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CSRMT Survey on Frozen Lake - A New Technique with an Example from the Stockholm Bypass Tunnel

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Summary

More than 7% of the Scandinavian landmass is covered with fresh-water bodies in the form of lakes and rivers. This poses a unique challenge to carry out electromagnetic survey on shallow-water bodies for various purposes for example geotechnical investigations. Recently boat-towed RMT (radio-magnetotelluric) technique was introduced and used for measurements over the Lake Mälaren in Stockholm, Sweden. The RMT covers a wide range of frequencies (10-250 kHz) and provides good resolution for shallow subsurface studies although it lacks resolution at greater depths. Using controlled-source frequencies in the range of 1-10 kHz sufficient penetration depths can be achieved for most of the near surface targets. In this study, we present the results from the combined use of controlled-source and RMT (CSRMT) data that were obtained over frozen Lake Mälaren. The objective of this study was to map bedrock surface and fractures in the middle of the profile where using only RMT data these were not adequate. We demonstrate a new technique where CSRMT surveys were carried out over frozen-shallow-water bodies and we expect the idea to be used in the near future for other applications where moderately-resistive water bodies are present.

Introduction

Application of frequency-domain electromagnetic (EM) methods for near-surface studies is rapidly increasing worldwide. Tensor-radio-magnetotelluric (RMT) method that uses distant-radio transmitters as source has extensively been utilised to delineate resistivity variations of shallow subsurface (Bastani *et al*., 2013). Recently, a new data acquisition technique was introduced by Bastani *et al*. (2015) to collect RMT data over shallow-water lakes with an example from Lake Mälaren in the outskirt of the city of Stockholm. The survey was conducted in conjunction with the multi-lane motorway underground tunnel, Stockholm bypass. The planned bypass is a-21-km-long motorway, out which 18 km will be in form of bedrock tunnel. It aims to reduce traffic overload in Stockholm city along the European E4 highway. The nomenclature given to this method was boat-towed RMT as the acquisition system was towed by a boat. Mehta *et al*. (2017) examined and provided a detailed analysis of the resolution of boat-towed RMT data. They found that the RMT data provided better depth resolution for near-surface studies when compared to VLF (very low frequency) data since RMT covers a broader range of frequencies. However, it was also evident that the tensor RMT data lacked the required penetration depth (> 50 m) due to the limited radio-frequency range (10 to 250 kHz) in addition to the low-resistivity background in the study area.
A straightforward solution is to use controlled-source EM method to study deeper structures and if the source is sufficiently far enough from the measuring site then plane-wave approximation is valid. Wannamaker (1997) provides perquisites for source–receiver separation to be 5 times the skin depth limit in order to avoid near-field effects. Pedersen *et al*. (2005) and Bastani *et al*. (2011) present the results of tensor-controlled-source RMT (CSRMT) measurements for different near-surface investigation. However, the logistical requirements to carry out CSRMT measurements over lakes or rivers are challenging and not straightforward. To overcome this problem, we took advantage of the Swedish winters and for the first time carried out the CSRMT at the same site as reported by Bastani *et al*. (2015) over the frozen Lake Mälaren during March 2016. The present study is in a continuation of the work by Bastani *et al*. (2015) and Mehta *et al*. (2017) where the EnviroMT system of Uppsala University (Bastani 2001) was used for the CSRMT data acquisition, the data were modelled to study bedrock level and possible presence of fracture systems within it, known also from existing boreholes (e.g., Ignea 2015).

