ERT and seismic refraction tomography test at Äspö Hard Rock Laboratory

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ABSTRACT
Tunnelling below water passages is a challenging task, as fracture zones in the underlying bedrock are often associated with these. Surveys prior to the construction phase that provide information of the subsurface can also be logistically difficult at water passages. An approach that combines refraction seismic and ERT (electrical resistivity tomography) at the Äspö Hard Rock Laboratory (HRL) is presented. The rock laboratory consists of an approximately 2 km long access tunnel and a spiral tunnel that reaches more than 450 m below ground.
The presented surveys cover a water passage along part of the access tunnel which is located around 100 m below the survey line. Seismic and ERT data with co-located sensor positions were collected. The profiles were roughly oriented in north-south direction with a length of about 780 m for ERT and 450 for the seismic survey. A sensor spacing of 5 m was used. Strong power grid noise, the geologic and the test site conditions were logistically challenging for the geophysical surveys. The large resistivity range made it difficult to fit the ERT data appropriately. The unexpected large thickness of the sediments in the southern part of the survey led to a poor signal quality of the seismic data. Nonetheless, inversion results of both data sets are promising, and show that previously unknown geological features can be found by the approach even in an unusually well documented geological environment. The joint interpretation showed that the sedimentary deposits as well as the fracture zones in the northern part could be imaged. A further quality enhancement of the inversion results is possible by including a-priori information and/or a joint inversion of both data sets.

Keywords: Refraction seismic, ERT, joint interpretation.

1 INTODUCTION

The construction of underground structures has attracted much attention recently. They are used for example in the transportation sector to challenge the growth of traffic in and around cities, for underground storage facilities, etc. Detailed subsurface information is essential for a successful completion. A critical point in order to ensure a smooth construction phase is to locate possible weak zones that might slow down the construction progress.

In Sweden, underground infrastructure is mostly built within the crystalline bedrock, where weakness zones are indicated by dry or water bearing fractures. Different methods exist for their location. For example a set of boreholes give information with a high resolution in depth. Nevertheless, these are very expensive and deliver only punctual information. For the extrapolation into 2D or even 3D geophysical surface based investigations can be used. Recently, Swedish transportation authority's started an increasing number of projects with the aim to develop a scheme of different geophysical methods to map fractures.

Seismic and ERT (electrical resistivity tomography) surveys were conducted to locate fracture zones at the Äspö Hard Rock laboratory (HRL). In order to increase the reliability of the results, the combination of both methods will be investigated. This can be done for example by a joint interpretation and inversion of both data-sets. Äspö HRL is an underground facility for research and tests around the concept of final disposal of nuclear waste material in hard rock (Rhén et al. 1997), which provides a research opportunity in a well documented and relatively undisturbed environment also for other branches of research.

2 SITE DESCRIPTION

The Äspö Hard Rock Laboratory is located on the Baltic east coast of Sweden, about 30 km north of Oskarshamn and 400 km south of Stockholm (see Figure 1). The Swedish Nuclear Fuel and Waste Management Company (SKB) started to design a deep final disposal for nuclear fuel. From 1990 – 1995 the excavation of a 3600 m long tunnel that connects the nuclear power plant with the disposal in approximately 450 m depth was conducted. During that phase, a detailed site characterization was done that included geological, hydrogeological and geochemical investigations.

Figure 1: Location of Äspö Hard Rock Laboratory, approx. 30 km north of Oskarshamn

The Äspö bedrock is part of the Trans-Scandinavian Igneous belt (TIB), which extends from southern Sweden towards north and northwest. Mainly granitoids and volcanic rocks can be found in the TIB. Four rock types are dominating: the Äspö diorites, Ävrö granite, greenstone and fine-grained granite. Wikbert et al. 1991 found out that continuous magma-mingling and mixing processes supported the development of dikes and mafic inclusions which form an inhomogeneous rock mass. The crystalline bedrock exhibits porosities of 0.4-0.45 % for the Äspö diorite and 0.23-0.27 % for the fine-grained granite (Stanfors et al. 1999). During the pre-investigation of Äspö HRL, fracture zones were divided into major (width > 5 m) and minor (width < 5 m) ones. The majority of the fractures are oriented northwest-southeast (Berglund et. al 2003), and the most important fractures are depicted in Figure 2. Minerals that fill the fractures were extracted from drill cores and analysed. Thus, unconsolidated material that might have been additionally filling the fractures was probably washed away.

