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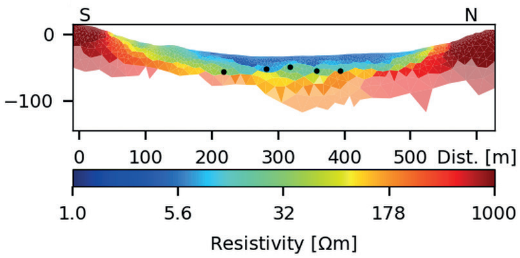

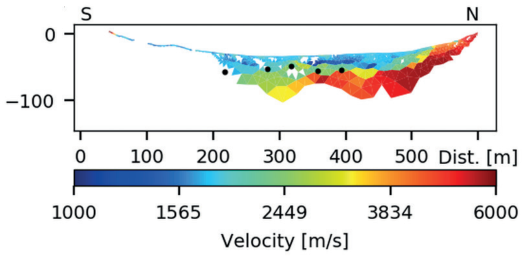

INTEGRATED USE AND INTERPRETATION OF DATA FROM GEOPHYSICAL AND NON-GEOPHYSICAL METHODS FOR SITE INVESTIGATION FOR UNDERGROUND CONSTRUCTION – Final report TRUST 4.2

Mathias Ronczka
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BeFo Report 179

Cover figure: See figure 19 in the report.

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INTEGRATED USE AND INTERPRETATION OF DATA FROM GEOPHYSICAL AND NON-GEOPHYSICAL METHODS FOR SITE INVESTIGATION FOR UNDERGROUND CONSTRUCTION – Final report TRUST 4.2

Integrerad användning och tolkning av data från geofysiska och icke-geofysiska metoder för planering och byggande i berg – Slutlig rapport TRUST 4.2

Mathias Ronczka

Kristofer Hellman

Roger Wisén

Torleif Dahlin

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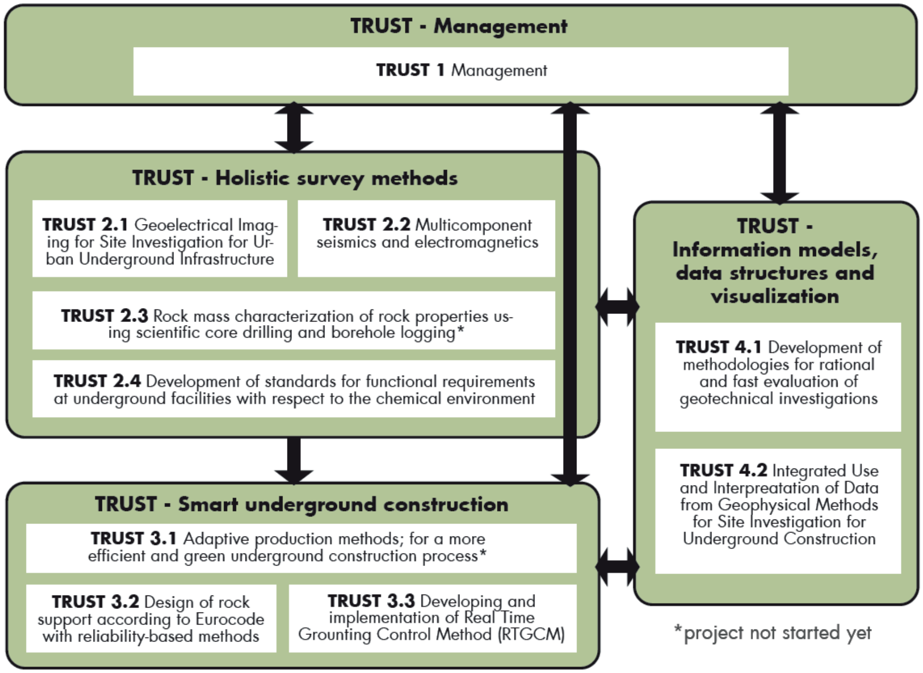
PREFACE

This project is a part of the TRUST (TRansparent Underground STructure) framework. The background of the TRUST project springs from a need to build more cost-efficient underground structures. While keeping costs at a minimum, the demands for sustainable, safe and easily maintainable underground structures are not to be neglected. Lifecycle costs for the structures must be considered. A significant driver for this is a recent development of stricter national and European regulations on energy and environment. The overall vision of the TRUST project is to:

- Promote research on development of sustainable urban underground infrastructure design
- Develop improved methods and tools for better planning, design, and construction of urban underground structures.

The TRUST framework consists of a set of subprojects focusing on holistic site investigation methods (TRUST 2.1, 2.2, 2.3 and 2.4), smart underground construction (TRUST 3.1, 3.2 and 3.3) and information models, data structure and visualization (TRUST 4.1 and 4.2). The structure of the TRUST framework is shown in the organisation chart below.

TRUST organization



*project not started yet

Subproject TRUST 4.2 deals with integrated use and interpretation of data from geophysical and non-geophysical methods for site investigation.

Researchers that participated in TRUST 4.2 are Marcus Wennermark, Kristofer Hellman, Mathias Ronczka, Thomas Günther, Torleif Dahlin, Roger Wisén and Matteo Rossi.

A reference group consisting of the following participants supported the project researchers with valuable suggestions and comments on the planning, activities, and results: Mehrdad Bastani (SGU), Lena Persson (SGU), Andreas Pfaffhuber (NGI), Sara Bazin (NGI), Christel Carlsson (SGI), Malin Norin (NCC), Robert Sturk (Skanska), Johanna Gottlander (Trafikverket), Thomas Sträng (SLL) and Per Tengborg (BeFo).

A scientific advisory board have contributed with valuable comments and advice. They consisted of the following persons: Lee Slater (Rutgers University, USA), Willian Powrie (University of Southhampton, UK), Geoff Watson as stand-in 2016 (University of Southhampton, UK), Andrew Binley (Lancaster University, UK), and Panagiotis Tsourlos joined the group 2016 (University of Thessaloniki, Greece).

The project was funded by Rock Engineering Research Foundation (BeFo) and SBUF, the latter with Skanska as industry partner with Robert Sturk as project responsible. Byggrådet provided complementary funding that made it possible to involve Roger Wisén. Lund University and LIAG (Leibnitz Institute of Applied Geophysics) contributed with in-kind funding. Additional funding that made the extensive field tests possibly came from Nova FoU, Skanska and the Swedish Transport Administration.

The seismic refraction and ERT measurements in the Lake Mälaren survey at Hägersten were collected in close collaboration with Rambøll Denmark A/S using the methodology developed in this project. Rambøll Denmark A/S also processed the seismic data. The survey was funded by Stockholm Water, and the project appreciate the permission to use the data as part of the research project.

Stockholm
Per Tengborg

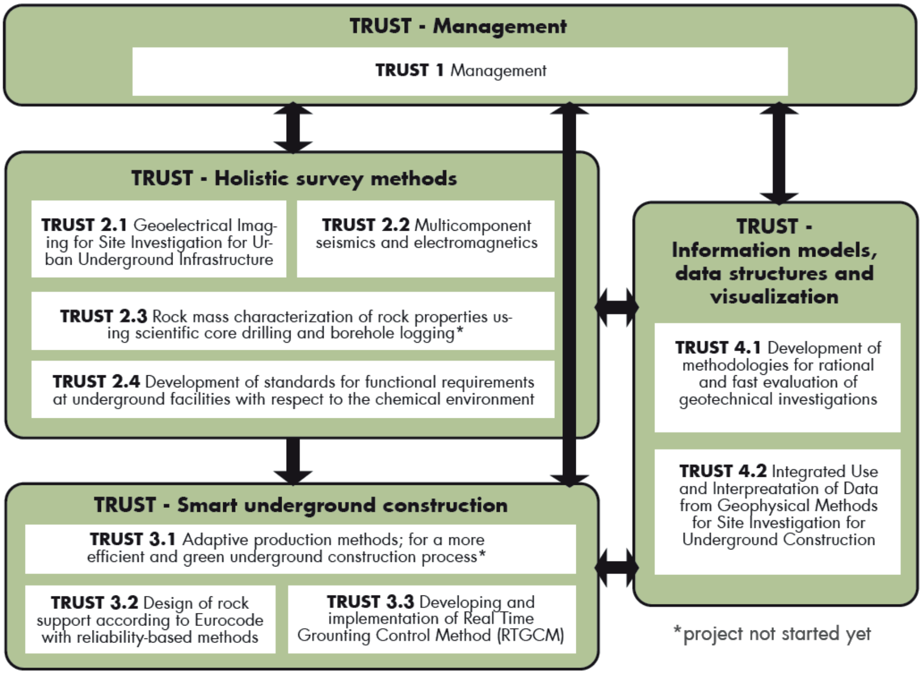
FÖRORD

Detta projekt är en del av TRUST (TRansparent Underground Structure) ramverket. Bakgrunden till TRUST-projektet kommer från ett behov av att bygga mer kostnadseffektiv underjordisk infrastruktur. Samtidigt som kostnaderna hålls nere får kraven på hållbar, säker och lättunderhållen infrastruktur inte försummas. Livscykelkostnader för infrastrukturen måste beaktas. En viktig drivkraft för detta är nya strängare nationella och europeiska bestämmelser om energi och miljö. Sammanfattningen av TRUST-projektet är att:

- Främja forskning om utveckling av hållbar urban infrastruktur under mark.
- Utveckla förbättrade metoder och verktyg för bättre planering, design och byggande av urban underjordisk infrastruktur.

TRUST-ramverket består av ett antal delprojekt som fokuserar på holistiska platsundersökningsmetoder (TRUST 2.1, 2.2, 2.3 och 2.4), smart underjordisk konstruktion (TRUST 3.1, 3.2 och 3.3) och informationsmodeller, datastruktur och visualisering (TRUST 4.1 och 4.2). Strukturen för TRUST-ramverket visas i organisationsschemat nedan.

TRUST organization



Delprojekt TRUST 4.2 behandlar integrerad användning och tolkning av data från geofysiska och icke-geofysiska metoder för platsundersökning.

De forskare som deltagit i TRUST 4.2 är Marcus Wennermark, Kristofer Hellman, Mathias Ronczka, Thomas Günther, Torleif Dahlin, Roger Wisén och Matteo Rossi.

En referensgrupp bestående av följande deltagare stödde projektets forskare med värdefulla förslag och kommentarer avseende planering, aktiviteter och resultat: Mehrdad Bastani (SGU), Lena Persson (SGU), Andreas Pfaffhuber (NGI), Sara Bazin (NGI), Christel Carlsson (SGI), Malin Norin (NCC), Robert Sturk (Skanska), Johanna Gottlander (Trafikverket), Thomas Sträng (SLL) and Per Tengborg (BeFo).

En vetenskaplig rådgivande kommitté bistod med värdefulla kommentarer och råd. Kommittén bestod av följande personer: Lee Slater (Rutgers University, USA), Willian Powrie (University of Southhampton, UK), Geoff Watson som stand-in 2016 (University of Southhampton, UK), Andrew Binley (Lancaster University, UK) och Panagiotis Tsourlos som anslöt 2016 (University of Thessaloniki, Greece).

Projektet finansierades av Stiftelsen Bergteknisk Forskning (BeFo) och SBUF, det senare med Skanska som branschpartner och Robert Sturk som projektansvarig. Byggrådet bidrog med ytterligare finansiering som gjorde det möjligt att knyta Roger Wisén till projektet. Lunds universitet och LIAG (Leibnitz Institute of Applied Geophysics) bidrog med in natura-finansiering. Ytterligare finansiering som möjliggjorde de omfattande fälttesterna kom från Nova FoU, Skanska och Trafikverket.

Mätningarna med resistivitetstomografi och refraktionsseismisk i Mälaren invid Hägersten genomfördes i nära samarbete med Rambøll Denmark A/S med hjälp av den metodik som utvecklats i detta projekt. Rambøll Denmark A/S deltog i processeringen av seismiska data. Undersökningen finansierades av Stockholm Vatten, och projektet uppskattar tillståndet att använda deras data som en del av forskningsprojektet.

Stockholm
Per Tengborg

SUMMARY

The purpose has been to develop and evaluate technology for the objective interpretation of geophysical and non-geophysical data to create better rock prognoses (engineering geological expectation models). This has been achieved by developing and adapting technologies for combined analysis and interpretation of geophysical, geological and geotechnical data in an objective and repeatable manner. Furthermore, it has been included to produce models that not only show the size of the (geo)physical properties but also the uncertainty about them.

The goal is new methodology for creating improved engineering geological models (rock quality predictions) based on integrated interpretation of geophysical and other data. The models shall provide information on the distribution of rock and rock qualities and uncertainty in the information. The project has focused on adapting, further developing and evaluating methods for so-called combined inverse numerical modeling (coupled or joint inversion). The work with interpretation software was based on existing algorithms using GIMLi (Geophysical Inverse Modeling Library), which is an open-source application library. Extensive efforts have been made to adapt, further develop, structure, improve and document the program code. In addition, different cluster analysis methods have been tested, which resulted in "mean shift clustering" being used in the continued work.

The focus has been on the geophysical methods of Electrical Resistivity Tomography (ERT) and Seismic Refraction Tomography (SRT). These are methods already in use for site-investigations for underground construction projects and are considered to be of greatest practical applicability. In addition, Induced Polarization Tomography (IPT, where IP gives chargeability) has been included because it can be measured simultaneously with resistivity with the same equipment, and so that data can therefore be collected without any significant additional cost. The algorithms have also been adapted to integrate data from drilling into the interpretation.

Calibration and evaluation of developed methodology and algorithms have been done against both synthetic model data and measurement data from actual tunnel objects. Extensive work with testing of algorithms against synthetic data examples based on different geological scenarios and real data has been performed to test its properties in different geological environments.

Field trials have been performed on a full scale to ensure that the right type of data with sufficiently good data quality control and positioning is available. An important factor in selecting test objects has been the availability of relevant reference data of sufficient quality. Field trials show that the developed concepts have high relevance and practical applicability. It is a great advantage to combine data acquisition with both methods, because the lack of data coverage or signal interference in data from one method is usually compensated by the other method's coverage there. This results in more complete results with less uncertainty. Joint interpretation through combined inversion makes image boundaries with changes in both electrical and seismic properties clearer and with less ambiguity. Subsequent cluster analysis can be a support for the engineering geological interpretation.

