The applicability of geoelectrical imaging as a tool for construction in rock

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Summary

Construction in rock is always combined with an uncertainty about ground conditions because the rock mass is very seldom completely homogenous. Unforeseen rock conditions pose a large risk to the project and can in the end entail delays and extra costs. To minimize the risks, as much information as possible has to be gathered in order to make the best decisions at each stage of the construction project. Different geophysical methods have been important in these investigations. Geoelectrical imaging is a geophysical method that has not been fully recognised as a useful tool.

In this work the applicability of geoelectrical imaging as a tool for construction in rock is investigated. This is done by evaluating its ability to resolve different properties of the rock mass. The work is presented and described in three articles. In each case data from the Hallandsås tunnel, Southern Sweden, is used as reference. The construction of the twin track railroad tunnels was initiated in 1992 and is still ongoing. Acting on the behalf of the Swedish Government, Banverket is the managing organisation of the tunnel project.

In the first article the documentation from the Hallandsås Tunnel is compared with 2D resistivity models. The parameters used for the comparison are lithology, Q, RQD, weathering and water leakage. The study indicates a correlation between change in resistivity and change in rock mass conditions. In general high resistivity corresponds to high quality gneiss whereas low resistivity is rock of poor quality, such as highly weathered rock. The low resistivity may also be caused by several highly fractured water bearing contacts between different rock types. An intermediate resistivity is often amphibolite of good quality or water bearing rock. Even though this is the general trend there are also exceptions. The reasons for this may be found in the difference in resolution of the data acquisition methods. The tunnel documentation is much more detailed than the geoelectrical imaging. The resistivity data is most certainly also influenced by the fact that the subsurface is 3D but assumed to be 2D.

In the second article the large scale geoelectrical imaging is compared with the detailed information from nine core drillings. The records from the drillings include lithology, weathering and hydraulic conductivity. This study show that in some cases there is low resistivity where there is highly weathered rock and high resistivity when the rock is of good quality. But in some of the investigated examples there is no correlation. Again the reason might be difference in scale of the measurements or 3D effects. The properties of the rock mass changes quite rapidly, so it might even be caused by a displacement between resistivity data and borehole data.

The third article describes the first attempt to use geoelectrical imaging in horizontal boreholes as a tool in the production stage. Boreholes drilled in front of the tunnel boring machine (TBM) as probe holes might be used for electrical resistivity tomography (ERT). Here the resolution of different measurement arrays is tested by numerical modelling. The sensitivity towards inaccurate borehole geometry and the influence of water in the boreholes was also investigated. Based on the model study the cross-hole dipole-dipole array, multiple gradient array and a combination of these were found to give the best result and therefore were used for test measurements in 28 metre long horizontal boreholes. Prototypes of semi-rigid borehole cables made it possible to insert multi-electrode cables in an efficient way, allowing fast measurement routines. The results indicate a high resistivity rock mass at the site and it appears as if the gneiss-granite has a slightly higher resistivity than the gneiss. Close to the tunnel wall shotcrete probably causes a low resistivity. The measurements seems to provide valuable information, but further development of the cables and streamlining of measuring routines have to be developed before resistivity tomography can be used routinely in pilot holes during construction in rock. By performing small scale resistivity tomography between boreholes a better image of the geological setting is obtained and the operator will be better prepared for ground conditions in the coming 40 metre ahead. The additional information might contribute to more effective use of the TBM.

The ability of geoelectrical imaging to indicate changes in rock conditions by means of varying resistivity makes it a valuable tool for the pre-investigation as well as the production stage. However it is not always possible to relate a resistivity change to a certain rock condition or property. The decision makers can use the changes in resistivity as a measure for caution when planning for example an underground rock construction. The experience from the Hallandsås tunnel construction can be used to improve the interpretation capability of resistivity image. It should be noted that the focus here will be on the changes in resistivity and not on the absolute numerical values. This is done because it is the change in the properties of the rock mass that is important. Even though the resistivity method is not able to interpret every change in the conditions it still contributes with important information, within the limitations of its resolution. The geoelectrical imaging contribution is that it reduces the level of uncertainties. In combination with other investigations the ambiguity and uncertainty about the subsurface may be further reduced.

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List of papers

Paper 1 Danielsen, B.E. and Dahlin, T. (2007) Comparison of geoelectrical imaging and tunnel documentation. Submitted for publication to *Engineering Geology*.

Paper 2 Danielsen, B.E. and Dahlin, T. (2006) Geophysical and hydraulic properties in rock. *Conference proceeding. 12th European Meeting of Environmental and Engineering Geophysics, 4-6 September 2004, Helsinki, Finland, 4p.*

Paper 3 Danielsen, B.E. and Dahlin, T. (2007) Numerical modelling of resolution and sensitivity of ERT in horizontal boreholes. Submitted for publication to *Journal of Applied Geophysics*.

Related conference papers

Danielsen, B.E., Dahlin, T. and Danielsen, J.E. (2005) Model study of the resolution of resistivity tomography with different electrode arrays. *Conference proceeding. 11th European Meeting of Environmental and Engineering Geophysics, 4-7 September 2005, Palermo, Italy, 4p.*

Danielsen, B.E. and Dahlin, T. (2007) Comparison between geoelectrical imaging and tunnel documentation. *Conference proceeding. 13th European Meeting of Environmental and Engineering Geophysics, 3-5 September 2007, Istanbul, Turkey, 4p.*

1. Introduction

A major problem when constructing tunnels is unforeseen rock conditions e.g. water leakage and changes in rock mechanical properties. The contractor needs as much information about the ground conditions as possible in order to provide a sound financial offer, prepare adequate equipment and to organize a relevant contingency plan. An unforeseen event can delay the project with further costs as a consequence. The International Society for Rock Mechanics (ISRM) has suggested the use of geophysics to obtain more information about the rock properties (Takahashi, 2004; Takahashi et al., 2006). The different geophysical methods exploit the contrast in the physical properties of the subsurface. Here geophysical methods such as geoelectrical imaging and seismic refraction are of interest. The latter has been used extensively as a normal part of the pre-investigation. The former has more recently become a common part of the pre-investigation. Several examples exist of successful geoelectrical imaging use in tunnel projects (Cavinato et al., 2006; Dahlin et al., 1999; Dölzlmüller et al., 2000; Ganerød et al., 2006; Rønning, 2003; Stanfors, 1987; Watzlaw et al., 1995). The geoelectrical imaging is a fast and cost efficient method, but should not stand alone. It should be used together with other geophysical methods and be supplemented with rock drilling and core drilling.

The results of the geophysical measurements usually have to be processed and evaluated by a geophysicist. Only the geophysicist knows the sensitivity and resolution of the methods. For the engineer with no experience with geophysics the geophysical data often seems quite vague. On top of that the geophysicist gives no clear answer in engineering terms, but says "perhaps" and "might" etc. 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 have detailed understanding of what the engineer requires; eg. at what scale is information needed? One task for the engineer and the geophysicist is to find a common language.

It is important to understand the advantages and limitations of the resistivity method for every application. As is the case with other geophysical methods, the resistivity of different geological materials can vary greatly and thus be ambiguous. A material which in geological terms is unambiguous can have a large variation in resistivity. In addition various materials with different mechanical properties can lie in the same resistivity interval and therefore be difficult to distinguish. Thus continued research is needed in order to obtain more knowledge about geoelectrical imaging applied for construction in rock. The scale and resolution of the geoelectrical imaging is very important for the applicability of the method because the measurements have to be acquired in accord with the requirements for detail.

This licentiate thesis deals with the everlasting question of how good the resolution of the geoelectrical imaging is and how to interpret the results in geological terms. The resolution is investigated for 2D profiles and for measurements between two horizontal boreholes. The construction of a tunnel provides an opportunity for a comparison between the geoelectrical imaging and the very detailed tunnel documentation. In this way the value of the resistivity measurements can be evaluated.

For evaluation of geoelectical imaging, a railway tunnel through Hallandsås Horst in southern Sweden (figure 1) has been used. The tunnel project is an example of how problems related to high ingress of water and difficult rock conditions can delay the work. The project was initiated in 1992 and is still ongoing. During these years substantial quantities of different geophysical measurements have been acquired, including geoelectrical imaging. There exists detailed tunnel documentation from the one third of the tunnel that has been completed. In addition a large number of core drillings have been done. These data provides a good base for evaluation of the resolution of the resistivity data.

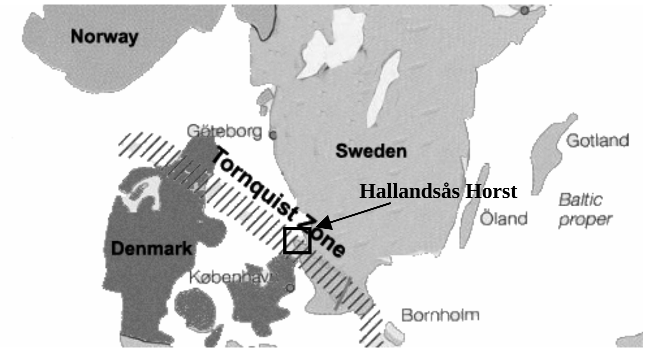

Figure 1. Location of the Hallandsås Horst (www.kristallin.de, 2007)

1.1 Objectives

The main objective of this work has been to investigate the applicability of geoelectrical imaging as a pre-investigation method in tunnel construction. The method has previously been used at the Hallandsås Horst tunnel project. An abundant database provided an opportunity to evaluate the old data. The work includes:

- Comparison between resistivity data and reference data e.g. tunnel documentation and geophysical logs. The tunnel documentation is mainly rock type, weathering, RQD, Q and water leakage.
- A comparison between resistivity data and detailed information from core drillings, e.g. weathering, lithology and hydraulic conductivity.
- Study of the resolution and sensitivity of resistivity measurements between horizontal boreholes.

With a background primarily in geophysics it has been essential for the author through a literature study to learn about engineering geology, the demands for information in engineering geology and rock mechanics and to find information about geoelectrical imaging used previously in construction work.

1.2 Limitations

This licentiate thesis focuses specifically on the use and applicability of geoelectrical imaging. It should be stressed that other types of geophysical methods can also be considered when planning a pre-investigation. Thus it has been essential for the author to also draw attention to other types of geophysical methods even though this is done very briefly. It is important to remember that the best pre-investigation is obtained by using more than one method.

1.3 Outline

This licentiate thesis summarizes the central parts of a two year project at Engineering Geology, Lund University. The work will be published as two papers in peer-reviewed journals and one extended abstract in a peer-reviewed conference proceeding. The two papers have been submitted but not accepted for publication at the time this thesis is to be presented for examination. The two papers are set in context by this summary section of the thesis.

The summary comprises a short introduction with objectives, limitations and the outline of the thesis. This is followed by a description and an example of the demand for detail in a pre-investigation in order to make the optimal decisions at different stages of a rock construction project. A short introduction to different geophysical methods is given in chapter three and here geoelectrical imaging is described in detail. In the first part of chapter four the geological setting of the Hallandsås Horst is described. The different geophysical measurements performed during the tunnel project are mentioned briefly, before each paper is presented. The methodology, a very brief presentation of the results, and a discussion of the results are given for each submitted journal paper. For a detailed presentation of the results, the reader is referred to the three papers in the enclosures. The succession of the papers is such that the investigations done at large scale are followed by those at smaller scale. A short general discussion and the conclusions from the most important results are presented in chapter five. The thesis paves the way for future work and therefore ideas for such work are presented in chapter six.

2. Engineering geological information and prognosis

Insufficient information and unforeseen conditions in the rock mass can lead to delays in any rock construction project and thereby extra costs. By doing thorough pre-investigations production and construction costs are likely to be reduced because the contactor is better prepared due to more precise rock mass problem identification. Since pre-investigation itself involves a cost, the goal of exploration planning is to minimize the total cost of the entire construction work inclusive of the pre-investigations (Einstein et al., 1978).

To be able to investigate and evaluate the relevant aspects of the bedrock, a number of key questions (demands for information on engineering geology issues) 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 aim with the pre-investigations is to prepare an engineering geological prognosis for the construction site which answers the key questions. The geological prognosis is a preliminary prediction that 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 that the 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 as the results of new investigations become available, further assessments are made 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 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 larger and the scale can be a block scale (10-100 metre) or a detailed scale (0-10 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 1.

The engineering geological information and prognosis have different purposes in different project stages. In the feasibility stage the aim is to compile the engineering geological prognosis so that it gives a general picture of the geological setting in the area. An important tool is investigation by site inspection and a study of the pre-existing material e.g. topographical maps, airborne geophysical maps, previously performed geophysical measurements and drillings. If the feasibility studies conclude that the project should continue, the next step is the design and production planning stage. In this stage the main questions are related to general design. This relates to the excavation and support methods that should be used and capacities and costs related to those methods. These considerations lead to an estimation of the cost of the project.

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?

Table 1. Examples of key questions and how they might be described during each stage. Modified after Almén et al. (1994) and Sturk (1998).

The key questions are the same as in each previous stage but the demand for detail is greater. (Almén et al., 1994; Bergman and Carlsson, 1988; Sturk, 1998). The decisions should be made based on data acquired by a surface geophysical mapping campaign that has been tailored to the given geological setting. Boreholes for verification and calibration of weak zones are required and core samples should be collected for determination of the rock mass quality (Danielsen and Dahlin, 2004). 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). Here borehole geophysics can play an important support role alongside other exploration methods such core drillings, hydraulic tests and direct measurements of mechanical properties. It is important is to use the experience obtained at earlier stages of the project, since the larger scale measurements might give valuable information and experience which can also be useful at a smaller scale. In the actual construction stage the geological prognosis can be evaluated against the true conditions which will provide fundamental references and valuable experience to be used in further interpretation and evaluation work. Thus it is essential at all stages to review the geological prognosis and continuously update and modify it when necessary.

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 uncertainty and the unexpected connected with construction in rock, but decisions made based on a thorough pre-investigation will reduce these uncertainty.

3. Applied geophysics in rock tunnel construction

3.1 Introduction

Geophysical methods exploit different physical properties of the sub-surface. Hence 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. For the interpretation of data, background information about the geological setting is required because of the ambiguity and variability in the physical properties of the geological material. The physical property is then interpreted in terms of geological properties and 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 velocity is a useful mechanical property and parameter. However often it is 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 a pre-investigation it is often large scale measurements. Core drillings provide detailed point information and in situ reference data whereas geophysical methods measure large volumes. Thus the resolution is lower than for core drillings but the continuous measurements provide an interpreted physical image of the variation in the physical properties of the rock mass.

The recommended work sequence is to first visit the site in question and to investigate already existing documentation such as geological maps, topographic maps, drilling reports, airborne geophysics etc. A geological model or a preliminary rock mass forecast has to be established before the first measurements are done. Then basic measurements with an appropriate geophysical method are carried out, preferably using a quick method to give an overview of the area at a large scale. The next step is to extend the geophysical survey using methods assumed to be appropriate in sensitive and critical areas, areas where information is scarce and areas where the interpretation is questionable. This could be done by using different types of geophysical methods that measure other rock mass physical properties or by 3D surveying. The development of computer power now makes it possible to process very large 3D data sets. The data from drillings and core sampling, possibly also from geophysical borehole logging can be used for final verification, correlation and interpretation of the surface geophysical data. The final step is to compile a more detailed geological model based on all available information. Steps in the work sequence might need to be repeated several times through the different stages of the project.

3.2 Overview of geophysical investigation methods

In the following a short description is given for some of the geophysical methods used in pre-investigations. Several other geophysical methods could be mentioned as useful in connection with rock tunnel construction or other types of construction in rock. For more information see Parasnis (1997), Reynolds (1997), Rønning (2003), Stanfors et al. (2001), Sturk (1998), Takahashi (2004) and Takahashi et al. (2006).

3.2.1 Seismic methods

The most commonly used geophysical method in tunnel construction is seismic refraction (Cardarelli et al., 2003; Ganerød et al., 2006). In seismic refraction surveying, the p-wave propagation in the sub-surface is measured. The method exploits the condition that different materials have different seismic velocities. Often the method is used with advantage for locating the bedrock surface and evaluating the mechanical properties of soil and rock. The interpretation of the seismic refraction data is seen as a true engineering geological property but as for other geophysical method there are some limitations. Investigations made by Rønning (2003) showed that modelling of seismic refraction can generate larger uncertainties than has been recognised by the users. It is shown that it is often impossible to detect the bottom of a depression in bedrock covered by sediments. This is often interpreted as a weak zone in the bedrock or a weathered layer with a lower velocity at the top of the bedrock. Thus the actual conditions are exaggerated, which might be preferred to the opposite case. But it is important to know the limitations of the method. Another seismic method is seismic reflection (Cavinato et al., 2006). Here the travel times of reflected seismic waves are measured. The travel time is proportional to the distance to the boundary. Thus it provides a direct measure of that distance. The method is most suitable if the boundaries are horizontal or only slightly dipping. Reflection seismic is costly and is not frequently used in tunnel construction. (Reynolds, 1997)

Sonic logging is a seismic method which is applied in boreholes. This is a method where high frequency acoustic waves are used as the source. The p-wave and s-wave velocities in the rock mass are measured. Based on the measured travel times the porosity of the rock mass can be calculated empirically. (Reynolds, 1997)

3.2.2 Electromagnetic methods

The very low frequency method (VLF) is an electromagnetic method that is often used for detecting sub-vertical electrical conductors such as fracture zones. Powerful electromagnetic (EM) waves transmitted primarily from military radio transmitters are used as the source (15-25 kHz). The alternating EM field induces currents in the electrical conductors in the sub-surface. The magnitude of these currents can then be measured by horizontal and vertical coils. This method only gives a result when an anomaly is present. The measurements are very fast but give only qualitative information about the sub-surface. These measurements can be done by airborne surveys. Another EM method using radio transmitters (10-250 kHz) as the source is the Radio Magnetotelluric (RMT). Here the response to both the electrical and the magnetic component of the alternating EM-field are measured. This is a more time consuming method than the VLF but it does give quantitative information. Other EM methods are Ground Penetrating Radar (GPR), Slingram and Transient

Electromagnetic Method (TEM). GPR measures the velocity and propagation of high frequency radar waves (reflections and refractions). These parameters depend on the electrical properties of the ground. Data processing and interpretation requirements are comparable to seismic reflection. This is a fast method but it is not feasible when silt, clay, saltwater or blocky till are present. Slingram consists of two separated coils. An alternating current is transmitted in one coil resulting in a magnetic field that induces a current in an electrical conducting feature or structure. This induced current then in turn induces a magnetic field and this property is measured in the second coil. These properties vary depending on the position and dip of the conducting structure. (Reynolds, 1997; Stanfors et al., 2001). TEM is based on the same principle as Slingram but the instrumentation is different and it is a time domain method where Slingram is a frequency domain method. TEM is also available as a helicopter born version called SkyTEM. This gives a very fast overview of the geological setting (Sørensen and Auken, 2004).

Most electromagnetic methods are very sensitive towards EM-noise and therefore have limited applicability in highly urbanized areas. (Reynolds, 1997; Stanfors et al., 2001)

3.2.3 Magnetic Resonance Sounding

A relatively new method within geophysics is Magnetic Resonance Sounding (MRS). The method allows the non-invasive detection of free water in the subsurface. The processed MRS data can provide the depth to, thickness and water content of aquifers. MRS is based on nuclear magnetic resonance, a phenomenon that can be observed in nuclei possessing a magnetic moment. The water content measured can be defined as the part of the total volume of the subsurface occupied by free water. By calibration using borehole pumping test data, it is possible to estimate the aquifer's hydrodynamic properties. MRS is a large-scale method. Since it provides results averaged over the entire loop area (usually 100 x 100 metre), it may not be sufficiently accurate for detecting small targets (for example a single fracture) (Legchenko et al., 2002; Legchenko and Valla, 2002). Vouillmoz et al. (2005) and Legchenko et al. (2006) have used the method with success where the hydrogeological context is mainly crystalline basement aquifers. A limitation is that the method is very sensitive towards EM-noise. Several research groups are working on making the method more robust towards noise and thereby improve its applicability in urban areas.

