Underwater ERT Surveys for Urban Underground Infrastructure Site Investigation in Central Stockholm

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ABSTRACT

Several underwater ERT surveys have been carried out in central Stockholm as part of pre-investigations for tunnels planned to pass under water, in the sea and in Lake Mälaren. The water passages are associated with major tectonic zones that can potentially be very difficult from a tunnel construction point of view.

The aim was to identify variations in depth of the bottom sediments as well as variations in rock quality including possible presence of weak zones in the rock. As a complement to refraction seismic that focuses on the mechanical properties ERT gives valuable information related to hydrogeological and petrophysical properties in the rock. Survey conditions are complicated by boat traffic, and electrical disturbances from the power grid and train traffic.

The ERT surveys were performed with different electrode cables placed on the sea bottom. The different cables used had either 64 electrodes at 7 meter intervals, 64 electrodes with 5 meter intervals or 128 electrodes with 5 meter intervals. Generally a multiple gradient array was used, but pole-dipole configuration was also employed in some cases in order reach deeper. The water depth was mapped using sonar combined with recording pressure transducers, and water resistivity as function of water depth was recorded using geophysical borehole logging equipment. Water resistivity as function of depth was integrated in the inversion model.

The results show that the rather difficult survey conditions could be handled in a satisfactory way thanks to adequate equipment, careful planning and attention to details. The measured data contains information that is relevant for creating coherent models of the variation in depth to rock, which corresponds well with data from drilling. The results also indicate that information in variation in rock quality that can be of critical importance for planning of underground construction can be derived from the data. Further comparisons against reference data are required for a full evaluation of the results.

Keywords: ERT, resistivity, underwater, tunnel, pre-investigation.

1 INTRODUCTION

Underwater Electrical Resistivity Tomography (ERT) surveys were carried out in a part of the sea called Saltsjön (Salt Lake) and Lake Mälaren in downtown Stockholm as part of pre-investigations for new tunnels. In one case for a new line for the Stockholm metro (T-bana) and in the other case for a road tunnel at Stockholm Förbifart. Measurements have also been performed for the Swedish Road Administration for road tunnels. The aim in all surveys was to identify variations in the depth of the bottom sediments, as well as variations in rock quality and the possible presence of weak zones in the rock.

The bedrock on the islands surrounding the investigated areas consists of granite, granodiorite and metagreywacke with mica schist. Several tectonic zones with different directions are expected, and tectonic breccia and myolinite have been mapped nearby. (Persson et al. 2001; Stockholm Municipality 1997) The soil layers covering the bedrock are expected to include till and various recent sediments.

The sites are rather difficult from a survey point of view. Seismic investigations nearby have not been successful due to gas in the bottom sediments. Electromagnetic methods were ruled out because of electric cables lying on the sea bottom. The variation in water depth, and vertical and lateral variation in salinity, requires attention. Furthermore the rather intense boat traffic in the Saltsjön area puts demands and restrictions on survey logistics.

2 METHOD DESCRIPTION

2.1 ERT

The ERT surveys, also known as CVES or 2D electrical imaging (e.g. Dahlin 1996), were performed using an electrode cable that was placed on the seabed. For the measurements in Saltsjön an electrode cable with 64 electrodes and a take-out spacing of 7 meters was used, giving a total layout of 441 meters. For the measurements in Mälaren the cable had 128 electrodes and 5 m spacing, giving a total length of 635m. In Mälaren the measurements were extended onto land using 21 extra land electrodes, resulting in a line of 735 m.

In Saltsjön five lines were measured using pole-dipole configuration in order to maximize depth penetration, where a 3500 metre cable was used for the remote electrode that was placed in the water east of the study area. The field survey was completed in 3 days, where one line was measured during the first day when time was also spent on installing the remote electrode apart from deploying the electrode cable etc. A measurement protocol with 3256 data points per measurement line was used to provide good resolution and depth penetration.