It is a strong recommendation to coordinate data collection with ERT and SRT, as inconsistencies in sensor and positioning often cause problems for combined inversion that are complicated and time-consuming to handle. In addition, it is generally considerably cheaper to conduct a coordinated field campaign with combined measurement of ERT and SRT than two separate, as planning, landowner contacts, logistics, interpretation and reporting are coordinated and need not be duplicated.

An important limitation of refraction seismic is that, in principle, the method does not provide any information about the properties of the rock below the upper surface of the rock. The refraction takes place in the upper surface of the rock; hence no part of the analysed signal penetrates below that level. This means that combined inversion of ERT and SRT as well as any subsequent cluster analysis will only yield results down to the top of the rock. This also means that the methodology we developed is of limited value in case of shallow rock, while the complementary ERT still gives valuable information below the depth of investigation (DOI) of SRT.

Continued work should include incorporating surface wave seismic data in the combined inversion. Surface wave seismic data have the advantage of providing information about the rock properties even below the upper surface of the rock, and that measurement results can be used for G modulus estimates. A challenge is being able to handle three-dimensional variation in the ground properties, and for surface wave seismic, also two-dimensional variation is a challenge. Furthermore, there is additional work required to include different types of a priori information in the combined inversion, as well as for cluster analysis. It would also be motivated to test other algorithms for structurally coupled inversion.

Keywords: Underground, infrastructure, urban, resistivity, induced polarisation, seismic refraction, tomography, inverse numerical modelling, inversion, coupled inversion, joint inversion, cluster analysis

SAMMANFATTNING

Syftet har varit att utveckla och utvärdera teknik för objektiv samtolkning av geofysiska och icke-geofysiska data för att skapa bättre bergprognoser (ingenjörsgeologiska förväntningsmodeller). Detta har skett genom att utveckla och anpassa teknik för kombinerad analys och tolkning av olika geofysiska, geologiska och geotekniska data på ett objektivt och repeterbart sätt. Vidare har det ingått att framställa modeller som inte enbart visar storleken av de (geo)fysikaliska egenskaperna utan också osäkerheten på dessa.

Målet är ny metodik för att skapa förbättrade bergtekniska modeller (bergkvalitets-prognoser) baserat på samtolkade geofysiska och andra data. Modellerna skall ge information om fördelningen av egenskaper i bergmassan och bergkvalitet, och osäkerhet i informationen. Projektet har fokuserat på att anpassa, vidareutveckla och utvärdera metoder för s.k. kombinerad invers numerisk modellering (kopplad eller kombinerad invers modellering). Arbetet med tolkningsprogramvara har utgått från existerande algoritmer med hjälp av GIMLi (Geophysical Inverse Modelling Library) som är ett programbibliotek med öppen källkod. Ett omfattande arbete har lagts ned på att anpassa, vidareutveckla, strukturera, förbättra och dokumentera programkoden. Vidare har olika metoder för klusteranalys testats, vilket lett till att ”mean shift clustering” företrädelsevis använts i det fortsatta arbetet.

Fokus har legat på de geofysiska metoderna Elektrisk Resistivitets Tomografi (ERT) och Seismisk Refraktions Tomografi (SRT). Det är metoder som redan används i anläggningsprojekt och som bedöms ha störst praktisk tillämpbarhet. Vidare har Inducerad Polarisations Tomografi (IPT, där IP ger uppladdningseffekt) ingått eftersom det kan mätas samtidigt med resistivitet med samma utrustning, och att data därför kan samlas in utan nämnvärd extrakostnad. Algoritmerna har anpassats för att integrera data från borrning och sondering i tolkningen.

Kalibrering och utvärdering av utvecklad metodik och algoritmer har skett mot både syntetiska modelldata och mätdata från verkliga tunnelobjekt. Omfattande arbete med test av algoritmerna mot syntetiska dataexempel baserade på olika geologiska scenarier samt verkliga data har utförts för att testa dess egenskaper i olika geologiska miljöer.

Fältförsök har utförts i full skala för att säkerställa att rätt typ av data med tillräckligt god kontroll av datakvalitet och positionering finns att tillgå. En viktig faktor i val av testobjekt har varit tillgången till relevanta referensdata av tillräckligt god kvalitet. Fältförsöken visar att de utvecklade koncepten har hög relevans och god tillämpbarhet. Det är en stor fördel att kombinera datainsamling med båda metoderna, eftersom bristande datatäckning eller signalstörningar i data från den ena metoden oftast kompenseras av att den andra metoden har täckning där. Detta medför mera kompletta resultat med mindre osäkerhet. Samtolkningen genom kombinerad inversion gör att lagergränser med förändring i både elektriska och seismiska egenskaper avbildas tydligare och med mindre osäkerhet. Påföljande klusteranalys kan vara ett stöd för den ingenjörsgeologiska tolkningen.

Det är en stark rekommendation att samordna datainsamling med ERT och SRT, eftersom skillnader i sensorpositionering och inkonsekvenser mellan inmätningarna ofta medför problem

för kombinerad inversion som är komplicerade och tidsödande att hantera. Vidare är det generellt sett betydligt billigare att genomföra en samordnad fältkampanj med kombinerad mätning av ERT och SRT än två separata, eftersom planering, markägarkontakter, logistik, tolkning och rapportering samordnas.

En viktig begränsning med refraktionsseismik är att metoden i princip inte ger någon information om bergets egenskaper under bergets överyta. Refraktionen sker i bergets överyta med följd av att ingen del av den signal man analyserar går djupare än så. Detta medför att kombinerad inversion av ERT och SRT, samt eventuell efterföljande klusteranalys, endast ger resultat ned till bergets översta del. Det gör att den metodik vi utvecklat är av begränsat värde i fall med ytligt berg, däremot ger ERT fortfarande viktig kompletterande information under det nedträngningsdjup som SRT ger.

Fortsatt arbete bör inkludera ytvågsseismik i den kombinerade inversionen. Ytvågsseismik har fördelen att ge information om bergets egenskaper även under bergets överyta, samt att det från mätresultaten går att uppskatta G-modulen. En utmaning är att kunna hantera tredimensionell variation i markens egenskaper, där även tvådimensionell variation är en utmaning för ytvågsseismik. Vidare finns det arbete kvar vad gäller att inkludera olika typer av a prioriinformation i den kombinerade inversionen, liksom för klusteranalys. Det skulle också vara motiverat att testa andra algoritmer för strukturellt kopplad inversion.

Nyckelord: Underjordisk, infrastruktur, urban, resistivitet, inducerad polarisation, refraktionsseismik, tomografi, invers numerisk modellering, inversion, kopplad inversion, saminversion, klusteranalys

TABLE OF CONTENTS

1. INTRODUCTION

There is clear trend that new infrastructure is placed underground in urban areas as a consequence of growing cities and associated lack of space, higher demands on communication facilities, environmental demands for example. Careful site investigations are essential to reduce the risk for delays and excessive costs in connection with potential problem zones, as well as negative impact on the environment. Mechanical and hydraulic properties of soil and bedrock are the primary focus of a site investigation for underground construction. Furthermore, the depth to bedrock is a key parameter for the design and construction of underground infrastructure. Geotechnical drilling and sounding are traditionally dominating in site investigation in many countries including Sweden. These methods provide one dimensional (1D) information with high vertical resolution but with very limited spatial resolution since there is no information between the investigation points. It is common to interpolate and extrapolate such point data to extend the information to 3D, but this can lead to severe problems because the conceptual models do not take into account the inherent complexity of the geo-environment.

Geophysical investigations have the advantage of providing continuous images of variation in the subsurface properties, but each method has limitations and ambiguities in the interpretation. Combination of different geophysical methods and high-quality geotechnical drilling is a way of securing a reliable base for an engineering geological conceptual model of good quality, which minimises the risk of encountering unexpected geological conditions. The geophysical investigations should be used in an early stage, so that the results can be used as a base when designing the detail investigations with drilling and sampling. The results of the drilling and sampling can then be used to refine the interpretation of the geophysical data.

In order to facilitate this understanding, the geophysical methods need to be cost effective and relatively easy to understand for someone who is not a professional geophysicist.

Electrical Resistivity Tomography (ERT) is an established site investigation method for tunnels, which has been used extensively in the last decades (e.g. Dahlin et al. 1999; Ganerød et al. 2006; Danielsen and Dahlin 2009; Rønning et al. 2014). The method provides continuous models of variations of the electrical properties in two (2D) or three dimensions (3D) that can be linked to variations in the hydraulic and mechanical properties of the rock.

Refraction seismic is since several decades an established method that gives information on the soil depth and mechanical properties of the rock (e.g. Sjögren 1984). If refraction seismic and ERT are used at an early stage in the site investigation, it provides a good overview of structural, mechanical and hydrogeological conditions and a basis for planning of drilling and sampling points so that these end up in representative positions and minimize the risk for missing critical areas (Ganerød et al. 2006; Wisén et al. 2012). The results of these in situ drilling studies are then used to verify and improve the preliminary interpretation of the geophysical results.

Combined interpretation of data from different geophysical methods and geotechnical drilling is not a trivial task, and different individuals might arrive at different conceptual models depending on background and experience. It is important to work on the development and adaption of an improved methodology for combining different methods to map variations in properties of the ground to increase the reliability of rock mass and rock quality evaluation. The approach of joint interpretation and inversion of geophysical and non-geophysical data sets lead to more reliable subsurface models and thus a better prediction of rock mass and rock quality. Furthermore, the aim is to develop the usability of geophysical methods by presenting a model that not only shows the magnitude of the physical properties but also the uncertainty in these.

This work addresses integrated interpretation between different types of geophysical data, with possible addition of other data. The use of more than one method can be motivated by using an analogy to the human sensory apparatus. In order to deduce the true nature of our surrounding, we need to use several of our sensory impressions (or data input) to produce a credible opinion about our reality. With experience, we can also deduce that it's an apple that we are first looking at, touching, smelling and finally tasting. With our geophysical instruments and geotechnical methods, we can locate and classify a possible fault zone without excavating it.

The concept of joint inversion of geophysical data was first introduced by Vozoff & Jupp (1975), their main motivation being the ability to avoid ambiguities following the use of a single method on its own. There are several ways to obtain multiple data for a description of the substrata:

1) Collecting several datasets with different methods that sense the same geophysical properties (e.g. Sasaki 1989),

2) Collecting several datasets with methods that sense different geophysical properties (e.g. Lines et al. 1988).

Using the first approach can be motivated by the fact that some methods have different resolution with depth and that several methods for a single parameter can facilitate a better overall resolution of a model. Using the second approach may be motivated by one methods ability to detect e.g one specific material layer boundary, while another method can detect fissures that may appear in the interface. Whatever reason, if the information obtained by several geophysical can be more useful while used in cooperation; this could be a good reason for the recovery of this information.

After the collection of site-specific geophysical data has been carried out, there are three main approaches for processing the data to create a unified site description:

1) Manual joint interpretation, the interpreter uses the data and experience to create a unified model.
2) Inversion methods that employ hydrological or petrophysical links to relate the geophysical properties to each other (e.g. Tryggvason and Flóvenz 2002). The links are often unknown and affected by a multitude of rock properties, including state variables regarding these properties (e.g. Nur et al. 1998).
3) The structural approach based on the assumption that near surface geophysical properties are co-dependent from a structural viewpoint (Haber and Oldenburg 1997; Gallardo and Meju 2004; Linde et al. 2008).

By assuming that the changes in the different geophysical parameters occur at the same interfaces, for example geological boundaries or the groundwater level, changes are handled by the use of a function. This function, referred to as the cross-gradient function, enables quantification of structural similarities between two separate models.

A major concern for someone who is not familiar with the joint inversion methods may be that the method can produce either one final model or one model for each method. Generally, when employing geophysical methods sensitive to the same physical parameter, the result is a single model. Conversely, when employing geophysical methods that are sensitive to different physical properties, the result is one model per geophysical method. In order to facilitate automated interpretation of the latter, the use of a statistical tool such as cluster analysis could prove useful (e.g. Tronicke et al. 2004; Paasche et al. 2006; Dietrich and Tronicke 2009).

2. AIMS AND DELIMITATIONS

The aim of this project is to develop and adapt methodology for combined analysis of geophysical and rock technical properties in an efficient and objective manner. The goal is to provide more relevant and reliable information on depth to bedrock and variations in rock quality for refinement of the engineering geological conceptual model than results from each method interpreted separately can do. The objective is to reduce the risk of delays and increased cost, as well as adverse environmental impact, in connection with underground infrastructure construction.

The aim is to develop and evaluate technologies for objective joint inversion of geophysical and non-geophysical data to provide better rock quality prognoses (expectation models) with analysis of uncertainty in the models (risk analysis) included. Furthermore the aim is to develop the usability of geophysical methods by presenting a model that not only shows the magnitude of the (geo)physical properties but also the uncertainty in these.

The geophysical methods that have been in focus are electrical resistivity tomography (ERT) and seismic refraction tomography (SRT), the latter restricted to seismic compression wave velocity. At one of the studied sites, radio magneto-telluric (RMT) data were also included, the results are however not presented in this report but available in an article published jointly with Uppsala University and SGU (see Appendix 1).

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3. METHODS

Geophysical methods have the advantage of making it possible to create two dimensional (2D) or three dimensional (3D) models of the variation in ground properties at a reasonable cost. This is not possible with methods such as geotechnical sounding and drilling, which can provide highly detailed data but only in the point where the drilling takes place. Hence, volume cover is a major advantage of geophysical methods, but it is important to be aware of the limitations that are associated with the techniques. All geophysical methods have limitations in depth coverage and resolution, which will vary depending on instrument, sensor separation, setup, geology, noise conditions, etc. With a smart combination of geophysics and point based investigations the methods can support each other to give a good overall picture of the site conditions.

3.1 Electrical Resistivity Tomography (ERT)

Geoelectric or electrical resistivity tomography (ERT) surveys is a standard tool for investigating the subsurface for a number of different applications. Usually, measurements are performed along profiles to image the subsurface resistivity distribution in vertical cross sections, i.e. two-dimensional (2D) surveying. However, three-dimensional (3D) and borehole survey approaches can also be used. In addition to land-based surveying, it is possible to measure in water, with the electrode floating at the surface or placed on the bottom of the lake or sea.