3.2.4 Geomagnetic method

The geomagnetic method measures the variation in the magnetic field of the Earth. Thus with magnetic profiling the variation in the content of magnetic minerals in the rock is measured. This is a fast method which can give information about e.g. the Scanian dolerite dykes that are very common in the Hallandsås Horst. A disadvantage is that the method is sensitive towards buried scrap metal and electrical installations (Stanfors et al., 2001). Large areas in Scandinavia have been surveyed by aero-magnetic measurements. This is a useful method in the very early stages of the investigations when looking for suitable building and construction sites.

3.2.5 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). This is a relatively old method which has developed greatly during the last 20 years. The method is relative fast and cost efficient compared to other profiling methods, e.g. seismic refraction. In order to interpret the data certain knowledge of the geological setting of the area is important. Reference data could be obtained from geological maps, previously core drilling and borehole geophysical measurements.

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. Most rock forming minerals are insulators so the resistivity of crystalline rock depends largely on the amount and quality of water present and the degree of weathering of the rock. Therefore rock without water bearing fractures or weathering has a high resistivity whereas clay-weathered rock or rock with water bearing fractures has a considerably lower resistivity. (Binley and Kemna, 2005; Parasnis, 1997).

When electrical resistivity measurements are made, a direct current is transmitted between two electrodes and the potential difference is measured between two other electrodes, see figure 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.

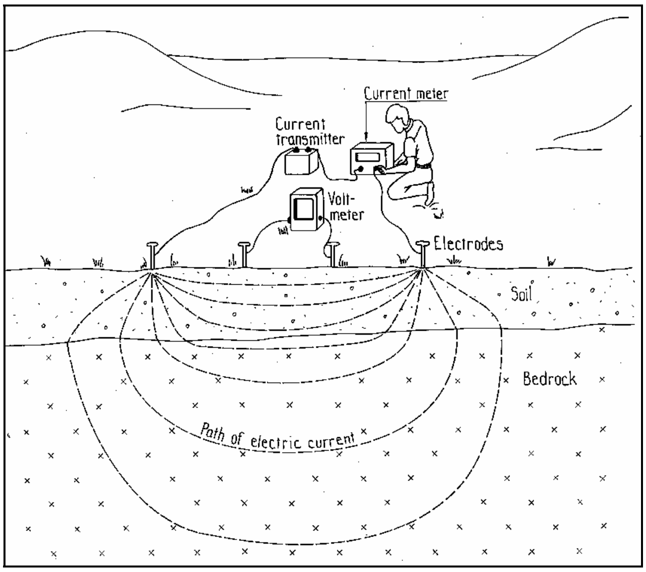

Figure 2. Principles of resistivity surveying. (Robinson and Coruh, 1988)

The result from this type of resistivity measurement is a set of apparent resistivities with corresponding midpoint and pseudo depth that can be presented as a pseudo section. This data can give an estimate of the resistivity distribution in the ground but does not show the true distribution. For an estimate of the actual resistivity distribution it is necessary to perform inverse modelling on the measured data. (Binley and Kemna, 2005). Techniques for acquisition and interpretation of resistivity data have been developing continuously during the last century and now there are advanced methods available for creating two dimensional as well as three dimensional resistivity models of the subsurface.

Generally the depth of investigation of the method increases with increasing electrode distance. As a rule of thumb the penetration depth for a Schlumberger array is L/4 where L is the distance between two outermost active current electrodes. For the Wenner array the penetration depth is around L/6 (Loke, 2004). However this is only the case if the sub-surface is a homogenous earth which is rarely the case. The current will seek to obtain 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. By contrast, a very high resistivity layer close to the surface would force the current down to a less resistive layer. The depth of investigation therefore depends very much on the resistivity of the different layers as well as the largest electrode separation.

Usually the resistivity data are measured as 2D profiles while the subsurface is 3D. To assume a 2D earth might in some cases be problematic. This would create 3D effects in the resistivity data, especially in this particular case where 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.

With the Continuous Vertical Electrical Sounding (CVES) method, it is possible to do so called roll-along, figure 3. Roll-along means that several multi-core electrode cables are rolled out along a straight line and moved successively thus giving continuous profiles. This is a rapid approach for getting information about the spatial distribution of the resistivity in the sub-surface. The roll-along method can also be applied for 3D measurements.

Geoelectrical imaging at small scale can be done between two or more boreholes, the so called Electrical Resistivity Tomography (ERT). In this study ERT resistivity 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 wells 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).

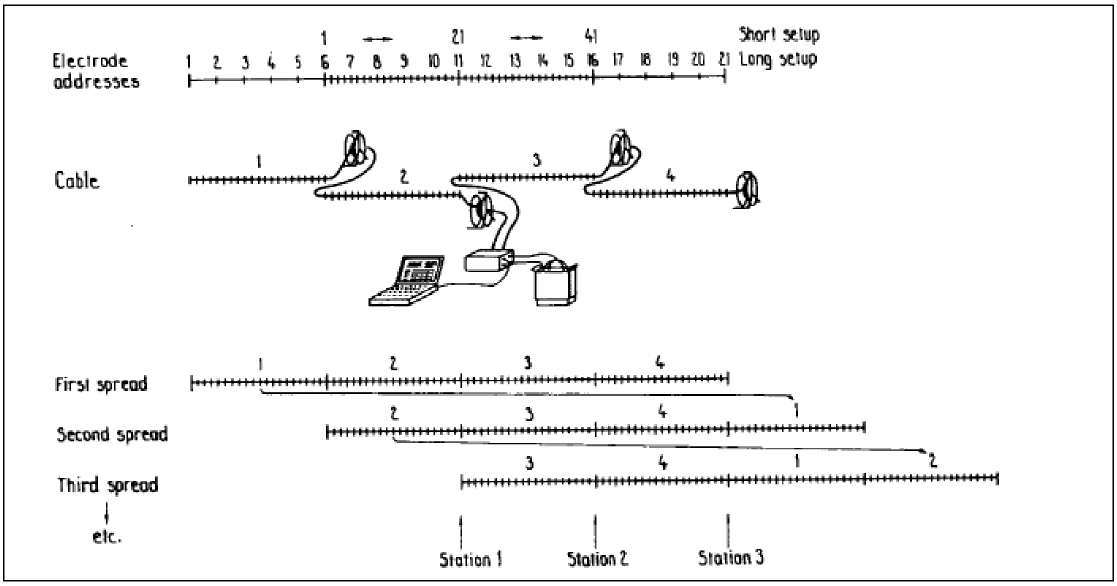

Figure 3. Schematic sketch of the roll-along system. (Dahlin, 1996)

Alternatively, detailed information can be obtained by resistivity logging in a single borehole. Different types of resistivity logs exist, but they all exploit the same properties as large scale geoelectrical imaging giving continuous information at a small scale. In a core drilled borehole the resistivity logs give valuable reference in situ measurements useful for the interpretation of the large scale geoelectrical imaging. Water is necessary in the borehole for the measurements to be performed and they can not be done in cased boreholes. (Parasnis, 1997)

Only a brief introduction to the geoelectrical imaging is given here. For more information see (Binley and Kemna, 2005; Parasnis, 1997; Reynolds, 1997; Takahashi, 2004).

4. Hallandsås Horst – A case history

4.1 Introduction

For this work the Hallandsås Horst is used as an example where different geophysical methods have been used. This particular railway tunnel project was chosen because of the large amount of already existing data and the access to tunnel documentation. In the extensive database there is reference data e.g. core drillings, hydraulic borehole measurements and pumping tests. With a tunnel project the possibility exists that the geophysical data can be evaluated because the answer to the unknown is given when the tunnel is constructed.

4.2 Geological setting

The Hallandsås Horst is the most northern of the Scanian horsts. These horsts are the result of tectonic activity, which has been going on since at least Silurian time. The uplifted blocks have a NW-SE orientation and occur within the so called Tornquist Zone. This tectonic element stretches all the way from the North Sea 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 to 200 metres (mamsl) in the tunnel area. Towards the north the slope is steep whereas it has a gentler slope towards the south. (Dahlin et al., 1999)

Crystalline Precambrian rocks make up most of the bedrock, whereas sedimentary rocks cover minor areas. Gneisses, presumably of intrusive origin, dominate the area. Several generations of amphibolites occur and the oldest are often seen as minor layers or schlieren parallel to the layering in the gneiss. The younger amphibolites have mostly distinct contacts and cut across the structures in the older bedrock. These younger dykes often trend in the NNE-SSW direction. (Wikman and Bergström, 1987)

The dominant fractures are oriented in NW-SE direction parallel to the Tornquist alignment. Another important fracture system has a NNE-SSW direction and is younger than the NW-system. The bedrock is intruded by a set of younger dolerite dykes with their trend parallel to the Scanian horsts. These so-called NW-dolerites are steeply dipping dykes that can have a width up to 50 metre. (Wikman and Bergström, 1987). These dolerite dykes are seen as very distinct positive linear anomalies on the aeromagnetic map (Swedish Geological Survey, 1987). On the aeromagnetic maps it is also possible to see the NNE and NE fracture system because they displace the positive anomalies associated with the dolerite dykes (Wikman and Bergström, 1987).

The substantial deep weathering of the bedrock began during Triassic times and periodically continued during the Cretaceous. This resulted in weathering to mainly kaolin. The weathering is documented in core drillings from the area. In the core drillings it is also clear that there is often secondary mineralization such as chlorite development in the fractures. (Wikman and Bergström, 1987).

The Hallandsås Horst is an important groundwater reservoir. There are two types of reservoirs; one in the soil layer (< 20 metre thick) and the other in the fractured basement. In the bedrock water flows in a large and complex web of fractures. The fractures created by the tectonic activity have made it possible for large amounts of water to be stored within the bedrock. The tunnel level is 100-150 metre below the water table resulting in high water pressures and continuous leakage during tunnel construction with the TBM machine. The groundwater level has been strongly influenced by the construction of the tunnel and, due to environmental restrictions, is monitored very thoroughly. (Banverket, 1996 and www.banverket.se)

4.3 Large scale geophysics with focus on geoelectrical imaging

During the pre-investigation in the feasibility stage and later in the planning stage there have been several large scale geophysical campaigns in connection with the Hallandsås tunnel. The geophysical measurements carried out during different campaigns the last 15 years are:

- 20 km of 2D resistivity imaging (incl. CVES)
- 25 km VLF.
- 6 km Slingram.
- 15 km magnetic surveys.
- TEM soundings.
- 15 km seismic refraction.
- Geophysical well logging.

The only geophysical method addressed in this licentiate thesis is CVES. Some of the remaining methods will be treated in the future work because, as previously indicated, one geophysical method is in most cases not enough for a thorough pre-investigation.

In connection with the Hallandsås tunnel project almost 20 km of 2D resistivity imaging profiles have been measured from 1995 to the present day. The measurements were done using the roll-along technique allowing continuous data acquisition. The resistivity data was measured using a Schlumberger electrode configuration with a cable layout of 800 metre and an electrode spacing of 10 metre. An exception is in the southern part of the profile where the measurements were done using a Wenner electrode configuration with cable layout of 400 metre and an electrode spacing of 5 metre. With the electrode layout and arrays used, the depth of investigation is 120-160 metre for the long Schlumberger layout and 60 metre for the shorter Wenner layouts. For long intervals, the tunnel is located 150 metre below ground surface. The resistivity profiles are more or less perpendicular to the NW-SE structures.

The resistivity surveys have provided information at a large scale about the three major weak zones, i.e. Northern Marginal Zone, Southern Marginal Zone and Mölleback Zone (Dahlin et al., 1999 and Sturk, 1998). These zones consist of large parts with deep clay weathering and fracture zones with large water flows. They are seen as large areas with low resistivity in an otherwise medium to high resistivity bedrock. A profile along the centreline of the tunnel is shown in figure 4. In the figure the Northern Marginal Zone is marked with NMZ, the Mölleback Zone with MBZ and the Southern Marginal Zone with SMZ. The profile does not fully cover the entire Northern Marginal and Southern Marginal Zones.

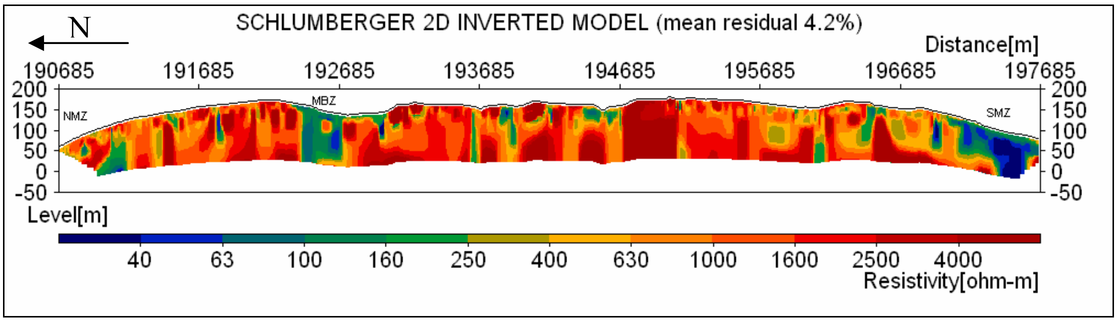

Figure 4. An overview of the variations in resistivity in the sub-surface along the tunnel line at Hallandsås Horst. Northern Marginal Zone is marked with NMZ, Southern Marginal Zone with SMZ and Mölleback Zone with MBZ. The profile is a collocation of data measured by Engineering Geology, Lund University, in 1998 using ABEM Lund Imaging System.

4.4 Comparison between geoelectrical imaging and tunnel documentation

4.4.1 Introduction

The geoelectrical imaging used at Hallandsås Horst show that the method is capable of resolving large zones of rock mass with problematic rock (Dahlin et al., 1999). The interesting question is what else can the method resolve? This is investigated in the paper *Comparison of geoelectrical imaging and tunnel documentation* in paper 1. In this chapter 4.4 references is made to figures in paper 1.

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. The comparison is done merely by visual evaluation of three different sections of the tunnel; in the following referred to as North, South and TBM. The distance between the centrelines of the two tunnels is 25 metre.

4.4.2 Method

Geoelectrical imaging

For the comparison in this work, old CVES data of a good quality has been re-processed using the newest version (ver. 3.55.77) of the software RES2DINV. This program uses a 2D finite element calculation method for inversion with topography included (Loke, 2004).

To make the evaluation of the results easier different resistivity zones are marked with a letter and a number. The data are divided into three categories i.e. low (L), high (H) and intermediate (I) 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.

To compensate for the inadequate penetration depth the full resistivity model is shown as well as sub-models extracted at different levels in the model. By showing the different sub-models a clear image of the resistivity change with depth is obtained. Instead of the commonly used colour resistivity images the images are shown in grey scale. This allows an easier comparison to mapped tunnel parameters such as RQD, Q, weathering, water inflow etc. which are also presented in a similar grey scale, see figure 3 in paper 1 as an example.

Tunnel documentation

The long history of the Hallandsås tunnel has given rise to different types of approaches both for tunnel construction and documentation. Documentation exists from regular drill and blast at the early stages of the tunnel construction. This was done from both ends and in both tunnels more or less concurrently. However the work was stopped because of problems caused by large amounts of ground water leaking into the tunnel. Therefore this type of mapping only exists for 1 km in the north and for 800 metres at the south end of the tunnel.

Use of a TBM (tunnel boring machine) has resulted in another type of documentation. The geologist can only get access for mapping the tunnel face when the TBM is stopped during mounting of the lining. This means the face is only visible every 2.2 metre. So far 1200 metre has been mapped in a single tunnel.

In both types of documentation the lithology is mapped. In several instances there are different types of rock present in one tunnel face. When there is more than 50% gneiss in a face but with different rock types also present, such as amphibolite, it is written as e.g. gneiss (amph).

Documentation from drill and blast

During the period when drill and blast was used as the tunnel excavation method the parameters mapped were rock type, fracture zones, weathering, RQD, Q, water leakage and amount of grout used. The water leakage was measured for every grouting round (fan). The weathering was only divided in two intervals; W1 to W2 and W3 to W5. W1-W2 is fresh rock while W3-W5 is weathered rock.

The relation between the RQD-value and the rock quality is shown in table 2.

RQD	ROCK QUALITY
90-100	Excellent
75-90	Good
50-75	Fair
25-50	Poor
< 25	Very poor

Table 2. The relation between RQD and rock quality. After Fagerström et al. (1983).

Barton et al. (1974) developed the rock mass quality system (Q-system) evaluating the rock quality using six different parameters. The six parameters are: RQD, the number of joint sets (J_n), the roughness of the weakest joints (J_r), the degree of alteration or filling along the weakest joints (J_a), and two parameters which accounts for the rock load (SRF) and water inflow (J_w). In combination these parameters represents the block size, the inter-block shear strength and the active stress. The relation between Q and the rock quality is shown in table 3.

The degree of fracturing is another parameter which was documented. The fracturing is divided into three different categories; normal, high and very high fracturing.

Q	ROCK MASS QUALITY
0.001-0.01	Exceptionally poor
0.01-0.1	Extremely poor
0.1-1	Very poor
1-4	Poor
4-10	Fair
10-40	Good
40-100	Very good
100-400	Extremely good
400-1000	Exceptionally good

Table 3. The relation between the Q-value and rock mass quality. After Barton et al. (1974).

During the tunnel construction the fractures are grouted to prevent water from leaking into the tunnel. The amount of grout is stated with the unit of *kg and/or l*. This is done because there were used two different types of grout; cement and chemical grout. The first has the unit kg and the latter has the unit litres.

Documentation from the TBM

For the use with the TBM, a site specific classification system was developed exclusively for the Hallandsås project. The rock mass is divided into 11 different classes based on RQD, block size and weathering. The classification can be seen in table 4.

ROCK CLASS	RQD	BLOCK SIZE (CM)	WEATHERING
1	75-100	>60	W1
2	50-75	20-60	W1
3	25-50	5-20	W1
4	0-25	0-5	W1
5	25-50	5-20	W2
6	0-25	0-5	W2
7a	25-50	5-20	W3
7	0-25	0-5	W3
8	25-50	5-20	W4
9	0-25	0-5	W4
10	0-25	0-5	W5

Table 4. The rock class defined exclusively for the Hallandsås tunnel. Based on Banverket (2002).

Thus the parameters mapped are rock type, weathering, block size and rock class. Based on the weathering and block size the RQD can be assessed (see table 4). For several probe drilling ahead of the TBM the water flow was measured as open hole measurements. The measured water flow is a mean value for the whole probe length of about 10 to 40 metres. The exact position of the water bearing fractures is therefore not identified in this analysis. In the zones where the water leakage is less than 10 l/min it shall be regarded as if there were no probe drillings or no flow measurements and not that there was no water leakage.

4.4.3 Results

In figure 5 the tunnel documentation from the use of a 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. In this part of the resistivity section three low resistive zones are identified. Only L7 and L9 are visible in both levels. Two high resistive areas and three areas with intermediate resistivity are visible. In table 5 the corresponding properties from the tunnel documentation are summarized. The most likely explanation for the resistivity value observed in each interval is indicated with ***bold and italic*** font. An intermediate amount of water is abbreviated Int.

Resi-stivity	**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***

Table 5. Summation of the dominating properties of the rock in the intervals based on the resistivity data for the TBM drilled part of the tunnel. L is low, H is high and I is intermediate resistivity. The most likely explanation to the resistivity value in the interval is indicated with **bold and italic**.