In Mälaren only one line was measured. The more resistive lake water allowed for a gradient configuration to be used. This saves a lot of work since it does not require the use of a remote electrode. The amount of data is similar to that of Saltsjön and the measurements were performed during one night. It should be noted that two full datasets were collected for the purpose of analysing effects of urban noise.

An ABEM Terrameter LS with 12 measurement channels was used for the measurements, where multi-channel measurement provided a quick measurement process despite the large number of data points. Interpreted sections of the resistivity distribution in the bottom sediments and bedrock were created using the inversion software Res2dinvx64. L1 norm (robust) inversion with water overlying the electrodes was used (Loke et al. 2003; Loke and Lane 2004). The inversion software was adapted to meet the requirements of this project by allowing several water layers with different resistivity.

2.2 Water Depth and Resistivity

In order to be able to get useful estimates of resistivity in soil and rock, it is necessary to integrate the water depth and the resistivity of the water in the interpretation model. Errors in water depth or resistivity leads to artefacts in the model as the inversion program compensates for surplus or deficit in conductance in the water model by corresponding increase or decrease in the resistivity. In this case the bottom topography varies greatly and the resistivity varies with depth in the sea, hence it is of utmost importance to measure both bottom topography and resistivity depth distribution in the water for each survey line to avoid misleading results.

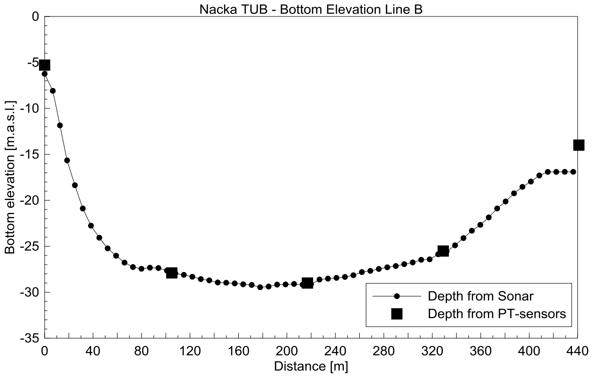

Figure 1 Example of depth profile determined with sonar and pressure sensors.

3 RESULTS AND INTERPRETATION

3.1 Saltsjön

The water depth in the study area was mapped using multi-beam sonar. The location of the survey lines were measured using side scan sonar where the measuring cable was identified in the measurement results. Depth profiles of the survey lines were then calculated by extracting information from the deep water model of the area along these lines. For quality assurance the electrode cable were fitted with 5 automatically recording pressure transducers of type Diver that were used to calculate the depth in a number of reference points.

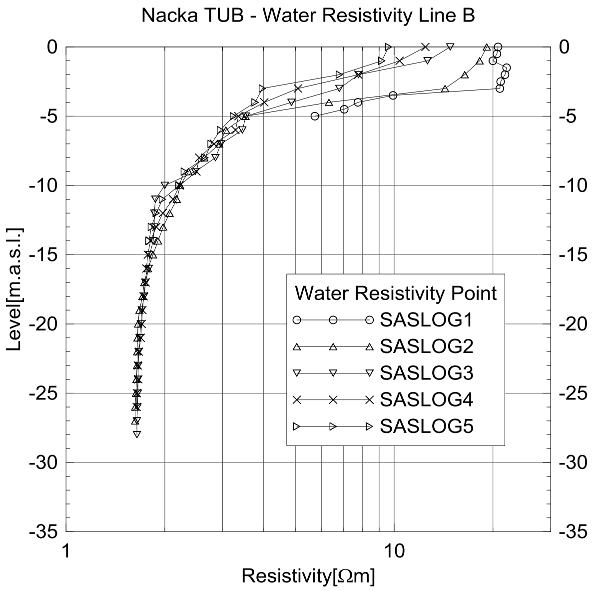

Figure 2 Example of water resistivity variation.

The water resistivity as a function of depth was measured with different geophysical borehole logging equipment for the two surveys. An ABEM Terrameter SAS4000 together with a SASLOG borehole log was used for measuring resistivity in both surveys.