A measurement is conducted using four electrodes, whereas two electrodes are used for the current transfer (current dipole) and two for the voltage measurement (potential dipole). A schematic sketch of an ERT measurement is shown in Figure 1. Current pulses are transmitted galvanically using stainless steel rods or metal plates connected to the ground. By increasing the distance between the current and potential dipole, information from larger depth can be obtained. In order to speed up the measurement process multi-electrode cables are laid out and connected to several tens of electrodes (Figure 2).

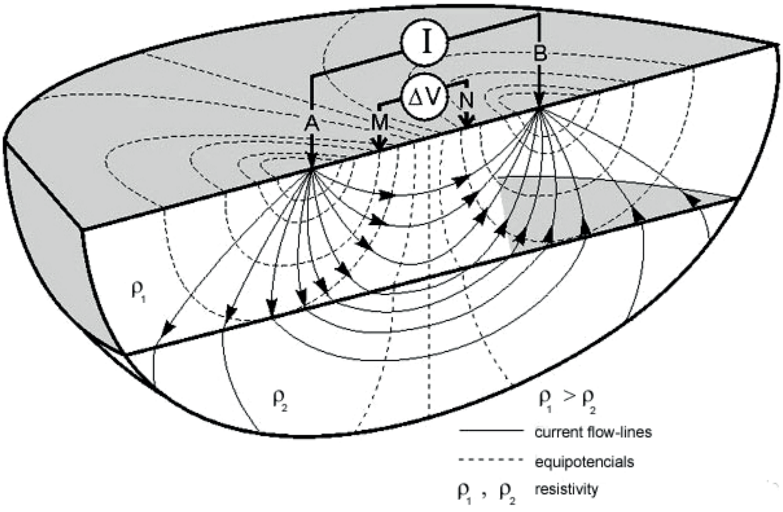

Figure 1. Schematic sketch of an ERT measurement (Knoedel et al. 1997) with the current electrodes A, B and the potential electrodes M, N. The equi-potential lines are dashed, while the current flow direction is shown by the solid lines.

Collected data are apparent resistivities, which are weighted means of the resistivites within the investigated volume. A data inversion is needed to reconstruct a subsurface model of the resistivity distribution that would produce the measured data within a specific error range.

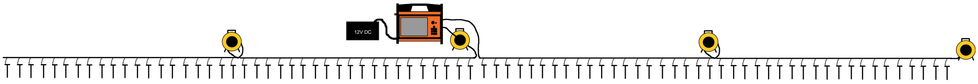

Figure 2. Schematic sketch of a typical multi-electrode ERT measurement spread.

Resolution is decreasing with depth, which means for example that a layer must be thicker to be detectable at a larger depth. Furthermore, the equivalence principle means that different combinations of resistivity and thickness for a layer can lead to very similar measured data, so that it with some uncertainty in data added is impossible to determine which the case is. This calls for combined interpretation with other types of data

3.2 Induced Polarisation Tomography (IPT)

Time-domain IP data (induced polarisation) can be measured together with resistivity, providing information about the electrical chargeability of the subsurface (e.g. Johansson 2016). The sketch in Figure 3 attempts to explain how the measurements are made. The chargeability provides information related to the inner structure of the materials and can sometimes be used for separating different geological materials that do not stand out with different resistivity. This can be for example different bedrock units or intrusive dykes, and it has been shown that in some cases the variations in chargeability can be related to variation in hydraulic properties. Furthermore, joint inversion of resistivity and IP data can in some cases reduce ambiguities in the resistivity model, thereby reducing the uncertainties in the results (Meldgaard Madsen et al. 2017).

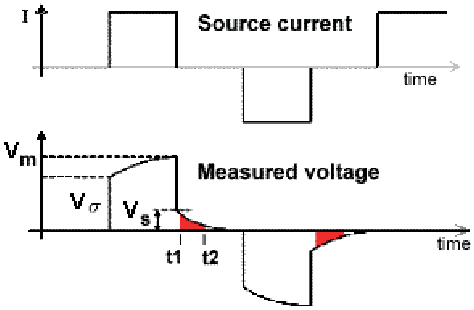

Figure 3. *Sketch of a transmitted current pulses and measured voltage for a case with significant IP effect (chargeability). Resistivity is calculated from voltages measured while current is transmitted whereas the IP effect is a measure of the remaining voltage after current has been turned off.*

A limitation of the IP method is that it is much more difficult from a measurement technical point of view compared to resistivity. This is related to the much smaller measured signals, which are measured closer to a transient change in transmitted current. In practical application this means that data are not always useful because of signal-to-noise problems, which can often be the case in urban environments.

3.3 Seismic Refraction Tomography (SRT)

Seismics is one of the oldest geophysical exploration methods. Generally, acoustic signals generated by a source (hammer, explosives or vibrator) and recorded by geophones (on land) or hydrophones (in water). One special application is seismic refraction, which is used for near surface investigations.

A seismogram consists of four major parts, direct-, refracted-, reflected wave and surface waves. A refracted wave only appears when the velocity of the acoustic wave increases with depth. Figure 4 shows the principle of refraction seismics. If the incidence angle is such that the wave is refracted by 90° it travels along the interface between two layers of different velocities. Seismic waves are emitted and travel back to the surface. The envelope of the returning waves moves with the velocity of the bottom layer. The refracted angle can only be larger than the incident angle, if the velocity increases with depth. If a low velocity layer is present, the seismic wave is refracted towards the normal of the interface and no refracted wave can occur. After the first arrival picking travel times between the source position and geophones are used to as data input for an inversion, which estimates a velocity distribution of the subsurface that would lead to the measured travel times. (Sjögren 1984)

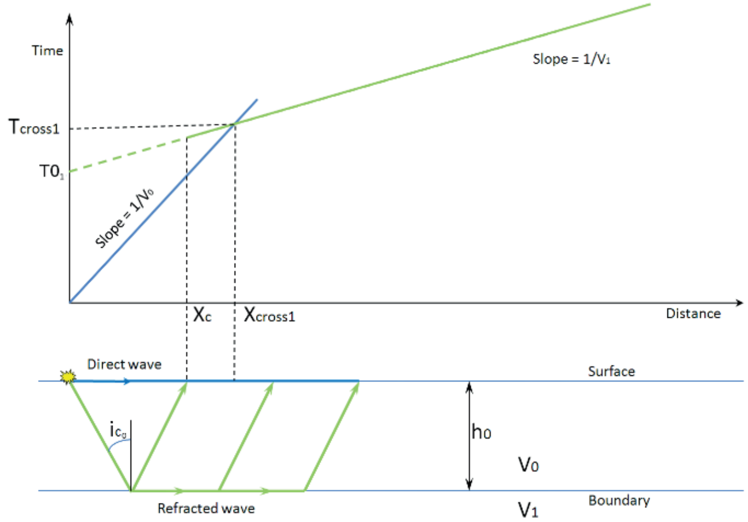

Figure 4. Principle of a seismic refraction measurement. The top picture shows the travel time vs. geophone offset indicating that the refracted wave occurs at x_c *for the first time and travels with the velocity of the lower medium.*

The seismic P wave velocity is an interesting parameter as it can be linked to strength, where Sharma and Singh (2008) showed a strong correlation for the seven types of rock they tested.

A limitation of seismic refraction is that it will not give any information about low velocity material below a high velocity layer, which means that the low velocity layer will be hidden for the method. In fact, no further information is revealed by the method below the upper edge of a high velocity layer, which in practical application means that the method gives very little depth coverage in situations with shallow hard rock. (Sjögren 1984)

3.4 Joint data acquisition

It is essential with accurate navigation and positioning when carrying out data acquisition for site investigation for infrastructure projects. Navigation in this case means to find the right location in relation to the planned infrastructure so that the data are acquired in the right area. For infrastructure projects this can be taken care of by having a surveyor put out stakes along the planned survey line, or by the use of GPS and compass in connection with placing the cables. Positioning on the other hand is done in immediate connection with the field data acquisition, for example by measuring the location of every sensor with a real time corrected GNSS (Global Navigation Satellite System, e.g. GPS).

Due to topography, vegetation, rock outcrops, etc. the actual sensor positions will generally differ from an ideal planned layout. This is not a problem when a single method is used, as long as the actual positions including the topography are determined in a sufficiently accurate way. If however the acquired data are intended for joint interpretation via joint inversion, as described below, it is likely that problems occur due to differences in sensor location between the methods and discrepancies in positioning accuracy. Such problems can normally be handled but it tends to require a lot of man-time which would make it expensive in routine application. A way to overcome such problems is to acquire the different types of data simultaneously, which makes it possible to ascertain that the sensors are located in exactly the same locations or immediately next to each other.

ERT and IPT data are acquired with the same instrument using the same electrode spread, so positioning is automatically the same. In the following ERT will refer to a combination of these. SRT data acquisition is carried out with geophones (on land) or hydrophones (in water) as sensors, with different cables than for ERT, so two complete sets of equipment must be set up in the field. A significant amount of the time and cost spent in connection with a field survey is however related to preparations such as reconnaissance, landowner contacts, staking out the line, mobilisation, etc., so the extra time and effort of acquiring data with and additional methods when doing ERT or SRT is less than for two separate surveys planned and carried out independently.

We have developed and tested methodology for simultaneous acquisition of land-based as well as underwater combined ERT and SRT. These have successfully been tested in full scale at a number of sites (Figure 5).

Figure 5. Field surveying with combined ERT and SRT across the water body between Äspö and Ävrö in progress (photo: Torleif Dahlin).

3.5 Inversion of geophysical data

In a general sense, inversion describes the estimation of a subsurface model from geophysical data, whereas the calculation of synthetic data based on a model is called forward calculation. Both are also known as forward modelling and inverse modelling. The basic equation behind inversion is

$$\mathbf{d} = \mathbf{G}\mathbf{m}$$

Here, the vector $\mathbf{d}$ holds the data (apparent resistivities, traveltimes) and $\mathbf{m}$ the model parameter (resistivities, velocities). Both are connected by the forward operator $\mathbf{G}$, which contains all the mathematical and physical relationships. If one chose a model $\mathbf{m}$ and $\mathbf{G}$ is given, synthetic data $\mathbf{d}^{syn}$ can be calculated. This process is called modelling. Now we could change the model vector and calculate synthetic data $\mathbf{d}^{syn}$ until they match the observed data $\mathbf{d}^{obs}$. The automated way of doing that is called inversion. Hereby, the forward operator $\mathbf{G}$ is brought on the left-hand side by inverting it.

$$\mathbf{m} = \mathbf{G}^{-g}\,\mathbf{d}$$

$\mathbf{G}^{-g}$ is called the generalized inverse of $\mathbf{G}$. Only a square matrix can be inverted (same number of rows and columns). So, $\mathbf{G}^{-g}$ contains every operation that is needed to make $\mathbf{G}$ invertible. Mathematical formulations behind inversion and modelling can be arbitrarily complicated. In case of ERT and refraction seismic, equation 1 is not linear. The process of linearization demands an iterative way to find a model that explains the observed data. In most cases more model parameter has to be estimated than data are available. This is known as an underdetermined inversion problem. Additional constrains for the model space are needed, which are known as smoothness constraints that prevent unreasonable sharp gradients of model parameter.

3.6 Joint inversion of different types of data

Software for joint interpretation of has been developed within the project. The development has been done within the framework of GIMLi (Geophysical Inversion and Modelling Library) (Rücker et al. 2017)[1]. The development required much more time and efforts than anticipated, largely because the software was ported from Matlab to Python in an early phase of the project. The migration of the software development environment was a much larger undertaking than foreseen, but it is now well functioning under Python which is a major step forward for future developments and availability.

A rather new approach is the structurally coupled joint inversion of different methods. The basic assumption is a correlation between model parameters of different methods, in this case ERT and SRT (see Figure 6). According to earlier research both are influenced by the pore structure and pore filling, making this assumption valid. In this project an algorithm was used that combines the roughness (contains structural information of the model) of the used methods (Hellman et al. 2017).

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[1] https://www.pygimli.org/

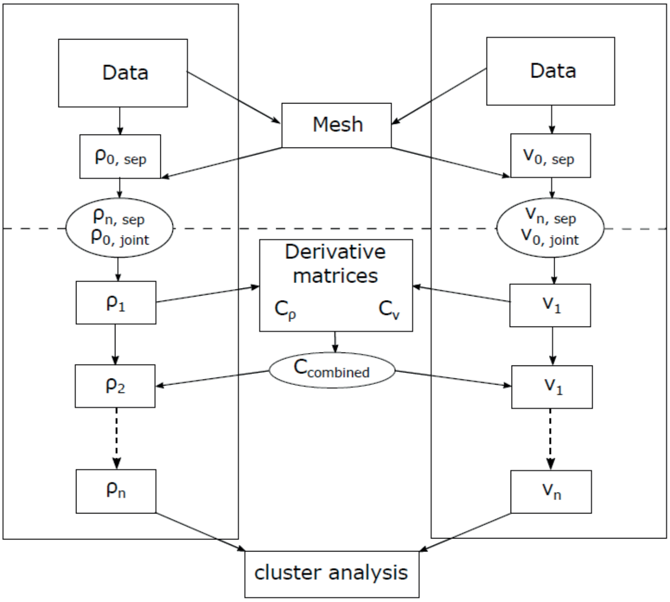

Figure 6. *Scheme of the coupled inversion approach, in which one inversion influences the roughness C of the other (Hellman et al. 2017).*

The algorithm for the structurally coupled joint inversion was first tested on several synthetic examples. One of them, the equivalence model, is shown here. It consists of a low resistive background with an imbedded thin layer of varying resistivity. The underlying geometry is shown in Figure 7. The resistivities and velocities assigned to the four different units are shown in Table 1. Thus, the resistivity model is a three-layer case with the second layer separated in three parts, whereas the seismic model shows just a two-layer case with a parameter contrast in 10m depth (lower boundary of the second layer). The main objective is to resolve the high resistive unit (3) in the middle of the model. This synthetic model also shows the equivalence inherent to ERT. That means, a layer with a certain geometry and resistivity would generate nearly the same response if its thickness is doubled and its resistivity halved, or vice versa.