Data quality and processing

The CSRMT data were collected along four profiles (Figure 1) on the frozen lake of Mälaren. All the four profiles are nearly parallel to each other and run in a SW-NE direction. The profiles are separated from each other with a distance of 50 m with station interval of 25 m. The EnviroMT system acquires data in two modes, namely RMT and CSAMT. At each station, first the data corresponding to the radio frequencies (15-250 KHz) are recorded and then the controlled-source signals generated in the frequency range of 1-10 KHz are recorded.
The system in the CSAMT mode employs a source, which consists of two orthogonal horizontal magnetic dipoles. The source can remotely be triggered from the CSAMT measurement point. The location of the source is shown in Figure 1 with a yellow star mark. Figure 2 shows the field setup used for the CSRMT measurement over the frozen lake. Based on the results of previous studies (Mehta *et al*. 2017) we selected 5 source frequencies of 2.5, 3.2, 5, 8 and 10 kHz. The source, when triggered transmits from one of the magnetic dipoles at the given list of frequencies. The scalar transfer function are estimated and displayed for each frequency as they are recorded. The second dipole is then activated and the same procedure is repeated (Bastani, 2001). In the collected data, the transition between the radio frequencies and controlled-source frequencies is smooth for both apparent resistivity and phase. This gives us an indication of being in the far field and thus to combine the two data sets for modeling. The typical signature of the near-field effect for a magnetic dipole source in case of homogeneous half space is that with decreasing frequency the phase rises above 45 degrees and apparent resistivity decreases. In this study, the closest station to the source was 440 m away and the furthest station was 750 m away. At few stations in the NW part of the area, some signatures for the near-field effects (NFE) were observed in the raw data at lower frequencies. Most of the measuring stations located at a distance

greater than 500 m from the source did not show any NFE and therefore source-receiver distance was sufficiently good for plane-wave approximation conditions to be valid.

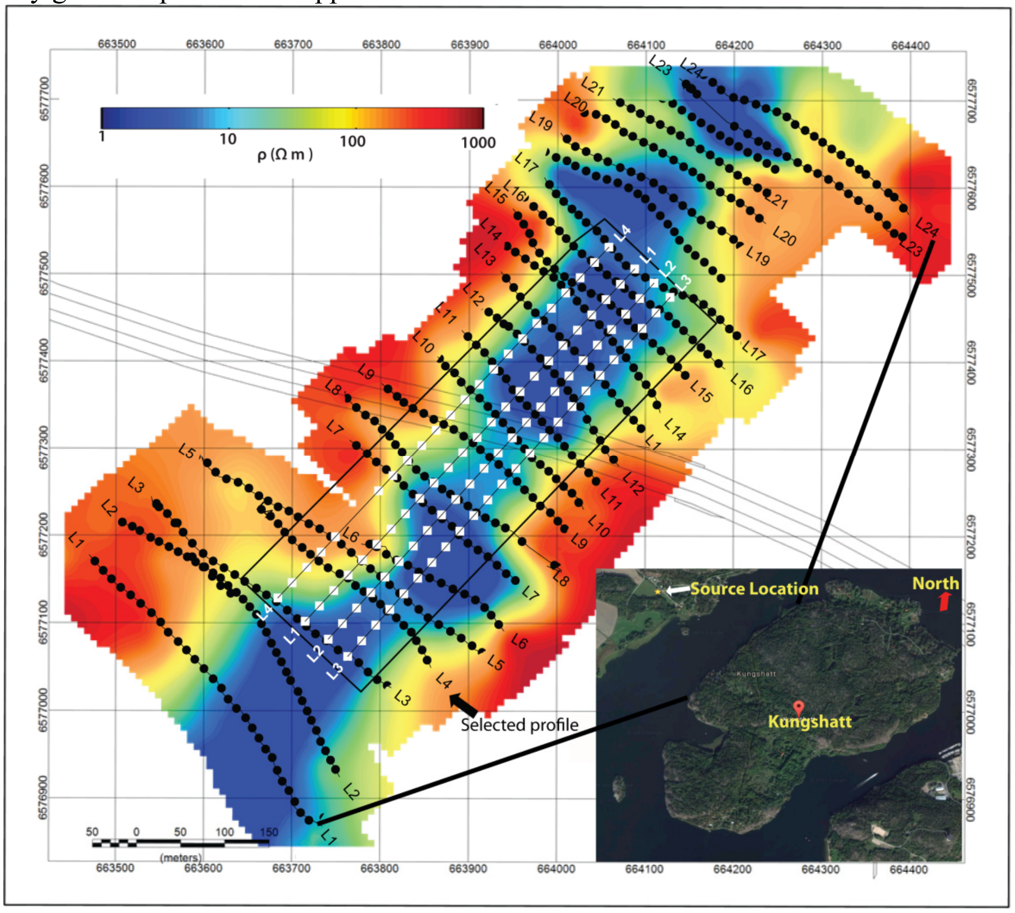

Figure 1 *Location of the existing RMT profiles marked from L1 to L24 on a resistivity slice at 38 m depth (an earlier 2D RMT study). The new acquired CSRMT profiles are marked as white rhombus. In the present study and to showcase the improvements, we used L4 RMT profile (marked with red arrow) along with the four controlled-source stations that lie along it.*