Inspection of full waveform recordings done throughout the measurements reveal that there are high noise levels including 50 Hz, 16⅔ Hz and strong variation in background levels within the measurement cycles. The 16⅔ Hz noise is most likely caused by train traffic as it is the operating frequency of the Swedish rail system. The variation in background level may be caused by e.g. the underground train system (T-bana) which operates with DC power supply, or variation in the load in the commuter and national rail systems. Despite the noise resistivity data are of sufficiently good quality so that no culling of data points was needed before further processing, showing that the digital filtering of the instrument functions well. The bottom topography based on a combination of sonar surveying and pressure sensors was included as part of the models. The water resistivity distribution was simplified to a model of 5 layers with different resistivity. Each layer is assumed to be homogeneous in the horizontal direction; the variation in resistivity close to the surface was considered to be of limited importance. The inversion resulted in models showing vertical sections of resistivity variation (see example in Figure 3). The models have acceptable residuals (about 6-7%), which shows that there is relatively good agreement between model and data.

The resistivity sections show fluctuations which can be interpreted as a superficial layer with lower resistivity, which probably can be associated with soil layers of varying thickness and composition. Below are generally higher but varying resistivities that can be interpreted as bedrock zones of weakness and possibly varying composition. The top of the inverted sections are characterized by resistivities substantially lower than 12 Ωm with maximum thicknesses of up to about 20 m in the central parts of the lines. This

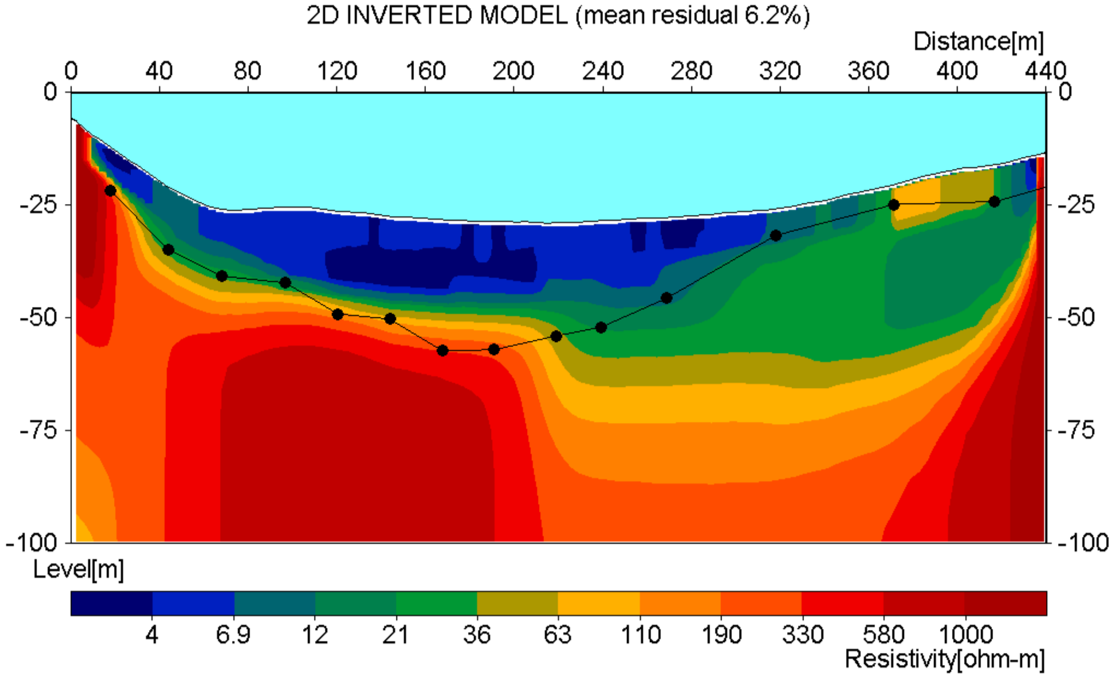

Figure 3. Resistivity model for Line A in Saltsjön, with water levels and interpreted depth to the bedrock from the geotechnical drilling indicated.

can be interpreted as unconsolidated sediments.