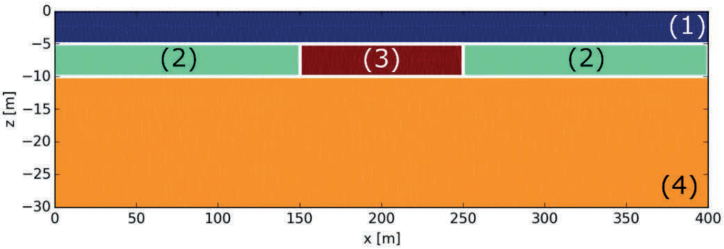

Figure 7. *Underlying geometry for the synthetic equivalence model with the different units numbered from 1 – 4.*

Synthetic data were generated using a 5m spacing for electrodes and geophones, using a gradient array type protocol for ERT and a shot point separation of 10m. Noise was added to simulate realistic conditions.

Table 1. Resistivity and velocities assigned to the model parts 1 – 4.

	Resistivity [Ωm]	**Velocity [m/s]**
(1)	50	2000
(2)	200	2000
(3)	500	2000
(4)	50	5000

The inversion results for the joint and separated inversions are shown in Figure 8 together with the underlying geometry (white outlines). As expected, the resistivity distribution of the separated inversion result in Figure 8a images the high resistive layer larger compared to the underlying geometry with a lower resistivity, whereas the velocity distribution in Figure 8b shows the two layer case with good depth agreement. The joint inversion uses the structural information from the seismic result, i.e. the lower interface of the second layer to constrain the ERT result. As a consequence, the high resistive layer in Figure 8c matches the underlying geometry better compared to the separated inversion result. The estimated resistivity is also very close to 500 Ωm, which was used for the modelling. This example shows that the structurally coupled joint inversion can overcome the inherent equivalence of ERT, by using structural information from seismic refraction.

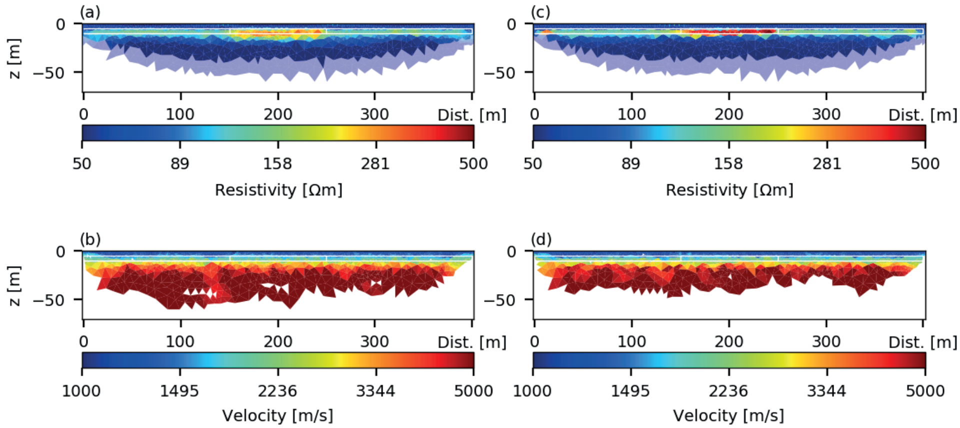

Figure 8. Inversion results for the synthetic equivalence case, showing the resistivity (a) and velocity (b) distribution of the separated inversion and the joint inversion results in (c) and (d).

In addition to using information from different geophysical methods to constrain the structure between each other, tests have been made using e.g. data from geotechnical drilling as a priori data to constrain the depth of layer interfaces.

3.7 Cluster analysis

Cluster analysis is a tool to find similarities and to group data sets automatically. Three of the most common algorithms were tested within the project, revealing advantages and limitations. Figure 9 shows the tested algorithms and how they perform for different data distributions. The k-means algorithm for example needs the number of clusters as an input, which means that a-priori information regarding geologic units are necessary making the choice of cluster numbers biased. The DBSCAN algorithm clusters the data based on their density centres. Two input parameters are necessary. The first is the length ε to an adjacent point and the second one is the minimum number of points which are reachable within the distance ε. However, a variation of the mean-shift algorithm has proven to be useful, as it is data driven and the only additional input parameter besides the data is a bandwidth. The bandwidth is given with a quantile as input, which is defined to be between zero and one. Generally, the smaller the quantile, the larger the number of clusters are used to represent the data.

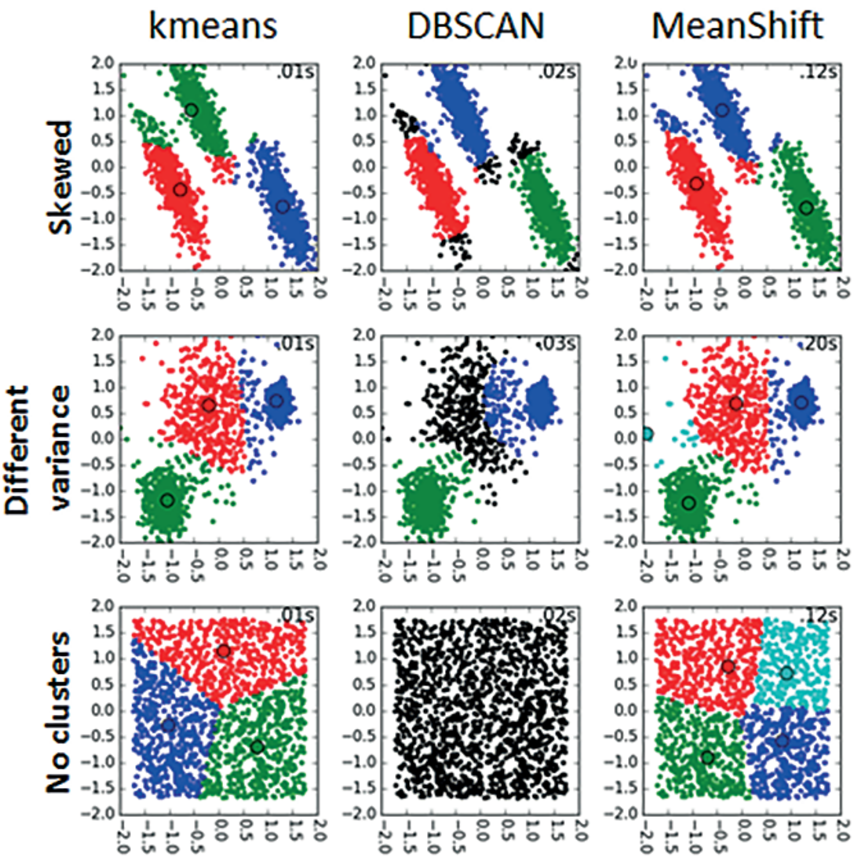

Figure 9. *Example of k-means, DBSCAN and mean shift clustering on different artificial data sets.*

3.8 Model reliability

One method to distinguish good and poor resolved model parts from each other is to use the coverage, which is based on the sensitivity of the geophysical method. The sensitivity gives information about how a measured data point changes if the model parameter changes. For example, how the measured apparent resistivity changes if the subsurface resistivity is changing. In general, it shows how a single 4-point measurement performs. The basis of a sensitivity calculation is generally a homogeneous half space. However, it can also be done for an arbitrary resistivity distribution as well, for example for a final inversion result.

One way of assessing the model reliability is to use the coverage, which is the cumulative sensitivity for one model cell, i.e. the sum of all 4-point sensitivities. This approach was used and explained briefly in Ronczka et al. (2017). The computationally more expensive method of calculating resolution radii after Friedel (2003) based on the model resolution was used as a comparison. Figure 10 shows that the coverage (bottom) is closely connected to the resolution radii (top). Both are showing the same pattern for the subsurface with high resolution radii corresponding to low coverages and low resolution radii to high coverages. The advantage of the coverage is that it is easy and fast to compute and comes together with the inversion result, whereas a comparable high effort is needed to compute resolution radii. To use the coverage for fading out unreliable model parts, the most convenient way is to map the coverage for a final model to the range 0 – 1. Then, two thresholds are defined separating model parts which high, medium and low reliability, whereas the low reliability zone is completely faded out.

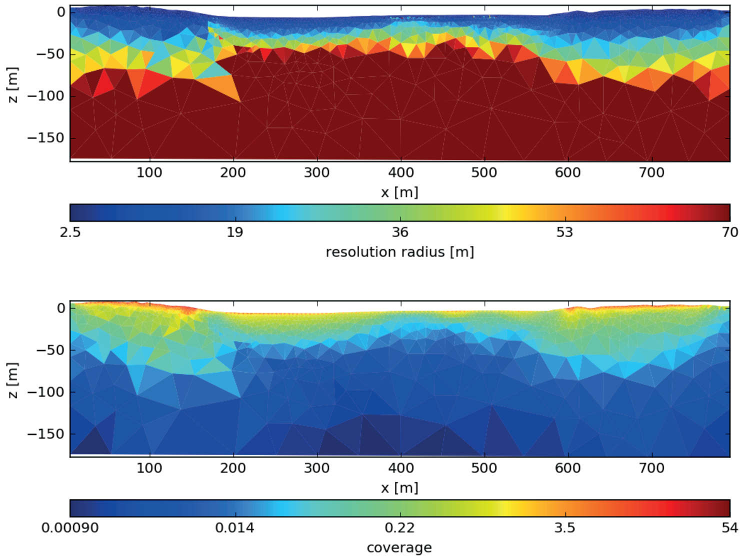

Figure 10 Distribution of resolution radii (top) and the coverage (bottom) for an arbitrary inversion result.

4. FIELD TESTS AND RESULTS

A number of selected examples from the field tests made in the project are presented below. In addition to these sites test have been carried out at ESS in Lund where we acquired ERT, IPT and SRT ourselves, and successfully inverted the data together.

At Kv Färgaren in Kristianstad and Varbergstunneln we acquired only the ERT and IPT data ourselves, which we intended to invert jointly with SRT data acquired within the TRUST 2.2 project. Because of problems with sensor coordinates and inconsistencies in data cover between the methods we did however not manage to do any meaningful joint inversion with these datasets.

We have also worked on data from pre-investigations for a new stretch of E16 in Norway. The different types of data were acquired simultaneously by Rambøll A/S so that the sensor locations were well controlled, and joint inversion of ERT, IPT and SRT worked well. Due to the velocity structure, with a thin soil cover on top of the bedrock, the depth information from SRT is however very shallow. As a consequence, the joint inversion cannot contribute with any enhancement of the models below the shallow soil layer.

4.1 Äspö Hard Rock Laboratory

The main objectives of the Äspö Hard Rock Laboratory survey were the fracture detection along the access tunnel of the underground storage and to use the data set as a test case for the joint inversion algorithm. The test site is located on the east coast in southern Sweden (see Figure 11) and managed by SKB to develop techniques for the underground storage of radioactive waste. Fracture zones were located during the pre-investigation phase for the tunnel construction.

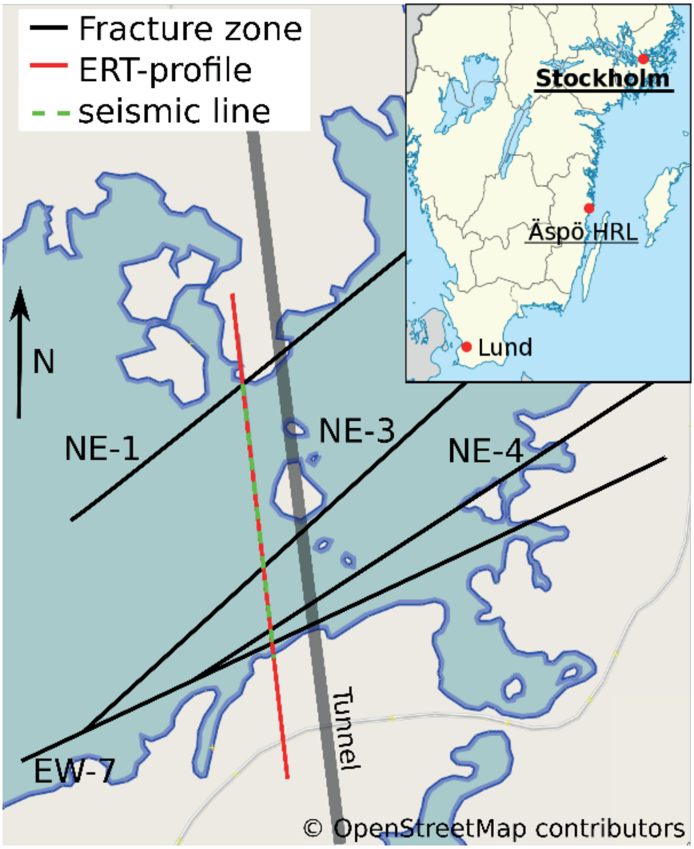

Figure 11. *Äspö HRL location and scheduled profile line for ERT and SRT measurements (red and green line). The tunnel is marked grey and the known fracture zones with black lines.*

Measurements were conducted along a profile following the direction of the access tunnel to the underground facilities (Figure 11). Electrode cables designed for underwater use, with electrode spacing 5 m, were deployed to the sea bottom from a small boat (Figure 5), and linked together with land-based electrode layouts. Hydrophone cables with sensor spacing 5 m were placed on the sea bottom alongside with the ERT cables so that the electrodes and hydrophones were placed next to each other.

The collected data were of good quality regarding the DC resistivity values. However, the recorded time domain IP (induced polarization) data could not be used. A synthetic study revealed that the ERT data are at some profile parts contaminated by 3D effects, which had to be considered during the interpretation. Results for separated and joint inversion is shown in Figure 12.

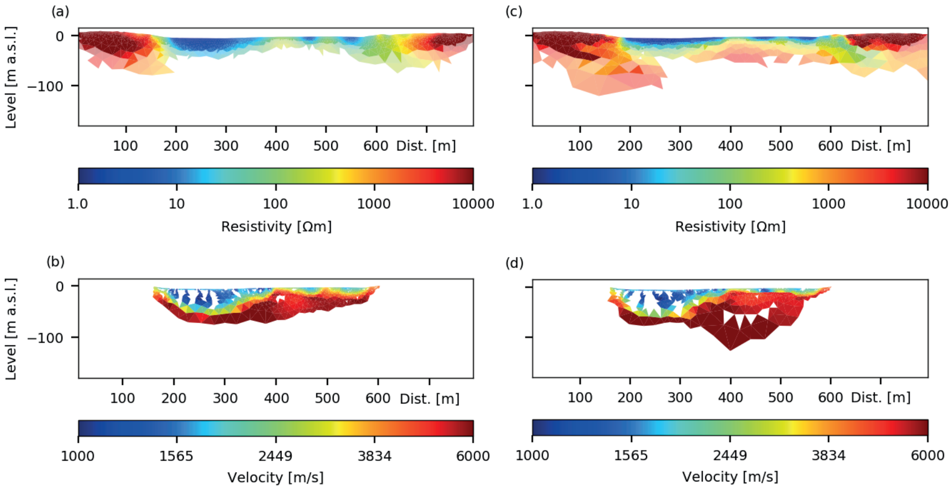

Figure 12. Inversion result for ERT (top) and seismic refraction (bottom), whereas separated inversions are shown in (a), (b) and the joint inversion in (c), (d).

