile is measured between KB5336 and KB6105. Maps are modified from Graversen (2009), Lantmäteriverket (2001) and Liboriussen et al. (1987).

5.2 Geoelectrical and IP imaging used for pre-investigation at a tunnel project

At the Hallandsås Tunnel geoelectrical and induced polarization (IP) measurements have been performed together with ground based magnetic measurements as part of this research project. The purpose of the investigations was to follow up on the geoelectrical data measured in 1998 and do a more detailed study of the selected area. By this some of the key questions regarding rock type, weathering/rock cover and water should be answered. The work was presented as a conference proceeding *Geoelectrical and IP imaging used for pre-investigation at a tunnel project* (paper 1).

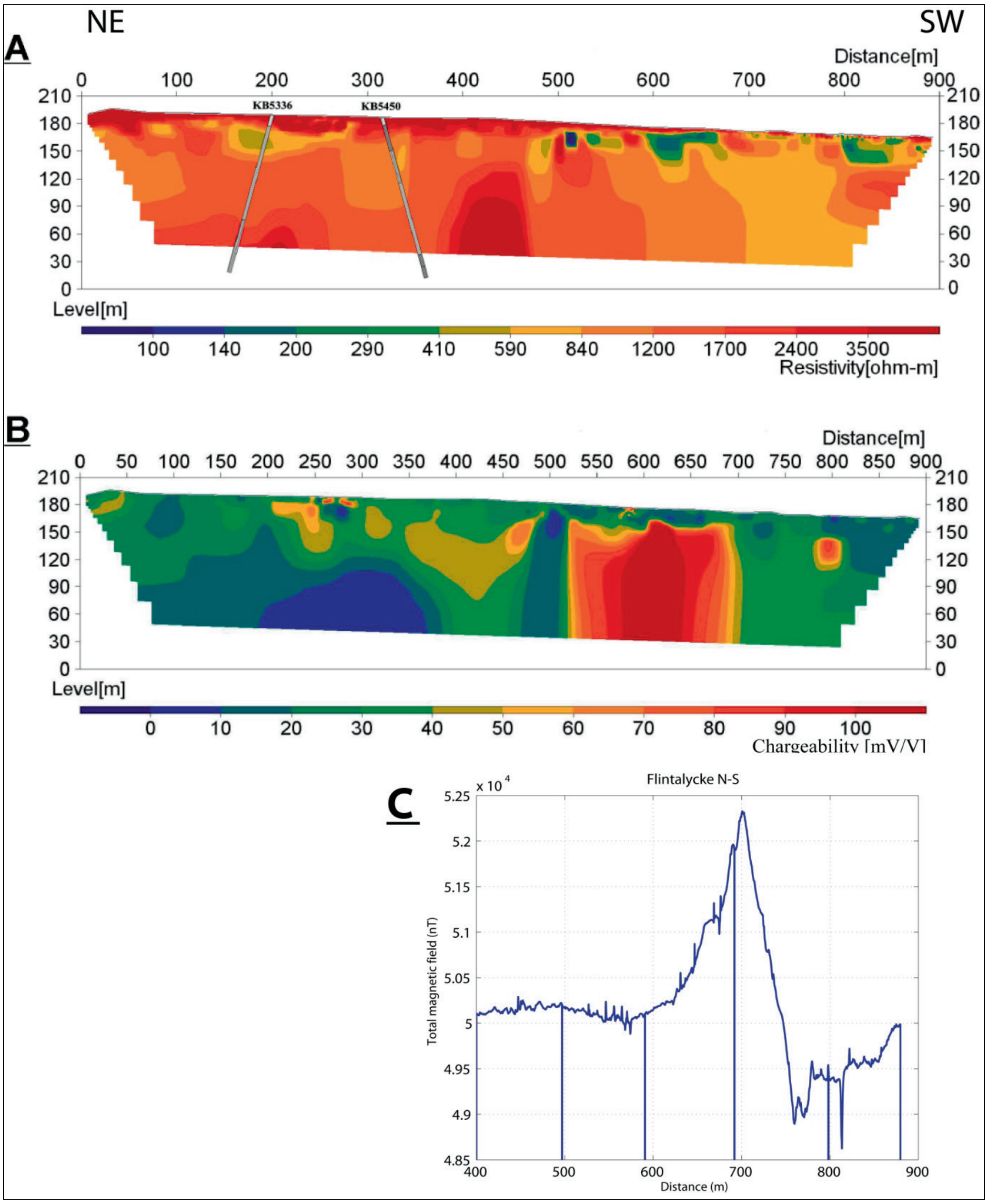

Figure 5.2. *(A) Inverted resistivity results for the 900 metre profile. The positions of two existing core drillings are marked in the profile. In (B) the inverted IP can be seen and in (C) the result from the magnetic measurement is shown.*

A 900 metre long resistivity and IP profile was measured using the pole-dipole array to obtain a larger median depth of penetration (Fig. 5.1). The measured data was inverted in the program Res2dinv using robust inversion. The magnetic profiles cover only 480 metres from x = 400 to x = 880 (Fig. 5.2). Two existing core drillings (KB5336 and KB5450) as well as geological maps were available as reference data.

The resistivity, IP and magnetic measurements can be seen in figure 5.2. Based on the resistivity data the investigated area can be divided into two sections. The northern most has a higher resistivity due to fewer fractures and the southernmost has slightly lower resistivity and more fractures. The IP and magnetic data adds information on a dolerite dyke occurring in the area and locates it with high precision (±5 m). If the position should be even more precise, modelling of the magnetic anomaly could be done. The dolerites in the area are known to contain high amounts of water in the fractures in the contact to neighbouring rock (Wikman and Bergström, 1987), thus the location of the dolerite is important with respect to water content. Combined with reference data from core drillings (Tab. 1 in paper 1) and general information about the geological setting a geological model is compiled (Fig. 5.3). By combining the different types of data a more detailed and reliable geological model can be compiled and the key questions answered.

Unfortunately the boreholes were drilled prior to the geophysical survey, and thus the boreholes are not positioned optimally for the present study. However the information from the boreholes still contributes with information about e.g. lithology and fracture frequency. With the borehole information the uncertainty of the geological model is reduced, but could have been further reduced if the boreholes would have contributed with information from the area at x = 600 m where there is a high IP effect.

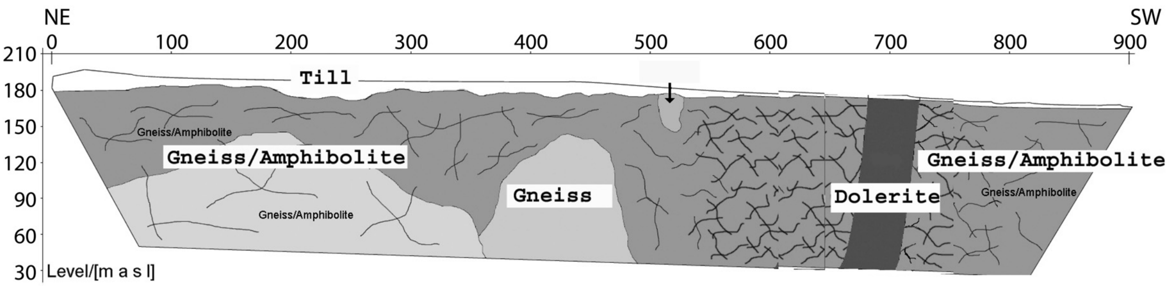

Figure 5.3. *Detailed geological interpretation of the 900 metre profile.*

When new information is obtained the geological model should be evaluated and updated if necessary. Thus the geological model in figure 5.3 should be updated with the information from the geophysical logging of KB5336 (Fig. 5.5). The geophysical logging (Fig. 5.5) confirms the low resistivity (<600 Ωm) at a depth of 40 metre (160 m.a.s.l.) which is due to fractures and weathered rock. Below this depth the rock is less fractured which is also reflected by higher resistivity to a depth of 120 metre (70 m.a.s.l.). Beneath this depth the borehole geophysics shows that the rock is highly fractured and weathered. As a consequence the geological model can at this depth be updated to contain fractured and weathered gneiss/amphibolite. The borehole geophysics is measured to below the tunnel level and can therefore contribute with information where the geoelectrical imaging is more uncertain due to lower resolution. That the rock is more fractured and weathered at tunnel depth is important information which would have been overlooked if only the geoelectrical imaging was used. So by adding the information from the detailed borehole geophysics the uncertainty in the interpreted geological model is reduced. If possible a joint inversion (modeling) of all types of data would be ideal.

Geoelectrical and IP imaging in combination with ground based magnetic measurements and geophysical and geological borehole information are useful in the design/production planning stage for compiling a geological model of the subsurface. The continuous geophysical measurements should be performed prior to drillings with the purpose to make a targeted and optimized drilling campaign and perhaps even reduce the number of drillings.

5.3 Numerical modelling of resolution and sensitivity of ERT in horizontal boreholes

Resistivity measurements in horizontal boreholes can give useful detailed information about the geological conditions for construction in rock, i.e. in front of a tunnel boring machine. This paper attempts to identify a suitable methodology for this type of geophysical measurements for an effective measuring routine under actual construction site conditions. The results from this study can be seen in the paper titled *Numerical modelling of resolution and sensitivity of ERT in horizontal boreholes* in paper 2. ERT is an abbreviation for Electrical Resistivity Tomography.

Prior to any measurements numerical modelling was done in order to evaluate the resolution of four different electrode arrays and a combination of the arrays. The sensitivity to inaccurate borehole geometry and the influence of water in the boreholes was also investigated.

Based on the model study the AB-BN array, multiple gradient arrays and a combination of these were found to give the best result and therefore were used for test measurements in horizontal boreholes. The boreholes were 28.5 metre long and drilled 6.5 metres apart. Prototypes of semi-rigid borehole cables made it possible to insert multi electrode cables in an efficient way, allowing fast measurement routines. These measurements were then studied to determine their accuracy and applicability.

Unfortunately the boreholes used for the test measurements were not core drilled so no direct information was available for the interpretation of the data. Instead the indirect information from a horizontal core drilling, called NA01, drilled perpendicular to the test holes was used (Fig. 11 in paper 2). The drilling report (left out here) showed that where it crosses the two test boreholes the lithology is gneiss. The geological structures here intersect the tunnel at an angle of 65–70^{o}. This information together with the data from NA01 gives a rough estimated position of fractures and formation changes in the test boreholes.

By comparing the measured result (Fig. 5.4) with the estimated position of the structures found in NA01, it is clear that no fractures are resolved by the resistivity method. The fractures may be too narrow to be resolved or the resolution of the data may be insufficient. The data are most likely also influenced by 3D effects.

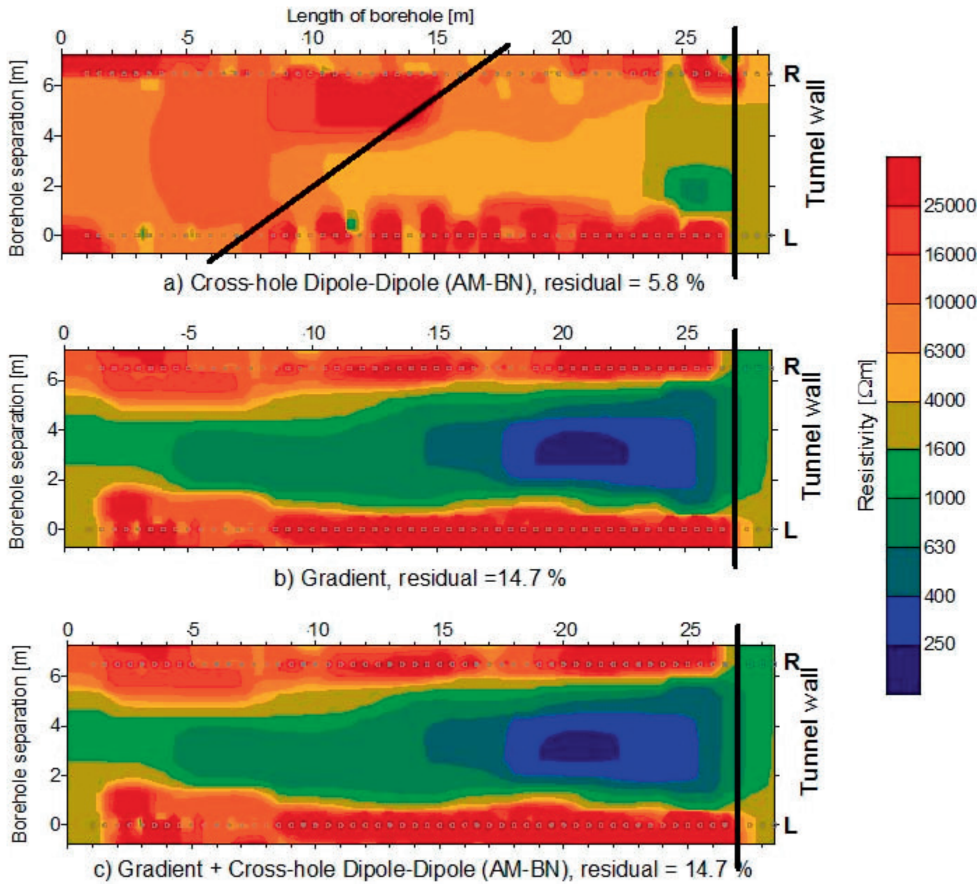

*Figure 5.4. The inversion results in a greyscale from the resistivity measurements using different electrode arrays. The boreholes are seen from above with the tunnel wall to the right in the figure. The left borehole, seen from the tunnel, is marked with **L** and the right borehole with **R**. The heavy black lines show probable structures. a) Cross-hole dipole-dipole array, b) Gradient array, c) Combination of gradient and cross-hole dipole-dipole. Grey circles mark the position of the electrodes. The electrode separation is 0.5 metre.*

The transition from high resistivity to lower resistivity is interpreted as a change in lithology from gneiss-granite to gneiss. The mineral composition of the rock mass is different and probably most important is that the gneiss-granite contains fewer fractures than the gneiss (Wikman and Bergström, 1987). This probably explains why the gneiss-granite has a higher resistivity than the gneiss. The low resistivity zone close to the tunnel wall is most likely caused by the shotcrete at the tunnel wall, which contains steel fibre reinforcements. In addition there might be rock reinforcements, e.g. rock bolts, which could affect the result. In an actual production phase shotcrete and rock reinforcement will not influence the measurements when performed in the tunnel front because they will not yet have been applied.