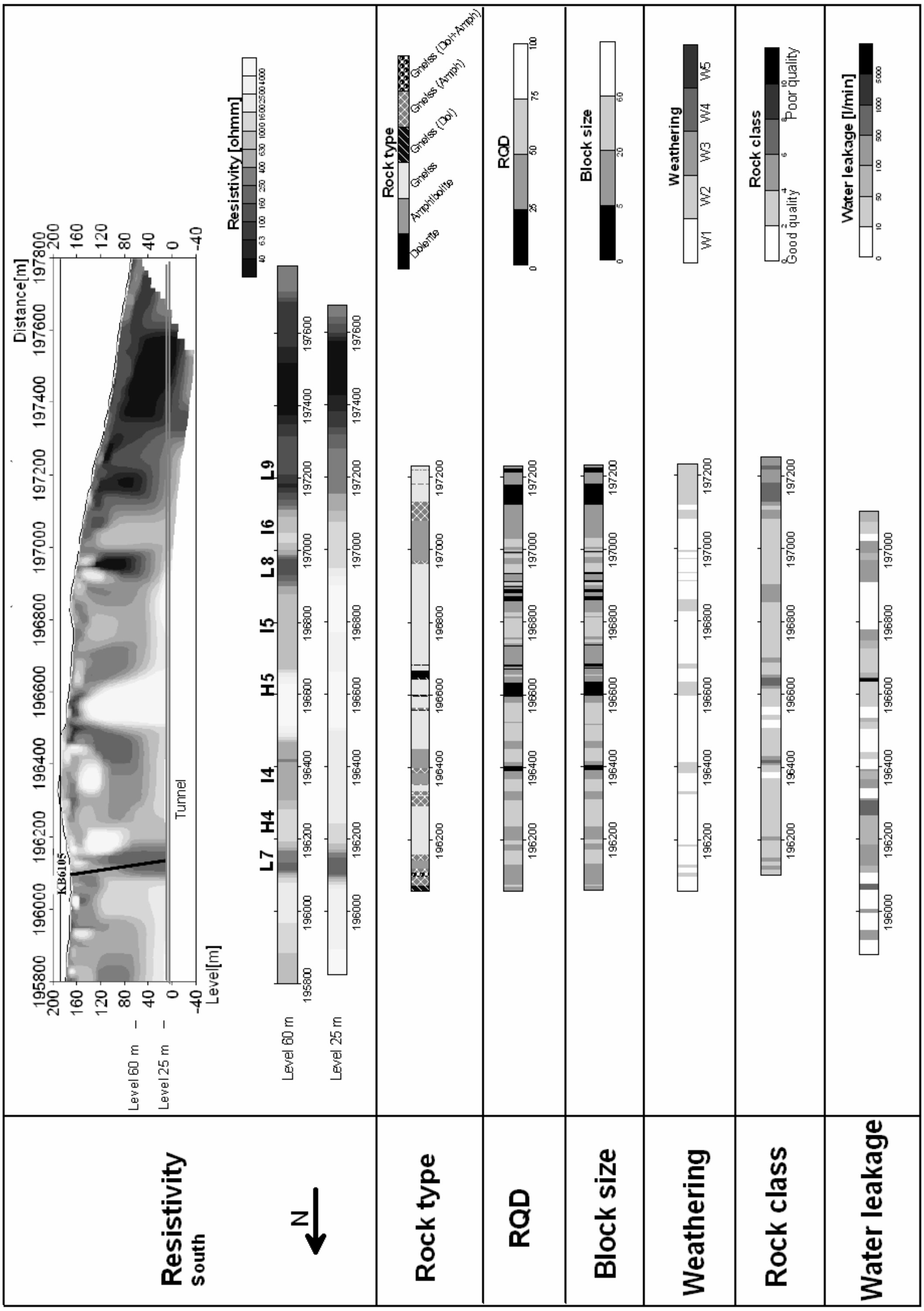

Figure 5. Visualization of resistivity and mapped data from the southern part of the Hallandsås tunnel. The mapping is done in front of the TBM at every operational stop. The mapped data were rock type, RQD, block size, weathering, rock class and water leakage. The resistivity data are shown as full 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.

4.4.4 Discussion

The comparison of resistivity data and tunnel documentations shows that changes in resistivity in most cases is related to some kind of change in rock conditions (see figure 5 and table 5 and figure 3 and 4 in paper 1). 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). A resistivity logging of a drill-hole positioned 30 metre west of the tunnel confirms that at the Hallandsås Horst the amphibolite often has a lower resistivity than good quality gneiss, figure 6. It is seen that the resistivity of three zones with amphibolite and dolerite is as low as 2000 Ωm, whereas the gneiss has a resistivity of 4000 to 10000 Ωm.

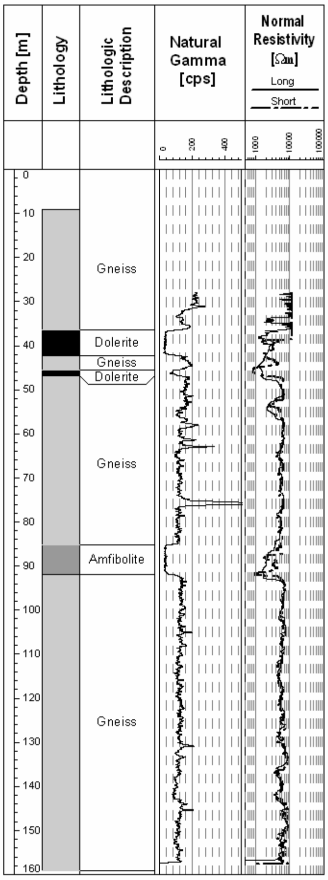

Figure 6. The lithology from the core drilling KB6105 plotted together with the natural gamma and long/short normal resistivity log.

The results in figure 5 and figures 3 and 4 in paper 1 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 a large depth giving poor 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. Thus 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 array, 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 geoelectrical imaging to be applicable in tunnel construction it is important to know that not every detail can be resolved and that there are some ambiguities in the interpretation of the result, as is the case for the Hallandsås Tunnel project. For the Hallandsås Tunnel project it was important to get information about 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. It is probable that more information useful for construction can still be extracted from the remaining part of the 2D profile. 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 but could contribute with important information for the engineering geological prognosis. In combination with other investigations the ambiguity and uncertainty might be further reduced.

4.5 Resistivity and hydraulic properties in rock

4.5.1 Introduction

The extensive database at Hallandsås Tunnel project provides an opportunity to investigate the correlation between resistivity and the hydraulic properties of the rock mass. The result is shown in the extended abstract titled *Geophysical and Hydraulic Properties in Rock* in paper 2. The material was presented as a poster on the Near Surface Geophysics Conference in Helsinki, September 2006. The figures referred to in chapter 4.5 are found in paper 2.

4.5.2 Method

Large scale geoelectrical imaging data were compared to small scale core drillings. Nine different core drillings, drilled close to the CVES profiles, were investigated. Two of the nine core drillings are shown in figure 2 and 3 in paper 2. The CVES data correspond to the profile in figure 4 in this summary section. The records from the drillings include lithology, weathering and hydraulic conductivity. Lithology and weathering are based on visual interpretation made by the site geologist. The weathering is given with values from 1 to 5, where 1 is fresh rock and 5 is highly weathered rock. The hydraulic conductivity is measured in intervals of 5 to 10 metres. The position and length of the intervals are based on the geology and the possibilities for placing the packers used in the measurements. From the inverted CVES profiles separate vertical sub-models are extracted from positions close to the core drillings, see figure 2 and 3 in paper 2.

It is anticipated that clay weathered rock has a low resistivity while fresh rock has a high resistivity. Occurrence of groundwater is expected to give an otherwise fresh rock a lower resistivity.

4.5.3 Results and discussion

The results from the comparison between large scale resistivity data and the detailed data from the core drilling are complex to interpret. This study show that in some cases there is low resistivity where there is highly weathered rock and high resistivity where the rock is of good quality (figure 2 and 3 in paper 2). But in some of the investigated examples there is no correlation. Thus there is no obvious connection between the information from the core drillings and the resistivity data. The problem might be that the resistivity measurements are too low resolution when compared to the very detailed observations from the core samples. It should also be taken into consideration that there are likely to be 3D effects in the resistivity measurements. Another problem could be that the core drilling and resistivity sounding are probably made at positions close to each other but not in the exact same place. Since the geology is complex with many fractures and weathered rock zones, small differences in position could explain the large differences between the resistivity and core samples.

This very rough comparison between resistivity and information from core drillings mainly showed that it is necessary to do a more thorough and systematic investigation in order to conclude anything. Here geophysical logging could prove to be useful giving in situ information. These in situ measurements could then be compared with the core drillings as in figure 6. The investigation also stresses that the large scale resistivity data can not directly be superimposed and reduced to a small scale.

4.6 Electrical resistivity tomography in horizontal boreholes

4.6.1 Introduction

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 section of the thesis attempts to identify a suitable methodology for an effective measuring routine for this type of geophysical measurements 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 3. The figures referred to in this chapter 4.6 can be seen in paper 3. ERT is an abbreviation for Electrical Resistivity Tomography.

4.6.2 Method

Prior to any measurements numerical modelling was done in order to evaluate the resolution of different electrode arrays. Four different arrays were tested; dipole-pole (AM-N), cross-hole dipole-dipole (AM-BN), cross-hole pole-tripole (A-BMN) and multiple gradient array. In the abbreviation of the array names A and B mark the current electrodes and M and N mark the potential electrodes. The hyphen shows that there is a left and a right borehole. In addition to the four single arrays the resolution of a combination of AM-BN and multiple gradient was assessed. The 2D sensitivity patterns for various arrangements of the cross-hole dipole-dipole and multiple gradient array were also examined. 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 array 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.

4.6.3 Results and discussion

Numerical modelling

The numerical modelling was divided into different parts. In the first part the influence of the water in the boreholes is investigated (figure 1 in paper 3). Even though the water in the model has been assigned a lower resistivity than in the actual case, since the diameter of the borehole is very small compared to the electrode separation, only a small influence is seen and therefore water filling the boreholes can be ignored in the further investigations.

Generally the numerical modelling showed that the best resolved area is close to the electrodes for all the arrays, see figure 7. The best resolution of the resistivity and position of the geological structures is obtained with the multiple gradient array and a combination of AM-BN and multiple gradient arrays. In both cases the matrix and the low resistivity close to the boreholes are well resolved. The AM-BN is good at resolving the resistivity of the matrix between the boreholes but there are some artefacts. The study of the 2D sensitivity patterns for the AM-BN and gradient array more or less supports these observations (figure 3 paper 3).

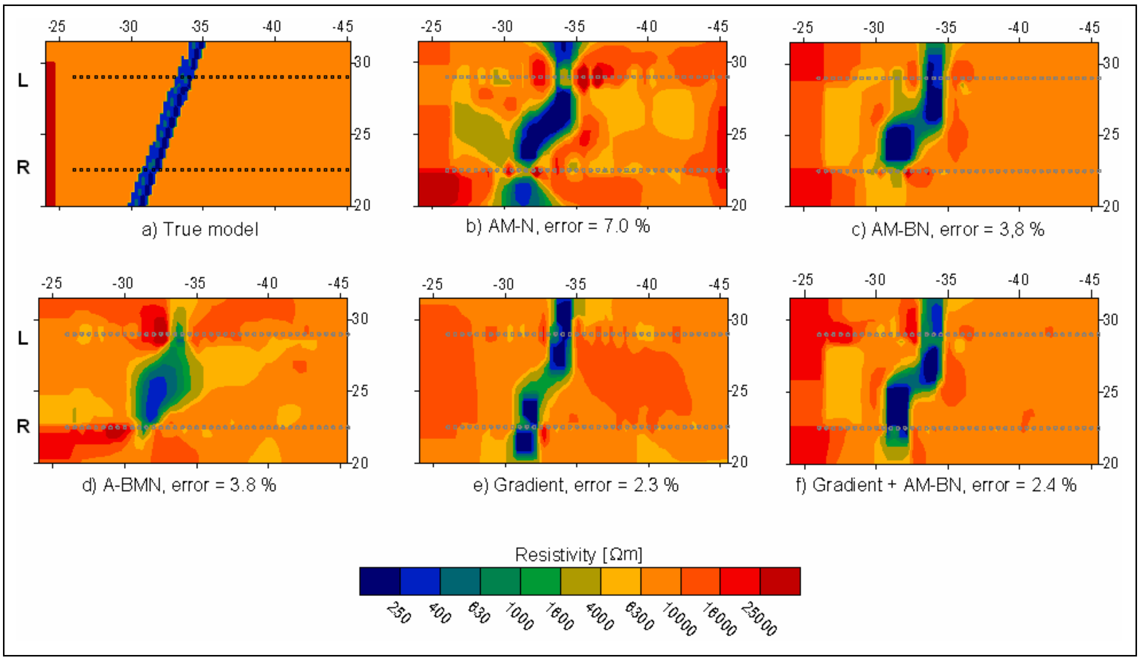

Figure 7. a) The true model made in RES2DMOD. Model of inclined fracture zone with a resistivity of 300 Ωm in a 8000 Ωm matrix. The model is seen from above with a left (L) and right (R) borehole. b) dipole-pole (AM-N), c) cross-hole dipole-dipole (AM-BN), d) pole-tripole (A-BMN), e) gradient, f) combination of gradient and cross-hole dipole-dipole. Black and grey dots are the electrodes in the boreholes. The distance is in metre.

The gradient array has a smaller sensitivity between the boreholes than the AM-BN. Results from other modelling carried out, but not shown here, emphasises that the resolution between and outside the boreholes is limited for the gradient array. On the other hand the resolution of the area close to the electrodes is very reliable. By combining the two arrays the structures are slightly better resolved. The AM-N is good at resolving the low resistivity zone, but is poor at resolving the matrix where there are quite a number of artefacts. The A-BMN configuration does not have the same resolution of this geological setting as AM-N, AM-BN and multiple gradient configurations.

The study of the sensitivity of the arrays towards the borehole geometry showed that the smallest difference is obtained using the AM-BN or A-BMN (figure 8). The sensitivity towards geometry errors was visualized by using the relative difference instead of the actual inversion model. This was done because the difference is difficult to distinguish when comparing the inversion models. This demonstrates that the geometry problem produces only small changes in the resistivity values. In most cases the difference is largest in those areas close to the low resistivity zone. A limitation in the study is that only one of the boreholes deviates because it is not possible to model two inclined boreholes in RES2DMOD. In reality it is probable that both boreholes deviate to some extent. In such a case there will be a larger difference, but it is supposed that for the array types discussed, this will still only produce a minor difference.

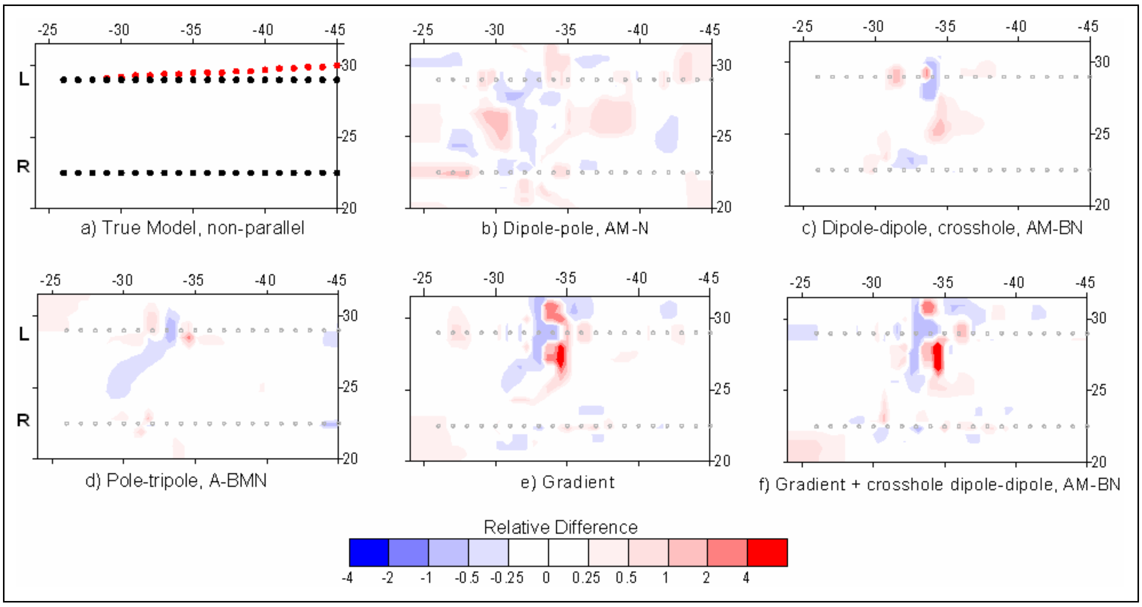

Figure 8. The relative difference between models measured with parallel and non-parallel boreholes. a) The red dots are the position of the electrodes while data are generated. The black dots are the position of the electrodes while the data are inverted. b) dipole-pole (AM-N), c) cross-hole dipole-dipole (AM-BN), d) pole-tripole (A-BMN), e) gradient, f) combination of gradient and cross-hole dipole-dipole (AM-BN). The grey dots are the electrodes in the boreholes assumed during inversion. The distance is in metre.

Based on the results from the numerical modelling the AM-BN and the gradient arrays were used in the field test measurements in the horizontal boreholes. It is then possible to combine the different datasets before inversion. Even though Goes and Meeks (2004) showed good results for the A-BMN it did not resolve the geology particularly well for the models studied. Thus the A-BMN was not used for the actual measurements in the boreholes. The AM-N array did not prove to be good at resolving the matrix, and was also sensitive towards unknown borehole geometry. In addition the array is more complicated to use in the field, because of the need for a remote electrode.

Electrical Resistivity Tomography in horizontal boreholes

Working in horizontal boreholes raises several practical questions, i.e. how to get the electrode cables into the boreholes. To solve this problem a prototype of a semi-rigid cable has been developed, using a thin fibreglass rod to create rigidity. A further requirement is that the cables can be wound up so that they can be handled in confined spaces. To avoid getting stuck in the boreholes the cables have to be streamlined. The need to have streamlined cables conflicts with the requirement for adequate electrode contact with the borehole walls. To overcome this both test holes were drilled at a couple of degrees inclination downwards in order to keep water in the holes thus creating better electrode contact. The downwards inclination also makes it possible to pour water into the hole if no water is present naturally.

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 core drilling drilled perpendicular to the test holes was used. The core drilling crosses the horizontal test holes approximately at electrode number 26 which is three metres from the tunnel wall, see figure 6 paper 3.

By comparing the measured result (figure 9) with the information from the core drilling it is clear that no fractures are resolved by the resistivity method. The fractures are presumably present but are not visible in the measured resistivity results. 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.

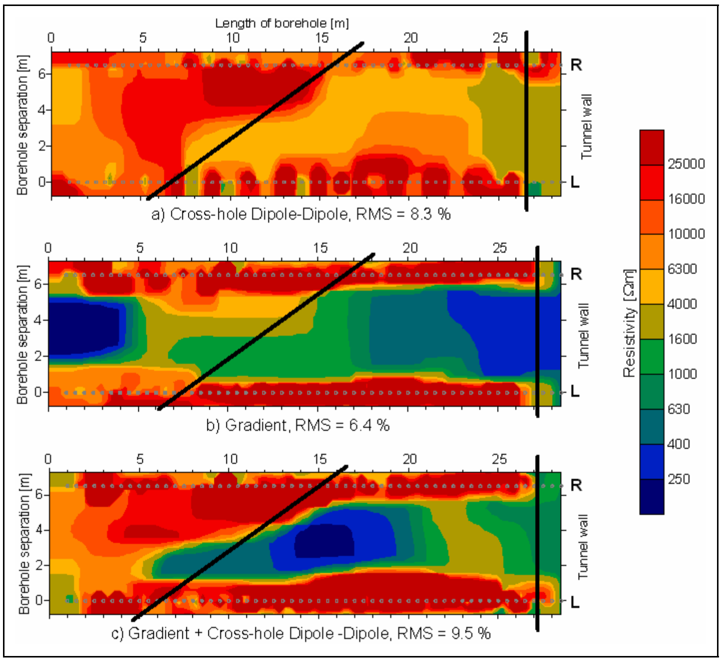

*Figure 9. The inversion results from the resistivity measurements using different electrode arrays. The boreholes are seen from above with the tunnel wall to the right in the figure. The left borehole, seen from the tunnel, is marked with **L** and the right borehole with **R**. The heavy black lines 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 could explain 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 metal 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.

The model residual for the first inverted models based on the measurements proved to be rather high (> 10%). Even though the investigated site was considered a low noise level area, approximately 5 to 10% of the data had to be removed in order to obtain an acceptable model residual for a repeated inversion. For some electrodes, contact was not optimal. Furthermore, rock bolts nearby would create serious disturbances. In addition the surrounding rock is highly resistive, limiting the transmitted current. To obtain better measurements the array measurement protocols and possibly the data acquisition software and hardware needs fine tuning.