A comparison between the separated (Figure 12a and b) and the joint inversion results (Figure 12c and d) shows a clear improvement when it comes to the detection of the bedrock. The sharp interface that was image by seismic refraction constrained the ERT inversion such that a better bedrock estimation is possible. Furthermore, the water bearing fracture zone at x > 600m appears more clearly as a low resistive zone. The gaps in the seismic models are caused by lack of raypath cover in the inverse model interpretation.

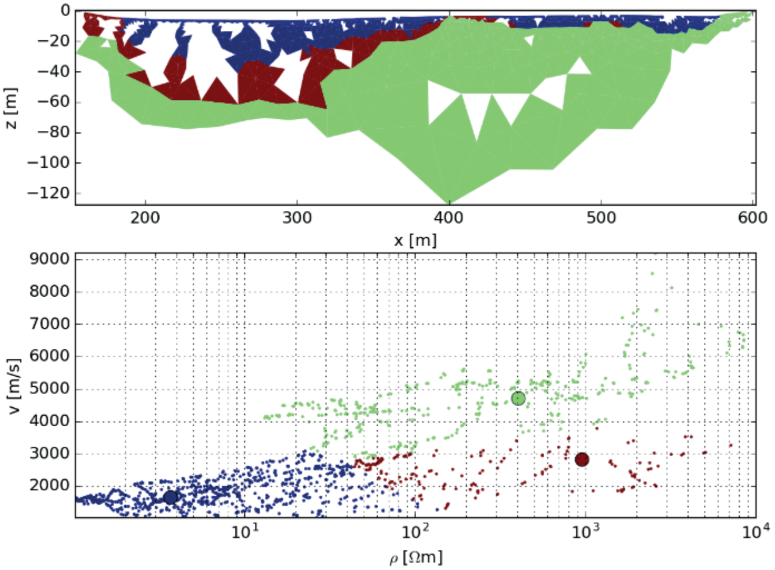

Figure 13. Mean shift clustering of the joint inversion result

The mean shift cluster algorithm was used to visualize areas that show the same behaviour or trend of the parameter (resistivity, velocity). Only the joint inversion result was clustered, as it is considered to be the final result for this test site. Figure 13 shows three main clusters representing the bedrock (green) with a sedimentary layer on top (blue) and an intermediate zone (brown) in between, as shown in the geological interpretation in Figure 14. The intermediate zone can be interpreted as till or coarse grained sediments, possibly in combination with fractured parts of the bedrock. The clustered result treats everything as bedrock with a seismic velocity > 3500 m/s. This part includes also very low resistivities, because the algorithm cannot distinguish between fractured water bearing bedrock (high velocity and low resistivity) and unfractured bedrock (high velocity and high resistivity).

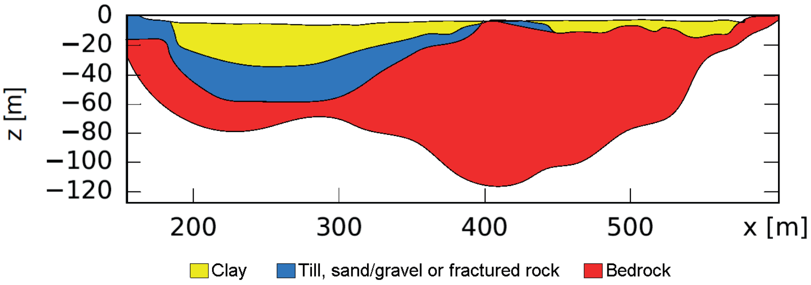

Figure 14. Geological interpretation based on cluster result.

4.2 Stockholm Water Passage

Combined surveys with underwater ERT and SRT layouts were carried out in two full scale tests in central Stockholm, one in Lake Mälaren and one in Saltsjön. The former was made in sweet water and the latter in brackish water, where the salinity of the water has an impact on the resolution capability of ERT dependent on the conductivity of the water. The surveys were conducted to appraise the feasibility of geophysical underwater surveys in an urban environment for mapping variations in depth to bedrock and to find water bearing fracture zones and variations in rock quality as pre-investigation for tunnel projects under water passages.

The data acquisition in Lake Mälaren was carried out along six profiles with location as shown in Figure 15.

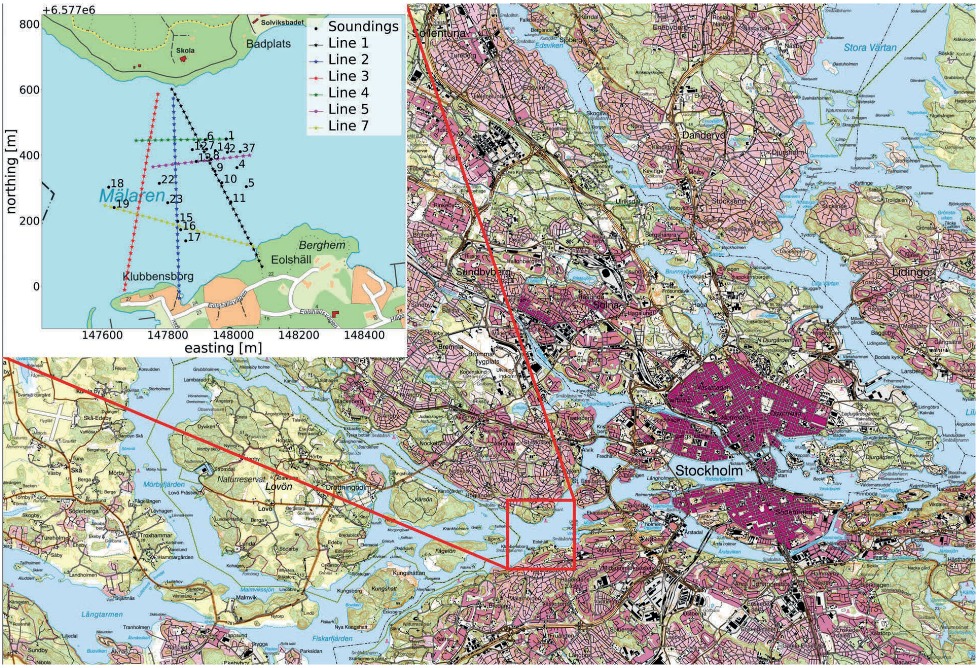

Figure 15. *Survey line positions in the sewage tunnel survey at Hägersten.*

At first the seismic measurements revealed an elevated noise level, mainly due to traffic, which led to poor signal-to-noise ratio and data quality problems. Furthermore gas in the bottom sediments attenuated the signal along parts of the lines which led to data losses. In order to improve the data quality all further seismic measurements were conducted during nighttime when noise levels are lowest which was necessary to achieve sufficient data quality. ERT data were acquired during daytime, mainly due to limited field resources and that there was no time to collect also the ERT data during night. For ERT the data collected during day showed a sufficient data quality, although it could have been improved by measuring during some hours after midnight.

ERT results for all six profiles is shown in Figure 16. The results show consistent variations in a low resistive top layer that corresponds to variation in depth of fine sediments. The ERT lines are generally in good agreement at the crossing points except Line 6, which is low resistivity throughout the depth of the model section along parts of the line. This latter is probably caused by the line running above and parallel to a fracture zone in the bedrock. Apart from this the bedrock is characterised by high resistivity, except for a zone that can be noted in Line 1, 2 and 3. This vertical zone is interpreted as a weak zone in the bedrock.

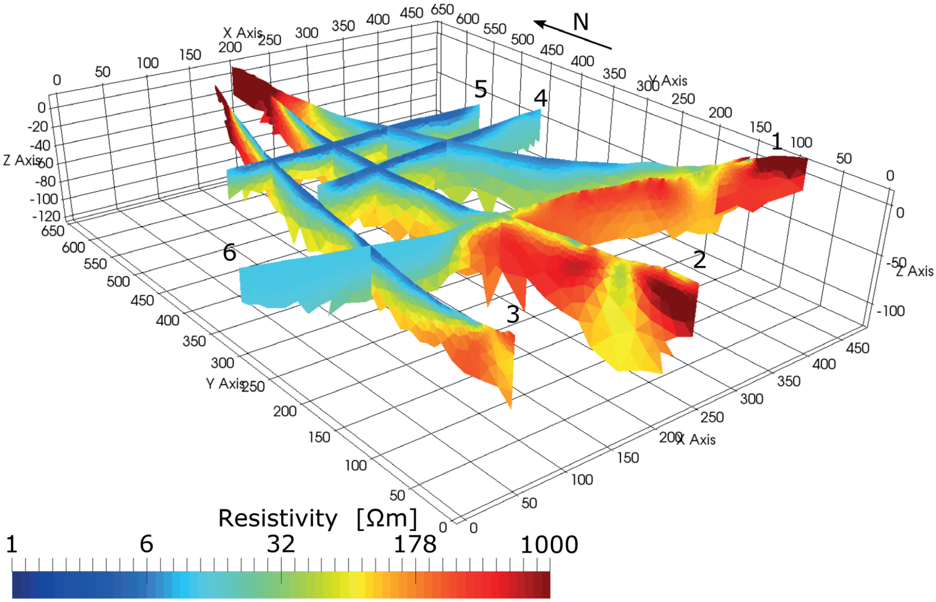

Figure 16. ERT inversion result of all six profiles in the sewage tunnel survey at Hägersten.

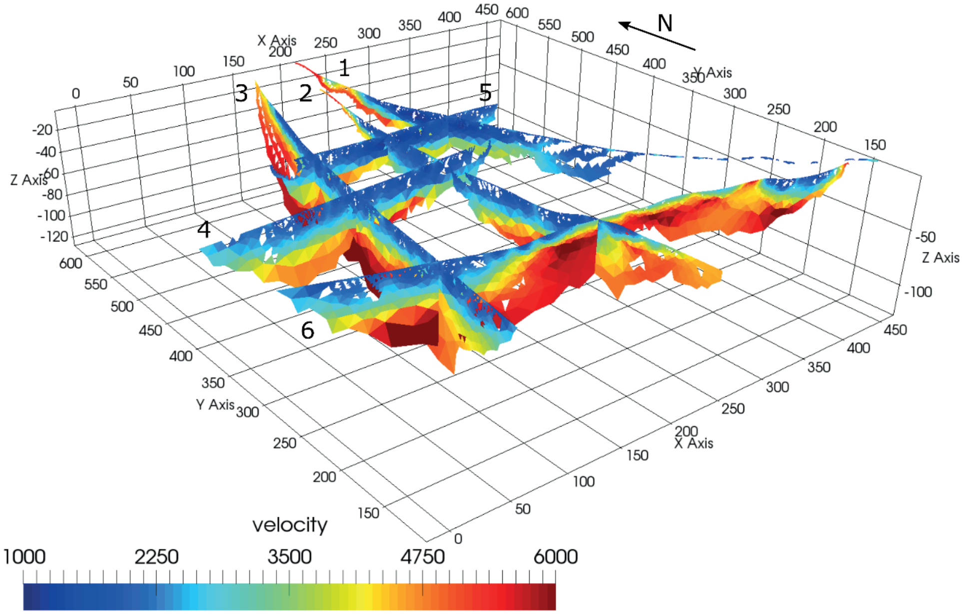

Figure 17. SRT inversion result of all six profiles in the sewage tunnel survey at Hägersten.

The SRT results show a picture that is largely in agreement with the ERT results, but with some important differences. The transition from the low velocity fine sediment top layer to underlying high velocity bedrock bottom layer is sharper than the corresponding transitions in the resistivity models. Line 1 lacks any useful depth penetration in the southern end due to attenuation of the signal in the gas filled sediments in combination with noise. The low resistivity zone in the bedrock which is clear in Line 1, 2, 3 and 6 is not seen in the SRT results. The low resistivity that extends to the full depth in the western end of Line 6 is not matched by similar large depth in the SRT model, and as would not be expected due to the different physical mechanism of seismic wave propagation around a narrow fractured zone. The low velocity upper zone that stands out clearly in the eastern end of Line 6 is not matched by a low resistivity zone, which indicates that it consists of coarse grained sediments rather than clayey sediments.

The ERT section for Line 2 (Figure 18) shows a very distinct low resistive layer, which is matched by low velocities, in the interval 250 – 580 m which is interpreted as predominantly clayey sediments. The zone below this has relatively low resistivity which can be interpreted as fractured and possibly weathered bedrock, although it is poorly resolved it is clear that it is lower in resistivity than in the ends of the profile. This is a zone with risk for rock with large water inflow and possibly mechanical instability. In the interval 150 – 250 m the upmost layer is characterised by low velocities whereas the resistivities are relatively high, which can be interpreted as coarse grained sediments or moraine. According to the drilling results the bedrock level is shallow and matches better the visual impression of the resistivity sections, maybe there is a zone of highly fractured rock. Around 75 m there is a distinct low resistive zone which is interpreted as a vertical fractured zone, which means risk for problems with underground construction. The joint inversion result shows that the transition from the low resistive soil layers in the top to the high resistive underlying strata below, is sharper than for the separate inversion.