An important outcome of this study was that the prototype of the semi-rigid cable proved to work well. For production measurements it is suggested that electrode cables with an integrated glass fibre rod would work well. Measuring of reciprocal data for data quality assessment is suggested at least in a test and development phase. For a better data evaluation it would be worthwhile to obtain accurate reference data by making measurements in core drilled boreholes so that the resistivity results can be compared to the borehole logs. A further optimization of the protocol files is also vital, and in particular a study of the different 2D sensitivity patterns is considered to be essential. It would be interesting to do the measurements between more than two boreholes and to reduce the distance between the holes. In this case 3D inversion would be useful.

5.4 Borehole geophysics provides detailed information in pre-investigation for rock tunnel construction

The scope with this paper is to show that borehole geophysics can give detailed information of lithology changes, fractures and weathering of crystalline bedrock. The work is presented in the paper *Geophysical logging for enhancement of borehole information in pre-investigation for rock tunnel construction* (paper 3).

In two core drilled boreholes at the Hallandsås Horst, geophysical logging was performed in order to evaluate the resolution and usefulness of the method. For evaluation the logs were compared with the cores. The result suggests that logging of non-cored boreholes potentially reveals very useful information especially when there are a few cored drill holes to correlate with. As an example geophysical logging was done in a percussion drilled borehole in the same area. The experience from the logging in the core drilled holes was then used for the interpretation. Only the result from the logging of KB5336 will be shown here in chapter 5.4. For the results from the logging of KB6105 and MK28 the reader is referred to paper 3.

In KB5336 (Fig. 5.5) the natural gamma log show lower counts in the amphibolite than in the gneiss. The caliper log shows several irregularities where the diameter of the borehole increases in a short interval. These intervals coincide with the intervals where the short resistivity log has low resistivity. Examples are at 53 m, 80 m and 104 m where especially the short resistivity log has large divergences. The resistivity differs between 10 Ωm and 10 000 Ωm. In the first 120 m of the borehole the resistivity is mainly high (10 000 Ωm) but with narrow areas with low resistivity (1 000 Ωm). Below 134 m the short resistivity log changes character and is dominated by lower resistivity (<1 000 Ωm). The visual observations showed that the low resistivity intervals coincide with fractures and/or joint sets. The fractures are often clay filled due to weathering. The high resistivity coincides with intervals with fresh rock without any fractures. The change in the behaviour at 134 m (Fig. 5.6A) was clearly due to higher fracture frequency and even a second fracture direction. The photograph in figure 5.6A shows an example of fractures, joint sets and clay weathering in KB5336 at 135 m. In figure 5.6B the fresh amphibolite in KB6105 at 88 m is seen.

From the logging in the core drilled boreholes the obtained experience can be used when interpreting the logging results in the percussion drilled borehole. The visual inspection of the cores from KB5336 and KB6105, illustrated by the photographs in figure 5.6, shows clearly that fractures, joint sets, weathering and in some cases even lithology change can be identified by geophysical logs in crystalline rock. Generally

KB6105 contains less fractures and weathered zones than KB5336 which is seen in a steadier resistivity and calliper log signal. Only a few joint sets and weathered zones were observed in KB6105. With the experience from the core drilling in mind the interpretation of the logging result of the percussion drilled MK28 becomes more detailed and less uncertain.

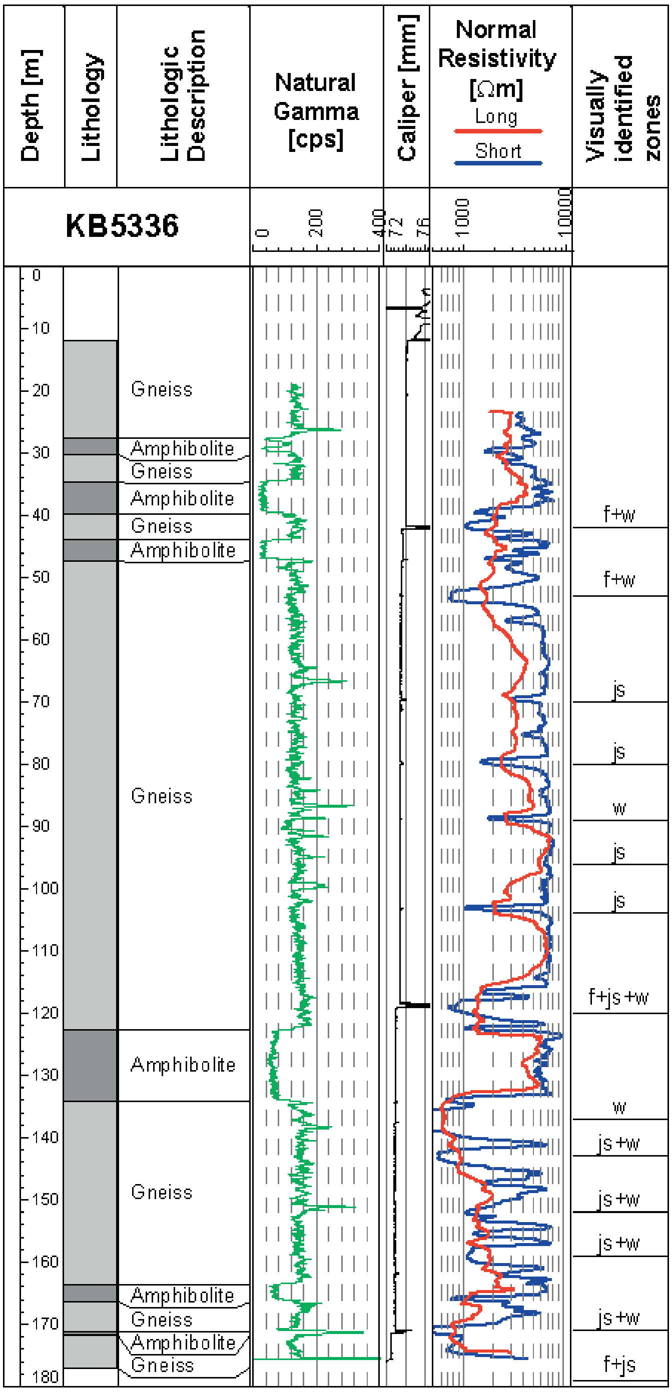

Figure 5.5. Lithological and petrophysical logs of KB5336. The identified occurrences are abbreviated fracture (f), weathering (w), joint set (js).

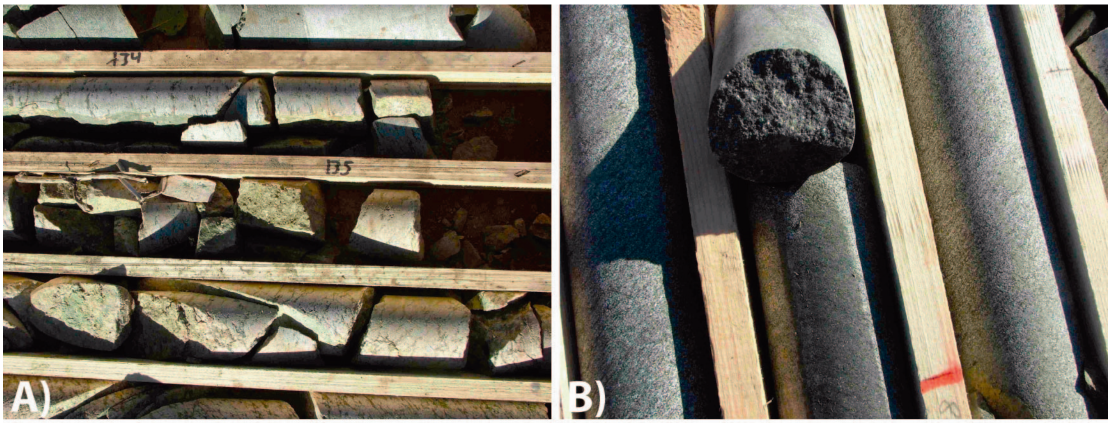

Figure 5.6. A) KB5336: highly weathered and fractured rock at 135 m. B) KB6105: fresh amphibolite at 88 m (the author broke the core in order to take a sample).

The different logs respond to different physical properties and in this case the three types of geophysical logs have the following characteristics:

Natural gamma: Low count when the lithology is amphibolite or dolerite and high count when the lithology is gneiss. The gneiss contains potassium rich minerals as K-feldspar and biotite and thus the gamma log has a higher count in these parts. This is regardless of fractures. It is however not possible to distinguish between amphibolite and dolerite, because mineralogically they are similar but with different texture.

Caliper: Increased diameter in a limited interval indicates fractured rock and the wider peaks are joint sets and weathered zones.

Normal resistivity: Low resistivity (800–2 000 Ωm) indicates where the rock is fractured and/or weathered. A high resistivity (>6 000 Ωm) indicates a homogeneous rock.

With this in mind the logging result of the percussion drilled borehole MK28 (Fig 5.7) can be interpreted with a higher degree of certainty.

A lithological description done at the drilling site is relatively detailed and is based on the drill cuttings (< 2x2 cm). This demands a very skilled driller and/or geologist at the site. Thus there might be some uncertainties in the determination of the lithology and the position of the different lithological contacts. An advantage with logging is that it is in situ measurements and that the data is recorded, so that any ambiguity in the result it can be viewed by more than one person. In MK28 some inconsistencies exist between the depth and presence of amphibolite/dolerite. Because logging is in situ measurements the gamma log gives a precise position and thickness of the amphibolites/dolerites. It is obvious that the discrepancy is due to the difficulties of determining the correct depth from cutting samples.

Due to the drilling method used in MK28 the caliper log has much larger variations than the core drilled boreholes. Consequently the log detects more fractures and irregularities. Some of these could have been introduced by the drilling method. Combined with the resistivity log, the location of the fractures and weathered zones becomes more certain. In those parts where the caliper log shows a larger borehole diameter and simultaneously the resistivity is decreased there is probably a fractured/weathered zone.

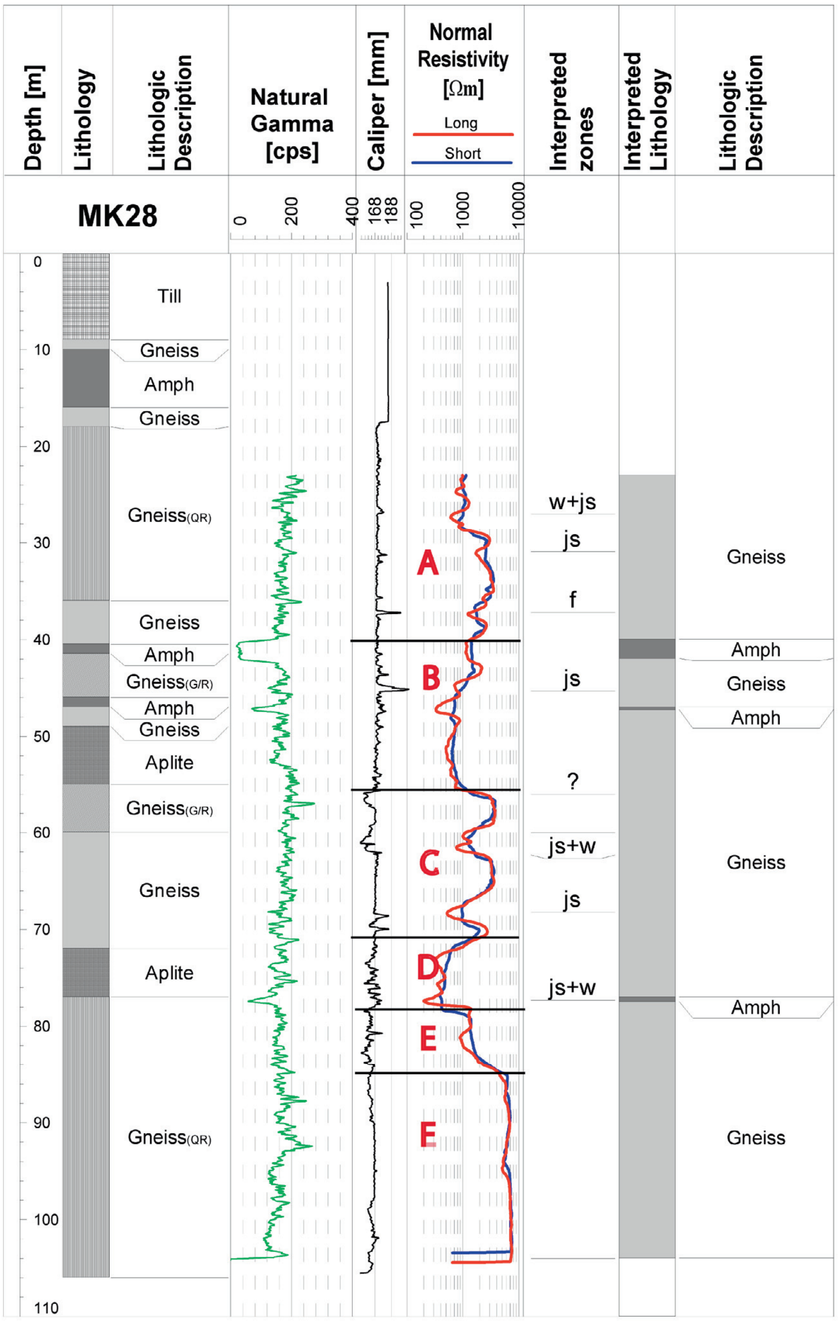

Figure 5.7. The geophysical log and interpretation of the percussion drilled borehole MK28. The lithology to the left is the observations from the drilling of the borehole. The lithology to the right is an interpretation based on the gamma log. The interpreted occurrences are based on the caliper and the resistivity log and are abbreviated fracture (f), weathering (w), and joint set (js). Additionally the caliper and the resistivity log are divided into six zones, A to F, based on their different characteristic.

Table 5.1. The characteristics of the six different zones A-F in MK28.

Zone	**Characteristic**
A	Few fractures
B	Several lithology contacts – might contain water
C	Changing quality
D	Very fractured + weathered – lithology change
E	Fractured + weathered
F	No fractures

The division of zones in MK28 (Fig 5.7) helps in characterizing the rock, with a different character in each zone. It can be expected that the rock has different mechanical properties in the six zones. The properties in the different zones are summarized in table 5.1.