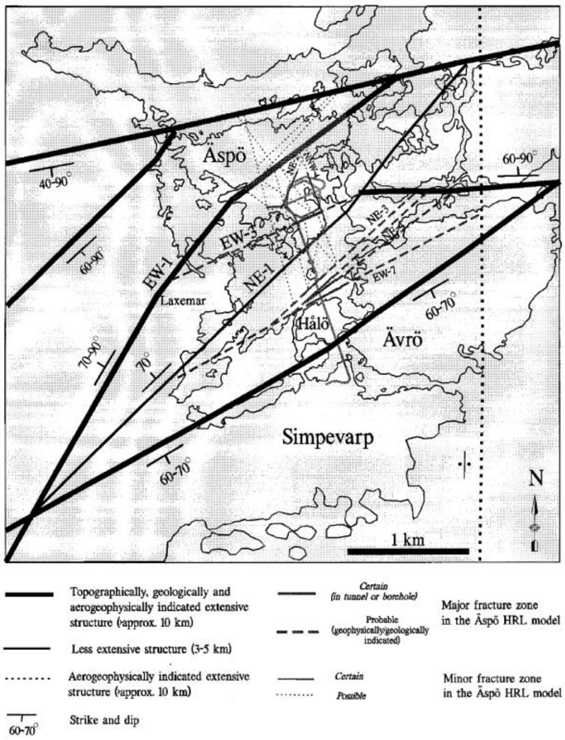

Figure 2: Fracture zones at Äspö HRL (Stanfors et al. 1999).

Quaternary sediments on top of the bedrock are scarce at the Äspö test site. Due to the deep target of the Äspö HRL within the bedrock, no detailed investigation of the Quaternary sediments were done. Vidstrand 2003 stated that the unconsolidated overburden rarely exceed 5 m thickness and consists mainly of clay, sand and gravel.

3 FIELD SURVEYS

3.1 Electrical resistivity tomography

ERT measurements were carried out along a profile in N-S direction directly above the tunnel line. The profile lies between Hålö and Äspö (see Figure 3) to the west of the tunnel line, about 10 m away from a small island. Electrodes were placed onshore and underwater, with a 5 m electrode spacing, along a profile with a length of about 780 m. Data were recorded using the ABEM Terrameter LS instrument. A multiple gradient array was employed to ensure fast progress. The ERT measurement was conducted simultaneously with the seismic survey on 20-24 April 2015.

3.2 Seismic survey

As indicated by Figure 3, seismic refraction data were collected on the sea bed. Hydrophone streamers were laid out with 91 hydrophones using 5 m spacing along a 450 m profile line. For data acquisition the instruments ABEM Terraloc and Geometrics Stratavizor were used, both with 48 channels and with a 5 channel overlap of the two streamers. Hydrophone positions were determined by a differential GNSS, while the topography of the sea bed was mapped with a multibeam echo sounder (Lasheras Maas 2015). For the excitation of seismic p-waves, small explosives were placed approximately 0.5m above the sea bed with a scheduled spacing of 20 m. Due to time constraints not all planed shots were fired and hence there are two small gaps in the data coverage in the northern part of the dataset.

Figure 3: Location of the seismic (red line) and ERT (blue line) profile at Äspö HRL (after Lasheras Maas 2015).