5. General discussion and conclusions

In this thesis the focus has been on the applicability of geoelectrical imaging as a tool for forecasting geological and rock mass conditions in tunnel construction. To establish the best foundation for making good prognoses it is generally advisable to use different geophysical investigation methods that measure different physical properties of the rock mass. Traditionally seismic refraction is the common method used in pre-investigations for tunnel construction. Geoelectrical imaging has previously proved to be useful (Cavinato et al., 2006; Dahlin et al., 1999; Dölzlmüller et al., 2000; Ganerød et al., 2006; Rønning, 2003; Stanfors, 1987; Watzlaw et al., 1995) but is still not fully appreciated as a valuable tool in the pre-investigations. There are probably several reasons for this. One issue may be the limited penetration depth. For tunnels deeper than 100 metre the cable layouts have to be long to reach the tunnel level, and this makes the field logistics more complicated. Another issue might be the presentation of the data. For those who are not used to interpreting the colourful resistivity images, there is a danger of misinterpretation. The most likely explanation is probably tradition. The seismic refraction is a well proven, and often quite feasible, method and therefore it is preferred for the pre-investigations in tunnel construction. Geoelectrical imaging has not yet attained the same status in this field.

It is important to question what one may expect from geoelectrical imaging used in a bedrock environment with variations in the rock mechanical properties. To answer such a question is complex, because the resolution of the method will differ from site to site. A basic requirement for all cases is that there must be a contrast in the electrical properties of the different materials, otherwise the method is unfeasible. Reference data from prior investigations and a fundamental knowledge about the geological setting are crucial. Here the engineer's key questions are important in order to identify plausible materials and problems.

An extensive database and the tunnel documentation makes the Hallandsås Tunnel project an evident opportunity to test and evaluate the resolution and applicability of geoelectrical imaging. It has previously been shown that three large zones with problematic rock conditions could be identified using geoelectrical imaging (Dahlin et al., 1999; Sturk, 1998). The three zones are marked on the 2D profile in figure 4. In this case the contrast in resistivity between rock of good quality and rock of poor quality is sufficiently large to be resolved beyond any doubt. It is probable that more information can be extracted from the remaining part of the 2D profile and used in the construction work.

In this study, the comparison between resistivity data and tunnel documentation demonstrates that the resistivity method is a valuable tool in pre-investigations. It shows that a change in resistivity in most cases corresponds to some kind of change in the rock conditions. In a geological environment such as the Hallandsås Horst with the tunnel drilled 150 metre beneath the surface, the scale of resolution of the resistivity method is tens of metres. Thus in this case the method can not resolve bodies or structures smaller than this.

For those sections investigated with geoelectrical measurements at the Hallandsås Horst, the resistivity can be divided into three categories, i.e. high, low and intermediate resistivity. These three categories can in many cases be correlated to different rock mass conditions. The high resistivity is likely to correspond with gneiss with a good quality. Intermediate resistivity is likely to be amphibolite with a relatively good rock quality. These correlations are also supported by in-situ measurements in the tunnel where the only rock with very high resistivity is gneiss. A resistivity log showed that amphibolite has lower resistivity than gneiss. In some cases the intermediate resistivity may also be water bearing rock. Low resistivity is likely to indicate rock of a poor quality that is deeply weathered or has many water filled contacts and fissures between different lithologies.

The different studies show that the resistivity method does not always correlate with the reference data, e.g. tunnel documentation, core data and flow measurements. This lack of correlation may have several different causes and be quite complex. One explanation is the difference in scale between the compared data sets; the resistivity data is measuring on a much larger scale than the tunnel documentation. Another reason may be 3D effects in the 2D resistivity profiles. In addition a certain amount of bias can occur in the mapping of the tunnel parameters due to the subjective opinion of the geologist.

Geoelectrical imaging does not give “the whole truth” but this is no different from any other geophysical method or from any conventional techniques. All methods have their advantages and limitations, which are crucial to understand. The importance of using complementary methods in order to reduce the uncertainties must be stressed.

The numerical modelling of the resolution of the different electrode arrays used in horizontal boreholes gave promising results. Further investigations still need to be done, but 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. Some further adjustment of the data acquisition hardware and software are required. It is also important to improve the data processing software so the quality of the data can be evaluated and edited before inversion. Other improvements are still required before resistivity measurements in probe holes can be implemented at a production stage in tunnel construction. But the study has nevertheless showed that there is good potential in the approach.

The ability of geoelectrical imaging to indicate changes in rock conditions by means of varying resistivity makes it a valuable tool in the pre-investigation as well as the production stage. However it is not always possible to relate these changes to a specific rock condition or property. The decision makers can use the changes in resistivity as an indication of the need for caution when planning for example an underground rock construction. The experience from the Hallandsås tunnel construction can be used to improve the interpretation capability of the resistivity image. Previously there has been a focus on low resistivity zones in order to identify poor rock conditions. The comparison has shown that the high resistivity zones tend to indicate good quality rock. This is as important for the contractor to know as the location of poor quality rock. Even though the resistivity method is not able to interpret every change in the conditions it still contributes with important information within the limitations of its resolution. Geoelectrical imaging contributes to reduce the number of uncertainties. In combination with other investigations the ambiguity and uncertainty might be further reduced.

At present in the Hallandsås Tunnel project, probe holes are drilled up to 40 metre ahead of the TBM in order investigate the rock conditions and the amount of water. These drilling campaigns could be planed more efficiently and cost effectively using information from geoelectrical imaging. If these probe holes could also be used for small scale measurements, much valuable information could be acquired. At the Hallandsås tunnel, where the geology is highly variable, representative information might not be obtained by drilling two or three probe holes because the area between the probes might be quite different. By performing small scale resistivity tomography between the boreholes a better image of the geological setting would be obtained and the operator would be better prepared the up-coming 40 metre ahead. The additional information might contribute to a more effective TBM advance.

6. Future work

The promising results obtained in this study suggest the need for further investigations. In the next part of the project a method should be developed and tested for a joint interpretation of geoelectrical data and different types of data e.g. geophysical data, core drillings, borehole logging and pump tests. Based on this a prognosis model for water leakage and parameters important for stability assessment may be developed. The prognoses should be adjusted throughout for different stages and scales in a construction project. A task is to develop a method for analysis and presentation of confidence and uncertainties in geophysical models, e.g. through equivalence analysis and depth-of-investigation analysis. The geophysical models and its uncertainty should be presented in the prognoses as reference for the engineer. A statistical analysis of the different data, e.g. analysis of the variation in the rock mass compared to variation and resolution in geophysical models, is a natural part of this work. Most likely two tunnel projects will be used as test examples, where the Hallandsås Tunnel project is one of them.

During the first two years of the project, additional measurement with CVES, magnetics, RMT and CSTMT (Controlled Source Tensor Magnetotelluric) were performed at the Hallandsås Horst but not evaluated and presented. The CVES was used for measuring resistivity and induced polarisation (IP) data using the pole-dipole array in order to obtain a larger penetration depth but also to exploit the fact that a non-symmetrical array is better at resolving dipping structures. The measuring campaign was concentrated at the same profiles making it possible to make a combined interpretation based on the different data to obtain a better result. The data will be used for the development of a prognosis model in the future work. Additionally there is an opportunity for complementing measurements such as different geophysical logs in order to get small scale information. There will also be done additional measurements at the surface if it is found necessary.

An overall objective is to develop a common language to make it easier for a non-geophysicist to understand and interpret the results in order to increase the degree of usefulness of geophysical methods.

The further development of Electrical Resistivity Tomography in horizontal boreholes does not lie within the scope of the future work of this project.

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Paper 1 Danielsen, B.E. and Dahlin, T. (2007)

Comparison of geoelectrical imaging and tunnel documentation.

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Comparison of geoelectrical imaging and tunnel documentation

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Abstract
For construction in rock a thorough pre-investigation is important in order to avoid unforeseen conditions which may delay the work. Different geophysical methods have proved valuable tools in such pre-investigations. In this work the electrical imaging is evaluated with regards to the method's applicability. The evaluation is done by comparing the electrical imaging with tunnel documentation from a tunnel in Southern Sweden. The parameters used for the comparison are lithology, Q, RQD, weathering and water leakage. The result was that a change in electrical resistivity image often coincides with a change in rock conditions. A high resistivity corresponds well 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. Geoelectrical imaging proved to give valuable information for a large scale pre-investigation of rock conditions. As is the case for other geophysical methods it is clear that for the interpretation of data a priori information about the geological setting is necessary.

Keywords: Comparison, tunnel documentation, geoelectrical imaging, lithology, Q, RQD, weathering, water leakage, resistivity.

Introduction
Construction in rock with unforeseen quality or conditions can result in delays which in the end are expensive. Therefore a thorough pre-investigation has to be carried out in order to establish the best geological model possible. Different geophysical methods have proven to be valuable tools in the early stages of the pre-investigations (Cavinato et al., 2006; Dahlin et al., 1999; Ganerød et al., 2006; Rønning, 2003). An engineering geological prognosis is based on the pre-investigation report and the purpose is to form the base for design and estimation of e.g. reinforcements and grouting. (Swindell and Rosengren, 2007)

The compilation of the prognosis is bound to involve uncertainties. A traditional method for obtaining information about the rock properties is core drilling. Core drillings are considered giving very exact information about the geological properties. However they have the limitation that they only give point information. An important issue is also that, to some degree, they are interpreted, preferably by a geologist. When considering the documentation from the core drillings the human factor has to be acknowledged; the geologist can misinterpret the rock quality when it is based on core drillings. For example the scale and orientation of a sample can give a wrong impression and in addition two different persons do evaluate the classification systems differently. For compiling a useable prognosis the geologist/engineering geologist has to be certain which parameters are important for the construction work. In some cases time is used for gathering information which is not necessary for the actual work, while other information is neglected. In order to make the classification easier the pre-investigation has to be planned and carried out so that it gives suitable information and is decision oriented. If the desired result of the investigations is unclear it might cause unnecessary time consuming and expensive investigations. (Stanfors et al., 2001). It is advisable to use multiple methods in any rock engineering investigation in order to reduce the uncertainty.

The International Society for Rock Mechanics (ISRM) has suggested the use of geophysics to obtain more information about the rock properties (Takahashi, 2004; Takahashi et al., 2006). The different geophysical methods exploit the contrast in the physical properties of the subsurface. Before deciding on a certain method, knowledge about the expected contrasts in physical properties has to be obtained from e.g. previous measurements, geological maps and geological history. Evaluations of the different geophysical methods used in connection to construction of a number of tunnels (Cavinato et al., 2006; Dahlin et al., 1999; Ganerød et al., 2006; Rønning, 2003) showed that geoelectrical imaging gave good results. In addition it was a time and cost effective method compared to other geophysical methods.

The recommended work sequence for pre-investigations is to first investigate already existing documentation such as geological maps, topographical maps, drilling reports, airborne geophysics etc. An impression of the geological setting has to be established before the first measurements are done. Then basic measurements with an appropriate geophysical method are carried out, preferably using a quick method to give a first overview over the area. The next step is to extend the geophysical survey using methods assumed to be appropriate in sensitive and critical areas and areas where the interpretation is questionable. Afterwards drillings can be made guided by the results of the geophysical surveys. The final step is to compile a more detailed model based on all available information.

The aim of this paper is to show what the resistivity method is able to resolve by comparing the results from geoelectrical imaging and tunnel documentation. Ongoing work in a tunnel provides the opportunity to compare actual rock type, Q, RQD, weathering, water leakage and amount of grout used with the measured resistivity profiles. The resistivity values are extracted at different levels from the inverted data. This allows a good evaluation of how the resistivity model varies with depth.

In this study the construction of twin track tunnels through the Hallandsås Horst in southern Sweden (Figure 1) is used. The work was initiated in 1992 and is ongoing. Problems related to high ingress of water and difficult rock conditions have resulted in major delays to the work. The tunnel has 100 to 150 metres overburden resulting in a high water pressure, which in combination with strict requirements on limiting the water ingress, even during the construction period, have caused problems for the project. Despite considerable pre-grouting operations a substantial amount of water has been leaking into the tunnels with a critical lowering of the groundwater table as a consequence. (Banverket, 2005). The use of an advanced shielded tunnel boring machine has mitigated these problems and the tunnel is now being built with a water tight segmental lining.

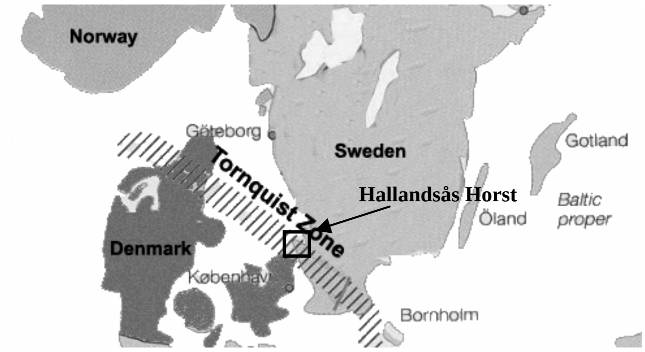

Figure 1. Location of the Hallandsås Horst (Kristallin.de, 2007)

Geological setting

The Hallandsås Horst is the most northern of the Scanian horsts. These are the result of a tectonic activity, which has been going on since Silurian time. The uplifted blocks have a NW-SE orientation and occur in the so called 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 to 200 metre in the tunnel area. Towards the north the slope is steep whereas it has a gentler slope towards the south. (Dahlin et al., 1999)

Crystalline Precambrian rocks make up most of the bedrock, whereas sedimentary rocks cover minor areas. Gneisses of presumably intrusive origin dominate the area. Amphibolites of several generations occur and the oldest often are seen as minor layers or schlieren parallel to the layering in the gneiss. The younger amphibolites have mostly distinct contacts and cut across the structures of the older bedrock. These younger dykes often run in the NNE-SSW direction. (Wikman and Bergström, 1987)

The dominant fractures are oriented in NW-SE direction corresponding to the Tornquist Line. Another important fracture system has a NNE-SSW direction and is younger than the NW-system. The bedrock is intruded by a set of younger dolerite dykes with their trend parallel to the Scanian horsts. These so-called NW-dolerites are steeply dippingg dykes that can have a width up to 50 metre. (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 the NNE and NE fracture system because they disconnect the positive anomalies associated with the dolerite dykes (Wikman and Bergström, 1987).

The substantial deep weathering of the bedrock began during Triassic time and periodically continued during the Cretaceous. This resulted in a weathering to mainly kaolinite. The weathering is documented in core drillings from the area. In the core drillings it is also clear that there is often chlorite in the fractures. (Wikman and Bergström, 1987).

The Hallandsås Horst is an important groundwater reservoir. There are two types of reservoirs; one in the soil layer (< 20 metre thick) and one in the bedrock. In the bedrock the water flows in a large and complex web of fractures. The tectonic activity has made it possible for the large amounts of water to be contained within the bedrock. At tunnel level there is a water column of 100-150 metre which results in high water pressure. The groundwater level is strongly influenced by the construction of the tunnel and is therefore monitored very thoroughly. (Banverket, 1996 and www.banverket.se)

Geoelectrical imaging

The resistivity method is used for measuring the spatial variation of 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. Most rock forming minerals are insulators so the resistivity of crystalline rock depends basically on the amount of water present and the degree of weathering of the rock. Therefore rock without water bearing fractures or weathering has a high resistivity whereas clay-weathered rock or rock with water bearing fractures has a considerably lower resistivity. (Binley and Kemna, 2005; Palacky, 1987; Parasnis, 1997)

For measuring the resistivity a direct or low-frequency alternating current is injected into the ground using two electrodes (e.g. stainless steel), and thus an electrical circuit is created. Measurement of the potential difference (voltage) between two other electrodes permits the determination of the apparent resistivity, see figure 2. To determine the variation of resistivity with depth, a vertical electrical sounding (VES) is used. Measurements with four electrodes are made with gradually larger spacing but retaining the same midpoint. By using the so called continuous vertical electrical sounding (CVES) the data can be acquired rapidly. This multi-electrode system is computer controlled and measures at different locations along the profile simultaneously. (Binley and Kemna, 2005; Palacky, 1987)
In this paper only a brief introduction to the geoelectrical imaging is given. For more information see Binley and Kemna (2005), Reynolds (1997) and Takahashi (2004).

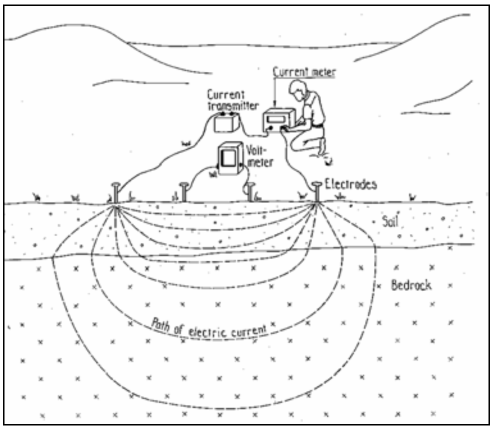

Figure 2. Principle of resistivity surveying. From Robinson and Coruh (1988)

Generally the depth of investigation of the method increases with increasing electrode distance. As a rule of thumb the penetration depth for a Schlumberger array is L/4 where L is the distance between two outermost active electrodes. For the Wenner array the penetration depth is around L/6. (Loke, 2004) However, this is only the case if the sub-surface is a homogenous earth which is rarely the case. The current will seek to obtain 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. By contrast, a very high resistive layer close to the surface would force the current down to a less resistive lower layer. The depth of investigation therefore depends very much on the resistivity of the different layers as well as the largest electrode separation.

The resistivity data were measured as 2D profiles while the subsurface is 3D. To assume a 2D earth might in some cases be problematic. This would create 3D effects in the resistivity data; especially in this particular case where the geology changes relatively fast. In order to obtain the best 2D situation the profiles should always be perpendicular to the geological structures. The Hallandsås Horst profiles are more or less perpendicular to the NW-SE structures.

Geoelectrical imaging at the Hallandsås Horst

In connection with the tunnel project almost 20 km of CVES profiles have been measured between 1995 and today using different versions of the ABEM Lund Imaging system. During this time the measuring instruments, computers and software have developed and become faster and with better resolution. The measurements were done using the roll-along technique allowing a continuous data acquisition. For more information about the technique used at the Hallandsås tunnel, the reader is referred to Dahlin et al. (1999).

For comparison in this paper, old data of good quality has been re-processed using the newest version (ver. 3.55.77) of the software RES2DINV. This program uses a 2D finite element calculation method (Loke, 2004a). The resistivity data was measured using a Schlumberger electrode configuration with a cable layout of 800 metre and an electrode spacing of 10 metre. An exception is in the southern part of the profile where the measurements were done using a Wenner electrode configuration with cable layout of 400 metre and an electrode spacing of 5 metre. With the electrode layout and arrays used, the depth of investigation is 120-160 metre for the long Schlumberger layout and 60 metre for the short Wenner layouts. For long intervals, the tunnel is located 150 metre below ground surface. To compensate for the inadequate penetration depth the full resistivity model is shown as well as sub-models extracted at different levels from the model. By showing the different sub-models a clear image of the resistivity change with depth is obtained. Instead of the commonly used colourful resistivity images, the images here are shown in grey scale. This allows an easier comparison (Figure 3) to mapped tunnel parameters such as RQD, Q, weathering, water inflow etc. which are also presented in a similar grey scale.

Tunnel documentation

The long history of the Hallandsås tunnel has given rise to different types of approaches both for tunnel construction and documentation. Documentation exists from regular drill and blast at the early stages of the tunnel construction. This was done from both ends and in both tunnels more or less concurrently. However the work was stopped because of problems caused by large amounts of ground water leaking into the tunnel. Therefore this type of mapping only exists for 1 km in the north and for 800 metres at the south end of the tunnel.

Use of a TBM (tunnel boring machine) has resulted in another type of documentation. The geologist can only get access for mapping the tunnel face when the TBM is stopped during mounting of the lining. This means the face is only visible every 2.2 metre. So far 1200 metre has been mapped in a single tunnel.

In both types of documentation the lithology is mapped. In several instances there are different types of rock present in one tunnel face. When there is more than 50% gneiss in a face but with different rock types also present, such as amphibolite, it is written as e.g. gneiss (amph).