Borehole geophysics can contribute with information about lithology, structural and rock mechanical properties. The borehole geophysics can also be used to calibrate the results from surface geophysics and should therefore be an integrated part at all stages in the pre-investigation. It can be recommended that borehole geophysics is done in the cheaper percussion drilled holes and thereby be a good alternative to the expensive core drilled holes. The logging probes used in the three boreholes is generally standard and part of most logging equipment. They provide useful information but additional logging probes could be used to give additional information. For example the sonic log that involves high frequency P-waves or acoustic waves can be used to obtain a detailed velocity profile along the borehole. The velocities of P- and S-waves obtained can be used to calculate the dynamic modulus of elasticity (Takahashi et al., 2006). Another logging probe which could be used with great advantage is the optical televiewer. The optical televiewer provides a continuous and oriented image of the borehole wall. This gives information about fracture condition, orientation, dip and strike as well as a visual image of the rock surrounding the borehole (Paillet and Ellefsen, 2005).

5.5 Geophysical logging as a tool for identifying initial weathering in crystalline rocks

Even though the logging of a cored drill hole gives many answers, there are however unanswered questions and it can become necessary to go into even more detail to get a clear answer.

The scope of this paper is to show how even low degrees of weathering of rocks affects the geophysical log response, by means of microscopy, point counting and logging. This was done on gneisses and amphibolites from two drill cores from the Hallandsås Horst. The work is presented in the paper *Geophysical logging as a tool for identifying initial weathering in crystalline rocks* (paper 4).

The original cores were placed on the ground in one succession and afterwards inspected visually. The core observations and details in the rock classification were documented by photographs, (Fig. 5.9). Finally, representative samples of the different rock types and rocks with unexplained resistivity anomalies were taken for thin sections.

The geophysical logging is supported by microscopy and point counting to evaluate the weathering stage and to quantify the mineral content. The point counting was done on thin sections by using a point counter and registering the mineral phase for every 0.7 mm in both x and y directions. The accuracy of the point counting ranges from 1 to 3% depending on how common the mineral is. For documentation microphotographs of the thin sections were done at 2.5 times magnification.

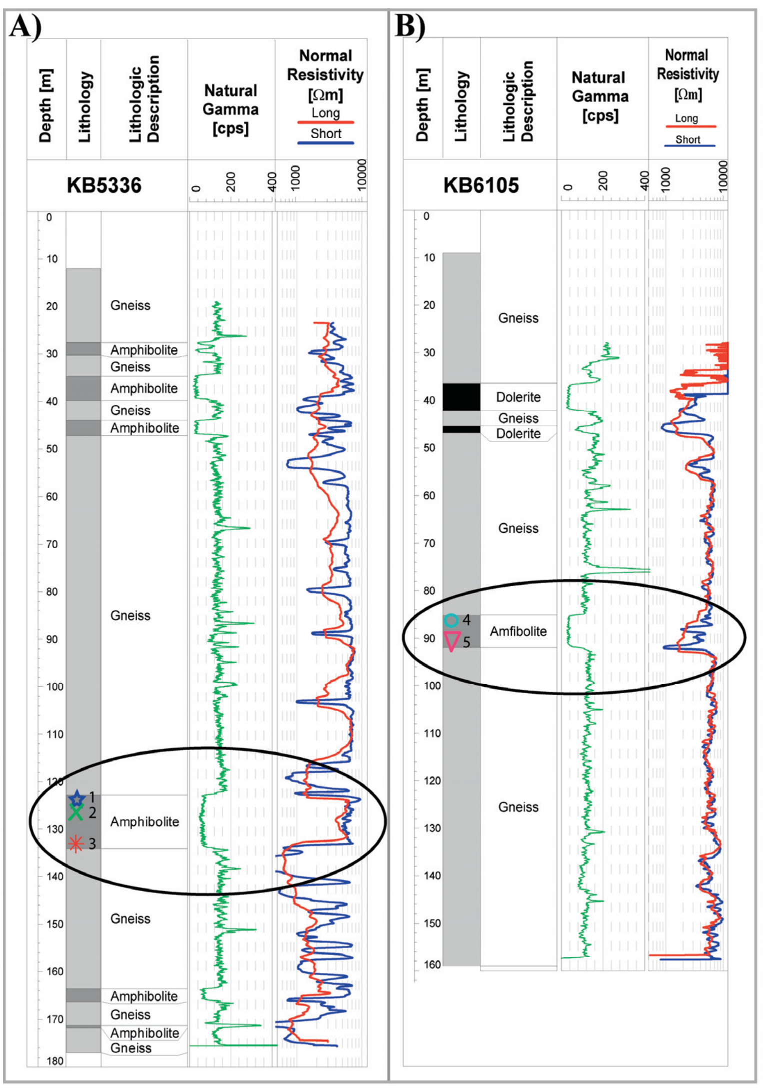

Figure 5.8. Lithology, gamma and resistivity logs for A) KB5336 and B) KB6105. The investigated amphibolites are highlighted with a ring. The positions of the samples are marked with the symbols used in figure 5.10.

The core observations showed that the low resistivity intervals coincide with weathering, fractures and/or joint sets that occasionally were clay filled. The high resistivity corresponds with intervals of fresh rock, both gneisses and amphibolites, without any fractures (Fig. 5.9).

The resistivities of the amphibolites in KB5336 (Fig. 5.8A and 5.9A) are around 7000 Ωm whereas the resistivity of the amphibolite and dolerites in KB6105 (Fig. 5.8B and 5.9B) are around 2000 Ωm. Further the resistivity is constant within amphibolite layers in KB5336 whereas it fluctuates in the amphibolite and dolerite layers in KB6105. The two boreholes are only separated by 770 metre so the large difference in resistivity is ambiguous. In both cases the amphibolites seemed to be fresh with no weathering and only few fractures or joints (Fig. 5.9). The overall theory is that the differences in resistivity in a lithological unit are caused by fractures and/or weathering. No obvious difference in the mineralogy or texture was observed that could explain the large difference in resistivity and can thus be ruled out as an explanation. But why is there a large difference in the resistivities of two apparently similar amphibolites? The visual inspection could not provide an explanation. Is this due to differences in mineralogy of two different generations of amphibolites? Is it conductive microfractures? Or weathering of minerals? Therefore the petrography and the mineral composition were investigated.

No obvious and visual explanations were found during the inspection of the core, thus samples were taken for petrographic investigations. Three samples of the amphibolite from KB5336 and 2 samples of the amphibolite from KB6105 were taken. Additionally, one gneiss sample was taken from each core. The positions of the samples of the amphibolites are shown in figure 5.8.

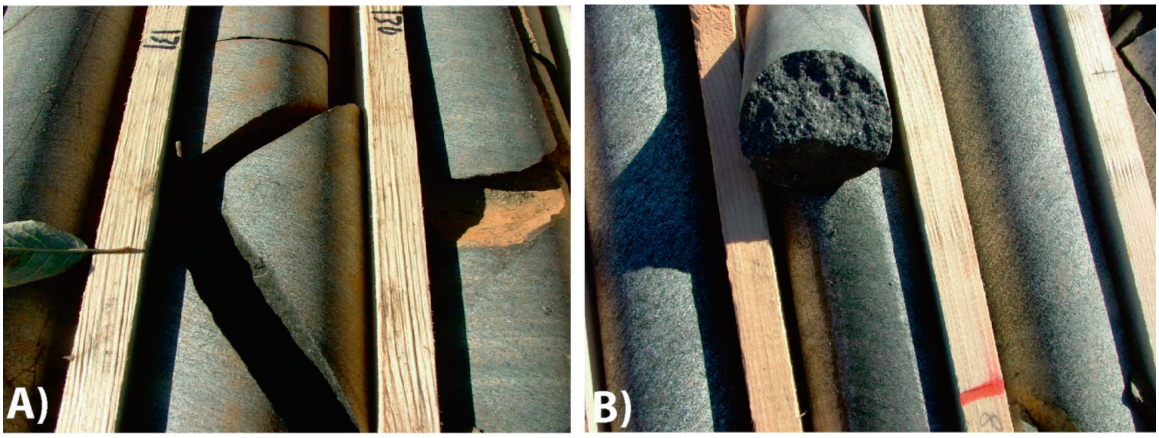

Figure 5.9. A) Unweathered amphibolites with joints at 130 metres depth in KB5336. B) Apparently unweathered amphibolites with no joints from KB6105 at 88 metre.

The initial petrographic investigation indicated that all the amphibolites are mainly comprised of plagioclase, amphiboles, pyroxenes, garnet with accessory quartz, biotite and an opaque phase probably low resistive oxides or sulphides (Fig. 5.11). However, the point counting showed very little variance in the mineral content (Fig. 5.10, Appendix A in paper 4). Based on this it can be ruled out that the difference in resistivity of the studied amphibolites is a result of difference in the primary mineral content.

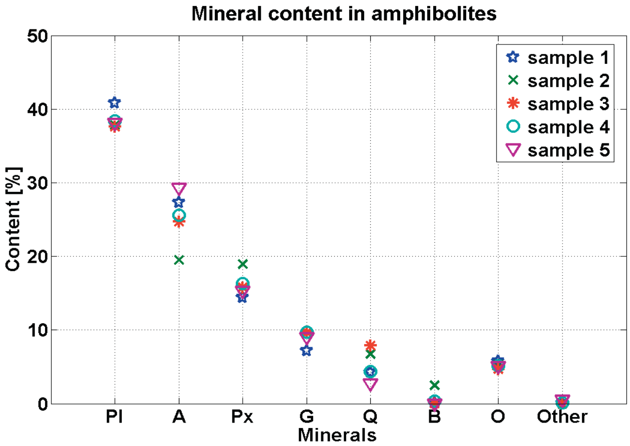

Figure 5.10. The mineral content [%] in the amphibolites. The minerals are abbreviated as follows: plagioclase (Pl), hornblende (A), pyroxene (Px), garnet (G), quartz (Q), biotite (B), opaque (O) and other minerals (Other).

The microscopy of the thin sections showed microfractures in sample 1, 3 and 5. The fractures were probably filled with ironhydroxides or chlorite. Opaque minerals occur as isolated crystals (Fig. 5.11). In sample 4 and 5 several of the pyroxenes appears to be altered (Fig. 5.11B) compared to the pyroxenes in samples 1, 2 and 3 (Fig. 5.11A).

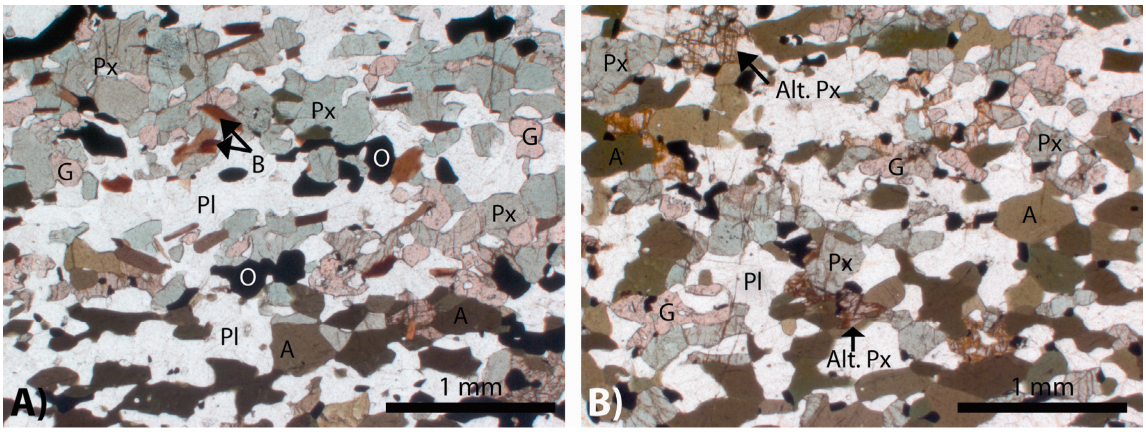

Figure 5.11. Microphotographs of A) an unaltered amphibolite from sample 2 and B) altered amphibolite from sample 5. The minerals are abbreviated as follows: plagioclase (Pl), amphibole (A), pyroxene (Px), garnet (G), quartz (Q), biotite (B), opaque (O)and altered (Alt.).

Oxides and sulphides are conductive minerals and would thus lower the resistivity of the rock (Carmichael, 1989). However, the opaque phase occurs as isolated crystals and therefore is not the reason for the lower resistivity of the amphibolite in KB6105 (Fig. 5.11). If the opaque phase should decrease the resistivity of the amphibolite significantly, it should form an interconnected conducting network. Such a network could be formed by microfractures probably filled with ironhydroxides and chlorite which are present in the studied amphibolites. However, microfractures are present in both the high and the low resistivity amphibolites and thus can not explain the difference in resistivity.

Initial weathering and alteration on the other hand can explain the lower resistivity of the amphibolites and dolerites in KB6105. This is evident from commonly altered pyroxenes in the amphibolite in sample 5 in KB6105, in particular in the bottom part of the amphibolite. The pyroxenes have clearly been hydrated forming new hydrous minerals along the edge and cleavage planes of the crystals. Hydrous minerals are more conductive than non-hydrous silicate minerals and have therefore lowered the resistivity of the weathered amphibolite. Simultaneously minor hydrous minerals have precipitated along grain boundaries, thus forming a conductive network able to decrease the resistivity of the amphibolite. The weathering was most likely initiated during uplift of the Hallandsås Horst, in this particular case, by introduction of water into the lithological contact between the bottom part of the amphibolite at sample 5 in KB6105 and the underlying gneiss.

This example shows that by going into details an explanation can be given to what seems to be artefacts in the geophysical data. The more knowledge obtained about the ground conditions the better. Even though the alteration of the minerals were not visible to the naked eye, it could become significant for the mechanical properties of the rock.

5.6 Comparison of geoelectrical imaging and tunnel documentation at the Hallandsås Tunnel, Sweden

The results in the previous chapters show that in a pre-investigation geoelectrical imaging and borehole geophysics provide useful information about the rock properties. However it is important to evaluate the data as the project progresses, because by calibrating with e.g. tunnel documentation the interpretation of the geophysical data can become even more certain. Thus the interesting question is: what else can be resolved by geoelectrical imaging? This is investigated in the paper *Comparison of geoelectrical imaging and tunnel documentation at the Hallandsås Tunnel, Sweden* (paper 5).