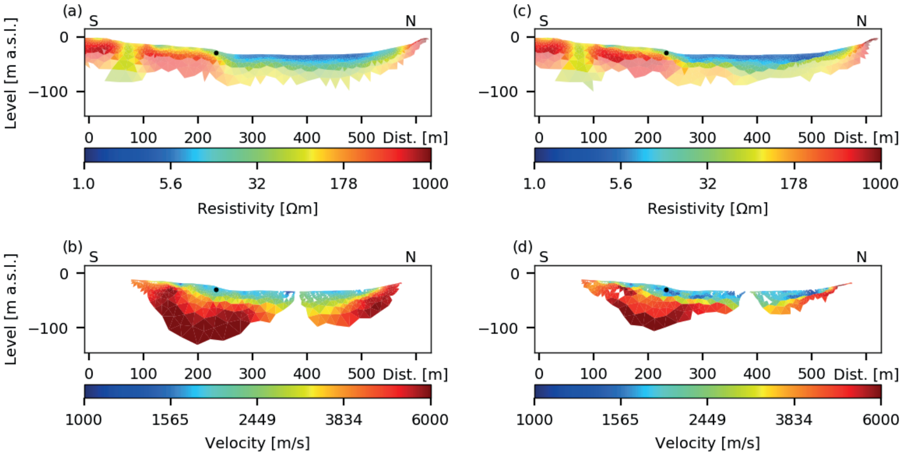

Figure 18. Separate inversion (left) and joint inversion (right) result of Line 2 in the sewage tunnel survey at Hägersten, showing the resistivity distribution (top) and the velocity distribution (bottom). The black dots mark the depth to bedrock obtained from geotechnical soundings.

For Line 1 (Figure 19) the joint inversion result shows that the transition from the low resistive soil layers in the top to the high resistive underlying strata below, is sharper than for the separate inversion. There is very low coverage in the southern part for the seismic result due to the higher noise level during daytime in combination with attenuation of the signal. Despite the reduced seismic information in the southern part, the ERT result still shows a continuous bedrock interface, due to the additional constraints by the joint inversion. Geotechnical soundings were available and gave depth to bedrock information at several points.

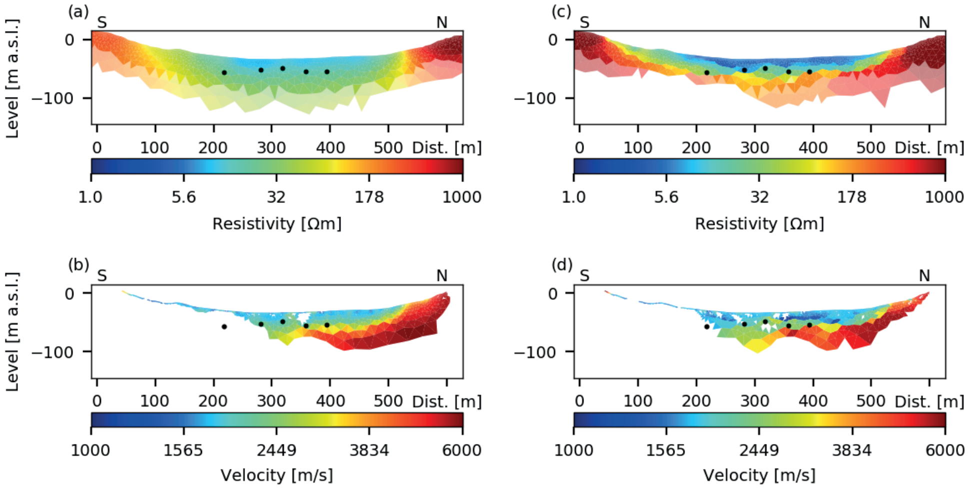

Figure 19. Separate inversion (left) and joint inversion (right) result of Line 1 in the sewage tunnel survey at Hägersten, showing the resistivity distribution (top) and the velocity distribution (bottom). The black dots mark the depth to bedrock obtained from geotechnical soundings.

The cluster analysis for the separated and joint inversion are shown in Figure 20. A clustering can only be done for model parts which are covered by both methods. Thus, only model parts covered by refraction seismic were used as input for the clustering, as the refraction seismic result covers smaller parts of the subsurface. The transition between blue and green in the cluster section is related to the bedrock surface, although not in perfect accordance with the bedrock level according to the geotechnical drilling results. Looking at the cluster cross plots it is obvious that a significant share of the points in the blue clusters have velocities that could be typical for fractured and weathered rock, which is unrealistically high for unconsolidated sediments. There may furthermore be coarse grained sediments and moraine deposits between the clayey sediments and the bedrock. The resistivities and seismic velocities of these will probably fall somewhere in between the top and bottom layer, which is a complication for the interpretation. The brown cluster corresponds to high velocity and high resistivity, which is interpreted as competent rock. There are possibilities to fine tune the cluster analysis by taking into account a priori data from e.g. drilling in the inversion as well as the cluster analysis.

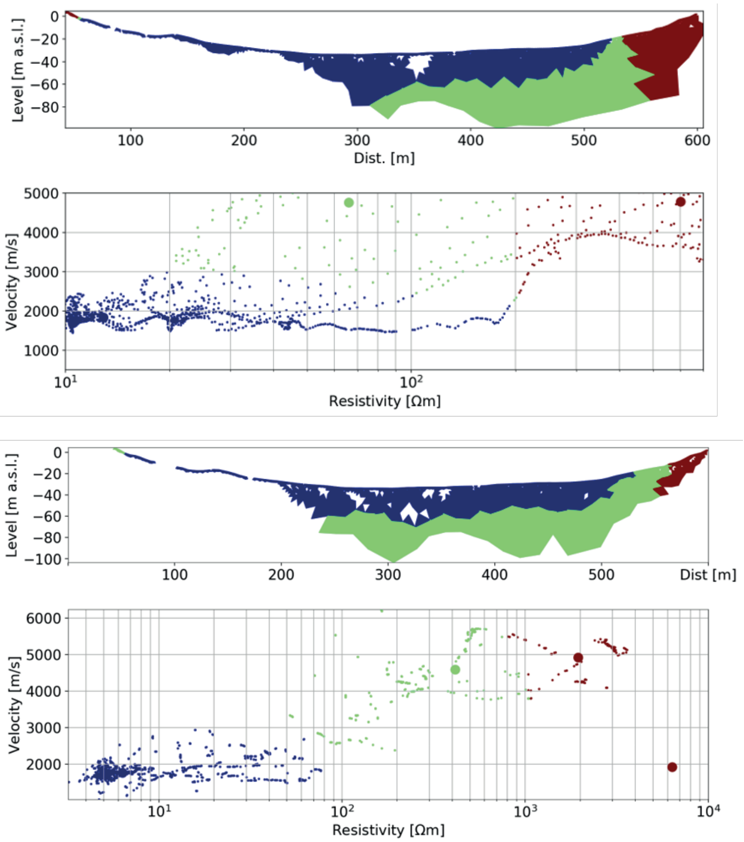

Figure 20 Mean shift cluster result for separated (top) and joint (bottom) inversion results.

Another way to enhance the inversion process is to include a priori data from e.g. drilling. For Line 1 the ERT data have also been inverted with layer interface position information from drilling as constrain, see example in Figure 21. For that rectangles were included into the mesh separating geologic units. All rectangles were decoupled in vertical direction, so that the resistivity is allowed to jump, and coupled with the inversion domain in horizontal direction. The information thus decouples the smoothness constrain thereby allowing sharp changes in resistivity at those levels. This has a very significant effect that is somewhat similar to what is achieved by combining with SRT data. A logical further step would be to use borehole information to constrain the joint inversion with both ERT and SRT data, but that is not yet implemented in the software.

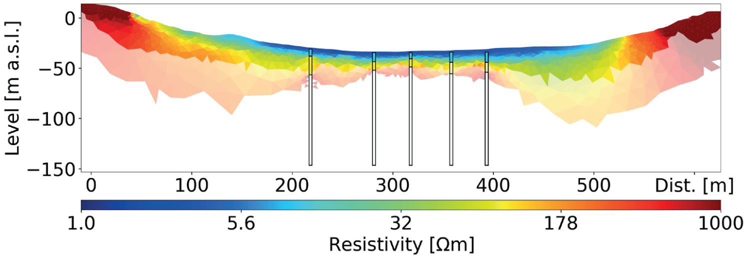

Figure 21. Hägersten Line 1 ERT inversion result with layer interface positions from geotechnical drilling as a-priori information.

4.3 Dalby-Önneslöv

The geophysical survey at Dalby-Önneslöv was done as a pre-investigation for an underground energy storage. The main objective was to map depth to bedrock and variation in rock quality, including locating fractured and weathered zones and possible dyke structures. Lund University acquired ERT (Direct Current resistivity tomography) and IPT (time domain induced polarisation tomography) data along four profiles, while seismic refraction data were measured by Uppsala University on profiles 2, 3 and 4 (Figure 22).

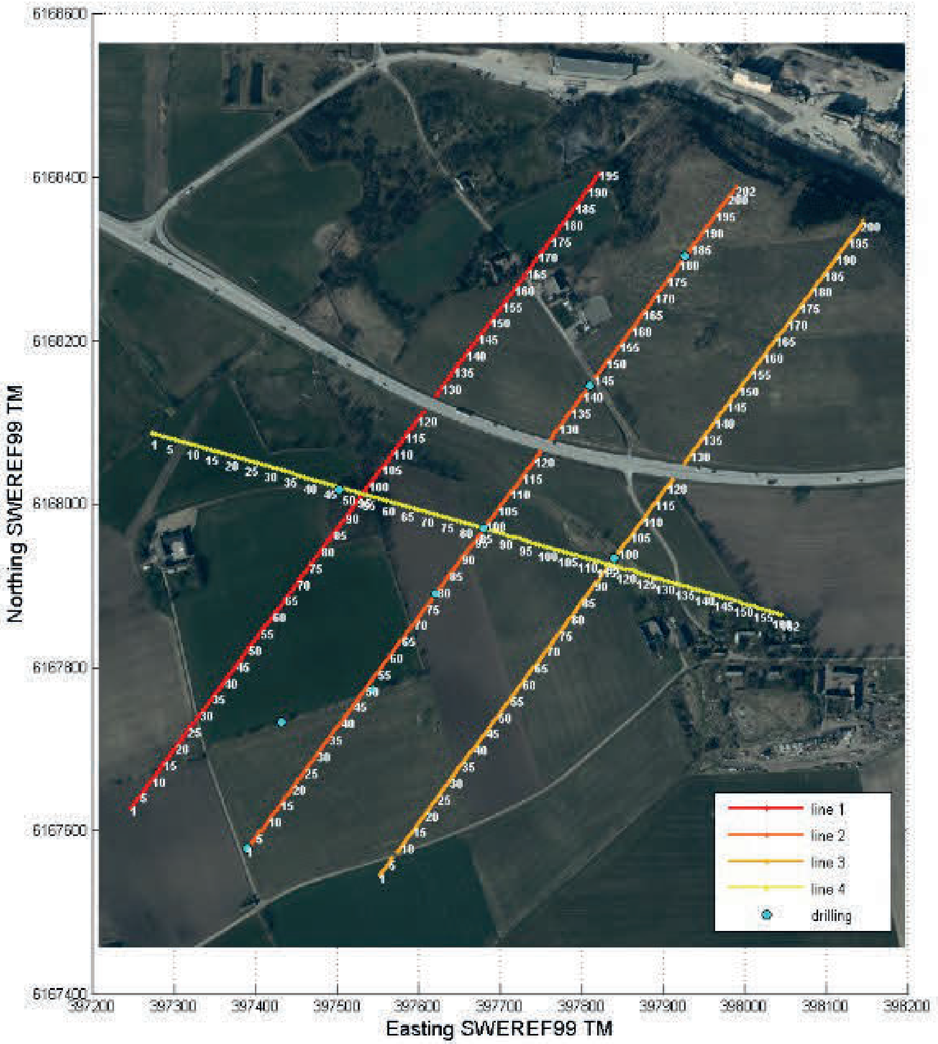

Figure 22. Position of the four profile lines and boreholes at Dalby-Önneslöv

An overview of the ERT and IPT results is shown in Figure 23. The four profiles show a NW-SE striking low resistivity zone, which could be identified a zone of increased depth to bedrock filled with sediments underlain by weathered bedrock. As expected, the interface towards the bedrock does not appear sharp. Dyke structures were clearly revealed by the ERT, and IPT added information to some of these.

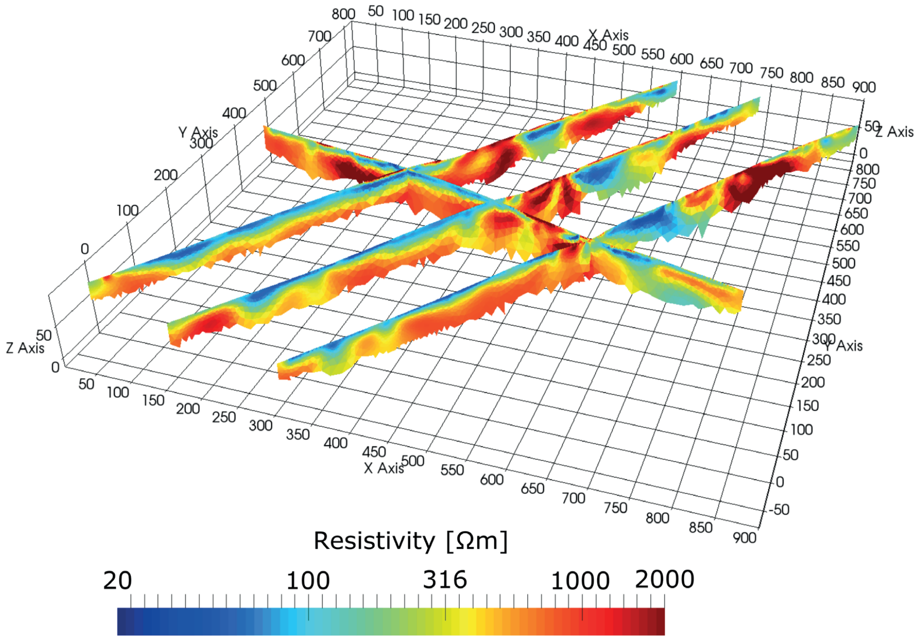

Figure 23. Overview of ERT inversion results.