In the distance range of 220 to 440 m on Line A there is a zone with resistivities in the range of 12 to 36 Ωm in the upper low-resistivity zone down to several tens of meters. A corresponding zone appears on the other nearby lines, and without access to other data from the region, this could have been interpreted as a zone of anomalous composition of the rock or fractured and weathered rock. Alternatively, it could be interpreted as a sharp increase depth to bedrock, where the rock is overlain by sediments with different composition or salinity than in the upper parts of the sediments. At the beginning of each line low resistivities indicate that there may be a zone of weakness in the rock. Since the zone is located at the edge of the lines, the resolution is however poor. The low resistivity at the edge might also be caused by structural elements in quay construction, but because the survey lines are oriented perpendicular to the layout direction impact should be relatively limited. There are more or less vertical structures in the deeper parts of the sections that can be interpreted as tectonic zones, and separating more highly resistive zones (> 1000 Ωm) from zones with intermediate resistivities (a few hundred Ωm). The high-resistivity zones can be interpreted as crystalline rock with low degree of fracturing, while the zones of lower resistivity can be interpreted as rock with differing quality that is probably fractured and weathered rock.

Interpreted depths to bedrock from geotechnical drilling have been superimposed in the resistivity section of Line A (Figure 3). Interpreted depth to rock is generally well consistent between methods. Local variations in the depths may be due for example to the rock surface topography varying in three dimensions while the ERT survey is based on a two-dimensional approximation of reality. Rock levels show that the zone of relatively low resistivity in the range 220 to 440 m on line A consists of low-resistivity rock, which may be the uppermost part of a larger zone of differing properties of the rock.

3.2 Mälaren

As for the first case from Saltsjön most of the background noise is expected to come from the underground train system (T-bana) which operates with DC power supply. While most noise from AC sources can be filtered out the DC noise can only be avoided by measuring when the trains do not run, i.e. at night. In this survey measurements were taken on two occasions to be able to study the effect of DC noise. These results show a variance of 0-4% on the data measured at night and 0-20% on the data measured during the rush hours in the morning. The data measured during rush hours are still possible to process and interpret, but the higher noise rate during the day indicates that it might be a good idea to perform sensitive measurements or measurements close to infrastructure during the night.

The resistivity data are of good quality. The bottom topography based on a combination of sonar surveying and pressure sensors was included as part of the models. There was no variation of resistivity in the water so the water resistivity distribution was simplified to a single layer model of 62.5 Ωm. The inversion resulted in a model showing vertical sections of resistivity variation (Figure 4). The models have a low mean residual (about 3%), which shows that there is good agreement between model and data.

The resistivity section shows a superficial layer characterized by resistivities lower than 10 Ωm, in the distance interval 150 – 550 m, with maximum thicknesses of up to about 20 m. This can be interpreted as unconsolidated and/or clayey sediments. Below are generally higher but varying resistivities that can be interpreted as bedrock zones of harder rock in each end of the profile and a broad weaker zone in the centre.

In the distance range of 315 to 385 m there is a vertical zone with resistivities in the range of 23 to 44 Ωm in the deeper parts of the profile. This can be interpreted as a tectonic zone. On each side of this there are zones of around 100 m width with intermediate resistivity (a few hundred Ωm) and outside of these there are zones of high resistivity (> 1000 Ωm). The high-resistivity zones can be interpreted as crystalline rock with low degree of fracturing, while the zones of lower resistivity can be interpreted as rock with differing quality that is probably fractured and weathered rock.

