Development of RMT techniques for urban infrastructure planning

Stockholm Bypass (Förbifart) case study

SUMAN MEHTA
Abstract


The tensor radio-magnetotelluric (RMT) method has extensively been used in near-surface investigations to obtain resistivity models of the subsurface. The main objective of this thesis is to further develop the RMT survey technique for a less paid attention and challenging environment namely on shallow water bodies and in the urban environment. The other objective is to develop a new processing technique to enhance the resolution and sensitivity of the tensor RMT method. For the first time a data acquisition system called ‘boat-towed RMT’ is introduced that has the capability to measure tensor RMT data on water bodies like lakes and rivers. A RMT survey carried out on Lake Mälaren near the city of Stockholm shows the capability and efficiency of the boat-towed RMT system. The resistivity models obtained from the RMT data are consistent from one line to another and show good correlation with the existing geological and drill core data. In general, a three-layer resistivity model was obtained that has a conductive layer interpreted as lake sediments, which is sandwiched between high resistive bedrock and resistive water column. A coherent discontinuity of low resistivity zone was observed in bedrock across all the lines. It was interpreted to originate from a major fracture zone striking in the direction of water bodies. However, due to the lack of penetration, RMT method alone was insufficient to provide a conclusive interpretation of this. Synthetic analysis was performed and showed that lower frequencies using controlled-sources are required to obtain the desired penetration depth. We took the advantage of the Swedish winters and carried out controlled-source RMT measurements on frozen lake at the same location. The new controlled-source models have enough depth penetration to delineate fractured bedrock. Furthermore, in order to improve the resolution and sensitivity of tensor RMT data, a new processing technique was developed that preserves the identity of each transmitter and allows improved resistivity model of the subsurface. These new acquisition and processing techniques should be useful in many different applications for urban infrastructure planning projects especially in Scandinavia where 7% of the land is covered by fresh water bodies and is poorly explored for these purposes.

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


In part II of the printed version of the thesis Papers I, II, III and IV are included in full text.

The following publications are not included in this thesis:


Contributions

The papers included in this thesis are the result of collaboration with several co-workers. The individual contributions of the author of this thesis are summarized below.

**Paper I:** Boat-towed radio-magnetotellurics (RMT) - a new technique and case study from the city of Stockholm.

My primary responsibility for the paper was to process the acquired data and to correct the coordinate location of all the stations. Further, I carried out the 2D modeling of the data. Finally, I was also involved in the discussions and writing of relevant sections of the manuscript and preparing figures.

**Paper II:** Resolution and sensitivity of boat-towed RMT data to delineate fracture zones – Example of the Stockholm bypass multi-lane tunnel.

In this paper, I was responsible for all the strike analyses, 2D modeling of the RMT data in different modes, synthetic analyses, constrained inversion and comparative studies with existing refraction seismic data. With the help of critical comments and suggestions of the co-authors, I was responsible to prepare the first draft of manuscript.

**Paper III:** Preserving the identity of VLF and LF transmitters for enhanced resolution of geoelectric models of RMT data

For this paper I developed a new RMT data processing technique and tested it on different datasets. The idea was triggered by Laust Pedersen and discussions with co-authors were critical to conclude the work.

**Paper IV:** CSRMT survey on frozen lakes: opportunities for urban applications

In this paper, I was involved in field survey planning and data acquisition. The processing, 2D modeling and interpretation of the data from the frozen Lake Mälaren were mostly carried out by me.
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## Abbreviations

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<th>Description</th>
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<tbody>
<tr>
<td>RMT</td>
<td>Radio magnetotelluric</td>
</tr>
<tr>
<td>CSRMT</td>
<td>Controlled-source radio magnetotelluric</td>
</tr>
<tr>
<td>CSAMT</td>
<td>Controlled-source audio magnetotelluric</td>
</tr>
<tr>
<td>CSTMT</td>
<td>Controlled-source tensor magnetotelluric</td>
</tr>
<tr>
<td>MT</td>
<td>Magnetotelluric</td>
</tr>
<tr>
<td>VLF</td>
<td>Very low frequency</td>
</tr>
<tr>
<td>LF</td>
<td>Low frequency</td>
</tr>
<tr>
<td>2D</td>
<td>Two dimension</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>kHz</td>
<td>Kilo Hertz</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse electric</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse magnetic</td>
</tr>
<tr>
<td>TEM</td>
<td>Transient electromagnetic</td>
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1. Introduction