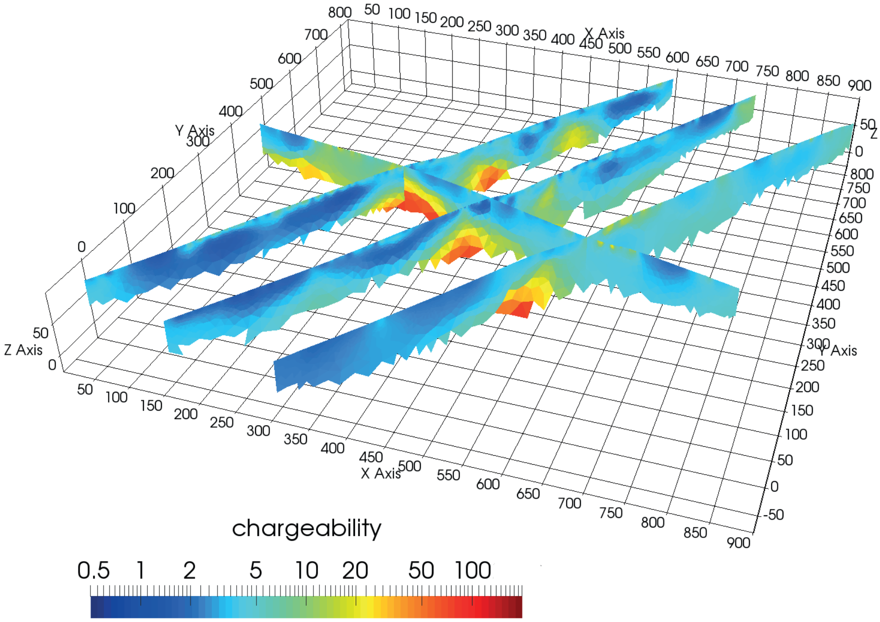

Figure 24. Overview of IPT inversion results.

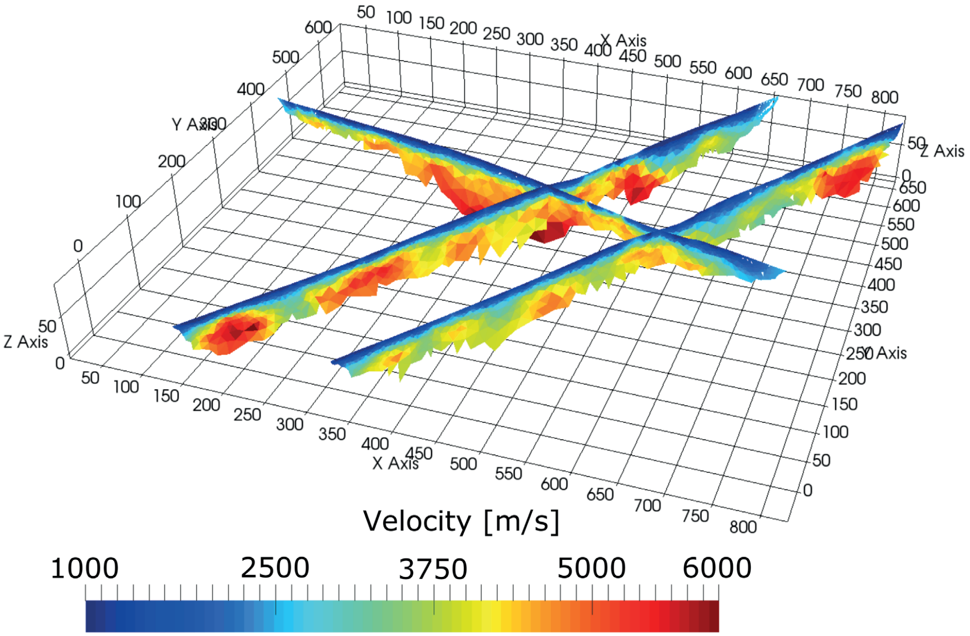

Figure 25. Overview of SRT inversion results from Dalby-Önneslöv.

Due to sensor positioning problems, a joint inversion could only be performed on profiles 2 and 3. The joint inversion of profile 2 in Figure 26 shows the same pattern as the separated inversion. Although the resistivity of the bedrock is still quite low, the interface appears more continuous compared to the separated inversion.

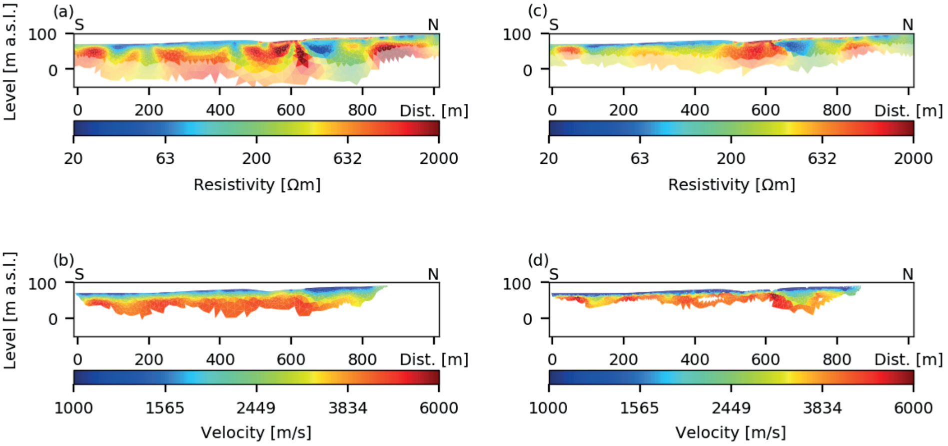

Figure 26. Dalby-Önneslöv Line 2 results; separate inversion (top) and joint inversion (bottom), with the resistivity distribution (left) and velocity distribution (right).

The cluster analysis result of line 2 using the mean shift algorithm is shown in Figure 27. Two different cluster analyses were made with different input parameter but the same quantile (q=0.22), which is used by the algorithm to cluster the input data. The top picture of Figure 27 shows the clustering of seismic velocities and resistivities (short CVR), whereas the bottom picture shows the clustering of chargeabilities and resistivites (CCR). While using the same input parameter for the clustering, the CVR plot only finds two cluster separating the bedrock from overburden. In comparison, the CCR plot shows three clusters separating a possible chargeable dyke-like structure but do not show the bedrock interface.

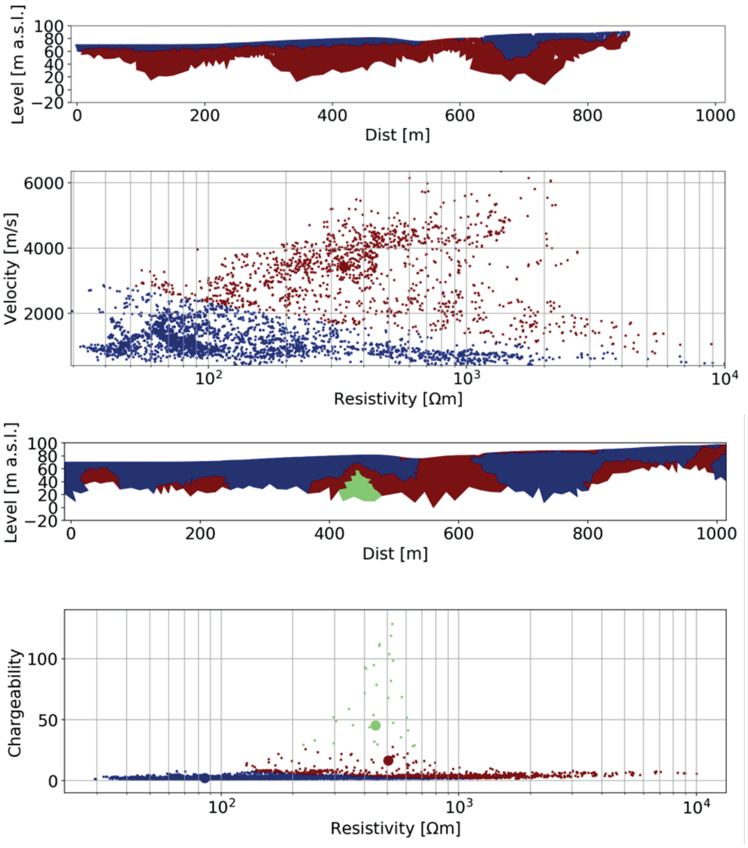

Figure 27. *Results of the mean shift cluster analysis for line 2. The top picture shows a clustering with SRT and ERT models as input and the bottom picture shows the clustering of IP and ERT model input. Both with a quantile of 0.22.*

Additionally, borehole information was directly included as constraints in the ERT inversion on profile 2 (Figure 28) in three positions. For this example, the added value of the structural information is marginal, because the shallow soil layer is well resolved by ERT in the first place, but on the other hand it does not corrupt the results.

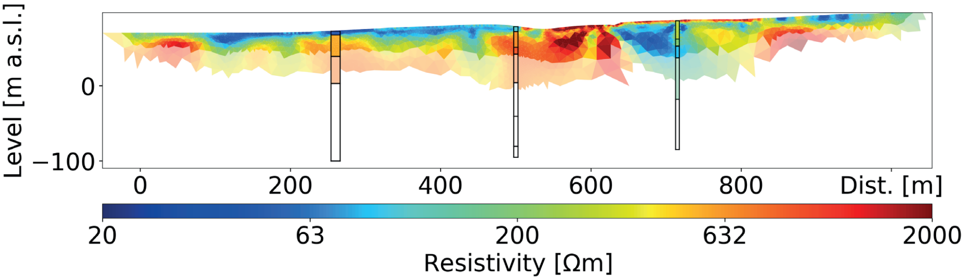

Figure 28. *Dalby-Önneslöv Line 2 ERT inversion result with borehole geology as a-priori information*

5. DISCUSSION

Software for joint inversion of different types of geophysical data has been developed within the project, where the development required much more time and efforts than anticipated. One important reason behind this is that the software was ported from Matlab to Python, which was a much larger undertaking than foreseen. Nevertheless, the software works in a stable way now, and it has been demonstrated on a number of full-scale datasets as shown above. Using the openly available GIML, we have paved the way for future work in the field where it is also possible to benefit from input and improvements to the library from other research groups that are using it. Furthermore, significant efforts have been invested in testing different clustering approaches.

Development of methodology for streamlined field data acquisition of joint datasets was not an explicit part of the project. One of the outcomes is however experienced on that coordinated data acquisition is a very important component for the practical applicability of joint inversion of different types of geophysical data, since inconsistencies between the data sets tend to be very time-consuming to sort out. In several cases where we have attempted to use the joint inversion algorithms on data acquired at different times by different field teams, it has turned out to require large amounts of extra work with data conditioning. Problems encountered include differences in sensor positions, uncertainties in positioning, question marks around data accuracy, etc. This makes the process complicated and time-consuming, which would hinder a practical application, and it is a strong motivation for planning and carrying out data acquisition with the different methods simultaneously with collocated sensors. Coordinated acquisition would also be a way of reducing the total cost, since time and costs for planning, logistics, getting access to land, etc. can be shared so that the total cost can be expected to be significantly less than for doing two separate field surveys.

We made a couple of tests with coordinated data acquisition for land-based data acquisition, and although we did not make any particular methodological adaptions, apart from carrying out the surveys in parallel and installing the sensors next to each other, it worked well and eliminated problems with sensor positions and positioning. We believe there is potential for significant benefits in streamlining the field data acquisition methodology by relatively small modifications of equipment and the field procedure. For underwater data acquisition it can be efficient to carry out the field data acquisition jointly for ERT and SRT, although method and equipment development that could streamline the process further can be envisioned. A challenge is to keep the weight and size of the sensor cables down, in order to avoid requirement of a large boat and heavy machinery to be operated as that would increase the daily field costs significantly. On the other hand, it would almost certainly lead to problems with sensor positions between the data sets if the surveying is carried out in separate field campaigns by different personnel.

The underwater survey results show that ERT and SRT complement each other well. This applies to the example from Äspö HRL as well as that from Lake Mälaren. The results from the two methods are generally in good agreement, and where they at first sight gives results that differ this contains valuable information regarding the geological materials. Furthermore, the results show that limitations for one method is often compensated by results from the other method, so that the combination prevents gaps in the cover of the survey that would otherwise occur. We achieved good results for all test lines, except one of the alternatives for Östlig förbindelse where too much gas in the bottom sediments attenuated the seismic signals completely. This is the only one of the underwater ERT lines that provided results that in parts are difficult to explain by the geology, but it is on good grounds suspected that steel casing left behind after geotechnical drilling corrupted the ERT data.

Offshore geotechnical drilling is costly and may require extensive logistics including anchored barges as drilling platform. For a couple of the lines we surveyed in Saltsjön (not presented in this report) temporary change of fairways for the ferry traffic to Finland etc. was needed for the geotechnical drilling. The cost of a geophysical survey line with combined ERT and SRT lies, in the projects we were involved in, in the same order as a single geotechnical sounding. It would therefore be very cost effective to initiate the site investigation surveys with a geophysical survey that could be used as the basis for an optimized drilling program.

In the interpretation of the underwater surveying results the following criteria were used:

- Low resistivity and low velocity; predominantly fine grained unconsolidated sediments.
- Intermediate resistivity and low velocity; coarse grained unconsolidated sediments.
- Intermediate resistivity and intermediate velocity; moraine or fractured rock.
- High resistivity and high velocity; fresh rock.

Joint inversion showed significant improvements of the inversion results, especially for underwater surveys, where very large contrasts in resistivity can occur. The usually applied smoothness constraint leads to larger transition zones, which are reduced by the structural constraints from the seismic refraction inversion. The Dalby-Önneslov case showed that even if the additional structural information from another method is small and model improvements are slight, the used joint inversion approach does not make the results worse compared to standard inversions. Geologic information from boreholes were taken into the single inversion of ERT data as additional constraints. In a first stage geologic interfaces from boreholes were used and in a second stage ERT logging data were set as starting values to ensure that the inverted resistivity goes in the same direction as the borehole resistivity.

Although the approach for structurally coupled inversion tested here shows useful results, it could also be of interest to test other algorithms on the same synthetic and field data, for example so called cross-gradient inversion (Gallardo and Meju 2004).

Cluster analysis with several different methods, including k-means, DBSCAN (density-based spatial clustering) and mean shift clustering, has been tested. It is a promising technique as part of an approach for objective and repeatable interpretation of multiple parameter survey results. With further adaption and fine tuning, and combination it can become a key part of an approach for automated interpretation, possibly in combination with machine learning.

6. CONCLUSIONS

Better rock quality predictions reduce the risk of delays, costs and litigation related to construction in rock and reduces the risk of negative impact on the environment. An engineering geological conceptual model of sufficient quality with sufficiently small uncertainties is essential for reducing the risk. The site investigation should be based on a combination of methods, since a single cannot give a comprehensive picture.