The evaluation is done by comparing the electrical imaging with tunnel documentation from the completed part of the Hallandsås Tunnel. The documentation includes information on e.g. rock type, weathering, water leakage, RQD and fracturing. (For more information about these parameters the reader is referred to paper 5). The comparison is done merely by visual evaluation of three different sections of the tunnel referred to as North, South and TBM in the following section. The distance between the centrelines of the two tunnels is 25 metre.

In figure 5.12 the tunnel documentation gathered in front of the TBM is compared with the resistivity data from the same section. The mapped data were rock type, RQD, block size, weathering, rock class and water leakage. The resistivity data are shown as the full model and as sub-models extracted at 60 metres and 25 metres above sea level. To make the evaluation of the results easier, different resistivity zones are marked with a letter

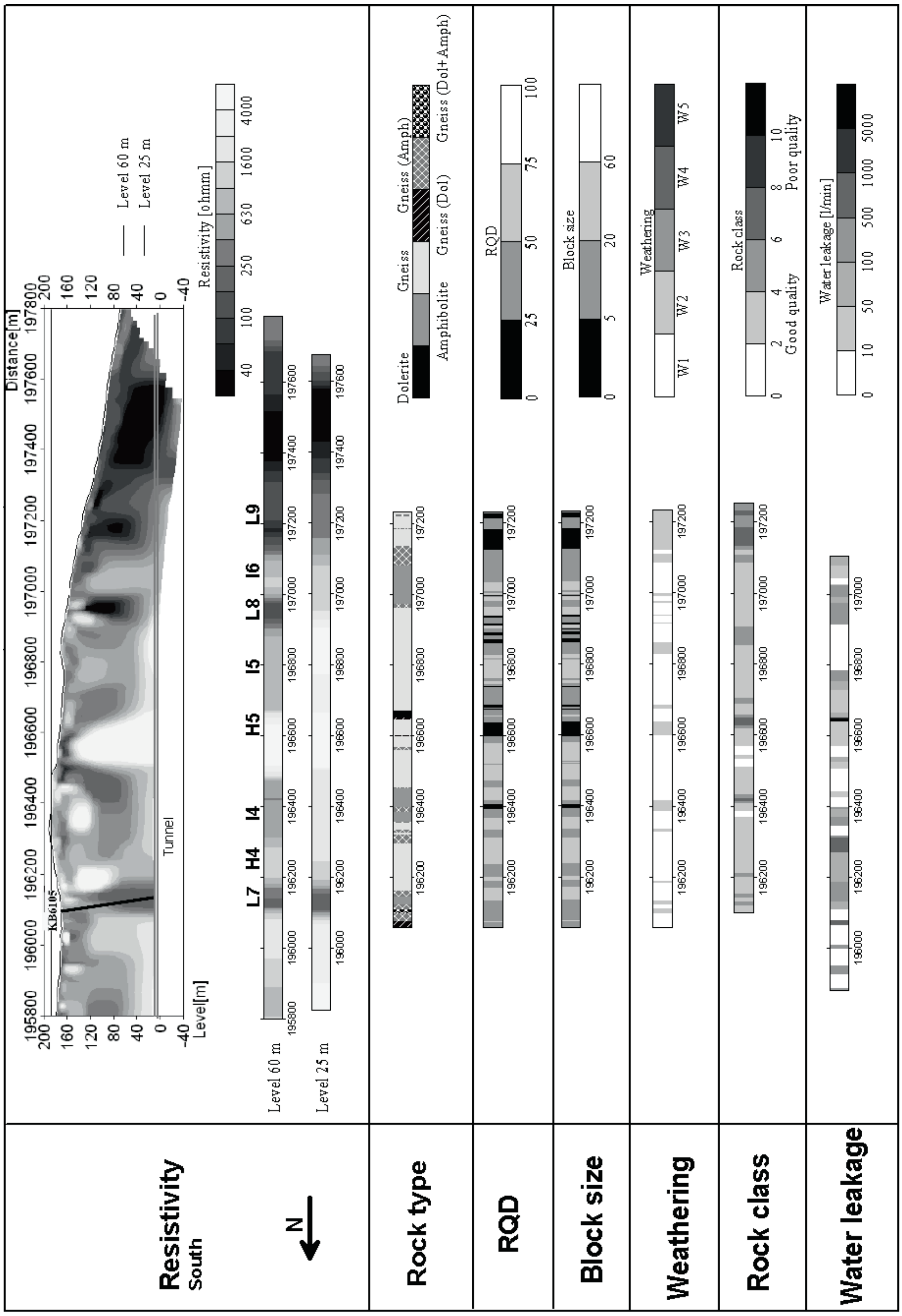

Figure 5.12. Visualization of resistivity and mapped data from the southern part of the Hallandsås tunnel. The mapping is done in front of the TBM at every operational stop. The mapped data were rock type, RQD, block size, weathering, rock class and water leakage. The resistivity data are shown as full model and as sub-models extracted at 60 metre and 25 metre above sea level. The low resistive zones are marked with L7, L8 and L9. High resistive zones are marked with H4 and H5. The areas with intermediate resistivity are marked I4, I5 and I6. Here the tunnel base is at approximately 15 metre above sea level.

and a number. The data are divided into three categories i.e. low (L), intermediate (I) and high (H) resistivity. The three categories cover the same resistivity interval in all three tunnel sections. The concept is to focus on the change in resistivity, e.g. from high to low, and not on the specific numerical value of the resistivity.

In this part of the resistivity section three low resistive zones are identified. Only L7 and L9 are visible in both levels (Fig. 5.12). Two high resistive areas and three areas with intermediate resistivity are detected. In table 5.2 the corresponding properties from the tunnel documentation are summarized.

*Table 5.2. Dominant properties of the rocks with corresponding low (L), intermediate (I) and high (H) resistivity sections for the TBM drilled part of the tunnel. The most likely explanation to the resistivity value in the interval is indicated with **bold italics**.*

Resistivity	Rock type	RQD	Weathering	Water
L7	***Several contacts***	25-50	W1	***Int. but increased***
L8	Gneiss/Amph.	***25-50***	W1	***Intermediate***
L9	Gneiss	***0-25***	W2	No values
H4	***Gneiss***	*25-50*	W1	***Low***
H5	***Gneiss***	***50-75***	W1	***Low/Very high***
I4	***Amphibolite***	***25-50***	W1	***Int./high***
I5	Gneiss	***25-75***	W1	Int./No values
I6	***Amphibolite***	***25-75***	W1	***Intermediate***

The comparison of resistivity data and tunnel documentations from the Hallandsås Tunnel shows that changes in resistivity in most cases is related to some kind of change in rock conditions (see figure 5.12 and table 5.2 and figure 3 and 4 in paper 5). High resistivity corresponds well with good quality gneiss as the dominant rock type. In general low resistivity corresponds to a varying lithology with several fractured contacts or merely rock with a poor quality (RQD<25). The intermediate resistivity often coincides with areas of amphibolite with an average RQD of 25-75 (fair quality). Danielsen and Madsen (2010) (and chapter 5.5) showed that intermediate resistivity in amphibolite indicate initial weathering of pyroxenes which can be expected to weaken the rock.

The results in figure 5.12 and figures 3 and 4 in paper 5 also show that in some cases the intermediate resistivity corresponds to increased water content. The presence of water can decrease the resistivity of a rock with an otherwise fair rock quality. As an example, very large amounts of water can originate from a single fracture and this is not synonymous with a low RQD. This clearly shows the ambiguity of geoelectrical imaging. Although in most cases there is a correlation between resistivity and rock conditions, there are also exceptions.

A disagreement in correlation between resistivity and rock conditions may have several different causes. The tunnels are only separated by 25 metres and even so there is still a significant difference between the lithology and rock properties documented in the eastern and western tunnels, emphasising the high variability in the rock mass properties. Thus 3D effects in the resistivity data should be expected. Another issue is the difference in the scale of the data. The tunnel documentation shows every small change in the rock conditions. For the resistivity method to be successful a zone has to be sufficiently large and have large enough contrast in the physical properties, otherwise it will show an average of the zones. A complicating factor in this particular tunnel project is that the tunnel is situated at great depth giving poor geophysical data resolution at tunnel level. Lack of resolution can cause a low resistivity body at a shallower depth to apparently extend down to tunnel level. The resistivity data are measured at the ground surface, 120─150 metre above the tunnel. Therefore these data have a much lower resolution at tunnel level than the detailed tunnel documentation. A zone can be too narrow to be visible in the resistivity data if the resistivity contrast with the surrounding rock is not sufficiently large. Longer layouts and a pole-dipole array would give a larger penetration depth and a better resolution at tunnel level. Furthermore, non-symmetrical arrays, such as pole-dipole and multiple gradient arrays, are better at resolving dipping structures than the Schlumberger and Wenner arrays. The latter tend to image inclined structures as vertical. A drawback, however, is that the field logistics are more complicated. In the mapping of the tunnel there is also the human factor to acknowledge. The mapping of RQD, weathering and lithology is a quasi-subjective assessment done by geologists at the tunnel site. There is no big difference in rock mass properties if the rock has a RQD of e.g. 28 or 23 but it means that the conditions look more serious in the plot intervals used in this study. So the mapping is somewhat subjective and might bias the results in some parts.

For the Hallandsås Tunnel project it was important to get information from geoelectrical imaging for the three large weak zones with problematic rock quality (Dahlin et al., 1999; Sturk, 1998). These main features are unmistakeably the most important findings from the geoelectrical imaging at the Hallandsås Horst. However it is probable that more information, useful for construction, can be extracted from the remaining part of the 2D profile. The comparison of resistivity data and tunnel documentations shows that changes in resistivity in most cases are related to some kind of change in rock conditions. It is shown here that the size of the structures resolved is on a scale of tens of metres and that the resistivity values are ambiguous, therefore the interpretation of the results is not always fully correct. Although the ambiguity of the resistivity cannot be resolved, the method still gives information which was not previously known and could contribute with important information for the engineering geological prognosis. In combination with other investigations, e.g. geophysical logging or ground based magnetic surveys, the ambiguity and uncertainty might be further reduced.

5.7 Summary and discussion

The results from the five studies at different scales elaborate the benefit of using geoelectrical methods in combination with other geophysical methods in pre-investigation for tunnel construction in hard rock. In table 5.3 the most important results from chapter 5.2-5.6 (paper 1-5) are summarised. The purposes, and thus the key-questions, are important to keep in mind when evaluating the results from the different studies. The geoelectrical method contributes with valuable information about changes in rock quality, i.e. fractures, weathering and lithology changes. In combination with other methods and by calibration with data measured in a smaller scale an engineering geological prognosis with a greater reliability can be compiled. The study also showed that data measured in the pre-investigation can be used later on in the construction work and give useful information as the work progresses.

The work with the geoelectrical method used at the Hallandsås Tunnel will form a basis for the VOIA developed in chapter 6. In the VOIA the probability that the geoelectrical and magnetic methods detect weak rock has to be estimated and for this the experience from the measurements is used. For this the comparison between geoelectrical imaging and tunnel documentation is an important part but also the more general impression of what the method is capable of in a hard rock environment is essential. The VOIA can be used to better plan future pre-investigations.

Table 5.3. Summary of the most import results from chapter 5.2-5.6 (paper 1−5).

Chap.	**Scale**	**Purpose**	**Results**
5.2	**10−100 m**	Compilation of detailed and more reliable geological model answering some of the key questions	**Geoelec:** fractured rock, **IP/magnetic:** dolerite, **Geophysical logging:** support the interpretation in part where resolution is poor.
5.3	**<10 m**	Development of prototype for geoelectrical measurements in horizontal boreholes	**Geoelec:** lithology change.
5.4	**<1 m**	Detailed information for increased reliability of geological model and calibration of surface geophysics	**Geophysical logging:** lithology change, fractures, weathering, good alternative to core drilled boreholes. Data for correlation and verification of surface data.
5.5	**mm**	Explanation for ambiguous resistivity of amphibolites	**Microscopy:** alteration of minerals, initial weathering.
5.6	**10−50 m**	Comparison of geoelectrical imaging data and tunnel documentation in an ongoing construction project. Lessons to be learned and brought forward in the project	**Geoelec:** changes in resistivity ~ changes in rock quality. Low res ~ several contacts, low RQD, fractures. High res ~good quality gneiss. Int. res ~ amphibolite with fair quality (RQD = 25−75).

6 Framework for the application of Value of Information Analysis

Developing a tunnel project involves many unknown factors and uncertainties which implies a considerable risk. But decisions have to be made through the whole project and thus risk management and decision analysis become important tools. In risk management and decision analysis the probable risks which can be encountered in a project are identified and a strategy for how to handle the risks is established. Several researchers have worked with decision making and tunnel construction e.g. Degn Eskesen et al. (2004), Einstein et al. (1978), Einstein (1996), Haas and Einstein (2002), Karam et al. (2007a), Karam et al. (2007b), Min et al. (2008) and Van Staveren (2006). In Sweden important research have also been done within the area e.g. Olsson and Stille (1980), Rosén (1995), Sturk (1996), Sturk et al. (1996) and Tengborg (1998).

Even though innumerable examples can be given on how geoelectrical imaging has been useful in pre-investigation it is not an obvious choice for decision-makers, because it might still be unclear how to use the results. The results of the geophysical measurements usually have to be processed and evaluated by a geophysicist and only the geophysicist knows the sensitivity and resolution of the methods. Thus the engineer does not always have appropriate expectations of the advantages and limitations of the geophysical methods. On the other hand the geophysicist does not always have detailed understanding of what the engineer requires; e.g. at what scale information is needed. One task for the engineer and the geophysicist is to find a common language (Danielsen, 2007). Value of information analysis (VOIA) might be an approach for communicating with the decision-makers.