4 RESULTS

About 6700 data points were gathered in the ERT survey. The surveying conditions were challenging with electrodes lying in brackish water as well as on outcropping rock, leading to contact resistances ranging from around 100 Ω to over 100 kΩ. Nevertheless, data quality is generally good judging from apparent resistivity pseudosection plots, although recorded full waveform data reveals high power grid noise levels.

While processing the raw data, electrodes with apparently wrong GNNS position were identified and combinations containing these electrodes deleted. For the inversion it was assumed that data were contaminated with 3% Gaussian noise and a voltage error of 0.1 mV. Data were interpreted as models of the resistivity distribution via inverse numerical modelling (inversion) using BERT (*add reference*). A smoothness constrained inversion was done with the abort criterion $\chi^2 = \Phi_d/N = 1$, whereas Φ_d is the data misfit and N the data amount.

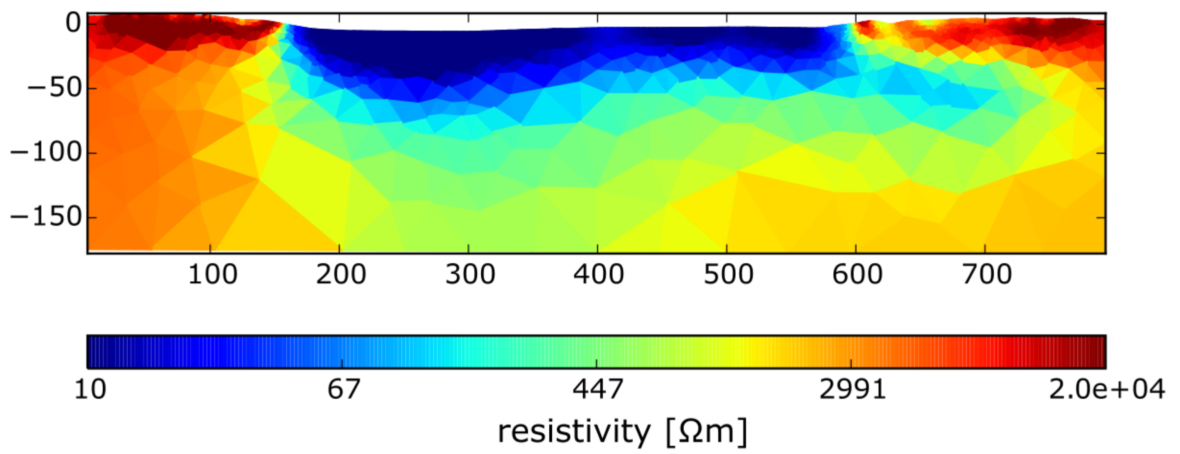

Figure 4: Inversion result of the ERT data set at Äspö HRL.

The L_1 norm (robust inversion) was used for Φ_d. Although some apparent resistivities that exhibit a high error and/or does not fit into the raw data distribution were deleted. One explanation for the difficult data fit is that the measured apparent resistivity distribution covers several orders of magnitude and that extraordinary high resistivity jumps occur, which is always a challenging task for ERT. It is also expected that 3D effects will occur due to the site characteristics, namely towards the end of the line and in the middle. The corresponding inversion result is given in Figure 4. The sea water was incorporated as a single region with a fixed resistivity of 1.4 Ωm, which is the mean fluid resistivity measurements in three different depths.
Outcrops of the bedrock lead to high resistivities of about 28000 Ωm at the northern and southern end of the profile. A low resistive zone appears at x = 200-600 m, directly below the sea, down to approximately 60-80 m depth, which could possibly be caused by a change of the geologic conditions that could be interpreted as a steep valley filled with sediments. This has not been documented previously. It might be caused by a graben structure formed between the well documented fracture zones NE3 and NE4. At the end of the sea (x = 600 m), a second low resistive zone appears that reaches down to 140 m depth, which correspond with the well-known fracture zone NE1. But is most likely possible that this is caused by 3D effects.