The application of magnetotelluric (MT) method for electrical imaging of the subsurface was established in the early 1950s (Tikhonov, 1950; Cagniard, 1953). Since then the method has evolved significantly and its applications have been proved successful for mineral and hydrocarbon exploration (Orange, 1989; Hoversten, 1996; Pandey et al., 2008; Mansoori et al., 2015) and for studying deep crustal and upper and lower mantle structures (Lizarralde et al., 1995; Xu et al., 2000; Ichiki et al., 2001; Dasgupta et al., 2013). MT is essentially a plane wave, natural source electromagnetic method that measures in the frequency band range of $10^{-4}$ Hz to a few hundred Hz. In the last few decades, with the development of new instrumentation and formulation, MT method has found its role in near-surface investigations as well. Radio signals from the distant radio transmitters can be approximated as a plane wave EM source. This method is known as radio-magnetotelluric method (RMT) and it works in the frequency range of 10-250 kHz. For practical purpose, Goldstein and Strangway (1975) showed that the plane wave criteria can be satisfied if the distance between source and receiver is at least three to five skin depths in the case of a homogeneous half space. Pedersen et al. (2006) shows the stability of the transfer functions obtained from RMT data collected at different sites in Europe. Application of RMT technique in scalar form, where only one horizontal electric field and the perpendicular magnetic horizontal component is measured, has been explored in numerous studies (Turberg et al., 1994; Bosch et al., 1999; Tezkan, 1999; Tezkan et al., 2000). The tensor RMT technique in which all electrical and magnetic components are measured simultaneously (Pedersen et al., 2005, 2006; Bastani, 2001; Bastani and Pedersen, 2001) has significant advantages over scalar measurements in case of complex geological conditions (3D structures). There are numerous publications showing wide application of the RMT method in mineral exploration, hydrogeological, environmental and engineering problems (Bastani et al., 2009, 2013; Malehmir et al., 2016; Newman et al., 2002; Tezkan et al., 2000). Furthermore, Oskooi and Pedersen (2005) discussed the importance of broader range multi frequency VLF/LF system in better resolving the very shallow as well as relatively deeper parts of the subsurface. Persson (2001) studied the resolution of RMT and VLF data using field VLF and RMT and synthetic modeling. Sometimes the limitation in the penetration depth for RMT methods leads to several ambiguities in the interpretation of the model obtained.
Controlled-source lower frequencies (1-10 kHz) can be employed to gain penetration depth. Goldstein and Strangway (1975) originally employed the controlled-source audio magnetotelluric (CSAMT) technique, using a grounded electric dipole source to overcome noise problems. The source in this technique is located sufficiently far enough from the measuring point to avoid near-field effects.

Recently, there has been a wide range of successful experiments to carry out electrical resistivity and electromagnetic surveys on shallow water bodies such as lakes and rivers. Some of the water-borne electrical resistivity studies related to near-surface geological and engineering problems were reported by Day-Lewis et al. (2006), Danielsen and Dahlin (2009) and Chang Ping-Yu et al. (2015). Tassi et al. (2015) carried out electrical resistivity tomography in a marine environment for delineating fracture zones for an underwater tunnel project in Norway. A persistent issue with electrical resistivity surveys on lakes is the lack of penetration depth. In a comparative study of floating electrode array and bottom array, Loke and Lane (2004) concluded that in case of a floating array, water depth should not be more than 25% of the depth of investigations.

Several transient electromagnetic (TEM) studies over lakes have been reported. TEM data acquired on the Sea of Galilee by Goldman et al. (1996 and 2005) was used for mapping saline groundwater. Mollidor et al. (2013) showed the applicability of water-borne floating in loop transient EM measurement on Lake Holzmaar, Germany, to estimate the thickness of lake sediments.

This thesis introduces, for the first time RMT measurements on lakes, with a focus on a case study from an urban setting where Sweden’s largest multi-lane underground bypass tunnel will be developed and intersects 3 water passages on its way. Also for the first time a controlled-source tensor RMT measurement was carried out on a frozen lake on one of the water passages to allow deeper penetrations and better delineation of fracture systems inferred by the RMT models. The studies were all conducted as part of a larger project, TRUST: TRansparent Underground STructure, where for example two new geophysical systems (boat-towed RMT and a multicomponent seismic landstreamer) were developed and tested in a number of related projects (Brodic et al., 2017; Bastani et al., 2015).