VOIA is an aid in decision-making in complex problems. It can help to create a rational design strategy for investigation programmes. The method is based on Bayesian statistics and cost-benefit analysis and is suitable for problems where different alternatives are evaluated and compared, e.g. the design of an investigation programme when the number of measurements or investigations needs to be determined. In VOIA the cost for new information is compared with the reduced risk for taking an economically unfavourable decision. The cost and the time it takes to obtain better information must be compared to what can be saved by modifying the investigation programme. New information is only interesting when it can change the outcome of the decision and thus is of value for the decision-maker. The cost of an investigation or measurement should be less than the expected savings; otherwise the investigation should not be made (Back, 2006; Bedford and Cooke, 2001; Freeze et al., 1992). Here VOIA is used for choosing the pre-investigation program best suited for the geological environment.

In the petroleum industry the VOIA approach has been used for evaluating if seismic and controlled-source electromagnetic data can reduce some of the uncertainty in the reservoir properties (Buland et al., 2010; Eidsvik et al., 2008). One of the central tasks is to evaluate how good geophysical methods are at detecting problematic rock conditions in otherwise good rock. Because, such an estimation can be biased (based on experience, affiliation etc.), the approach is to ask geophysical experts to judge this in order to get a more objective result. The experts use a number of simulations of possible rock volumes as a basis for estimating the probability. The expert's opinion is then, together with data from evaluation of real geophysical investigations, the foundation for the probability used in the VOIA. The example is hypothetical but is inspired by the construction of the Hallberg tunnel in Sweden.

6.1 Theory

There are two predominant ways of conceiving probability. The traditionalists (also called frequentists) consider probability as a frequency with which things occur in a long series of trials, e.g. rolling a dice. The Bayesians on the other hand consider probability as a degree of belief and therefore admit probability statements on states of nature. In this way states of nature are considered as variables, and not unknown constants. This is consistent with engineering geology which is heavily depending on observations and uncertainty of the observations. The expert might have discretely sampled data (measurements) of how the state of nature is. Based on this the engineering geologist is expected to make a statement about the state of nature without actually having solid proofs. The engineering geologist makes an estimation of how the geological conditions are and what events are probable (Baecher and Christian, 2003).

Tunnel construction is decision making under risk where pre-investigation should reduce the risk of something unexpected happening. If the unexpected happens it will in most cases cost more time and money than a thorough pre-investigation. However a thorough pre-investigation is no guarantee that no problems will arise, because there is a probability that problematic zones are missed or underestimated. Nevertheless is an optimised pre-investigation necessary for making the best decisions with the information available in order to reduce the risk for unexpected geological problems. In VOIA the data worth is assessed by comparing the cost of data collection with the expected value of the risk reduction the data provides. The data worth assessment lead to a strategy for a rational design of a field investigation program. Such a strategy must address the questions 1) what to measure, 2) how many methods to use, succession of the methods and how many profiles, and 3) where to make the measurements (Freeze et al., 1992; Norberg and Rosén, 2006).

Additional information should always aim at reducing uncertainties and the decision to make measurements or change the design of the pre-investigation program is based on cost-effectiveness. A pre-investigation program is regarded as cost effective as long as the expected benefit associated with the new information is larger than the measurement costs. Another way of expressing this is that measurements are only justified if the sampling has potential to change decisions (Andersson et al., 2004). An insufficient pre-investigation will make it difficult to distinguish between *nothing found* because there was nothing there or *nothing found* because of deficiencies in the site-investigation (Back, 2007).

In a VOIA different action alternatives are considered and an objective function φ_j is applied for each alternative *j* (Back, 2007):

$$\phi_j = B_j - C_j - P(F)_j \cdot C_{Fj}$$

(Eq. 6.1)

where B_j is the benefit and C_j is the investment cost. The last term is the risk term, where $P(F)_j$ is the probability of failure and C_{Fj} is the cost of failure. Failure could also be seen as an event or that something unexpected occurs. In this particular VOIA, failure in the prior analysis is when the rock is weak.

By collecting more information (more measurements/drillings), the value of the risk term is reduced and therefore the expected value of the objective function increases. The decrease in the risk term is proportional to the probability of failure. The expected increase in the objective function, ϕ_j, is the value of the pre-investigation (Back, 2007).

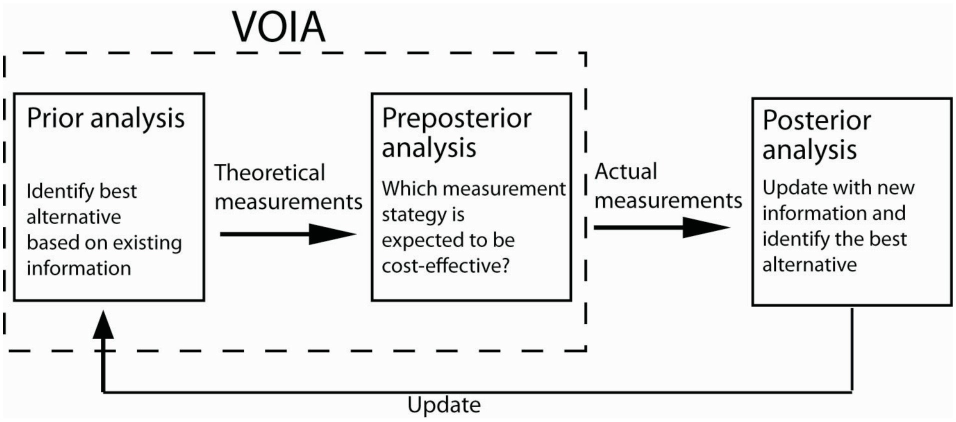

Figure 6.1. The central parts of the VOIA (modified from Back, 2006).

The VOIA consists of a *prior analysis* and a *preposterior analysis*, see figure 6.1. A part of the preposterior analysis is to calculate the *value of new information.* The VOIA only covers the planning of the pre-investigation and no calculation of the posterior value with actual data is performed. However the VOIA can be updated if another round of measurement is considered and in that case any new information should be considered when the probabilities are estimated.

The *prior analysis* is solely based on the knowledge available before any pre-investigation is carried out. It results in an expected total cost or benefit. The Bayesian inference allows the use of prior knowledge, which is very important when there is little data. Prior knowledge might come from old data (e.g. from before pre-investigation), or from some form of expert judgement (Bedford and Cooke, 2001).

The prior value of the best decision alternative is calculated as the prior objective, ϕ_{prior} (Back, 2006; Back, 2007):

$$\phi_1 prior = \max(0, P(F) \cdot C_1F - C)$$

(Eq. 6.2)

where P(F) is the probability for failure (weak rock), C_F is the cost if failure occur and C is the cost for preventing failure. The cost if failure occurs is in this case the additional cost if the project is unprepared for weak rock and it entails a delay.

The probability *P(F)* that an event F happens is said to be the marginal probability or the prior probability. An event can happen, *F*, or not happen *F'*. Two events might be related somehow, and the joint probability are said to be *conditional*. Thus given that an event happens, it can either be detected, *P(D│F)*, or not detected, *P (D'│F)*. Given that an event does not happen, it can either be detected, *P (D│F)'*, or not detected, *P (D'│F')*. This is illustrated by the event tree in figure 6.2. (Baecher and Christian, 2003; Davis, 2002). The *P(D'│F)* and *P(D│F')* are the reliability of the different alternatives and describes the accuracy of the investigation.

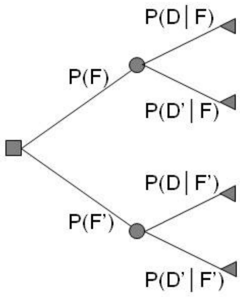

Figure 6.2. Event tree of the preposterior analysis. The square is a decision node, circles are chance nodes and triangles are terminal nodes, indicating the outcomes (modified from Back (2006)).

The *preposterior analysis* is done after the pre-investigation program is defined, but before the actual measurements are carried out (Back, 2006; Back, 2007). The preposterior analysis is also calculated using equation 6.1 but is based on the expected information from the pre-investigations. This results in an objective function, $\phi_{prepost}$:

$$\Phi_{prepost} = \max(0, P(F|D')\cdot C_F - C)\cdot P(D') + \max(0, P(F|D)\cdot C_F - C)\cdot P(D)$$
(Eq. 6.3)

The investigations have no value if both parts of the sum are negative. In order to calculate the conditional probabilities *P(F│D')* and *P(F│D)* Bayes' theorem is used. It relates the conditional and prior probabilities of event *F* and *D*:

$$P(F|D) = \frac{P(D|F)P(F)}{P(D|F)P(F) + P(D|F')P(F')}$$

(Eq. 6.4)

and from the law of probability (Back, 2007; Bedford and Cooke, 2001; Olofsson, 2005; Sturk, 1998):

$$P(D) = P(F)P(D|F) + P(F')P(D|F')$$

(Eq. 6.5)

The value of the new information (or *Expected Value of Information (EVI)*) is calculated as (Back, 2006):

$$EVI = \Phi_{prepost} - \Phi_{prior}$$

(Eq. 6.6)

The EVI is always nonnegative and a value of information is only obtained if the pre-investigation has the potential to change the decision. The expected preposterior value is equal to or larger than the prior value because we make better-informed decisions (Eidsvik et al., 2008).

It is possible to estimate the value of a perfect sampling program, thus there are no errors in the measurements, without performing a preposterior analysis. This is the *expected value of perfect information* (EVPI) and represents an upper limit on EVI and the maximum exploration budget that can be justified without performing a preposterior analysis (Back, 2007).

The EVI does not consider the cost, C_{preinv}, of the pre-investigation program. If the cost of the investigations should be considered the *Expected Net Value (ENV)* is calculated:

$$ENV = EVI - C_{preinv}$$

(Eq. 6.7)

A *posterior analysis* should be performed after the actual pre-investigation has taken place. In this analysis the real worth of the obtained information is calculated and a new updated VOIA is performed using the posterior as prior information (Bedford and Cooke, 2001).

The idea of updating a prior distribution to obtain a posterior distribution gives an important role to the expert. The expert has to decide on the form of the prior distribution. This combination of giving weight to experts but still allowing for scientific evidence makes Bayesian reliability very useful in geo-science (Bedford and Cooke, 2001).

6.2 Tunnel project

The tunnel project used in this example is hypothetical but derived from a real tunnel case in the central part of Sweden; an 800 metre long railway tunnel called Hallberg tunnel. In the central parts of this tunnel the maximum overburden is 25 to 30 metres. The tunnel is constructed using drill and blast with a tunnel face of 6x6 m^2. The geological setting in the area is dominated by greywacke and granite. There are elongated sections with pegmatite and dolerite dykes. The valleys that are found on both sides of the tunnel coincide with regional fracture zones that vary between 10 and 20 metres wide. The soil deposits are relatively thin and in some areas the bedrock is exposed or covered by a thin layer of lichen and moss. The terrain is dominated by forested till and marsh.

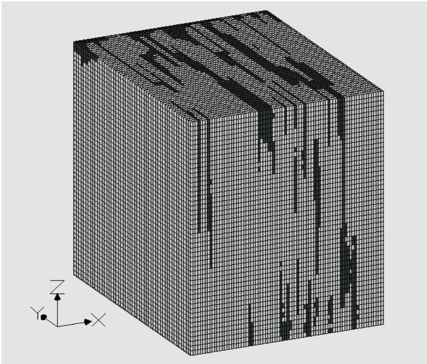

Figure 6.3. An example of a 3D simulation. Modified from Zetterlund (2009)

For this hypothetical example a simple geological model was generated in the statistical software T-PROGS (part of the computer program GMS from Aquaveo). The simulations are kindly made available by Miriam Zetterlund (Zetterlund, 2009). For more details about the simulations see paper 6 in Danielsen (2010) and Zetterlund (2009). The realization of the possible rock volume (example shown in figure 6.3):

- Each cell is 1x2x2 metre (i.e. 80x100x100 metre)
- The virtual tunnel will be constructed in the central cells (3x3 cells)
- Two rock classes, good rock (RC1) and poor rock (RC2)
- Problematic rock are fracture zones and clay weathered rock (poor rock)
- Good rock is unaltered
- 10 % poor rock (black)

6.3 Estimation of probabilities

It is difficult to obtain an un-biased estimation of the value of geophysics because the concept of the methods can vary from expert to expert and accordingly geophysics is not easily amenable to mathematical representation. Nevertheless the probability that geophysics detects weak rock is essential to this VOIA. The study of the applicability of the geoelectrical method (Chap. 5) is a natural and important base for the author to estimate these probabilities. In an attempt to make the used probability more reliable seven experts were asked their opinion of how good a geophysical method is in the geological environment of the hypothetical example. The experts have all worked with the application of geophysical methods in hard rock environment in national and/or international tunnel projects. How the answers from the experts were used is described in more details in Danielsen (2010).

As part of the evaluation of the geophysical methods, the experience from geophysics in other tunnel projects is used, so that not only the experts opinions are considered for estimating the probability. The experience from Hallandsås Tunnel (Chap. 5 and Danielsen and Dahlin, 2009) and Bolmen Tunnel (Stanfors, 1987) both in southern Sweden, are used together with work done by NGU in Norway (Rønning, 2003). The geological settings in the examples are different but still it is possible to obtain an impression of the probability of finding a weak zone using the different geophysical methods.

6.4 Framework

In the following a framework is presented where the value of geophysical measurement in pre-investigation for rock tunnel construction is evaluated. The geophysical methods are geoelectrical imaging and ground based magnetic measurements. The suggested pre-investigation program is discussed further in paper 6 in Danielsen (2010). In this framework a responsible authority (e.g. Trafikverket) plans to build a tunnel and orders a pre-investigation from a consultant (Fig. 6.4). The first step for the consultant is to produce an early (rough) engineering geological prognosis (based on archive data and field visits). The consultant has to decide what the major concerns are and how to proceed with the pre-investigations. Should a detailed prognosis be done or is the early prognosis enough as basis for contract negotiation? If a detailed prognosis is made, should it then consist only of drillings or also geophysics? These question marks are answered by VOIA. When the basis for contract negotiation is ready the contractors can start giving offers on the work.

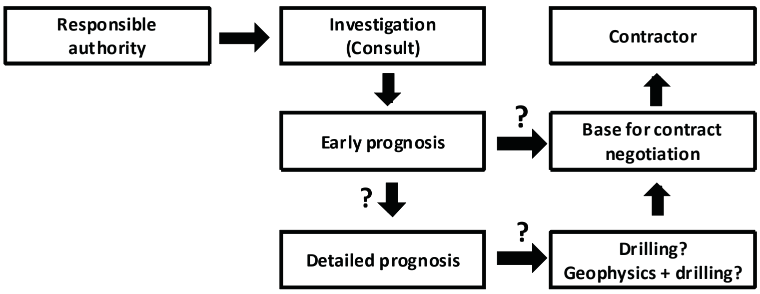

Figure 6.4. The flow in the decision process for a construction work. The question marks are answered by VOIA.