The project results clearly illustrate that joint surveying with two or more geophysical methods is advantageous. By combining methods, uncertainties and ambiguities, as well as gaps in data cover, in the results from one method can be compensated by the other method(s). For underground construction in rock electrical resistivity tomography (ERT) and seismic refraction tomography (SRT) is a useful combination. The underwater survey examples highlight the benefits of this concept for surveying across water passages.

At sites where there is a shallow low velocity layer on top of the bedrock the seismic refraction method is blind below the soil layer. This depends on the physical mechanism behind the seismic technique. In such cases the added value of joint inversion will be very limited because the ERT already resolves the shallow layers well, but on the other hand it does not produce any misleading results.

The joint inversion of the data facilitates co-interpretation, as it can be done in an objective repeatable way. The joint inversion approach we have tested leads to significantly better models in some cases, whereas in others there is no particular improvement of the results. As mentioned, a requirement is that the seismic refraction method provides substantial depth coverage, which depends on the geological setting. On the other hand, the combined inversion does not lead to erroneous or misleading results, which means that the approach can be used in all relevant cases without risk.

The incorporation of borehole information is useful and leads to more reasonable results, as ground truth information goes into the inversion. Further research is suggested, as not all possibilities of the incorporation of geophysical and non-geophysical data could be investigated in detail. Especially borehole information could not yet be incorporated in the joint inversion. The influence of inversion parameters on additional constraints has also to be investigated in detail.

Cluster analysis of the inverted models is a promising technique for providing objective and repeatable support for the interpretation of multiple parameter survey results: It needs further adaption and fine tuning before it can be used as a routine tool.

7. OUTLOOK

There are many possible ways to further advance the methodologies and techniques developed in this project. These include the following ideas and suggestions for future work:

- Include seismic shear wave velocity and seismic surface waves in the joint inversion.
- Incorporation of borehole resistivity-IP measurements to constrain surface ERT and IPT inversion.
- Incorporation of seismic borehole information in SRT.
- Include support for structural a priori data and all the above combinations in joint inversion.
- Refine the induced polarisation (chargeability) tomography (IPT) inversion.
- Testing other algorithms for structurally coupled inversion.
- Further work on selecting cluster analysis tools and adapting and optimising their use.
- Cluster analysis could prove to be a step towards implementing machine learning and computer aided interpretation into the field of geophysics.

8. REFERENCES

Cavinato, G. P., Di Luzio, E., Moscatelli, M., Vallone, R., Averardi, M., Valente, A. & Papale, S. (2006). The new Col di Tenda tunnel between Italy and France: Integrated geological investigations and geophysical prospections for preliminary studies on the Italian side. *Engineering Geology*, 88(1), 90–109.

Danielsen, B. E. (2007). The applicability of geoelectrical imaging as a tool for construction in rock. *Quarterly Journal of Engineering Geology*, 32, 163–172.

Danielsen, B.E. & Dahlin, T. (2009) Comparison of geoelectrical imaging and tunnel documentation. *Engineering Geology*, 107, 118–129.

Dahlin, T., Bjelm, L. & Svensson, C. (1999). Use of electrical imaging in site investigations for a railway tunnel through the Hallandsas Horst, Sweden. *Quarterly Journal of Engineering Geology and Hydrogeology*, 32, 163–172.

Di, Q. & Wang, M. (2010). Determining areas of leakage in the Da Ye Dam using multi-electrode resistivity. *Bulletin of Engineering Geology and the Environment*, 69(1), 105–109.

Dietrich, P. & Tronicke, J. (2009). Integrated analysis and interpretation of cross-hole P-and S-wave tomograms: a case study. *Near Surface Geophysics*, *7*(2), 101–109.

Friedel, S. (2003). Resolution, stability and efficiency of resistivity tomography estimated from a generalized inversion approach. *Geophysical Journal International*, 153, 305-316

Ganerød GV, Rønning JS, Dalsegg E, Elvebakk H, Holmøy KH, Nilsen B & Braathen A (2006) Comparison of geophysical methods for subsurface mapping of faults and fracture zones in a section of the Viggja road tunnel, Norway. *Bull Eng Geol Environ* 65: 231–243. ISSN: 1435-9529

Gallardo, L. A., & Meju, M. A. (2004). Joint two-dimensional DC resistivity and seismic travel time inversion with cross-gradients constraints. *Journal of Geophysical Research*, *109*(B3), B03311.

Günther, T. (2004). *Inversion Methods and Resolution Analysis for the 2D/3D Reconstruction of Resistivity Structures from DC Measurements*. PhD thesis, TU Bergakademie Freiberg.

Günther, T., Bentley, L. & Hirsch, M., 2006. A new joint inversion algorithm applied to the interpretation of dc resistivity and refraction data. In Proceedings of XVI International Conference on Computational Methods in Water Resources.

Haber, E., & Oldenburg, D. (1997). Joint inversion: a structural approach. *Inverse Problems*, *13*(1), 63.

Hellman, K., Ronczka, M., Günter T., Wennermark, M., Rücker C. & Dahlin T. (2017) Structurally coupled inversion of ERT and refraction seismic data combined with cluster-based model integration, *Journal of Applied Geophysics*, 143, 169-181

Johansson S. (2016) From microstructure to subsurface characterization. Spectral information from field scale time domain induced polarization. Licentiate thesis, Lund University, ISBN 978-91-7623-674-1, 99p.

Joydeep, G., & Alexander, L. (2009). K-Means. In *The Top Ten Algorithms in Data Mining* (pp. 21–35). Chapman and Hall/CRC.

Knödel, K., Lange, G. & Voigt, H.J. (2007) Environmental Geology – Handbook of Field Methods and Case Studies. Chapter 4.6 Seismic Methods. Schuck, A. & Lange G. *Springer*, 337 – 402.

Linde, N., Tryggvason, A., Peterson, J. E., & Hubbard, S. S. (2008). Joint inversion of crosshole radar and seismic traveltimes acquired at the South Oyster Bacterial Transport Site. *Geophysics*, *73*(4), G29–G37.

Lines, L. R., Schultz, A. K., & Treitel, S. (1988). Cooperative inversion of geophysical data. *Geophysics*, *53*(1), 8–20.

Meldgaard Madsen L., Fiandaca G., Vest Christiansen A. & Auken E. (2017) Resolution of well-known resistivity equivalences by inclusion of time-domain induced polarization data. Geophysics, https://doi.org/10.1190/geo2017-0009.1

Nur, A., Mavko, G., Dvorkin, J., & Galmudi, D. (1998). Critical porosity: A key to relating physical properties to porosity in rocks. *The Leading Edge*, *17*(3), 357–362.

Paasche, H., Tronicke, J., Holliger, K., Green, A. G., & Maurer, H. (2006). Integration of diverse physical-property models: Subsurface zonation and petrophysical parameter estimation based on fuzzy c-means cluster analyses. *Geophysics*, *71*(3), H33–H44.

Rambøll, 2012. Grundundersøgelser for ny E16 mellem Bjørum og Skaret,

Reiser F., Dalsegg E., Dahlin T., Ganerød G.V. & Rønning J.S. 2009. Resistivity Modelling of Fracture Zones and Horizontal Layers in Bedrock. NGU rapport 2009. 070., 120p.

Rønning, J.S. et al., 2009. NGU Rapport 2009.064 Resistivitetsmålinger og retolking av seismikk langs E6 og Dovrebanen ved Mjøsa.,

Rønning JS, Ganerød GV, Dalsegg E & Reiser F. (2014) Resistivity mapping as a tool for identification and characterisation of weakness zones in crystalline bedrock: definition and testing of an interpretational model. *Bull Eng Geol Environ* 73:1225–1244.

Rücker, C., Günther, T. & Wagner, F.M. (2017) pyGIMLi: An open-source library for modelling and inversion in geophysics, *Computers and Geosciences*, 109, 106-123

Sasaki, Y. (1989). Two-dimensional joint inversion of magnetotelluric and dipole-dipole resistivity data. *Geophysics*, *54*(2), 254–262.

Sharma, P.K. & Singh, T.N. (2008) A correlation between P-wave velocity, impact strength index, slake durability index and uniaxial compressive strength, *Bull. Eng. Geol.Environ.,* 67, 17–22.

Sjögren B. (1984) *Shallow refraction seismics*, ISBN 9400955464, Chapman and Hall, London, 270p.

Tronicke, J., Holliger, K., Barrash, W., & Knoll, M. D. (2004). Multivariate analysis of cross-hole georadar velocity and attenuation tomograms for aquifer zonation. *Water Resources Research*, *40*(1).

Tryggvason, A., & Flóvenz, Ó. G. (2002). Three-dimensional imaging of the P-and S-wave velocity structure and earthquake locations beneath Southwest Iceland. *Geophysical Journal International*, *151*(3), 848–866.

Vozoff, K., & Jupp, D. L. B. (1975). Joint inversion of geophysical data. *Geophysical Journal of the Royal Astronomical Society*, *42*(3), 977–991.

Wikbert, P, Gustafsson, G, Rhen, I. & Stanfors, R. (1991). *Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986-1990.* Technical Report, SKB (Swedish Nuclear Fuel and Waste Management Company), 91-22.

Wisén R, Mykland J., Rønning J.S., Elvebakk H. & Olsen F.W.G. (2012) Experience from multidisciplinary geophysical survey for tunneling in Norway Refraction seismic, resistivity profiling and borehole logging, in *Procs. NGM 2012 (Nordic Geotechnical Meeting)*, 9-12 May 2012, Copenhagen.

APPENDIX 1. SCIENTIFIC OUTPUT

International Scientific Journal Articles

1. Ronczka M., Wisén R. and Dahlin T. (in review) Geophysical pre-investigation for a Stockholm tunnel project: Joint inversion and interpretation of geoelectric and seismic refraction data with the Python BERT/GIMLi package, Special issue on urban geophysics, *Near Surface Geophysics*.
2. Wang S, Kalscheuer T, Bastani M, Malehmir A, Pedersen L B, Dahlin T and Meqbel N (2017) Joint inversion of lake-floor direct current resistivity and on-lake radio magnetotelluric data and an example application from the Äspö Hard Rock Laboratory site, Sweden, *Geophysical Journal International*, on-line publication och accepted manuscript.
3. Hellman K, Ronczka M, Günther T, Wennermark M, Rücker C & Dahlin T (2017) Structurally coupled inversion of ERT and refraction seismic data combined with cluster-based model integration, *Journal of Applied Geophysics*, 143, 169-181.
4. Ronczka M, Hellman K, Günther T, Wisén R & Dahlin T (2017) Electric resistivity and seismic refraction tomography, a challenging joint underwater survey at Äspö Hard Rock Laboratory. *Solid Earth*, 8, 671–682.

Conference Articles

1. Ronczka M., Olsson P.-I., Rossi M., Malehmir A., Dahlin T. (2017) Geophysical Site Investigation at Dalby-Önneslöv Using Joint Inversion in *Procs. 23rd European Meeting on Environmental and Engineering Geophysics*, 3-6 September 2017, Malmö, Sweden, Mo 23 A08, 5p.
2. Dahlin T. and Wisén R. (2017) Geofysisk kartläggning av sedimentdjup och strukturer i berg under vatten, in *Procs. Grundläggningsdagen 2017*, 16 March 2017, Stockholm, 129-142.
3. Dahlin T, Wisén R and Rossi M (2016) Urban Underwater ERT for Site Investigation in Lake Mälaren, Sweden. in *Procs. 22nd European Meeting on Environmental and Engineering Geophysics*, 5-6 September 2016, Barcelona, Spain, We 22 B15, 5p.
4. Hellman K, Johansson S, Olsson P-I and Dahlin T (2016) Resistivity Inversion Software Comparison. in *Procs. 22nd European Meeting on Environmental and Engineering Geophysics*, 5-6 September 2016, Barcelona, Spain, We 22 A02, 5p.
5. Wang S., Kalscheuer T., Bastani M., Malehmir A., Pedersen L.B., Dahlin T., Meqbel N. (2016) Joint inversion of on-lake radiomagnetotelluric and lake-floor direct current resistivity data and its application, in *Procs. 23rd Electromagnetic Induction Workshop*, 14 - 20 August 2016, Chiang Mai, Thailand.
6. Ronczka M, Wisén R, Wennermark M, Dahlin T & Hellman K (2016) ERT and seismic refraction tomography test at Äspö Hard Rock Laboratory, *Procs. NGM 2016*, 17th Nordic Geotechnical Meeting, Reykjavik, Iceland, 25th - 28th of May 2016.
7. Dahlin T & Wisén R (2016) Underwater ERT Surveys for Urban Underground Infrastructure Site Investigation in Central Stockholm, *Procs. NGM 2016*, 17th Nordic Geotechnical Meeting, Reykjavik, Iceland, 25th - 28th of May 2016.

8. Hellman K, Wisén R, Dahlin T & Ronczka M (2016) Automated co-interpretation of geophysical data for site investigation, *Procs. NGM 2016*, 17th Nordic Geotechnical Meeting, Reykjavik, Iceland, 25th - 28th of May 2016.
9. Wennermark M, Olsson P-I, Johansson S & Hellman K (2015) A Comparison of DCIP Inversion Software, *Procs. Near Surface Geoscience 2015*, 6-10 September 2015, Torino, Italy, 5p.
10. Wennermark M., Hellman K., Dahlin T. & Günther T. (2014) Joint inversion and interpretation of seismic refraction and resistivity-time domain IP data from the ESS site at Lund, Sweden, in Procs. *SAGEEP 2014, 16-20 March 2014, Boston, MA, USA*, 1p.

Student Theses

1. Lindvall E & Warberg Larsson E (2016) *Kombinerad förundersökning för tunnlar med resistivitet och refraktionsseismik i urban undervattensmiljö*, MSc Thesis, Engineering Geology, Lund University, VTG820, ISRN LUTVDG / (TVTG-5145) / 1-80 /(2016).
2. Lasheras Maas N (2015) *Site Characterization at the Äspö Hard Rock Laboratory through Seismic Refraction method*, BSc Thesis, Engineering Geology, Lund University, ISRN LUTVDG/(TVTG--5141)/1-33/(2015)/BACHELOR.

BeFo

Box 5501
SE-114 85 Stockholm

info@befoonline.org • www.befoonline.org
Visiting address: Storgatan 19, Stockholm

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