The objective of this thesis is to study the adaptability, feasibility and analysis of resolution and sensitivity of tensor RMT and CSRMT data acquired on Lake Mälaren located in the outskirt of Stockholm. Also, this thesis reexamines the traditional processing techniques involved applied for tensor RMT data. A new processing technique is introduced for enhanced resolution of geoelectric models of RMT data.

In Paper I, details about the method and required modification in the set-up and field procedures are provided. It presents the effectiveness, challenges and shortcomings of the boat-towed RMT data acquisition set up. It illus-
trates the quality of raw data and the efficiency of the system compared to land survey.

**Paper II** extends the studies carried out in the previous work (**Paper I**) with more focus on the interpretation and securitization of the data to analyze the resolving capacity and sensitivity of the method in delineating weakness zones in crystalline bedrock with the help of synthetic analyses. A comparative study with existing seismic results and available bathymetry data of the lake were made to better constrain the interpretations. The study also shows the necessity for controlled-source low frequencies to obtain desired depth of penetration for verification of the interpreted weakness zones.

**Paper III** presents a new TE-TM processing technique that preserves the identity of VLF and LF transmitters for enhanced resolution of geoelectric models of RMT data. Data from two locations in Sweden and Greece are used to test this approach and compared with the results from standard band averaging processing technique. The first dataset is from the boat-towed RMT survey on Lake Mälaren (Bastani et al., 2015) and the second dataset is from the Volvi Basin in Greece (Bastani et al., 2011). Principal impedance elements at some given frequencies were analyzed and 2D models were obtained.

In **Paper IV**, for the first time, the measurement of controlled-source RMT was done on frozen lake over one of the three water passages intersecting the planned Stockholm Bypass. Detailed information about the field procedure, source setup and data processing is provided. 2D resistivity models are obtained by inverting the CSRMT dataset measured over frozen Lake Mälaren and compared with previous RMT models (Mehta et al., 2017) and available reflection seismic (Nilsson, 2008) data to map and interpret bedrock surface and potential weakness zones within it.

### 1.1 Study area

Stockholm Bypass (Förbifart Stockholm) is a new multi-lane underground motorway project planned by the Swedish Transport Administration (Trafikverket) that aims to reduce the increasing traffic pressure on the city of Stockholm from one of the major European highways connecting south and north of Sweden to other major destinations in Europe. It is a 21-km long motorway of which 18 km will be in the form of bedrock tunnel that will bypass the city and connect the southern and northern parts of Stockholm (see http://www.trafikverket.se/). The proposed path of the tunnel will pass under Lake Mälaren at three locations. These water passages and path of the tunnel is shown in Figure 1.1 (Bastani et al., 2015). Boat-towed RMT setup was tested and data were collected over these water passages with an objective to model the crystalline bedrock and identify location and geometry of
possible weakness zones. Sweden has 7% of its land covered by fresh water bodies and the developed boat-towed RMT equipment would be significantly relevant for future applications.

Figure 1.1 (a) The Stockholm Bypass project plan. The green line is the planned tunnel track, and the frame on the top-right corner shows the location of the study area in Sweden. (b) Cross section of part of the planned tunnel (marked with the dashed white box) below Lake Mälaren. Sites 1, 2, and 3 are where the case study was conducted (modified from Bastani et al., 2015).
1.2 Geological background

The study area is situated within the Svecofennian (> 1.75 Ga) metavolcanic and metasedimentary rocks of the Bergslagen mineral district of Sweden (Stephens et al., 2009). Around Lake Mälaren most rocks are granitic to granodioritic in composition and sometimes with lenses of mafic rocks within them; occasionally comprising of monzonite and metasediments (Persson, 2001). Fine to medium-grained granitic rocks are common in the Stockholm area and occur predominately in the island between site 2 and 3 (Figure 1.1). Major deformation zones along the water passages have been reported by Persson (2001) and Ignea (2015). Multi-phase deformation zones and topographic lineaments associated with them are typically found in the Bergslagen as reported in Malehmir et al. (2011).