Documentation from drill and blast

During the period when drill and blast was done the parameters mapped were rock type, fracture zones, weathering, RQD, Q, water leakage and amount of grout used. The water leakage was measured for every grouting round (fan). The weathering was only divided in two intervals; W1 to W2 and W3 to W5. W1-W2 is fresh rock while W3-W5 is weathered rock.

The relation between the RQD-value and the rock quality is as seen in table 1.

RQD	Rock quality
90-100	Excellent
75-90	Good
50-75	Fair
25-50	Poor
< 25	Very poor

Table 1. The relation between RQD and rock quality. After Fagerström et al. (1983).

Q	Rock mass quality
0.001-0.01	Exceptionally poor
0.01-0.1	Extremely poor
0.1-1	Very poor
1-4	Poor
4-10	Fair
10-40	Good
40-100	Very good
100-400	Extremely good
400-1000	Exceptionally good

Table 2. The relation between the Q-value and rock mass quality. After Barton et al. (1974).

Barton et al. (1974) developed the rock mass quality system (Q-system) evaluating the rock quality using six different parameters. The six parameters are: RQD, the number of joint sets (J_n), the roughness of the weakest joints (J_r), the degree of alteration or filling along the weakest joints (J_a), and two parameters which accounts for the rock load (SRF) and water inflow (J_w). In combination these parameters represent the block size, the inter-block shear strength and the active stress. The relation between Q and the rock quality is shown in table 2.

The degree of fracturing is another parameter which was observed. As a starting point the rock is all fractured, but the degree of fracturing increases at several places. Thus the fracturing is divided into three different categories; normal, high and very high fracturing.

During the tunnel construction the fractures are grouted to water from leaking into the tunnel. The amount of grout is stated with the unit of *kg and/or l*. This is done because there were used two different types of grout; cement and chemical grout. The first has the unit kg and the latter has the unit litres.

Documentation from the TBM

For the use with the TBM, a site specific classification system was developed exclusively for the Hallandsås. The rock masses were divided into 11 different classes based on RQD, block size and weathering. The classification can be seen in table 3.

Rock class	RQD	Block size (cm)	Weathering
1	75-100	>60	W1
2	50-75	20-60	W1
3	25-50	5-20	W1
4	0-25	0-5	W1
5	25-50	5-20	W2
6	0-25	0-5	W2
7a	25-50	5-20	W3
7	0-25	0-5	W3
8	25-50	5-20	W4
9	0-25	0-5	W4
10	0-25	0-5	W5

Table 3. The rock class defined exclusively for the Hallandsås tunnel. Based on Banverket (2002).

Thus the parameters mapped are rock type, weathering, block size and rock class. Based on the weathering and block size the RQD can be assessed (see table 3). For several probe drilling ahead of the TBM the water flow was measured. The measured water flow is a mean value for the whole probe length of 10 to 40 metres. The exact position of the water bearing fractures is therefore not distinguished in this analysis. In the zones where the water leakage is less than 10 it shall be regarded as if there were no probe drillings or no flow measurements and not that there was no water leakage.

Comparison of resistivity data and tunnel documentation

In order to evaluate the results from the resistivity method the data are compared with the existing tunnel documentation. The comparison is done merely by visual evaluation. All data is plotted in grey scale in order to give a rapid impression of the rock quality. Dark colours are poor quality while light colours are good quality. The only exception is rock type where the colour does not have any significance with regards to the mechanical quality of the rock.
The coordinate system used is the chainage system used by the Swedish National Rail Administration.

Results

The comparison between resistivity and the mapped data is done for three different sections of the tunnel here referred to as North, South and TBM. The distance between the centrelines of the two tunnels is 25 metre.

To make the evaluation of the results easier different resistivity zones are marked with a letter and number. The resistivity data are divided into three types e.g. low (L), high (H) and intermediate (I). The dividing into the different resistivity zone is done so that it covers the same resistivity intervals in all three tunnel sections. The intervals can be disputed and discussed.

North

Figure 3 shows the resistivity and the mapped data from the northern part of the twin track tunnel. The mapped data are rock type, fracture zones, RQD, Q, weathering, water leakage and amount of grout. What is obvious when evaluating the water leakage from the two parallel tunnels is that the amount of water in the western tunnel is much higher than in the eastern tunnel (~factor 10). This is probably due to the fact that the western tunnel was constructed prior to the eastern. Therefore the ground water reservoir was drained by the first tunnel and there where not the large amount of water accessible for leaking into the second tunnel. Furthermore, considerable pre-grouting was carried out for the west tunnel which may influence also the east tunnel. As a consequence the water leakage data for the eastern tunnel is biased.

The mapping of the lithology in the two parallel tunnels shows a displacement of the dolerite which makes it clear that the dykes are striking NE-SW following the structural trend.

The sub-models of the resistivity data shows three zones with low resistivity along the part with tunnel documentation, but only two, L2 and L3, are clearly seen in all three depth slices. Interesting zones in the resistivity data can also be areas with very high resistivity. Three areas with high resistivity (~4000 Ωm) are visible in the depth slices. A zone with intermediate resistivity (~1000 Ωm) is marked with I1. In table 4 the dominant observations are summarized for the different resistivity zones. The most interesting observations are marked with ***bold and italic***.

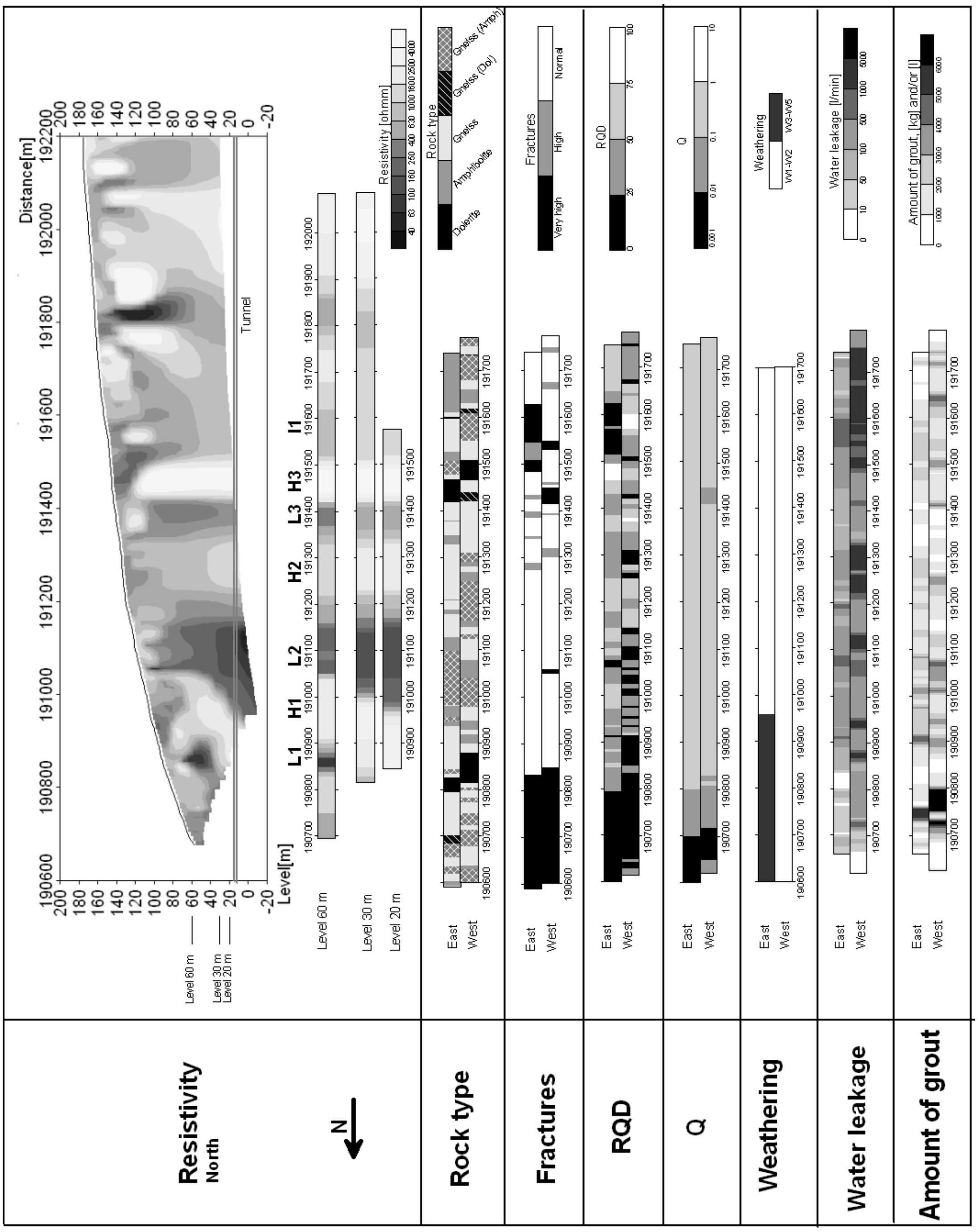

Figure 3. Visualization of resistivity and mapped data from both tunnels in the northern part of the Hallandsås tunnel. The mapped data were rock type, fractures, RQD, Q, weathering, water leakage and amount of grout. The resistivity data are shown as full model and as sub-models extracted at 60 metre, 30 metre and 20 metre above sea level. The low resistive zones are marked with L1, L2 and L3. High resistive zones are marked with H1, H2 and H3. The area with intermediate resistivity is marked I1. Here the tunnel base is at approximately 15 metre above sea level.

Resi-stivity	**Rock type**	**Fracturing**	**RQD**	**Q**	**Weathering**	**Water**
L1	Dolerite	***Very high***	***0-25***	0.1-1	E: ***W3-W5*** W: W1-W2	E: Low W: ***High***
L2	Gneiss(amph)	Normal	E: 25-50 W: ***0-25***	0.1-1	W1-W2	E: Low W: ***High***
L3	Gneiss	Normal	E: ***25-50*** W: 50-75	0.1-1	W1-W2	Med.
H1	***E: Gneiss*** ***W: Gneiss/Amph***	Normal	E: 25-50 W: ***0-25***	0.1-1	E: ***W3-W5*** W: W1-W2	E: ***Low*** W: **High**
H2	***E: Gneiss*** ***W: Gneiss(amph)***	Normal	E: 25-50 W: ***0-25***	0.1-1	***W1-W2***	E: Low W: ***High***
H3	***Dolerite/Gneiss***	Normal	***E: 75-100*** ***W: 25-50***	0.1-1	***W1-W2***	***Low***
I1	E: Gneiss W: Gneiss(amph)	***E: Very high*** ***W: Normal***	***E: 0-25*** ***W: 75-100***	0.1-1	W1-W2	***High***

Table 4. Summation of the dominating properties of the rock in the intervals based on the resistivity data for the northern part of the tunnel. L is low, H is high and I is intermediate resistivity. The most likely explanation to the resistivity value in the interval is indicated with ***bold and italic****.*

South

Figure 4 shows the resistivity data and the tunnel documentation for the southern part of the Hallandsås tunnel. This part of the tunnel is dominated by poor rock quality. The resistivity data was measured with Wenner array and had a maximum layout on 400 metre. This might have implications for the resolution at the tunnel level. In a later field campaign resistivity was measured from chainage 190800 to 197600 using the Schlumberger array and layouts of 800 metre. The southern-most part of this can be seen in figure 5. Thus there is an overlap between the resistivity sections shown in figures 4 and 5. The deeper model in figure 5 confirms that the resistivity at tunnel level between chainage 197300 and 197950 is low.

In this part of the resistivity section three areas are categorized as low resistive zones and two as intermediate zones. In table 5 the dominant observations from the tunnel documentation are summarized. The most interesting observations are marked with ***bold and italic***. An intermediate amount of water inflow is abbreviated Int.

Resi-stivity	**Rock type**	**Fracturing**	**RQD**	**Q**	**Weathering**	**Water**
L4	Gneiss/ Amphibolite	***Very high***	***0-25***	***<0.01***	***W3-W5***	E: Int. W: Low
L5	E: Gneiss W: Gneiss(amph)	E: Very high W: Normal	25-50	***0.01-0.1***	***W3-W5***	E: Int. W: Low
L6	E: Gneiss W: Gneiss(amph)	Normal	50-75	1-10	W1-W2	***High***
I2	E:Gneiss(amph) W: Gneiss	***Very high***	E: 0-25 W: 25-50	0.1-1	W1-W2	***Int.***
I3	E: ***Amphibolite*** W: Gneiss(amph)	Normal	50-75	1-10	W1-W2	Low

Table 5. Summation of the dominating properties of the rock in the intervals based on the resistivity data for the southern part of the tunnel. L is low, H is high and I is intermediate resistivity. The most likely explanation to the resistivity value in the interval is indicated with **bold and italic**.

TBM

In figure 5 the tunnel documentation from the use of a 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 metre and 25 metre above sea level.
In this part of the resistivity section three low resistive zones are identified. Only L7 and L9 are visible in both levels. Two high resistive areas and three areas with intermediate resistivity are visible. In table 6 the corresponding properties from the tunnel documentation are summarized. The most likely explanation for the resistivity value observed in each interval is indicated with ***bold and italic*** font. An intermediate amount of water is abbreviated Int.

Resi-stivity	**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***

Table 6. Summation of the dominating properties of the rock in the intervals based on the resistivity data for the TBM drilled part of the tunnel. L is low, H is high and I is intermediate resistivity. The most likely explanation to the resistivity value in the interval is indicated with **bold and italic**.

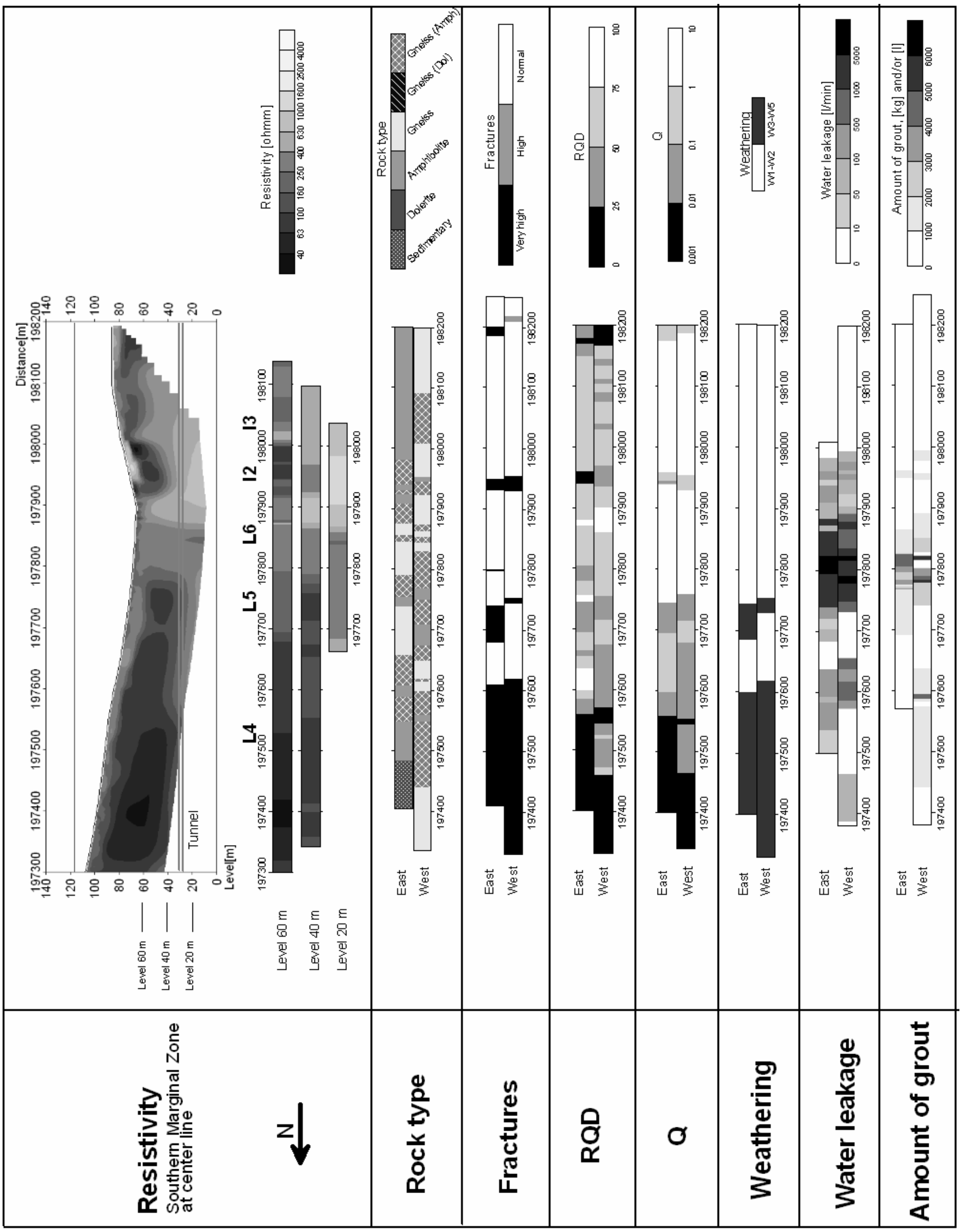

Figure 4. Visualization of resistivity and mapped data from both tunnels in the southern part of the Hallandsås tunnel. The mapped data were rock type, fractures, RQD, Q, weathering, water leakage and amount of grout. The resistivity data are shown as full model and as sub-models extracted at 60 metre, 40 metre and 20 metre above sea level. The low resistive zones are marked L4, L5 and L3. The zones with intermediate resistivity are marked I2 and I3. Here the tunnel base is at approximately 15 metre above sea level.

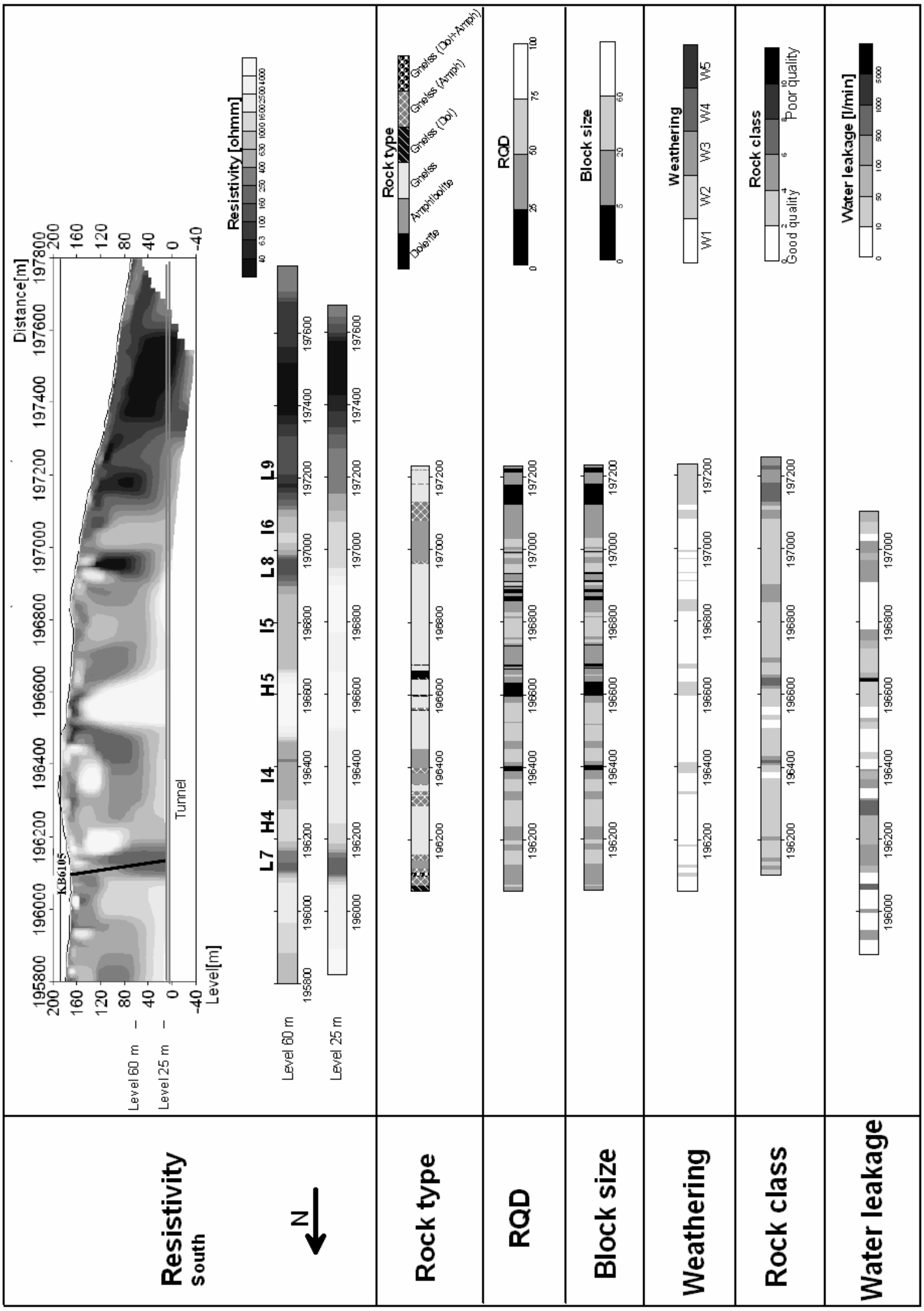

Figure 5. Visualization of resistivity and mapped data from the southern part of the Hallandsås tunnel. The mapping is done in front of the TBM at every operational stop. The mapped data were rock type, RQD, block size, weathering, rock class and water leakage. The resistivity data are shown as full 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. The position of core drilling KB6105 is marked with a line.