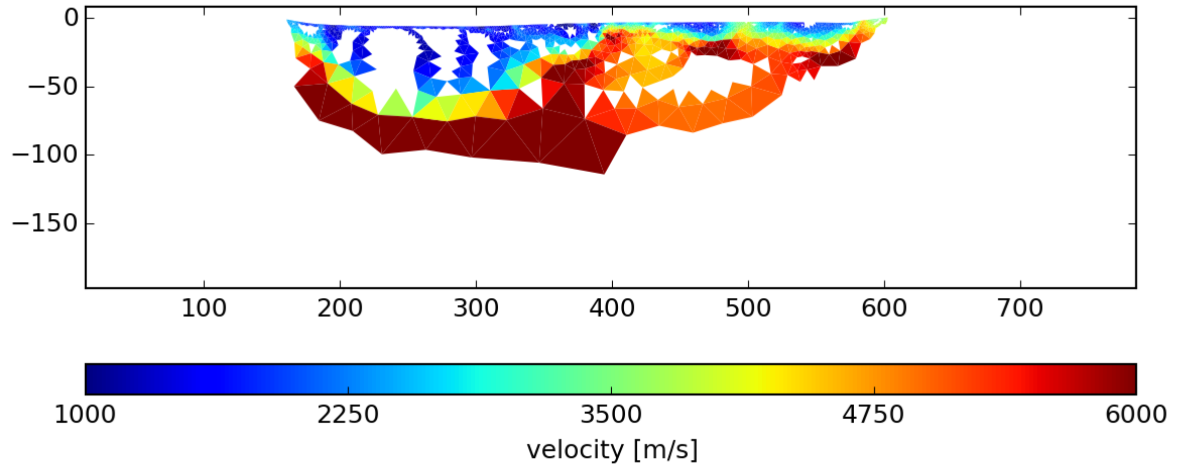

Figure 5: Inversion result of the seismic survey at Äspö HRL

A clear identification for the reason that might cause the low resistive zones can be possibly made using the results of the seismic refraction survey. As stated before, it covers the middle part of the ERT profile below the sea. Prior to the data fitting, negative travel times were deleted. For data inverse modelling, the software GIMLi for geophysical modelling and inversion was used. The fitted p-wave velocity distribution is shown in Figure 5.The crystalline bedrock appears as a high velocity zone of about 5600 m/s. Towards the northern part, the velocity of the bedrock decreases down to 5000 m/s. At the southern part, between x = 200-300 m, the result shows a low velocity zone down to 60 m depth, which is extended towards the north for shallow parts of the model, above 20 m depth. This finding coincides with the low resistive part in ERT result and is interpreted as sedimentary deposits that exhibit low velocities and, if water saturated, low resistivities. The sediments damp the seismic signal significantly that leads to a poor data quality below the sediments in the southern part. No further low velocity zones at larger depth appear, but at the near surface zone down to approximately 20 m depth. The fracture zone is not visible in the seismic result, due to the low data coverage in this part of the model.

5 CONCLUSION AND OUTLOOK

The inversion of the ERT data shows that the fracture zone in the northern part could be imaged as a low resistive zone. Additionally, a second low resistive anomaly in the southern part appears, which is interpreted as a previously unknown steep sediment valley. A comparison with the seismic result shows a low velocity zone in the same region, which is verification for sedimentary deposits. Due to insufficient data coverage, the fracture zone in the northern part of the profile could not be imaged by the seismic survey. An extension of the profile would be one way to ensure sufficient coverage.

In conclusion the preliminary evaluation shows that the approach has given very promising results, which illustrates that continuous information provided by geophysics can reveal previously unknown geological features even in an unusually well documented geological environment. There are possibilities for further developments of the interpretation of the data without costly additional data acquisition. For example, the reliability of the inversion results can be enhanced by implementing a-priori information, which could confine the ambiguity of the model space. Another possibility is to implement structurally coupled inversion, in which the data from the different geophysical models supports each other to reduce ambiguities.

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