In the VOIA there are different decision alternatives. In the *prior analysis* it has to be decided which of the construction alternatives to use:

1. 10% of the rock is assumed to be poor (reference alternative). This means that when constructing the tunnel reinforcement class BFK3b is used in 10% of the tunnel length. For a description of the reinforcement classes see appendix B in paper 6 in Danielsen (2010).
2. 40% of the rock is assumed to be poor and requires reinforcement with BFK3b. Thus the construction is more expensive.

In the *preposterior analysis* it has to be decided which of the pre-investigation programs to use:

1. Two core drillings
2. Geoelectrical imaging, ground based magnetic (in the following called geophysics) and two core drillings positioned based on the geophysics.

It is important to stress that this analysis not only comprise a cost-benefit analysis but also a Bayesian update. Thus the risk reduction is considered and the probabilities necessary for the cost-benefit analysis are based on 10 simulations of possible rock volumes (different from those evaluated by the seven experts). It is decided that failure in the prior analysis is when the rock is weak (RC2).

6.4.1 Prior analysis

In the prior analysis it has to be decided which construction alternative to use, standard or extensive. In the standard approach the cost for the construction is lower than in the more extensive approach. The input data and results are given in table 6.1 and 6.2 and the calculations in the prior analysis are shown in appendix B in paper 6 in Danielsen (2010). The probability of failure is calculated using the simulations as described in paper 6 (step 2). It turned out that P(F) is 0.5 and thus P(F') is also 0.5. This is so even if there in the T-PROGS simulation only is 10% RC2. However it has to be acknowledged that the sections are regarded as poor if more than 1 pixel in each section is RC2. It is assumed that in the construction of the tunnel it is not possible to switch reinforcement class for each metre, so there has to be a *reaction length*, which is said to be a full section.

If the unexpected occurs the construction cost might increase because of the increased amount of materials needed (e.g. shotcrete + bolts) but more importantly due to the increase in construction time. In Malmtorp and Lundman (2010) and Kim and Bruland (2009) it is estimated that it takes 50% longer time to construct a tunnel if e.g. BFK3 is used instead of BFK1. Therefore it is assumed here that the cost is 50% higher when the change from one strategy to another is unexpected. This additional cost if the unexpected happens ($C_{F,}$ failure) is calculated for each alternative. The probability, P(F), that something unexpected happens was 0.5 and when the strategy is to only use the extensive reinforcement in 10 out of 100 sections the project is unprepared in 40 out of 100 sections. In alternative 2 the project is only unprepared in 10 out of 100 sections. The difference between the cost of failure in the two alternatives is called the switchover cost, C_{switch}, and is the cost for the additional time needed because the project is unprepared for the required reinforcement. The failure cost is lowest in alternative 2 and thus the $C_{switch} = C_{F1} - C_{F2} = 13770$ kSEK. 1 kSEK is 105 euro (September 2010).

Table 6.1. The input data for the prior analysis.

Cost		kSEK
Cost of tunnel (alternative 1)	C_1	10085
Cost of tunnel (alternative 2)	C_2	14389
Difference	$C_i = C_2 - C_1$	4304
Probability		
Probability for RC2	P(F)	0.5
Probability for RC1	P(F')	0.5

The risk in alternative 1 is that the construction strategy has to be changed if something unexpected happens. The risk is calculated as: $R_1 = P(F)\ C_{switch}$. For alternative 2 the risk is $R_2 = R_1/4$, because the project only is unprepared in 10/100 sections and not 40/100 sections.

In the first alternative with the standard approach the benefit is zero whereas the benefit of using the extensive and more expensive approach is a lower risk for something unexpected to happen: $B_2 = R_1 - R_2$. In other words the benefit is what is saved if the project is prepared for change in reinforcement strategies. In the prior analysis the prior objective function is calculated for both alternatives using equation 6.2, i.e. $\phi_i = B_i - C_i$, and is the expected net benefit with present information. The best alternative is the one with the highest value for the project. The value of the prior analysis is calculated as $\phi_{prior} = \max(\phi_{1prior}, \phi_{2prior}) = \max(0, 860\ \text{kSEK}) = 860$ kSEK. Therefore the alternative 2 with the extensive construction approach is the best decision.

Table 6.2. The calculated output data from the prior analysis.

Alternative 1		kSEK
Cost of tunnel	C_1	0
Cost of failure	C_{F1}	110160
Risk cost	R_1	6885
Benefit	B_1	0
Alternative 2		
Cost of tunnel	$C_i = C_2 - C_1$	4304
Cost of failure	C_{F2}	96390
Risk cost	R_2	1721
Benefit	B_2	5164
Objective functions		
C_{switch}	$C_{F1} - C_{F2}$	13770
Value of alternative 1	ϕ_{1prior}	0
Value of alternative 2	ϕ_{2prior}	860
Value of prior analysis	ϕ_{prior}	860

6.4.2 Preposterior analysis

In the preposterior analysis the value of a pre-investigation is calculated before the measurements are done and is therefore the expected net benefit with information from the planned sampling program. It has to be decided if the best alternative is to only do core drillings or if the best alternative is to do geophysics prior to core drillings. The probability for detecting failure using geophysics or no geophysics is estimated as described in paper 6 in Danielsen (2010) (step 3). The input data for the preposterior analysis are given in table 6.3 and the calculations can be seen in appendix B, paper 6 in Danielsen (2010).

The preposterior value, $\phi_{prepost}$, for both alternatives is calculated using equation 6.3:

$$\phi_{prepost} = \max(0, C_{switch}P(F \mid D') - C_i)P(D') + \max(0, C_{switch}P(F \mid D) - C_i)P(D)$$

The conditional probabilities used in the preposterior analysis is calculated using Bayes' theorem (Eq. 6.4) and P(D) from the law of probability (Eq. 6.5). The results are summarised in table 6.4.

Table 6.3. The input data for the preposterior analysis.

		Only boreholes	**Geophysics and boreholes**	**EVPI**
Probability for RC2	P(F)	0.50	0.50	0.50

Probability to detect RC2	P(D│F)	0.40	0.68	1
Probability to detect RC2 that not exist	P(D│F')	0.27	0.03	0

The preposterior value, $\phi_{prepost}$, of only drilling boreholes in the pre-investigation is 2581 kSEK, whereas the value of a combination of geophysics and a borehole is 3123 kSEK. And therefore geophysics combined with a borehole is the best alternative. In the calculation of the preposterior value in appendix A (paper 6 in Danielsen (2010)) it is seen that the value of not achieving data (D') is zero whereas the value of achieving the data (D) is 8777 kSEK.

Table 6.4. The results from the preposterior analysis.

		Only boreholes	**Geophysics and boreholes**	**EVPI**
Conditional probability	P(F│D)	0.60	0.95	1
Conditional probability	P(F│D')	0.45	0.25	0
Probability of detection	P(D)	0.33	0.35	0.50
		kSEK	kSEK	kSEK
Preposterior value	$\phi_{prepost}$	2581	3123	4733
Expected value	EVI	1721	2253	3873
Exp. Net value	ENV	1441	1863	

6.4.3 Value of perfect information

Calculating the EVPI means that the probabilities P(D'│F) and P(D│F') both are zero and perfect information is obtained. The EVI for the perfect information (EVPI) is 3873 kSEK. This is regardless of which alternative is chosen for the pre-investigations.

6.4.4 Expected value and expected net value

The expected value EVI, that is the value of new information, is calculated EVI = $\phi_{prepost} - \phi_{prior}$ (Eq. 6.6). For the project the information has a value or worth even though there is a cost combined with the decision. For using geophysics the EVI is 2253 kSEK. The EVI for only drilling boreholes is 1721 kSEK and therefore this alternative has a lower value for the project. If the cost for the pre-investigation should be considered the expected net value for geophysics, ENV is calculated to 1863 kSEK using equation 6.7. However the pre-investigation program should in the best case also contain geophysical borehole logging and pumping tests. But in the ENV only the methods considered here are used in the calculations.

6.5 Sensitivity analysis

An essential part of this VOIA is the sensitivity analysis of the different input variables. For the analysis of the different variable's uncertainty a Monte Carlo simulation is made where a large number of random solutions ("qualified guesses") are calculated. In this case 10^5 simulations were done. The parameters are systematically altered to determine the effects of such changes. In this way the robustness of the study is investigated. Monte Carlo uses statistical distributions to represent different kinds of uncertainty and for the analysis a probability density function (pdf) has to be chosen for each of the stochastic variables (Burgman, 2005). This is a difficult part and in this case a beta-distribution is applied. For the pdf's the mean and standard variation is calculated.

In this analysis the only cost-variables to consider is the cost of failure, C_{F1} and C_{F2}. The other costs in the calculations depend on these two variables and therefore it is not reasonable to analyse any other. It is assumed that the two costs are normal distributed and that they to some extent are dependent on each other and therefore the correlation is said to be 0.6. The probabilities P(F), P(D│F) and P(D│F') are said to be beta-distributed in all alternatives. The input data for the simulations and the probabilities are seen in table 6 and 7 in paper 6 in Danielsen (2010).

Table 6.5. The results from the simulations of the preposterior analysis.

		Only boreholes	**Geophysics and boreholes**	**EVPI**
Expected value > 0	EVI > 0	~100%	100%	~100%
		kSEK	kSEK	kSEK
Mean value (given that EVI > 0)		1683	2218	3826
Standard deviation		351	312	301
Exp. Net value	ENV	1403	1828	

In 13.4% of the 10^5 simulations the construction alternative 1 was the best solution in the prior analysis. In the remaining 86.6% of the simulations the alternative 2 was the best solution. For the preposterior analysis the results of the simulations can be seen in table 6.5. The mean value of only drillings is 1683 kSEK and the standard deviation is 351 kSEK. For the combination of geophysics and drillings the mean value is 2218 kSEK and standard deviation is 312. In only 13 of the 96634 simulations (with EVI > 0) the solution with only drillings is the best alternative.

6.6 Discussion

In the prior analysis conducted in this example it was seen that the extensive construction approach is the best alternative. The value of the standard approach is zero and the value of the extensive is 860 kSEK and therefore the latter is the best alternative because the prior function (Eq. 6.2) is maximised. The sensitivity analysis showed that the standard approach is the best solution in 13.4% of the 10^5 simulations. It is notable that the best alternative is to assume that it is necessary to use BFK3 instead of BFK1 in 40% of the tunnel, even though in this simulation only 10% of the rock is classed as poor rock (RC2). The reason is probably that it is assumed that in the construction of the tunnel it is not possible to switch reinforcement class for each metre and therefore a larger ratio of the volume is regarded as RC2.

The preposterior analysis showed that the highest value is obtained by using a combination of ground based magnetic measurements, geoelectrical imaging and core drillings as base for compiling an engineering geological prognosis. The expected value of new information (EVI) is approximately 2250 kSEK which should be seen in relation to a total construction cost of 104800 kSEK. The expected value of using the information from only core drillings is approximately 1700 kSEK. However there are uncertainties in the calculations from both the probabilities and the cost. In an attempt to reduce the uncertainty seven experts were asked their opinions. Nevertheless an un-biased estimation of the value of geophysics is still difficult to obtain because the confidence in the methods can vary from expert to expert. The answers from the experts are further discussed in paper 6 in Danielsen (2010). A combination of the experts opinions and the experience from the use of the geoelectrical method in chapter 5 and other tunnel projects is a good foundation for estimating the probabilities for this specific project. However the probabilities used in the example are calculated based on 10 simulations, which means they are rather uncertain in statistical terms. A sensitivity analysis is therefore conducted to support the results. Even though the framework originates from a real tunnel case it has been a challenge to estimate the cost if failure occurs (switchover cost) because such a cost is first negotiated if delay occurs and/or increased material expenses exceeds the budget. Consequently the question is very complex and beyond the scope of this framework. The main focus is the value of pre-investigation and not contractual problems. Here a switchover factor based on literature examples (Malmtorp and Lundman, 2010); Kim and Bruland, 2009) is estimated and used in the calculations.

The sensitivity analysis showed that in nearly 100% of the simulations it would have a value to perform only core drillings. However the analysis also showed that the alternative with only drillings had the highest ENV in only 13 of the 96634 simulations where ENV was positive. Otherwise alternative 2 including geophysics have the highest ENV. The chance/risk that the highest data value is obtained with performing only drillings is therefore minimal. However it should be taken into consideration that the drillings in this case only has the purpose to detect RC1 or RC2 based on what is seen at the surface. The drilling gives point information and might miss a weak zone nearby. In reality a core drilling is also used for e.g. laboratory tests, and therefore has a value for a project in that sense, but this value is not taken into account in the analysis. Nevertheless the difference in EVI between the two decision alternatives is relatively large and therefore implies that it can be strongly recommended for the decision-makers to perform a profound pre-investigation including geophysics (in this case ground based magnetic measurements and geoelectrical imaging) as guideline for where to do the drillings.

The value of perfect information (EVPI) is 3873 kSEK and can be considered as the maximum cost for the investigations to be worthwhile to perform. However perfect information is hypothetical and in a construction project it is impossible to obtain so much information that the risk for something unexpected to happen is zero. The sensitivity analysis of the EVPI (for EVI > 0) gives a mean value of 3826 kSEK with a standard deviation on 301 kSEK. Thus it can be concluded that not even geophysics and boreholes gives perfect information. As for the alternative with only boreholes the geophysical data can also have additional value in a later project phase that not is considered here.

The geological model and the problems considered in this VOIA are a simplification of reality. The model can be further developed and become more complex. However this VOIA is meant as a demonstration of the general idea behind VOIA and the considerations behind the framework are generally valid when geophysics is evaluated.