2D inversion of CSRMT data

2D inversion of CSRMT data was carried out using the modified REBOCC program (Kalscheuer *et al*., 2008, Siripunvaraporn and Egbert, 2000). For the inversion, the error floor applied on the resistivity was 4 percent and 1.2 degree on the phase data. The TM (transverse magnetic) mode gives a better fit than the TE (transverse electric) mode in the TE+TM mode inversion. Figure 3 shows the inverted models of profile L4, which is collected with the four CSRMT data points that collocate this profile. Both datasets with only RMT and with controlled-source stations effectively resolve the shallow features of the subsurface. The shallowest layer (300 Ω-m) is the resistive water column of the lake, which has known thickness of 10-12 m and well resolved. The highly-conductive lake sediments can also reliably be interpreted in all the models. Models from only RMT dataset (Figure 3 (b), (d) and (f)) resolve the depth to bedrock at both ends of the profile as it is relatively shallow.

The four CSRMT stations that lie in the middle of the profile provide better resolution at greater depth when compared with the RMT data s*et al*one (Figure 3). Previous results (Bastani *et al*. 2015 and Mehta *et al*. 2017) with only RMT dataset could not resolve the bedrock in the middle of the profile and left an ambiguity in the interpretation of their models from the central part of the water passages. The bedrock can now be resolved in the middle of the profile where the sediments are thickest and it is also known from the borehole data (Ignea, 2015) that a fracture system is present which has infilling of conductive minerals like graphite and chlorite. Thus, we can visualize the fractured bedrock in the middle of the profile that is relatively more conductive when compared to the bedrock at both ends (Figure 3). The depth to bedrock in the middle of the profile is also supported by the initial results from the reflection seismic section available along L4 (Nilsson, 2008).The nearest control source station on profile 4 is located at a distance of 460 m and the farthest is located at 670 m away from the source. Thus a possible near-filed effect (NFE) can be observed at the north-western side of the profile that is closer to the source station, and requiring to be fully investigated in further studies.