Discussion

The comparison shows that a change in resistivity in most cases is related to some kind of change in the rock conditions. High resistivity corresponds well with good quality gneiss as the dominant rock type. For the northern part this is seen at H2 and H3, figure 3 (table 4). In the part drilled with a TBM, figure 5 (table 6), it is observed at H4 and H5. In general low resistivity corresponds to a varying lithology with fractured contacts or merely rock with very poor quality (RQD < 25). This is very clear in large areas of the southern part of the tunnel, figure 4. The intermediate resistivity often coincides with areas of amphibolite with an average RQD of 25-75 (fair quality). An example of this is in figure 4 and figure 5 where the I3, I4 and I6 all are amphibolites. But 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. This is the case in the northern part, figure 3 (table 4) at I1 where there is an increased amount of water.

For reference, in-situ measurements of the resistivity were performed on some representative samples of the different rock types in the tunnel. For this purpose a special device was made for measuring the resistivity using a Wenner-configuration with *a*, the spacing between electrodes, equal to 0.05 m and to 0.1 m. The apparent resistivities measured are shown in figure 6. It is seen that the resistivity of the amphibolite is between 800 and 4000 Ωm, whereas it for gneiss is scattered between 1000 and 11500 Ωm. This emphasises the difficulty in distinguishing between these two lithologies. But it is quite clear that the amphibolite does not attain the same high resistivity as the gneiss. High resistivity is clearly an indication of gneiss whereas an intermediate resistivity is often amphibolite that to some degree may be mixed with gneiss. This supports the observations from the comparing tunnel documentation with the resistivity data.

This is also confirmed by geophysical logging of the core drilling KB6105. The position of the drill-hole is marked with a line in figure 5. The drill-hole is positioned 30 metre west of the tunnel line inclined at an angle of 20 degree from vertical. From the full resistivity section it is seen that the drill-hole passes through a low resistivity zone (250-600 Ωm), L7. In figure 7 the lithology is plotted together with the long/short resistivity log and natural gamma log. The core drilling is dominated by gneiss but with two layers of dolerite at 37 metre and 47 metre. From 85 metre to 92 metre the lithology is amphibolite. What is interesting is that the resistivity of these three zones is as low as 2000 Ωm, whereas the gneiss has a resistivity of 4000 to 10000 Ωm. In addition they give low gamma readings. In the gneiss there is a thin layer with a very high gamma count which is seen neither in the lithology log nor the resistivity log. The low resistive zone L7 is well explained in the tunnel documentation by several lithology contacts. Thus the disagreement between the resistivity seen in the profile and in the resistivity log might be explained by the fact that the geology is very complex and that the drilling is made 30 metre from the resistivity profile. The different scale of resolution of the methods is also essential for the result.

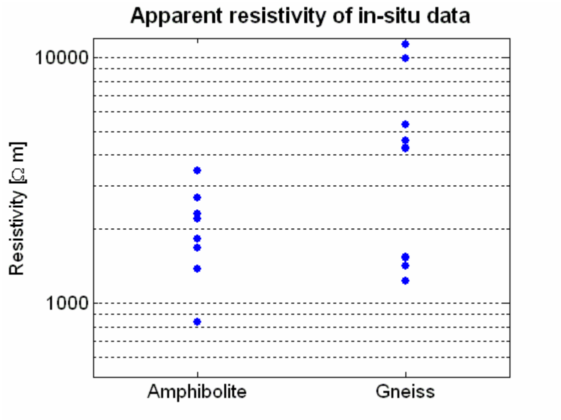

Figure 6. The apparent resistivity of amphibolite and gneiss measured at different locations in the tunnel.

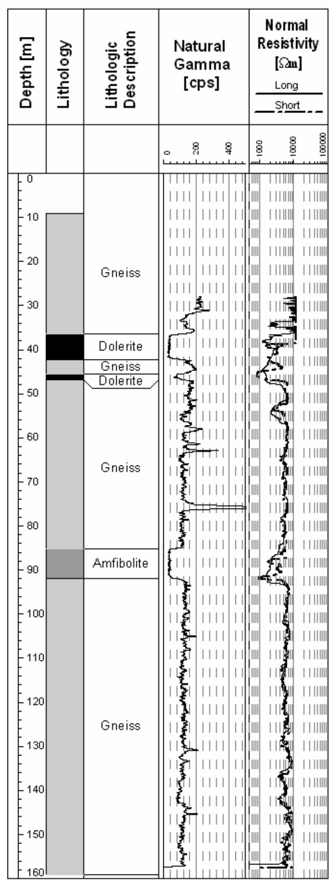

Figure 7. The lithology from the core drilling KB6105 plotted together with the natural gamma and long/short normal resistivity log.

Although in most cases there is a correlation between resistivity and rock conditions, there are also exceptions. The example from the northern part of the tunnel is at H1, figure 3 (table 4). There is a high resistivity and therefore it is expected to be good quality rock without weathering and water. The rock in the eastern tunnel is highly weathered whereas the western tunnel is fresh. On the other hand the RQD is lower in the western than in the eastern tunnel. In agreement with the expectation there is gneiss, mixed with amphibolite in some places. The result from the investigation at L3 is also difficult to interpret. There is increased water leakage but the RQD is not as low as expected. Thus the low resistivity here might be an effect of the inversion or 3D effects. Lack of resolution can also cause a low resistive body at a shallower depth to apparently extend down to tunnel level. For I1 the documentation, especially for the eastern tunnel, shows that the rock has a low RQD and is very highly fractured. On the other hand the western tunnel has a very high RQD. Additionally there is a large amount of water in the western tunnel. A low RQD is expected to give low resistivity while the high amount of water is expected to give an intermediate resistivity. But in this case it is also interesting to see that the rock is fresh. Therefore in this instance it has an intermediate resistivity due to increased water content.

In the documentation from the TBM, figure 5, the RQD at H5 shows a relatively large area with a value of less than 25 and a very high water leakage in an otherwise fair rock quality. It is expected that such a large area with poor rock quality and very high water leakage would give low resistivity. Instead there is quite high resistivity. The water might flow in few fractures and the high water leakage may be caused by the high pressure. The nature of the fractures can not be evaluated in this type of flow measurement. The conclusion is that the zone most likely is too small to create an anomaly in high resistivity gneiss with good quality. Another example is at L8 in the same section where the RQD shows many narrow zones with values lower than 25. The water leakage shows an intermediate flow that is slightly increased. There is no clear indication of this problematic area because the resistivity data at tunnel level does not show any low resistivity whereas at 60 m.a.s.l. it does. Here the problem might be that 20 m.a.s.l. is deeper than the resistivity method can resolve with the layout and electrode array used.

A probable reason for the divergence between the tunnel documentation and the resistivity data might be the 3D effects in data. The tunnels are separated by 25 metres and still there is a large difference between the lithology and rock properties in the eastern and western tunnels, emphasising the high variability in the rock mass properties.

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. A complicating factor in this particular tunnel project is that the tunnel is situated at a large depth giving poor resolution at tunnel level. The resistivity data are measured at the ground surface 120-150 metre above the tunnel. Therefore these data have a lower resolution at tunnel level than the detailed tunnel documentation. Thus 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.

In the mapping of the tunnel there is the human factor to acknowledge. The mapping of RQD, weathering and lithology is a subjective assessment done by geologists at the tunnel site. There is not a big difference in the rock 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. So the mapping is somewhat subjective and might bias the results of this study in some parts.

Conclusion

For the Hallandsås tunnel project in southern Sweden several kilometres of resistivity measurements (CVES) have been made. Therefore the tunnel documentation gives a good opportunity to perform an evaluation of the resistivity data. It has previously been shown that three large zones with problematic rock conditions could be identified using geoelectrical imaging (Dahlin et al., 1999). In this case the contrast in resistivity between rock of good quality and rock of poor quality is sufficiently large to be resolved beyond any doubt. It is probable that more information can be extracted from the remaining part of the 2D profile and used in the construction work.

The ability of geoelectrical imaging to indicate changes in rock conditions by means of varying resistivity makes it a valuable tool in the pre-investigation. With the tunnel drilled 150 metre beneath the surface and in an area with this type of geology, the scale of resolution is tens of metres. Thus in this example the method can not resolve bodies smaller than this. The comparison of the tunnel documentation and the geoelectrical imaging showed that a change in resistivity often corresponds to some kind of change in the rock mass properties. The resistivity can be divided into three categories, i.e. high, low and intermediate resistivity. These three categories can generally be correlated to certain types of rock mass conditions. The high resistivity corresponds well with gneiss with a good quality. Intermediate resistivity is most likely amphibolite with a relatively good rock quality. This is also supported by in-situ measurements in the tunnel where the only rock with very high resistivity is gneiss. Also the resistivity log showed that amphibolite has lower resistivity than gneiss. In some cases the intermediate resistivity can also be water bearing rock. The low resistivity is rock of a poor quality which is deeply weathered or has many contacts between different lithologies.

However it is not always possible to relate the changes in resistivity to a specific rock condition or property. This may be caused by differences in the scale of the compared data. The resistivity data has a much lower resolution than the tunnel documentation. Another reason can be 3D effects in the 2D resistivity profiles. In addition a certain amount of bias can occur in the mapping of the tunnel parameters because different geologists may interpret the conditions differently.

The decision makers can use the changes in resistivity as an indication of the need for caution when planning for example an underground rock construction. The experience from the Hallandsås tunnel construction can be used to improve the interpretation capability of the resistivity image. Previously there has been a focus on low resistivity zones in order to identify poor rock conditions. The comparison has shown that the high resistivity zones tend to indicate good quality rock. This is as important for the contractor to know as the location of poor quality rock. Even though the resistivity method is not able to interpret every change in the conditions it still contributes with important information within the limitations of its resolution. Geoelectrical imaging contributes to reduce the number of uncertainties. In combination with other investigations the ambiguity and uncertainty might be further reduced.

As a tool for pre-investigations, resistivity imaging has the advantage that it is more time and cost efficient than other alternatives, e.g. seismic refraction. It has to be stressed that the method should not stand alone. A priori information about the geological setting is crucial and the results have to be followed up by additional measurements, i.e. with other types of geophysical methods exploiting other physical parameters or by 3D resistivity measurements. The measurements can then be used as a base for deciding where to perform geotechnical drillings.

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Geophysical and Hydraulic Properties in Rock

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Summary
An extensive database with data from southern Sweden invites for a thorough investigation of the geophysical and hydraulic properties. In the first attempt to find a relation between geophysical and hydraulic properties the information from core drillings and CVES are used. The records from the drillings include lithology, weathering and hydraulic conductivity. From the inverted CVES profiles separate soundings are extracted at positions close to the core drillings.
The results from the investigation are not easy to interpret. Some drillings and resistivity soundings shows good correlation and some do not. The problem might be that the resistivity measurements have a too low resolution compared to the very detailed observations from the core sample. Another problem could be that the core drilling and resistivity sounding most likely are made at positions close to each other but not the exact same place.
As expected this type of investigation is too simple for a complex relationship as the one that might exist between geophysical and hydraulic properties. It shows the importance of further investigations of existing and new data.

Introduction
Large efforts are put into finding a relationship between geophysical and hydraulic properties (de Lima and Niwas, 2000; Guérin, 2005; Heigold et al., 1979; Kosinski and Kelly, 1981; Kowalsky et al., 2004; Linde, 2005; Purvance and Andricevic, 2000; Slater and Lesmes, 2000). No general petrophysical relationship between electrical conductivity and hydraulic conductivity exists, which is not either too simplified to be useful or does not assume unrealistic details in the available information about the rocks (Linde, 2005). An extensive database with data from southern Sweden invites for a thorough investigation of the geophysical and hydraulic properties.
The extensive database exists because of problems with rock properties at construction of a railway tunnel in southern Sweden. In 1992 the construction of an 8.6 km long twin-track tunnel was initiated. Only one third of it is completed so far because of severe problems with clay weathered zones and high water pressure in fractured water bearing rock. During the years the difficult conditions have resulted in extensive use of geophysical methods and hydrological measurements. In all there exists a substantial amount of data from the area. These data should give a good basis for finding a link between geophysical and hydraulic properties of the rocks.

Method
During the last 15 years there has been measured more than 20 km of CVES, 25 km VLF, 6 km Slingram, 15 km magnetic surveys, several TEM soundings and 15 km seismic refraction. Additionally the ground water level has been measured twice a month in 80 shallow wells. There are more than 100 deep wells and 50 core drillings. Since year 2000 there is manually measured stream discharge twice a month at 15 observation points scattered at 7 small streams. Of these 15 observation points 6 have also been measured automatically once an hour. Pumping tests and different well loggings have been conducted and the precipitation is measured daily.
In the first attempt to find a relation between geophysical and hydraulic properties the information from core drillings and CVES are used. A motivation for finding a link between the geophysical properties and the properties of the rock is that is would enhance the possibility to save money by doing the more cost efficient geophysical measurements instead

of the expensive core drillings. More important is that CVES gives a continuous cross section whereas the core drillings are point observations.
The records from the drillings include lithology, weathering and hydraulic conductivity. Lithology and weathering are based on visual interpretation made by the site geologist. The weathering is given with values from 1 to 5, where 1 is fresh rock and 5 is highly weathered rock. The hydraulic conductivity is measured in intervals of 5 to 10 meters. The position and length of the intervals are based on the geology and the possibilities for placing the packer used for the measurements. The CVES profiles were measured with an electrode spacing of 5 or 10 meter and a layout of 400 or 800 meter. The penetration depth is around 60 meter for

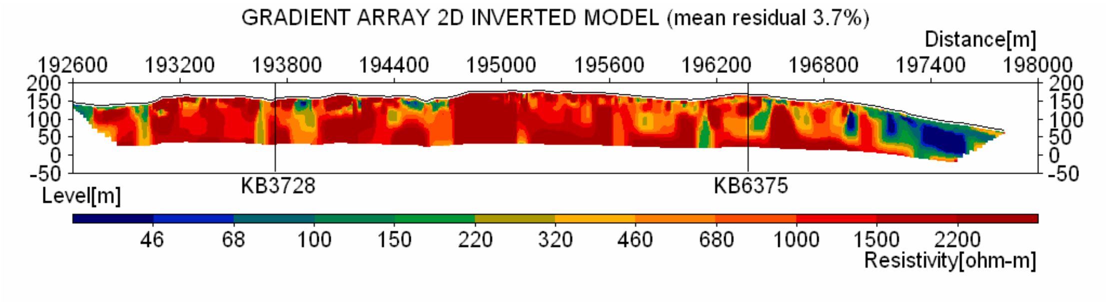

Figure 1. The CVES profile used for the extraction of resistivity soundings. KB3728 and KB6375 are core drillings.

the former and 120 meter for the latter. The data is inverted using the program RES2DINV From the inverted CVES profiles separate sub-models are extracted at positions close to the core drillings. Figure 1 shows an example of a CVES profile used for the extraction of models. The profile is part of a longer profile and was measured with layouts of 800 meter. The extraction resulted in a multiple layer model where the layer thickness is controlled by the inversion program. All information is plotted as a function of depth.

Results

Nine core drillings were found to be adequately close to the resistivity profile for a comparison. In figure 2 the data are shown for core drilling KB6375 and for a resistivity

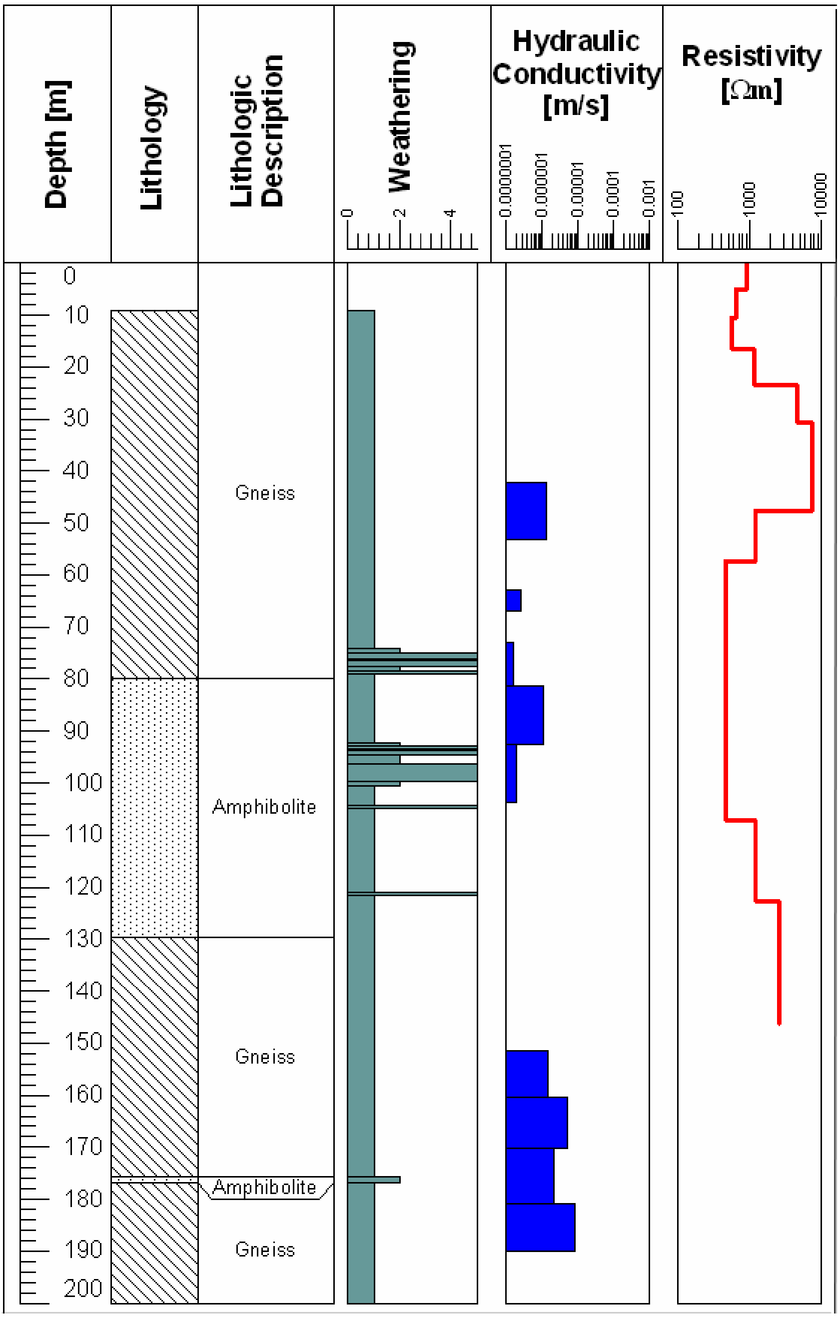

Figure 2. Data from core drilling KB6375 and extracted resistivity model at 196375.