The aim with this VOIA was to show that it is important to use a suitable geophysical method prior to drilling; however there will always remain some uncertainties in the engineering geological prognosis no matter how many measurements are made. But with the VOIA the value of new information from ground based magnetic measurements and geoelectrical imaging is assessed by estimating the reliability in the present information compared to the expected increase in reliability following collection of new information. New information is only interesting when it can change the outcome of the decision and thus is of value for the decision-maker. The benefit of having the most certain engineering geological prognosis is less risk and a more predictable cost. The benefit should be seen as the amount of money saved when the best decision is made. The cost of an investigation or measurement should be less than what is expected to be saved; otherwise the investigation should not be made (Back, 2006; Bedford and Cooke, 2001; Freeze et al., 1992). Applying these lines of thought to geophysics gives the decision-maker the opportunity to evaluate the reliability in an approach without actually being an expert in either VOIA or geophysics. A cost-benefit analysis shows in clear terms if it is worthwhile to incur the cost of additional measurements or not. VOIA is a model of reality and is therefore also encumbered with uncertainty, but a sensitivity analysis gives a clear idea of the reliability.

VOIA is an aid for decision-makers to evaluate the value of different alternatives before taking action and is therefore in this case an attempt to show the value of geophysics by using an approach the decision-makers understand. The framework developed here has the potential to become an integral part of pre-investigation. The analysis should be done after the archive study and prior to the first geophysical measurements. In many construction projects some kind of geophysical method is used e.g. refraction seismic, but this is not always the case. In some projects it might be very beneficial to use another or additional geophysical method, e.g. geoelectrical imaging, seismic, magnetic or a combination. VOIA can help evaluate and design the best measurement program for a specific geological setting. An important issue with a VOIA is that it is constructed specifically for every problem and cannot be re-used from project to project. The cost-benefit calculations are relatively simple to perform and with the framework developed it is straightforward to change the costs and probabilities in the calculations.

7 Discussion

Different geophysical methods are important parts of a profound pre-investigation and as shown in chapter 2.1 and 5 the use of for example the geoelectrical method at different scales contributes to the understanding of the geological setting. In the following the possibilities, strengths and weaknesses of the geoelectrical method as well as the application of value of information analysis (VOIA) are discussed.

7.1 Evaluation of Geoelectrical methods

It is important that the expectations as to what the geoelectrical method can accomplish are realistic for successful use of this method. Geoelectrical imaging is relatively unknown in Sweden whereas e.g. refraction seismic has been a natural part of pre-investigation for decades, so people have experience with how to use the seismic data with respect to advantages and limitations. The examples in chapter 5 show how the geoelectrical method can be applied in rock tunnel construction where not only the advantages but also the limitations are addressed. This will hopefully contribute to realistic expectations to what can be accomplished using the geoelectrical method.

A successful outcome of the use of the geoelectrical method depends on the physical properties in the investigated area. Before the method is used it has to be investigated if the approach is suitable in the specific geological setting. The method has its strength in areas where the resistivity contrast between the poor and good rock is sufficiently large, e.g. weathered zones or water bearing fractures in crystalline rock. It is the transition between the different rock properties that are important to detect because problems during construction arise if the poor rock is not anticipated. The size of the zones that can be detected depends very much on the resistivity contrast but also on the target depth and scale of the measurements.

An important task is to interpret the data and translate the resistivity data to a property useful to the decision makers. The resistivity is ambiguous, and thus for interpretation a general knowledge of the geological setting and reference data is needed. However the need for reference data for calibration of the geological model based on the geoelectrical imaging should not be seen as a limitation of the method. Reference data can be found in the initial archive study, but the optimal is drilling data and borehole geophysics which can be considered ground truth at a single point. An integrated part of the pre-investigation is core drilling, thus reference data exist or will be procured in most cases. Boreholes provide point information that can be used for in situ correlation with the geoelectrical imaging (CVES) data. The CVES provides a continuous 2D (or 3D) model of the subsurface in a profile line between the drilled boreholes. The cores from the drillings can also be used for laboratory tests. With continuous data supplied by the CVES the uncertainty of the ground conditions is greatly reduced.

The geoelectrical method can be used at different scales and at different stages of a project. The geoelectrical imaging is used at large scale in the design/production planning stage (Chap. 2.1 and 5.2 , paper 1) and in the construction stage (Chap. 5.6, paper 5). Electrical Resistivity Tomography (ERT) is measurements between boreholes and is therefore performed at a smaller scale mainly in the construction stage (Chap. 5.3, paper 2). For even more details the resistivity logs can be part of a borehole geophysical campaign (Chap. 5.4 and 5.5, paper 3 and 4). Borehole geophysics is normally applied late in the design/production planning stage.

In the design/production planning stage the geoelectrical imaging (CVES) is the basis for a geological model. The method detects variations in the physical properties of the rock and in a combination of several geophysical methods that measure different physical properties, a realistic view of the rock mass can be obtained. By using CVES in the pre-investigation in the Pungwe water tunnel the intended tunnel line was moved to an area with better rock quality. Thereby problems with weathered rock were avoided in an area with high environmental demands. The combination of CVES (resistivity and IP) and ground based magnetic data has proven to be useful in the geological environment at the Hallandsås Horst. Prior to drillings an evaluation of the geophysical data should be done so the drillings can be positioned to ensure that as much representative information as possible is obtained for calibration of the geological model. In the construction stage the geoelectrical imaging data can be calibrated with the tunnel documentation to update the geological model and thereby reduce the uncertainty in the model. Continuous update of the model is especially important if the Observational Method is used (e.g. Peck, 1969; Terzaghi and Peck, 1948).

What is important to anticipate when using geoelectrical imaging is that the target area, i.e. the depth of the tunnel, should be within the depth where the method has acceptable resolution. The resolution decreases with depth. The penetration depth depends on different factors, e.g. resistivity, array type and largest electrode distance. Generally a penetration depth of 60 metre is achieved with a standard 400 metre cable layout. This entails two persons in the field. If the penetration depth should be larger (~120 metre) a cable layout of 800 metre is necessary. As an example this was done at the Hallandsås Horst when the data in figure 2.2 was measured. Alternatively, the more demanding pole-dipole measurement can be used, as was the case for the data in figure 5.2. For the longer cable layout, the pole-dipole measurement is more time consuming in the field due to the requirement for a remote electrode and will therefore be more expensive.

The continuous CVES data in 2D, or even 3D, are measured in a relatively fast and cost efficient way compared to refraction seismic. The geoelectrical imaging should not blindly be used instead of refraction seismic but should be seen as an alternative in the geological environments where the geoelectrical method has its strengths. At the Hallandsås Horst geoelectrical imaging, correlated with e.g. drillings and geophysical logging, indicates fractured, water bearing rock, weathered rock and to some extent lithology changes in the crystalline bedrock. In this particular geological environment with the tunnel occasionally drilled 150 metre beneath the surface, the scale of resolution of the resistivity method is tens of metres at tunnel level. Thus in this case the method cannot resolve bodies or structures smaller than this.

The ERT can contribute to the understanding of the ground condition both in the design/production planning stage and in the construction stage. However measurements done in horizontal boreholes, as described in chapter 5.3 (paper 2) are mainly justified in the construction stage in front of a TBM. If the geology varies on a small scale, the boreholes drilled in front of the TBM might not be representative of the rock mass between the boreholes. The initial attempts to use the approach as described in chapter 5.3 (paper 2) give promising results. However, the measuring routines have to be optimized to be used in an actual construction stage.

As part of borehole geophysics, the resistivity logs give detailed information in a design/production planning stage. Unfortunately only a few sets of geophysical logging equipment exists in Sweden and therefore borehole geophysics is normally not an integrated part of pre-investigations and is often disregarded due to the additional cost. However percussion drilling, including geophysical logging with the probes used in chapter 5.4, is approximately one third of the cost of core drilling. The strength of borehole geophysics is the high resolution and the detailed in-situ data. Additionally continuous data are obtained even in weak rock where there might not be full core recovery. Furthermore data are saved for later re-interpretation of the ground conditions as they were when the data was recorded. The logging data is very valuable for calibration of the surface geophysical data. With this calibration the uncertainty of the geological model is reduced. However when surface based data are calibrated with logging data it is important to acknowledge the difference in scale. The surface based CVES data are measured over a large rock volume where small scale variations are seen as average values, whereas the logging data can resolve every small variation.

The fewer question marks there are in an engineering geological prognosis the higher the chance that problematic ground conditions will be predicted. Ground conditions can be very complex and different factors contribute to the physical properties of a rock so that it is sometimes necessary to go into very great detail for an explanation. Even though geophysical logging gives great details there might still be some ambiguity in the interpretation of the results. To answer some of the questions it can become necessary to go into even greater details. The example in chapter 5.5 (paper 4) shows clearly that what seems to be some artefact actually has a physical explanation. It stresses that the geophysical data are right, but that the interpretation might be difficult to make because the geology is complex. Microscopy of thin sections can help answering some of the questions that might be raised during interpretation of geophysical data. However there is often neither time nor money to seek an explanation for a problem like this because it has limited importance for the tunnel construction. However the practical importance is not always possible to predict and who knows which detail is of great significance to a project? The initial weathering of the amphibolite may turn out to have real significance for the rock mechanical properties and this would not have been detected without geophysical logging and microscopy of the thin sections.

Numerical modelling is valuable for obtaining experience and learning more about the advantages and limitations of the geoelectrical method in a specific geological environment. In the conference proceeding Danielsen and Dahlin (2008) and in chapter 5.3 (paper 2) numerical modelling is used to clarify some questions in the interpretation of data.

7.2 Value of Information Analysis

The VOIA framework developed in chapter 6 shows that geoelectrical imaging and ground based magnetic measurements as a basis for positioning core drillings give valuable information that can reduce the uncertainty and thereby the risk in the current tunnel project. The example used is a relatively simple case with an 800-metre long tunnel constructed using drill and blast. Even with a fairly moderate budget and time schedule it is still worthwhile to perform the more profound pre-investigation. With a 50% higher cost of a strategy change due to unexpected geological conditions, the extra cost for the geophysics will in most cases be worthwhile. For a major tunnel project with more complex geological settings the costs if something unexpected happens might even be much higher. A worst case scenario could be if the work has to be stopped or an incorrect construction approach is used. This would naturally make the cost of failure even higher than the 50% assumed in the example.

Several examples of the successful use of geophysical methods in pre-investigations are given in chapter 5 and by others (e.g. Cavinato et al., 2006; Dahlin et al., 1999; Danielsen and Dahlin, 2009; Ganerød et al., 2006; Rønning, 2003; Stanfors, 1987), but presenting the methods in a VOIA emphasizes the importance in terms decision-makers are familiar with. The VOIA is a simple cost-benefit calculation where the value of different alternatives is evaluated before taking action. Applying VOIA to geophysics gives the decision-maker the opportunity to evaluate the uncertainty in an approach without actually being an expert in either VOIA or geophysics. A cost-benefit analysis shows if it is worthwhile to take the cost for additional measurements or not. VOIA is a model of reality and is therefore also encumbered with uncertainty; however a sensitivity analysis gives a clear idea about the uncertainty of the different variables.

The VOIA framework developed here has the potential to become an integrated part of pre-investigation. The analysis should be done after the archive study and prior to the first geophysical measurements so that VOIA can help evaluate and design the best measurement program for a specific geological setting. An important issue with VOIA is that it is constructed specifically for every problem and cannot be re-used from project to project. The cost-benefit calculations are relatively simple to perform and with the framework developed it is straightforward to change the costs and probabilities in the calculations.

7.3 Essentials for successful pre-investigation

This work on the applicability of geoelectrical methods in pre-investigations has lead to some more general reflections on what is essential for a successful pre-investigation and construction project. In the following sections several important issues are discussed.

7.3.1 Geological setting (complexity, hazards)

The complexity and the expected hazards in the geological environment are decisive for the form of the pre-investigation. The more complex a geological setting is the more extensive the investigation program has to be. Thus it is immediately after the archive study that the pre-investigation program should be decided. The VOIA of pre-investigation methods presented in this report would be a natural aid for this decision.

Additionally a program should be dynamic and flexible so that it is possible to do more or fewer investigations. This may be a problem because there is normally no budget for doing more investigations in most projects. However it has to be stressed that having the flexibility to extend the investigation program might in the end save large sums of. By applying VOIA in the planning of a pre-investigation the program can be optimised and the money can be used in the best way.

A significant area of concern is where the scope of the pre-investigation is determined by the project owner with a limited budget and little or no understanding of the engineering geological requirements of the project (Baynes, 2003). Often a way of saving money is to e.g. cut down additional measurements or borehole measurements. The chain of reasoning is often that enough information is obtained and that there is neither time nor money for more investigations. But what is enough? What has to be taken into account is that the certainty of the prognosis will increase considerably by doing an optimised pre-investigation program. Malmtorp and Lundman (2010) have shown that the uncertainty of the pre-investigation is important for the outcome of the project. An uncertain pre-investigation result is a contributory reason for delays and increased budgets. However a thorough and optimised pre-investigation is no guarantee that no problems will arise, because there is a risk that problematic zones are missed or underestimated. Nevertheless an optimised pre-investigation is necessary for making the best decisions with the information available in order to reduce the risk.

7.3.2 Existing information in a national geo-database

Prior knowledge of an area is essential for a pre-investigation. The more existing information there is the easier it will be to plan the best possible investigation program and to estimate the costs for the program. But often it is difficult to get hold of the existing material because it is archived at the consultants who carried out the previous investigations. Thus if an individual at the consultant company who did the survey changes job, it can become difficult to locate the data and reports. It would be beneficial if a national database is established in Sweden so that all types of geo-data can be saved and made available. It should be a natural part of a project to report the raw data and interpreted models to this database. The idea is that whenever a new project is planned it should be possible for the involved parties to extract information from the national geo-database. In this way all data are preserved for future projects. During the last decades Denmark has developed a high quality database, initiated as part of the national groundwater mapping (Møller et al., 2008). This database facilitates the interpretation and analysis of data covering large areas and allows for visualization of the data. The different tools in the system connect to and interact with each other in a transparent and intelligent manner. Work must be carried out directly on a copy of the database, and all relevant information on each data point and model must be accessible for use any time during the analysis and interpretation procedure.