Interpreted depths to bedrock from seismic measurements and geotechnical drilling have been superimposed in the resistivity section (Figure 4). Interpreted depth to rock is generally well consistent between methods. The interpreted weak zone in the centre of the profile is found both in drillings and in seismic. The weak zone in seismic at 550-600 m cannot be seen in the resistivity results, but it should be noted that the seismic line is placed about 20 m offline in the North end of the profile. The seismic data was collected in 2008 and raw data has not been available for analysis here.

4 CONCLUSIONS

The results show that the rather difficult survey conditions could be handled in a satisfactory way thanks to adequate equipment, careful planning and attention to details. The measured data contains information that is relevant for creating coherent models of the variation in depth to rock together with data from drilling. The results also indicate that information in variation in rock quality that can be of critical importance for planning of underground construction can be derived from the data. Further comparisons against reference data are required for a full evaluation of the results. It would have been helpful if geophysical borehole logging was conducted as a supplement in some drill holes along the lines. Such data could provide an interpretative key of the connection between rock resistivity and rock quality.

With about 20 m of water, as we have in these cases, a significant part of the current is transferred in the water instead of in the ground. The resistivity of about 1.5 Ωm, as in Saltsjön, means that more current is transmitted in the water than in the ground. This puts strict requirements on correct input of geometry of the seabed and resistivity of the water in order to get a good result. The surveying conditions are more favourable in Lake Mälaren thanks to the much higher water resistivity.

With the results presented here we conclude that resistivity measurement is an important contribution in urban investigations over water passages.

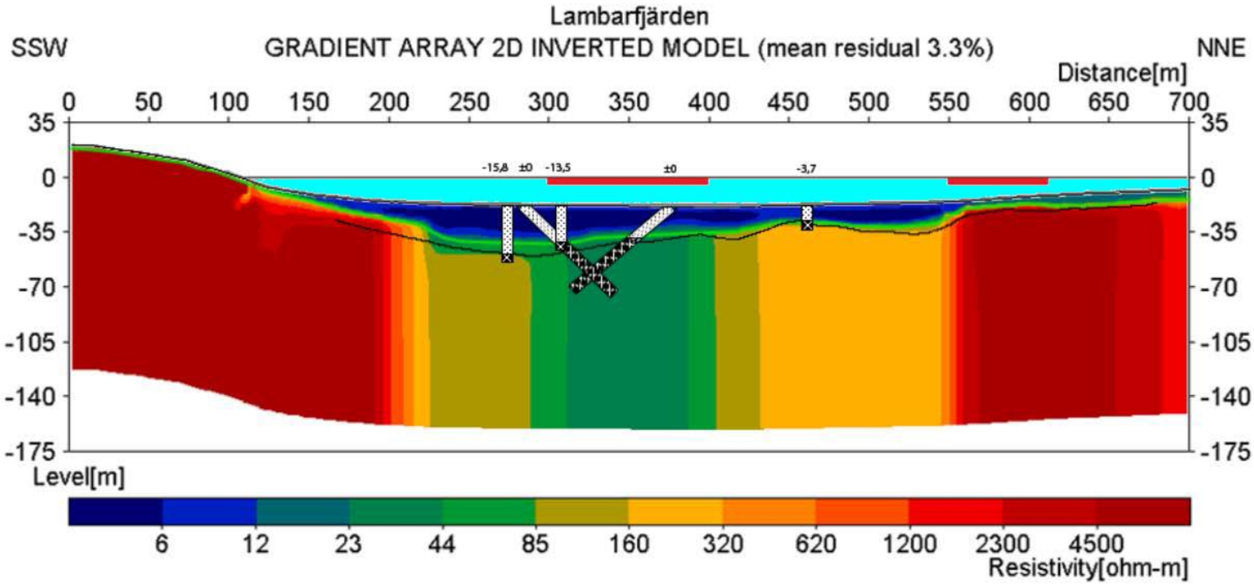

Figure 4. Resistivity model for Line in Mälaren, with water levels, drillings with noted weak rock (black fill in drillings), interpreted bedrock from drilling and seismic (black line) and interpreted weak zones in seismic (red lines in top of profile).

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