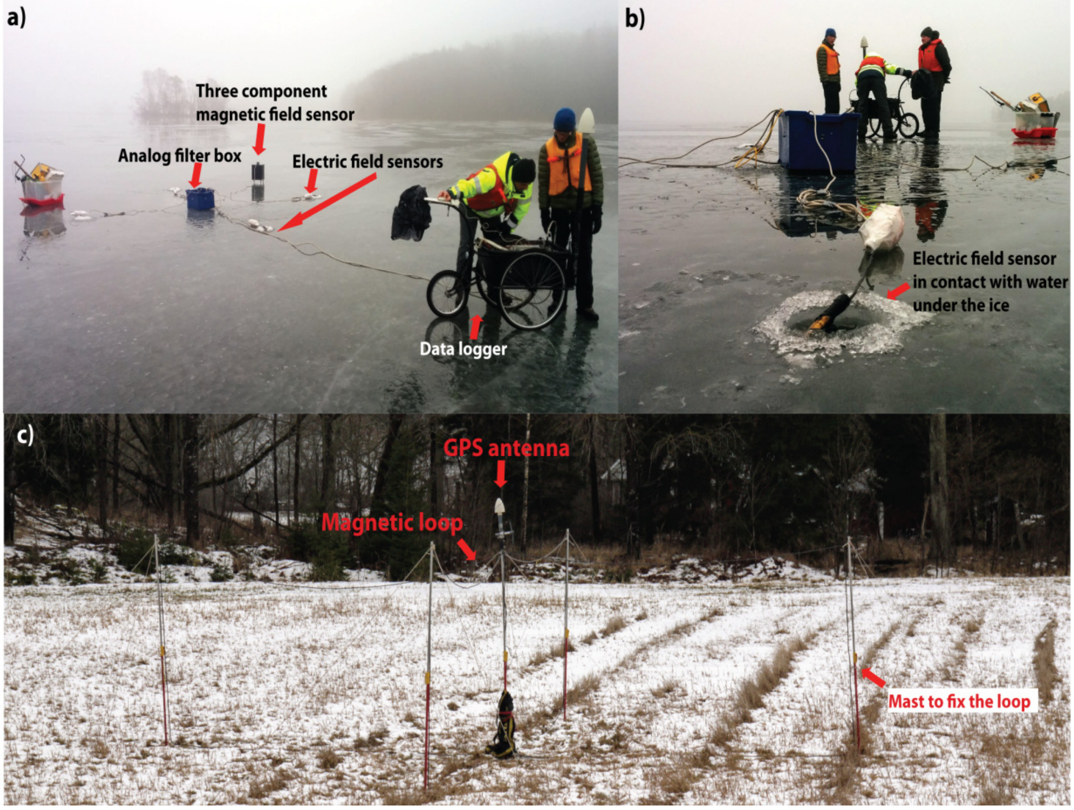

Figure 2 *(a) Photo showing the EnviroMT CSRMT field setup while measuring on the Lake Mälaren near the city of Stockholm, Sweden. Different components of the setup are also shown. (b) A close look at the drill hole made in the ice crust for making the electric electrode contact with water. (c) The setup of the double magnetic dipole transmitter (source).*

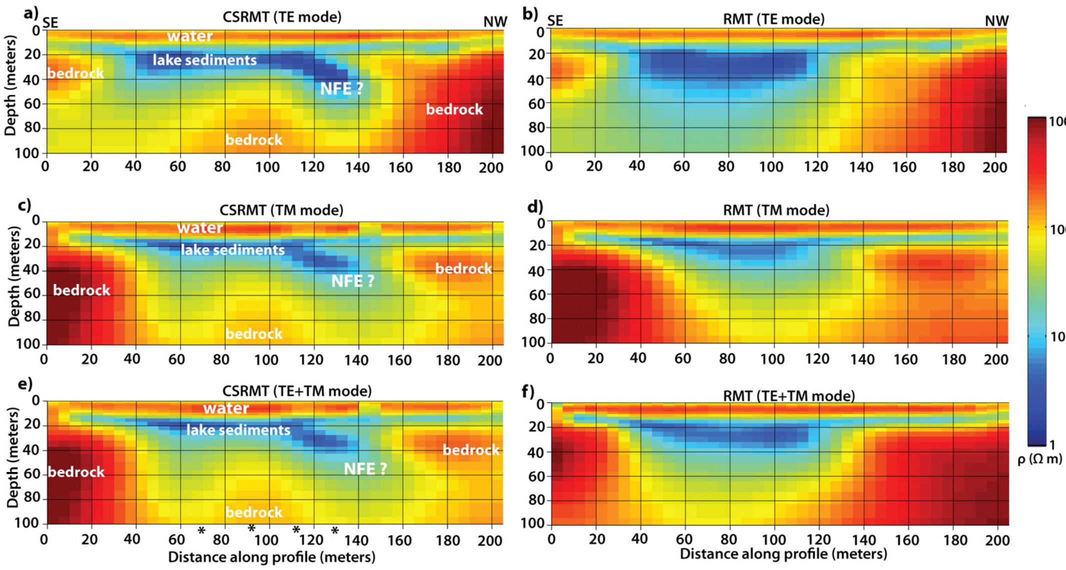

Figure 3 *2D inversion results of CSRMT and RMT dataset. (a), (c) and (e) are CSRMT models corresponding to TE, TM and joint TE+TM modes, respectively. (b), (d) and (f) are RMT models that correspond to TE, TM and joint TE+TM modes, respectively. The location of the controlled-source stations along the profile is marked by '*' in (e).*

Conclusions

For the first time CSRMT data over a frozen-water body was acquired successfully in an area close to Stockholm City. The main objective of this study was to resolve the bedrock surface and possible fracture zones within it where previous RMT data collected at the same area were incapable of resolving such a details. Variation of the modelled resistivity well correlates with the results reported in the previous studies, available boreholes and seismic data. Quality of the CSRMT data collected was in general good although at some stations closer to the transmitter near-field effect could be expected. Future studies will employ all controlled-source stations for modelling along with the other available geophysical data such as reflection seismic, to obtain a wider perspective in understanding geometry of the fractured bedrock at this site where part of the Stockholm bypass tunnel will be constructed.

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