7.3.3 Central project database to handle geo-data

A central project database makes it possible to access and manage the geo-data at all times. This makes it easier to update the engineering geological prognosis. The database should contain both raw data and interpreted models. Having both types of data in the database makes it possible without difficulty to make a reinterpretation of the raw data if e.g. additional data is gathered or better interpretation tools evolve. The obtained information becomes more transparent and thus better decisions can be taken on engineering issues. If it should come to a dispute within the project, then the documentation is still easily accessed. Additionally the project would not be so sensitive towards changing personnel. The central database should also become part of the national geo-database so that the data can be preserved for the future and easily be accessed and used in other projects.

Documentation from the tunnel projects should also be a natural part of the database (see chapter 5.1). By integrating the tunnel documentation the engineering geological prognosis can be updated and the tunnel construction can be done more safely with less uncertainty. This is especially an advantage when the Observational Method is applied (Peck, 1969; Terzaghi and Peck, 1948). The Observational Method is applicable when the uncertainties in the pre-investigations are high. The method is often used when it is possible to alter the design of the construction.

7.3.4 Consistency in pre-investigation report

If a project is large with several tunnels, e.g. Ådalsbanan or Botniabanan in Sweden, the pre-investigation report from the single tunnels should be compiled in the same way. It is advisable that the flow of the investigation (top-down) is maintained through all reports. It is often seen that different consultant companies investigate the different tunnels. To avoid any misunderstandings and make it easier for e.g. the contractor to locate the information, the project owner should put up guidelines for the report form. The succession should be top down giving the large scale information first ending up with small scale information.

7.3.5 Communication

Above all else good communication is fundamental to a project's successful outcome. This requires engineering geologists/geologists/geophysicists who are aware of the engineering issues and rock mechanics engineers and construction engineers who can appreciate the value of geological advice. The project manager, the technical specialist, and the geophysicist form an interdisciplinary team to meet the objectives. Therefore it is important that the involved parties are capable of communicating sensibly and are able to express clearly their requirements and expectations from the pre-investigations. The consultant is responsible for understanding the overall needs of a project owner/contractor and effectively communicating the relevant geologic findings and ideas. Here the central project database becomes essential in that it allows all the involved parties to easily access the data.

7.3.6 Integration of knowledge

Often it is not the methods used that are the problem but rather how the results are presented and integrated. From the first attempt (1992-1995) at the Hallandsås Tunnel (Chap. 2.2) it can be learned that it does not matter how many different geophysical methods are used if the information is not considered in the decision making process. Therefore the knowledge obtained has to be promoted into the project and integrated into the decisions, as has been the case in the Hallandsås project from 2003 onwards.

The knowledge that experienced staff possesses has to be integrated and acknowledged in the decision process. However the term *"we always do like that"* has to be avoided since it might not be the best solution in all cases. It is important to be open minded through the whole project and make the best and optimal decisions with the information available. Here it is especially important that the best suited geophysical method is used in the current geological setting. There is a tendency to use the geophysical method and the instrument which is available at the time. However in some cases it might be an advantage to think differently and use another method. This might be more expensive if the instruments has to be hired along with a field crew and experienced personnel for processing the data. Nevertheless the obtained knowledge might be so important for the outcome of the project that the extra cost is acceptable.

7.3.7 Realistic expectations

It is important to acknowledge, when interpreting geophysical data that the measurements are done in order to answer specific questions and that each project is unique. This means that considerations have to be made before the data is used for other purposes. The data might contain more information, especially if calibrated with other types of data, but it is important to know the limitations of e.g. resolution of the method.

The construction phase of the Pungwe water tunnel in Zimbabwe is a good example (chapter 2.1) of how data measured for another purpose is over-interpreted. An attempt was made to determine the depth to the crystalline basement by means of the resistivity data. However what was interpreted as the surface of the crystalline basement turned out to be large boulders succeeded by soil at the proposed water intake (Uden, 2010). Since the resistivity contrast between dry soil and crystalline bedrock is small, defining the transition would be a difficult task. In such a geological setting it is crucial that borehole information is available for calibration of the model. This stresses the importance of having the right expectations and knowing the advantages and limitations of the methods in very specific geological environments before interpretation of the data. Otherwise there is a tendency to focus on the examples where the methods did not live up to the expectations as opposed to examples where the method was successful.

7.3.8 Experience/skills

A project owner has to be skilled and experienced enough in order to avoid unnecessary risks, ask the right questions and demand that the best possible pre-investigation is done. Often an external consultant is hired to perform the pre-investigations. A limitation could be that the consultant does not know the overall needs for a project owner/contractor to make the best decisions. A pitfall is the tendency for the consultant (i.e. geophysicist/geologist) to focus on what can be measured, and not on the needs of the contractor/project owner.

Generally it can be said that the measured geophysical data are correct; however the interpretation of the model might be wrong. To avoid this it is advisable to engage experienced and skilled geophysicists for the interpretation of the models based on the geophysical data and supported by other type of geo-data. Only few consultancy companies in Sweden have experienced geophysicists to process and interpret data and to handle a fully integrated pre-investigation for large infra structure projects. In addition the field crew performing the measurements has to be skilled and very meticulous to avoid that e.g. data are measured at an inexact position or with unfavourable instrument settings. Another important issue is how the data, results and models are presented regarding scale, colours and succession. For laymen these parameters can be very deceptive and easily lead to an incorrect interpretation.

The foundation for skilled personnel is a good education. A tendency is unfortunately that the students at universities have very little or no experience with hands on pre-investigation techniques. Field trips are relatively expensive and are therefore under prioritized. It is always easier to comprehend the advantages and limitations of the many different methods by hands on experience. Furthermore in-service courses that present the latest developments and the state of the art for pre-investigations should be accorded a high priority for all parties involved in construction work in rock. The development within the topic is fast due to faster computers and the demand for higher data quality. Universities and research organisations have an especially large responsibility to ensure that the latest developments are disseminated within the construction community.

7.3.9 The importance of the contract form

For the involved parties the importance and meaning of the pre-investigation depends very much on the contract form and who carries the risk and responsibility. The form of the contract can vary where the responsibility more or less rest with the project owner or contractor. It is important to predict and anticipate possible risks before writing the contract and should also include actions to be taken if deviations occur during construction, not least deviations from original geological assumptions (Tengborg, 1998).

The project owner does always have responsibility for characterization of the ground conditions, i.e. they have the responsibility for planning and completion of the pre-investigation. This means that if the ground conditions are different than anticipated a dispute can arise between the project owner and the contractor. Thus it should be in the project owner's interest that the pre-investigation is as good as possible and with low uncertainty. However the project owner has to avoid increased budgets and often do not have any incentive to spend under budget. The consultant's objective is to make the project owner satisfied and do a good job economically. Thus for the consultant it is important to establish a good relationship with the project owner, to be considered serious and to maintain a good reputation. As a consequence the consultant is often not interested in taking risks and will choose solutions *on the safe side* that will not necessarily lead to the lowest cost (Tengborg, 1998). The problem with the *safe side* approach is also discussed by Malmtorp and Lundman (2010) where an over pessimistic approach may be taken in the estimation of the rock quality. Here the rock quality is estimated to be weaker than is the actual case, and this makes it difficult to calculate the correct price and the project might become more expensive than necessary. This can lead to a negative attitude towards pre-investigation because the impression is that the investigation is wrong and a consequence is that a certain method might be disregarded in the next project.

By dividing the risk all involved parties becomes interested in a good pre-investigation because the financial profit becomes larger. The consequences of delays are too large for all the involved parties. It is an advantage for the outcome of the project if there is an inducement or bonus for all parties if the project goals are attained either, below budget or ahead of schedule. An inducement for a thorough pre-investigation could be in the form of a financial bonus if the project is ahead of schedule.

8 Conclusions

In this report the main focus has been on the applicability of the geoelectrical method as a tool for predicting geological and rock mass conditions. Applying the geoelectrical method at different scales has proven to provide useful information at different stages of rock tunnel construction. The large scale geoelectrical imaging is useful in the design/production planning stage and in the construction stage. Electrical Resistivity Tomography (ERT) is performed in a smaller scale in mainly the construction stage. At even smaller scale the geoelectrical method can be combined with other geophysical methods in borehole logging and applied late in the design/production planning stage.

Before the geoelectrical method is used it is important to ask what can be expected when applied in a specific bedrock environment with regards to rock mass variations. Here the engineer's key questions are important in order to identify plausible problems. To answer such questions is complex, because the resolution of the method will differ from site to site. The method responds to changes in resistivity and the range of the variations to be detected; the resistivity contrast and size of the different zones have to be sufficiently large for the method to resolve. When interpreting geoelectrical data it is important to keep in mind that the resolution of the method decreases with depth. The penetration depth of the method depends on several factors, e.g. maximum electrode separation, array types and resistivity of the bedrock. In general the target depth should not be more than half of the penetration depth in order to obtain a reasonable resolution. Nevertheless it is feasible for the target depth to be larger, but this has to be acknowledged in the interpretation of the result. The advantage with geoelectrical imaging is that it gives continuous data in 2D or 3D whereas drilling provides only point information. When considering using geoelectrical imaging it is vital that reference data, such as borehole geophysics and drill cores, exist for calibration and interpretation of the data. However reference data is also needed for the interpretation of any other geophysical data. Geoelectrical imaging is generally cheaper than seismic refraction. Yet the two methods should not be compared because they respond to completely different physical properties and should rather be used in combination instead of at the expense of each other.

The use of geoelectrical imaging at the Hallandsås Horst demonstrates that the method can indicate fractured, water bearing rock, weathered rock and to some extent lithology changes in crystalline bedrock. In this particular geological environment with the tunnel drilled 150 metre beneath the surface, the scale of resolution of the resistivity method is tens of metres at tunnel level. Thus in this case the method cannot resolve bodies or structures smaller than this. The numerical modelling and the application of geoelectrical imaging in horizontal boreholes gave promising results. An important outcome of the study was that the prototype of the semi-rigid cable proved to work well. Further adjustments of the acquisition hardware and software have to be done before geoelectrical measurements in probe holes can be implemented at a production stage in tunnel construction. Borehole geophysics (incl. resistivity logs) supply valuable small scale information late in the pre-investigation. The advantage with borehole geophysics is that they provide high resolution in-situ data. These data are useful for calibration of the large-scale measurements and are especially important because they give information about weak rock at localities where there might not be full core recovery. In addition the data are recorded and can be re-interpreted at a later date if that becomes necessary. The combination of borehole geophysics in percussion drilled boreholes is a cheaper alternative to core drilling, especially if a core drilled hole exists for calibration. By going into even smaller details with microscopy of thin section an explanation was found to an ambiguous resistivity of amphibolites in two boreholes. Initial stage of weathering explains the lower resistivity of an amphibolite which otherwise seems un-weathered. This proves that the measured geoelectrical data are correct but the interpretation might be difficult and therefore it can help to investigate even greater details.

The framework for a VOIA of geophysical methods used in pre-investigation showed that the value of performing geoelectrical imaging and ground based magnetic measurements prior to positioning drillings has a higher value than to perform drillings only. This result is only valid for this particular geological setting and is site specific. Nevertheless the framework is applicable to all projects where geophysics used in pre-investigation should be evaluated. It can help in designing the best measurement program for a specific geological setting if the VOIA is to decide between different geophysical methods, e.g. geoelectrical imaging, seismic, magnetic or a combination. The framework developed here has the potential to become an integrated part of a pre-investigation.

Several factors are important for a successful pre-investigation and tunnel construction. The pre-investigation should be performed top down so that the investigations start at large scale and continue into more and more details which follows the need for information in the different project stages. The focus should all the time be on the key questions necessary for making the best decisions through the project. The pre-investigation should be a dynamic process where the prognosis is updated when new information is available. The report presenting the results from the investigations should be structured in a consistent way following the top down approach. The examples from the Pungwe water tunnel, Zimbabwe, and Citytunneln, Sweden, show that geoelectrical imaging and a profound pre-investigation is of great value for a project. The substantial pre-investigations from the Hallandsås Tunnel and the Citytunneln, Sweden, are examples on the importance of integration of information obtained throughout the project life. Communication within a project and thereby also the integration of the knowledge is essential for the outcome of the project. It does not matter how many methods are used if the results are disregarded. A project database with all geo-data helps the integration of information and keeps a dynamic flow in the project.

With profound and optimised pre-investigation and well-integrated results, the reliability of the engineering geological prognosis is higher and the risk that something unexpected happens is thereby reduced. Geoelectrical imaging and borehole geophysics contribute to reduce the uncertainties and should therefore be considered as a prospective part of all pre-investigations as well as of the production stage.

9 Recommendations

The VOIA presented in this report has the potential to become an integrated part of a pre-investigation. However it needs to be further developed and tested using other geological models and geophysical methods.

During my work with the applicability of geoelectrical methods and borehole geophysics for rock tunnel construction I have realized that for the methods to be fully accepted it has to become clear what advantages and limitations the method has. The aim with my work is to show how to use the methods, and it is also important to acknowledge that the methods should only be used when it has the potential to answer questions and thereby reducing the uncertainty. If the methods are used in unfavorable geological settings it will not supply the necessary information and as a consequence it will get a bad reputation. Therefore it is important that the advantages and limitations are clear. The best way for this to become clear is education. It is crucial that students at the universities are educated in pre-investigation methods and that they get the opportunity to try the different methods in the field. It is also important that the different parties involved in pre-investigations have the possibility to follow progress and developments within the area by attending workshops and courses. I highly recommend that more focus is put on education of all the parties involved in pre-investigation.

Only a few sets of borehole geophysical logging equipment exist in Sweden but I sincerely hope that the results of the borehole geophysics presented in this project support the increased use of this method. The approach has a high potential and I can only recommend that it is used more often.

During my work I have become aware of that the information in the pre-investigation reports often is given in the following succession: field visit, core drillings and geophysics (often refraction seismic, if anything at all). This is an illogical succession, and violates the suggested pre-investigation progression shown in figure 3.2. Instead the large-scale information should be gathered prior to the small-scale information. This makes it easier for the reader of the reports, i.e. project owner and contractor, to find and evaluate the information they need at the right time.

Additionally a national geo-database should be developed. Such a database would be beneficial to all pre-investigation thus it would make it possible to get access to geo-data from past projects. As the situation now stands valuable information is lost because it is up to each consultant and projects to archive the data in any format they choose. The database could be maintained by the Geological Survey of Sweden (SGU) and be financed by the users. The Swedish society would also benefit of such a database and could therefore contribute to financing the development and construction of the database.

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