model extracted at the same position, with coordinate 196375 at the resistivity profile in figure 1. The drilling is 200 meter deep and penetrates gneiss and amphibolite. Most of the core is appraised to be fresh rock. In the depth of 75 to 80 meters and 95 to 105 meters there are thin layers which are highly weathered (class 5). The hydraulic conductivity is measured to lie between $1.1 \cdot 10^{-6}$ m/s and $1.5 \cdot 10^{-6}$ m/s in the intervals at 42 to 53 meter, 81 to 92 meter and 155 to 190 meter. The resistivity model in the right side of figure 2 shows resistivities between 500 and 1000 Ωm to a depth of 25 meters. Between 25 and 50 meters the resistivity is more than 1000 Ωm. In the interval between 50 and 110 meters the resistivity is close to 300 Ωm. Figure 3 shows the data from KB3728 and the resistivity model at that position corresponding to coordinate 193728 at the resistivity profile in figure 1. The drilling is 190 meter deep and penetrates gneiss with several thin amphibolite layers. The core consists of thin horizons which are slightly weathered (class 2). In the depth intervals from 100 to 105

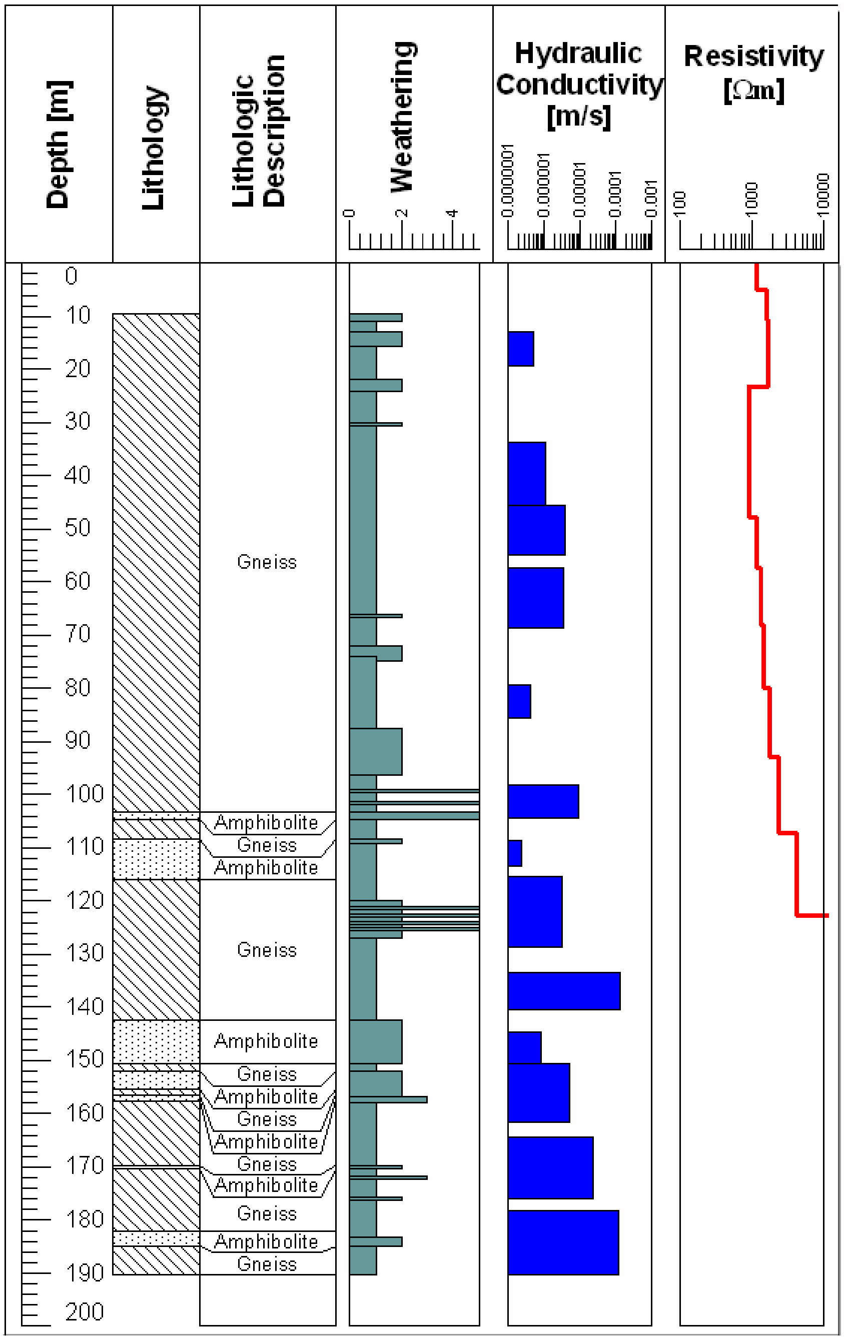

Figure 3. Data from core drilling KB3728 and extracted resistivity model at 193728.

meter and from 120 to 125 meter there are thin layers with strong weathering (class 5). The hydraulic conductivity increases with depth from values of $5 \cdot 10^{-6}$ m/s to $1 \cdot 10^{-4}$ m/s. To the right in figure 3 the resistivity is shown. The first 25 meters the resistivity is 1600 Ωm. In the depth of 25 meter the resistivity decreases to 900 Ωm. With increasing depth the resistivity increases to a value of more than 10.000 Ωm at a depth of 120 meter.

Discussion and Conclusions

The results presented are not easy to interpret. KB6375 has low resistivity in the intervals with high weathering. This is expected because clay weathered rock has a lower resistivity then fresh rocks. KB3728 has an increasing resistivity even though the rock is weathered and there is an increased inflow of water. This result does not agree with the expectations. Examination of the seven other core drillings (not shown here) shows that some lives up to the expectations and some do not. There is no obvious connection between the information from the core drillings and the resistivity soundings. The problem might be that the resistivity measurements have a too low resolution compared to the very detailed observations from the core sample. It should also be taking into consideration that there is likely to be 3D effects in the resistivity measurements. Another problem could be that the core drilling and resistivity most likely are made at positions close to each other but not the exact same place. The geology being so complex with fractures and weathered rock makes these feasible explanations.

As expected this type of investigation is too simple for a complex relationship as the one that might exist between geophysical and hydraulic properties. It shows the importance of further investigations of existing and new data. For the further investigations within the area an additional field campaign with a combination of methods is planned in the summer 2006.

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Paper 3 Danielsen, B.E. and Dahlin, T. (2007)

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

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

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Abstract
Resistivity in horizontal boreholes can give useful detailed information about the geological conditions for construction in rock, i.e. in front of a tunnel bore machine. This paper 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 in order to evaluate the resolution of different electrode arrays. Four different arrays were tested; dipole-pole, cross-hole dipole-dipole, cross-hole pole-tripole and multiple gradient array. Additionally the resolution of a combination of cross-hole dipole-dipole and multiple gradient was assessed. The 2D sensitivity patterns for various arrangements of the cross-hole dipole-dipole and multiple gradient array were examined. The sensitivity towards inaccurate borehole geometry and the influence of water in the boreholes was also investigated. Based on the model study the cross-hole dipole-dipole array, multiple gradient array 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. The results showed a high resistivity rock mass at the site. A transition from high resistivity to slightly lower resistivity coincides well with a change in lithology from gneiss-granite to gneiss. It is likely that the shotcrete on the tunnel wall is seen as a low resistivity zone.
The measurements are a valuable tool, but further development of the cables and streamlining of measuring routines have to be performed before the resistivity tomography can be used routinely in pilot holes during construction in rocks.

Keywords: ERT, horizontal boreholes, numerical modelling, arrays, 2D sensitivity patterns, non-parallel, water filled boreholes.

Introduction
Pre-investigations are vital for time efficient, cost efficient and safe construction in rock. This requires sufficient knowledge about the rock properties such as water flow and stability. During tunnel drilling with a tunnel boring machine (TBM) probe drillings are made in front of the TBM on a regular basis. If the geology varies on a small scale, then probe drillings might not be representative of the rock mass between the boreholes. Thus the aim with this study is to investigate the possibility of using these boreholes for electrical resistivity tomography (ERT). ERT can be done between two or more boreholes and gives information about the rock mass between the boreholes. An important task is to make the whole measuring routine fast and efficient in order to avoid any delay for the TBM.

At geotechnical site investigations electrical imaging in combination with core drilling and geophysical logging has proven to be valuable for providing information about rock properties (Dahlin et al., 1999). Rønning (2003) investigated the usefulness of geophysical methods in the early stages of construction work. The conclusion is that 2D resistivity investigations often are better and more cost efficient than traditional refraction seismic, but more knowledge is needed (Rønning, 2003). Electrical imaging made from the surface gives limited resolution at greater depths, and for more detailed information borehole measurements are required.

Previously ERT in vertical boreholes has proven useful for environmental investigations (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 wells drilled during geotechnical pre-investigation of a tunnelling site to obtain a 2D image of the resistivity close to a TBM (Denis et al., 2002).

Even though model studies investigating the resolution of different electrode arrays have been done previously (Bing and Greenhalgh, 2000; Danielsen et al., 2002; Goes and Meekes, 2004) it was found necessary to perform a new study focussing on the specific scenario at the tunnel site. The influence of water in the boreholes is investigated for a 3D model which is inverted as 2D. For a 2D model the resolution of different electrode arrays is investigated in order to find the array with the best resolution. The 2D sensitivity patterns for various arrangements of the cross-hole dipole-dipole and multiple gradient array are examined in order to clarify the modelling results. The importance of the geometry of the probe drillings was also investigated through numerical modelling. The geometry of the boreholes is in reality very uncertain because they are drilled without precision. Therefore it is uncertain how parallel the holes actually are. What is interesting and relevant is to observe the magnitude of the error in data when data is inverted assuming that the boreholes are parallel. Even though 3D inversion is possible it is not considered here.

Measurement using ERT in horizontal boreholes was carried out on an experimental stage. The first measurements were made in a tunnel where problems with poor rock quality have delayed the work seriously. The boreholes used were similar to those drilled as probe drillings in front of the TBM. They were 28.5 metre long and drilled 6.5 metres apart, with a diameter of 64 mm.

Numerical modelling

The numerical modelling is divided into two parts. The first part comprises the resolution of different array types, and in the second part the sensitivity of different array types towards uncertainty in the geometry of the boreholes is assessed. In all cases two 19.5 metre long boreholes separated with 6.5 metre are modelled. A robust inversion (L_1-norm) was done with RES2DINV because of the relatively sharp boundaries and large contrast in the resistivity (Loke et al., 2003).

Resolution of different electrode arrays

Before the resolution of different electrode arrays is assessed the influence of water in the boreholes is considered. During actual measurements water is present in the boreholes. In reality the world is 3D but in this case only 2D measurements and 2D inversion are considered. Thus the forward modelling is made with RES3DMOD and afterwards the data are extracted as 2D data and inverted in RES2DINV. The electrode arrays have one metre electrode spacing. The model is a homogeneous matrix with a resistivity of 8000 Ωm and two low resistivity boreholes, see Figure 1. Since the forward modelling program uses a rectangular grid the boreholes have to be approximated as having square cross section. Furthermore, the model of each borehole is 0.5 metre by 0.5 metre even though the actual diameter of the boreholes is 0.06 metre. To obtain a correct total conductance the resistivity of the boreholes in the model has to be approximately 100 times larger than in the actual case. The resistivity of the water in wells at the investigation area is measured to be 50 Ωm on average. Therefore the resistivity of the boreholes in the model should be 5000 Ωm. This means that the contrast between the boreholes and matrix is very small and consequently the water in the boreholes is unimportant. In some cases the actual water might have a much lower resistivity so the modelling was carried out using a resistivity of 500 Ωm (i.e. the actual water resistivity is 5 Ωm). Four different electrode arrays were tested in the study; dipole-pole (AM-N), cross-hole dipole-dipole (AM-BN), cross-hole pole-tripole (A-BMN) (Goes and Meekes, 2004) and multiple gradient array.

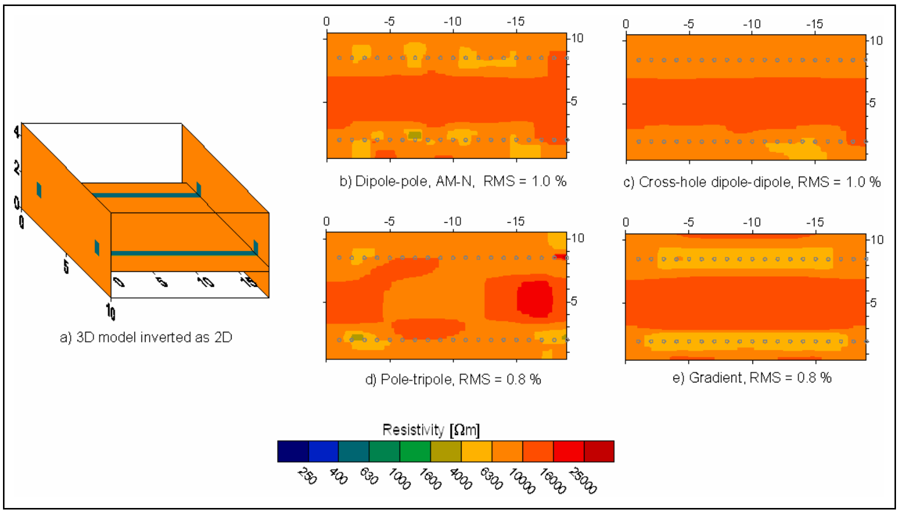

Figure 1. a) The 3D model is inverted as 2D. The matrix has a resistivity of 8000 Ωm and the borehole has a resistivity of 500 Ωm. b) dipole-pole (AM-N), c) cross-hole dipole-dipole(AM-BN), d) pole-tripole (A-BMN), e) multiple gradient. The distance is in metre.

In Figure 1 the 2D inversion of the 3D model shows that the very low resistivity of the boreholes does not influence the resistivity of the matrix much, except for the modelling using the A-BMN array. Here the resistivity contrast is even larger than it probably would be in reality. Therefore the boreholes are assumed to be inconsequential with regards to the resistivity results and are excluded from the further study of the data resolution.

The model used for the study of the resolution has an inclined fracture zone with a resistivity of 300 Ωm in an 8000 Ωm matrix, see Figure 2a. The high resistivity area in the left side of the model is the air-filled tunnel front.
The electrode arrays have a 0.5 metre electrode spacing, thus there are 40 electrodes in each borehole. The total number of electrodes is larger than the maximum possible in the forward modelling program RES2DMOD. Therefore the generation of data is

done twice with 1 metre electrode spacing, where the second is displaced by 0.5 metre compared to the first. Before inversion the two data files were imposed with 5% noise. This is done in Matlab using a random function which gives Gauss generated values with average 0 and variation 1.The Gauss generated values are multiplied by 5% and then added to the original data.

The four electrode arrays were tested again; dipole-pole (AM-N), cross-hole dipole-dipole (AM-BN), cross-hole pole-tripole (A-BMN) (Goes and Meekes, 2004) and multiple gradient. Then different combinations of gradient, AM-BN and A-BMN were tested but only the combination of AM-BN and multiple gradient is shown here. The combinations with A-BMN are left out because the results are disturbed by artefacts. The dipole-dipole configuration AB-MN was also tested at an initial stage but without satisfactory results, as was the case in the study by Bing and Greenhalgh (2000). Bing and Greenhalgh (2000) showed that the cross-hole pole-dipole A-MN, dipole-pole AB-M and the dipole-dipole AB-MN have singularity problem in data acquisition, giving many near-to-zero potential values. Therefore these alternatives are not considered here.

The different arrays results in different number of data points, as listed in table 1. The number of data points influences the time used for measuring and inversion of the data. The arrays are generated using Matlab.

ARRAY	NUMBER OF DATA POINTS FOR 2D
Dipole-pole (AM-N)	640
Dipole-dipole (AM-BN)	268
Pole-tripole (A-BMN)	720
Gradient	248
Gradient + AM-BN	516

Table 1. Number of data points in the four different electrode arrays and the combined array used in this numerical modelling.

The 2D sensitivity patterns for various arrangements for the electrode arrays are calculated using RES2DMOD. The boreholes here are also separated by 6.5 metre. The configurations are the same the modelling as for the field measurements.

Sensitivity towards borehole geometry

The sensitivity towards the geometry of the boreholes is very important to understand because the probe drillings in front of a TBM are not drilled with great precision. In the worst case the accuracy is of the order of 1-2 metre on a 40 metre long borehole. It is too expensive and time consuming to measure the geometry of the boreholes. As a consequence the electrodes are most likely in different real positions when the data are measured than the position assumed in the data inversion. This means that when performing the inversion some inaccurate assumptions are made because the electrode geometry will be imprecise.

For modelling this scenario the same model is used as in the section on electrode array resolution, where the electrodes in the left borehole diverge increasingly from a straight line with depth as illustrated by the red dots in Figure 4a. The modelling is done for smaller and larger distances between the boreholes. The results were similar, thus only the latter is shown here.

The left borehole deviates 1 metre in 19 metres. Data is generated with these two non-parallel boreholes, but when inverting data, parallel boreholes are assumed. For evaluating the result the inverted data are compared with the ideal situation where the boreholes are in fact parallel when generating the data. This comparison is made by calculating the relative change. The difference in resistivity between the normal and diverging dataset is divide by the resistivity of the diverging dataset.

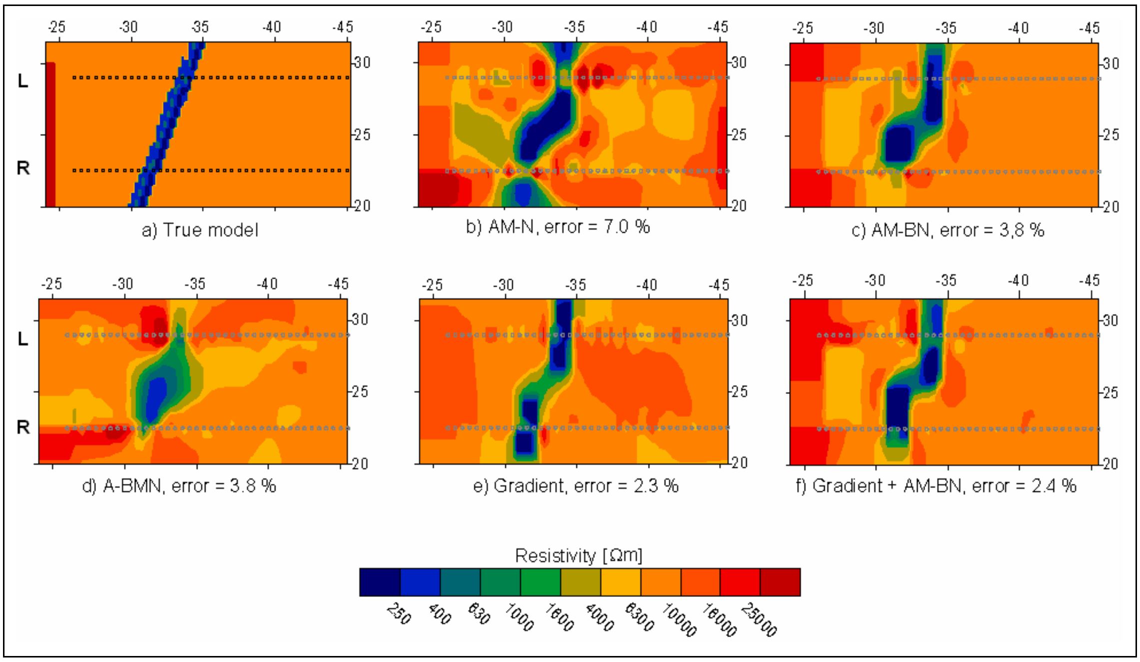

Figure 2. a) The true model made in RES2DMOD. Model of inclined fracture zone with a resistivity of 300 Ωm in a 8000 Ωm matrix. The model is seen from above with a left (L) and right (R) borehole. b) dipole-pole (AM-N), c) cross-hole dipole-dipole (AM-BN), d) pole-tripole (A-BMN), e) gradient, f) combination of gradient and cross-hole dipole-dipole. Black and grey dots are the electrodes in the boreholes. The distance is in metre.

Results of the numerical modelling

Resolution of different arrays

Modelling the resolution of the different arrays showed differences in their ability to resolve the resistivity and location of the geological features. The results from the modelling of the synthetic model are shown in Figure 2. Figure 2a shows the true model created in RES2DMOD. The model is seen from above with a left (L) and right (R) borehole. It is quite clear that the low resistivity zone is more or less resolved in all cases.

In Figure 2b-2e the results are shown where only one array type is used. For all four arrays the correct thickness and position of the low resistivity zone is resolved accurately only at the boreholes. Therefore the best resolution is close to the electrodes. Except for the A-BMN the arrays have a slightly higher resistivity in a large area at the tunnel front. Experiments with adding a priori information to the data before inversion, e.g. fixed region and known boundaries, did not improve the result. Comparing the four results it is clear that the A-BMN in Figure 2d has most difficulties in resolving the low resistivity zone. The zone is more diffuse and has a higher resistivity at the edges of the model than the AM-N, AM-BN and multiple gradient arrays (Figure 2b, 2c and 2e). These three arrays resolve the resistivity of the inclined zone very well. With AM-N the inclined zone is resolved as continuous and with a homogeneous resistivity. The matrix is not well resolved and there are several artefacts. The multiple gradient array is good at resolving both the matrix and the inclined layer and the transition between high and low resistivity is particularly narrow. For the AM-BN array the inclined zone is diffuse and too large. Close to the tunnel front the resistivity of the matrix is too low. There are a few artefacts but the array resolves the matrix well.

The combination of AM-BN and multiple gradient array is seen in Figure 2f. The low resistivity zone appears in steps but has more or less the true resistivity. The transition from high to low resistivity is narrow. As in the case for the AM-BN array, the resistivity close to the tunnel front is too low.

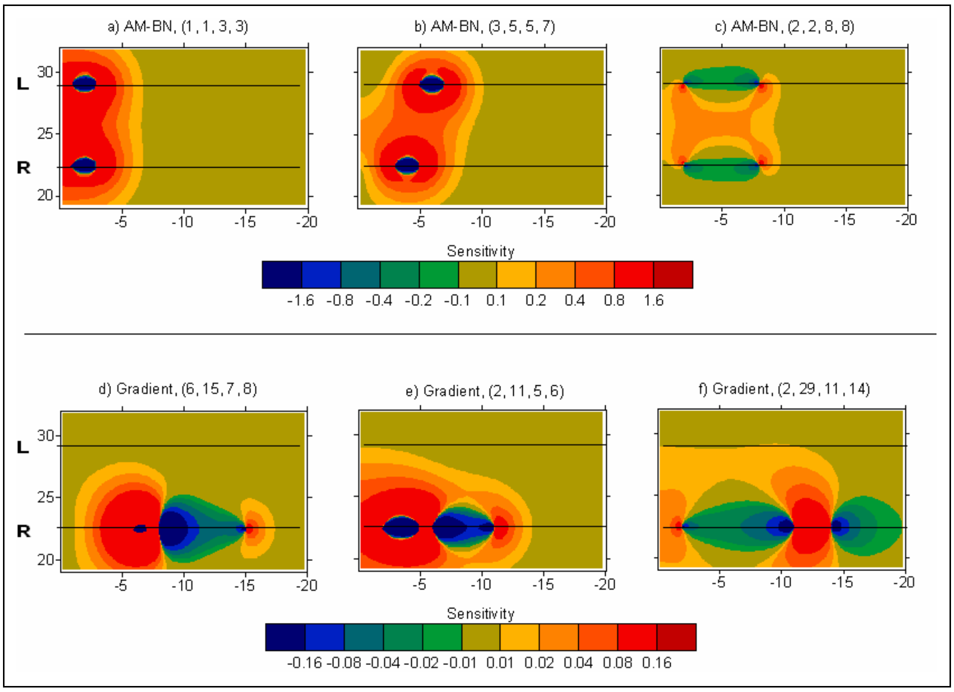

Figure 3. The 2D sensitivity pattern in horizontal boreholes using AM-BN, a)-c), and multiple gradient, d)-f). The position of the electrodes (C1, C2, P1, P2) are given in the brackets. The horizontal black lines mark the position of the two boreholes. The distance is in metre. Notice the difference of a factor ten between the sensitivity of AM-BN and multiple gradient.

Figure 3 shows the 2D sensitivity pattern for three AM-BN (3a-3c) and three gradient (3d-3f) electrode configurations. Other combinations were studied and these are some representative examples. Observe that the scale used for the AM-BN configurations is one magnitude larger than the scale used for the gradient configurations. It is quite clear that the AM-BN has a greater sensitivity between the boreholes. It can be seen that the sensitivity decreases quite rapidly when the separation between the current and potential electrodes increase. The gradient configuration has a smaller sensitivity between the boreholes, but has a much larger sensitivity close to the electrodes.

Sensitivity towards borehole geometry

Figure 4 shows the results from modelling the sensitivity to different degrees of divergence from parallel between the boreholes. The figures show the relative change instead of the resistivity image since the difference in the resistivity image is small. A change between -0.25 and 0.25 (white) indicates zones that show almost no difference between the case when the boreholes are perfectly parallel and when they are not. The red colour indicates that the resistivity obtained by the inclined borehole is smaller than for the parallel boreholes. The opposite is the case for the blue colour.

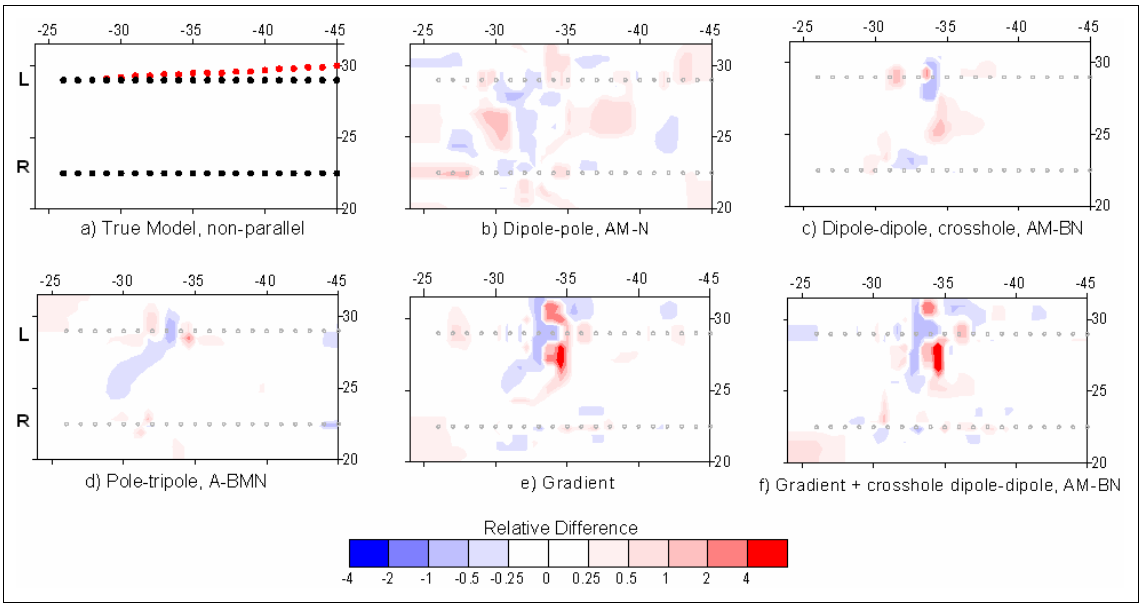

Figure 4. The relative difference between models measured with parallel and non-parallel boreholes. a) The red dots are the position of the electrodes while data are generated. The black dots are the position of the electrodes while the data are inverted. b) dipole-pole (AM-N), c) cross-hole dipole-dipole (AM-BN), d) pole-tripole (A-BMN), e) gradient, f) combination of gradient and cross-hole dipole-dipole (AM-BN). The grey dots are the electrodes in the boreholes assumed during inversion. The distance is in metre.

The AM-N array in Figure 4b, is relatively sensitive towards changes in borehole geometry. The AM-BN array, Figure 4c, and the A-BMN, Figure 4d, are sensitive close to the low resistivity zone but are generally insensitive elsewhere. The largest difference is seen with the gradient array in Figure 4e. At the low resistivity zone in the left borehole the relative difference is large. The combination of gradient and AM-BN more or less sums up the differences from the individual arrays (Figure 4f).

Discussion of the numerical modelling
Generally the numerical modelling showed that the best resolved area is close to the electrodes for all the arrays.

The best resolution of the resistivity and position of the geological structures is obtained with multiple gradient array and a combination of AM-BN and multiple gradient array. In both cases the matrix and the low resistivity close to the boreholes are well resolved. The AM-BN is good at resolving the resistivity of the matrix between the boreholes but there are some artefacts. The study of the 2D sensitivity patterns for the AM-BN and gradient array more or less supports these observations. The gradient array has a smaller sensitivity between the boreholes than the AM-BN. Results from other modelling carried out, but not shown here, emphasises that the resolution between and outside the boreholes is limited for the gradient array. On the other hand the resolution of the area close to the electrodes is very reliable. By combining the two arrays the structures are slightly better resolved. The AM-N is good at resolving the low resistivity zone, but is poor at resolving the matrix where there are quite a number of artefacts. The A-BMN configuration does not have the same resolution of this geological setting as AM-N, AM-BN and multiple gradient configurations.

The study of the sensitivity of the arrays towards the borehole geometry showed that the smallest difference is obtained using the AM-BN or A-BMN. The sensitivity towards geometry errors was visualized by using the relative difference instead of the actual inversion model. This was done because the difference is difficult to distinguish when comparing the inversion models. This demonstrates that the geometry problem produces only small changes in the resistivity values. In most cases the difference is largest in those areas close to the low resistivity zone. A limitation in the study is that only one of the boreholes is deviates because it is not possible to model two inclined boreholes in RES2DMOD. In reality the geometry is probably that both boreholes are deviating. In such a case there will be a larger difference, but it is expected that for the array types discussed, this will produce only a minor difference.

Based on the results from the numerical modelling the AM-BN and the gradient arrays were used in the field test measurements in the horizontal boreholes. It is then possible to combine the different datasets before inversion. Even though Goes and Meeks (2004) showed good results for the A-BMN, it did not resolve the geology particularly well for the models studied. Thus the A-BMN was not used for the actual measurements in the boreholes. The AM-N array did not prove to be good at resolving the matrix, and was also sensitive towards unknown borehole geometry. In addition the array is more complicated to use in the field, because of the need for a remote electrode.

ERT in horizontal boreholes
Horizontal boreholes raise several practical questions, i.e. how to get the electrode cables into the boreholes. For solving this problem a prototype of a semi-rigid cable has been developed, using a thin fibreglass rod to create rigidity. A further requirement is that the cables can be wound up so that they can be handled in confined spaces. To avoid getting stuck in the boreholes the cables have to be streamlined. The need to have streamlined cables conflicts with the requirement for adequate electrode contact with the borehole walls. To overcome this both test holes

were drilled with a couple of degrees inclination downwards in order to keep water in the holes thus creating better electrode contact. The inclination also makes it possible to pour water into the hole if no water is present naturally.

For the test measurements the electrode spacing was 1 metre, but by pulling back the electrode cable half a metre after the first measurement and then measuring a second time the data interval was reduced to 0.5 metre. It should be noted, however, that any measurements with 0.5 metre electrode spacing could not be done.

For the measurements the Lund Imaging system was used, in this case consisting of Terraohm RIP924, ABEM Electrode Selector ES10-64C and ABEM SAS2000 Booster. This is a 7 channel system which makes the data acquisition fast. The protocol files used for the measurements are constructed so the data coverage is equally spaced over the whole length of the borehole. This is the case even when some electrodes have to be excluded if the borehole for some reason is not long enough to take the whole cable.

The inversion program RES2DINV does not allow viewing and editing of the borehole resistivity data before inversion. This is a complication because the user blindly produces an inversion result. The only indication of the data quality is obtained subsequently with the absolute error or root-mean-square (RMS) error, for the robust and least squares inversion respectively. This is a value which gives the difference between the calculated and measured apparent resistivity (Loke, 2004). Preferably the model residual should be relatively small. Without the possibility of editing the data before inversion the only option is to use the possibility to display the RMS error statistic after the inversion. This option displays the distribution of the percentage difference between the logarithms of the observed and calculated apparent resistivity values (Loke, 2004).

Results from measurements in horizontal boreholes

The prototype of the stiff electrode cables was effective and easy to use in practice, but problems still occurred during the measurements. One cable got stuck in a borehole and had to be left in the hole during the first stages of developing the prototype. This stimulated the development of a cable without any protuberances. Still it does not completely prevent the problem from recurring. Another problem was that a borehole collapsed before the measurements were done. As a consequence measurements were performed in holes of different length which gives an asymmetrical result. In this particular case the boreholes were re-drilled and the measurements could be performed in holes of equal length. However, it is too expensive and time consuming to re-drill the holes when the measurements are being used for regular production purposes.

The first inversion of the borehole data gave an absolute error higher than 15%. Therefore the option for removing data points with an error larger than 30-40% was used. Subsequently the datasets were inverted again, obtaining an absolute error of between 6 and 10% for the resistivity data. Ideally this is still too high but at present time it is not possible to obtain a better result without the possibility to view, evaluate and edit the data before inversion. The poor data quality means that the results are regarded with scepticism and only the large structures are considered valid.

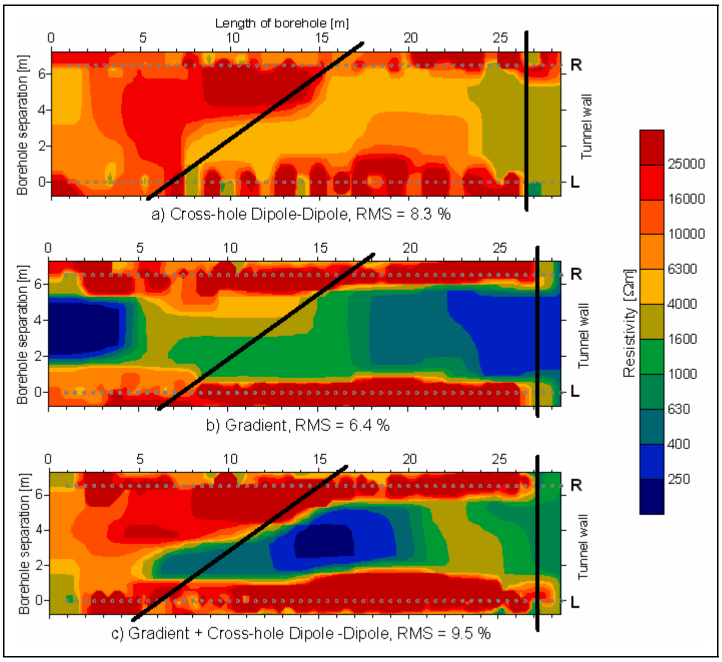

Figure 5. The inversion results from the resistivity measurements using different electrode arrays. The boreholes are seen from above with the tunnel wall to the right in the figure. The left borehole, seen from the tunnel, is marked with **L** *and the right borehole with* ***R****. The lines show probable 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.*

Figure 5 show the inversion results of the resistivity measurements with the different array types and the combined data. The grey circles mark the positions of the electrodes in the two boreholes. The innermost electrode in both boreholes is positioned at 1 metre and the tunnel wall is at 28.5 metre. The results are viewed from above with the tunnel wall to the right in the figures. The left borehole, seen from the tunnel, is marked with **L** whereas the right borehole is marked with **R**.

For all three results the resistivity close to the borehole is higher than 16000 Ωm. Even though the results have a large difference in the resistivity of the area between the boreholes there is still a trend in the resistivity images. The line from 5 metre in the left borehole to 17 metre in the right borehole marks a transition from high resistivity to a slightly lower resistivity. Close to the tunnel wall the resistivity is low in all three examples.

Discussion of measurements in horizontal boreholes

As reference data for the interpretation of the resistivity data the information from a horizontal core drilling, called NA01, is used. NA01 is drilled perpendicular to the two boreholes and thereby parallel to the tunnel wall and therefore the information can not be applied directly. 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 an estimated position of fractures and formation changes in the test boreholes, see Figure 6.

By comparing the result from Figure 5 with the estimated position of the structures found in NA01, it is clear that no fractures are resolved by the resistivity method. The fractures are presumably present but are not visible in the data. The fractures might be too narrow to be resolved or the data quality might be too poor. The data are most likely also influenced by 3D effects.

The transition from high resistivity to lower resistivity is probably a change in lithology from gneiss-granite to gneiss. The mineral composition of the rock mass is different and probably most important is the gneiss-granite contains less fractures than the gneiss (Wikman and Bergström, 1987). This would explain 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 metal 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.

D	Fracture with water, 40 l/min
E	Fracture with water + very fractured formation, 17 l/min
F	Fracture with water, 73 l/min
G	Formation change, left is Gneiss-Granite, right is Gneiss
H	Fracture with water, 30 l/min
I	Clay deposit ~ 0.1 m

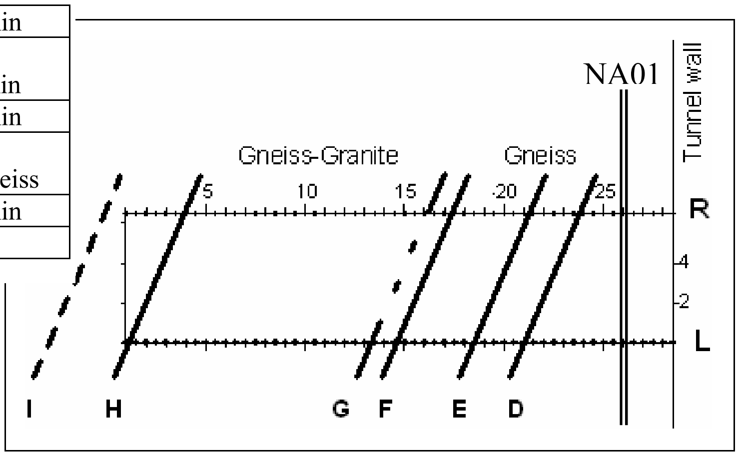

Figure 6. The estimated projected position of the structures found in NA01. The nature of these fractures is seen in the table at the left. The approximated position of NA01 is shown with two parallel lines three metre from the tunnel wall.

The numerical modelling showed that the water in the boreholes should not influence the resolution of the different arrays. The very high resistivity at the boreholes indicates clearly that the measurements not are influenced by the water in the boreholes.

The absolute error for the measurements proved to be rather high. Even though the investigated site was considered a low noise level area, approximately 5 to 10% of the data had to be removed in order to obtain an acceptable absolute error. For some of the electrodes the contact was not optimal. In addition the surrounding rock is highly resistive, limiting the transmitted current. To obtain better measurements the array measurement protocols and possibly the data acquisition software needs fine tuning.

Conclusion

Probe holes are drilled up to 40 metre ahead of a TBM in order investigate the rock conditions and the amount of water. If the geology is highly variable, representative information might not be obtained by drilling two or three probe holes because the area between the probes might be quite different. By performing small scale resistivity tomography between the boreholes a better image of the geological setting would be obtained and the operator would be better prepared the up-coming 40 metre ahead. The additional information might contribute to a more effective TBM advance. A development of an ERT system for horizontal boreholes is therefore important.

The numerical modelling showed that the best resolution of the inclined fracture zone was obtained using the multiple gradient array and a combination of AM-BN and multiple gradient. In addition the AM-BN proved to be the most insensitive towards non-parallel boreholes. The sensitivity pattern made it clear that the AM-BN has the largest sensitivity between the boreholes while the gradient has the largest close to the electrodes. This result can be used in the optimization of the protocols. The main conclusion was that AM-BN and multiple gradient array are the best for the actual measurements. The numerical modelling also showed that the water filled boreholes should not influence the results much.

The measurements in test boreholes showed that it most likely is possible to resolve the change from gneiss to gneiss-granite. The resistivity is low close to the tunnel wall because of the shotcrete. The very high resistivity at the boreholes proved that the low resistivity water in the boreholes did not have any visible effect on the result.

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. Some further adjustment of the data acquisition hardware and software is required. It is also important to improve the data processing software so the quality of the data can be evaluated and edited before inversion. 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.

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