Several drillings in the study area suggest the presence of frequent fractures in the bedrock. Detailed study of drill cores suggests occurrences of various rock types including amphibolite, granite, pegmatite, gneiss and clastic rock (Svensson et al., 2012). Fractures are moderately to highly-altered. The cores display evidence of both ductile and brittle deformation (Ignea, 2015). These fractures are often filled with graphite and chlorite but sometimes also with pyrite, clay minerals.
2. Theoretical background

2.1. Radio magnetotelluric method

The RMT method uses electromagnetic signals from distant radio transmitters in the frequency band of 10 kHz to 250 kHz and has sufficient penetration depth in the Scandinavian conditions for investigations. Turberg et al. (1994) were the first to use RMT method for hydrogeological studies. Since then there has been a vast number of publication covering wide range of hydrological, environmental and geotechnical as well as mineral exploration applications (Bastani et al., 2009 and 2011; Shan et al., 2014; Tezkan et al., 1996; Tezkan et al., 2000; Bastani and Pedersen 2001).

The detailed analysis of the RMT data collected at different sites in Europe by Pedersen et al. (2006) confirmed that considerable number of transmitters with a horizontal magnetic field signal to noise ratio larger than 12 dB exists. These transmitters can be used as cost effective EM source to study electrical resistivity variations for near-surface applications. The RMT time variation of two components of electric field ($e_x(t)$ and $e_y(t)$) and three components of magnetic field ($h_x(t)$, $h_y(t)$ and $h_z(t)$) are measured simultaneously. These measured components are related to each other via transfer functions, which contain detailed information about the variation of electrical resistivity of the subsurface. Fourier transformation of these time series provides a simple linear relationship between the horizontal components in the frequency domain (Pedersen, 1982). For a given angular frequency, $\omega$, the relationship can be expressed as:

$$
\begin{bmatrix}
E_x(\omega) \\
E_y(\omega)
\end{bmatrix}
= \begin{bmatrix}
Z_{xx}(\omega) & Z_{xy}(\omega) \\
Z_{yx}(\omega) & Z_{yy}(\omega)
\end{bmatrix}
\begin{bmatrix}
H_x(\omega) \\
H_y(\omega)
\end{bmatrix}
$$

or

$$
E(\omega) = Z(\omega)H(\omega), \quad (2.1)
$$

where $E$ and $H$ are the Fourier transforms of $e$ and horizontal components of $h$, respectively; $Z(\omega)$ denotes the impedance tensor, which is a 2 x 2 complex matrix.

The diagonal elements are zero in case of a two-dimensional earth model and $Z_{xy}$ represents transverse electric (TE) mode and $Z_{yx}$ corresponds to transverse magnetic TM mode. TE mode refers to a case when current flows in the strike direction, whereas in TM mode current flows perpendicular to
the strike (Berdichevsky et al., 1998; Tuncer et al., 2006). The impedances can be estimated (assuming noise-free magnetic fields) using a least-square approach as

\[
Z = EH^T(HH^T)^{-1},
\]  

(2.2)

where the autocorrelation of the magnetic fields leads to the estimate to be downward biased. The superscript \( T \) denotes matrix transposition.

Conversely, assuming that the electric fields are free of noise, we define bias estimates as below.

\[
Z = EE^T(HE)^{-1}.
\]  

(2.3)

Now, in case the 2D assumption is valid and the strike direction is known, the impedance tensor can be rotated to obtain the form

\[
Z' = RZRT = \begin{pmatrix} 0 & Z'_{TE} \\ Z'_{TM} & 0 \end{pmatrix},
\]  

(2.4)

where \( Z' \) denotes the rotated impedance tensor matrix and \( R \) is a rotation matrix defined by:

\[
R = \begin{bmatrix} \cos \Phi & -\sin \Phi \\ \sin \Phi & \cos \Phi \end{bmatrix}, \text{ where } \Phi \text{ is the rotation angle.}
\]

After rotation the strike direction corresponds to the \( x' \)-direction, \( E_{x'} \) and \( H_{y'} \) form the TE mode, the TM mode is defined by \( E_{y'} \) and \( H_{x'} \). We can then write

\[
H' = \begin{pmatrix} H_{x'} \\ 0 \\ H_{y'} \end{pmatrix} \quad \text{and} \quad E' = \begin{pmatrix} 0 \\ E_{y'} \\ E_{x'} \end{pmatrix}.
\]  

(2.5)

Now, by substituting the TM fields (\( E_{y'} \) and \( H_{x'} \)) and the TE fields (\( E_{x'} \) and \( H_{y'} \)) in equation (2) and (3) we get for downward biased estimates as below:

\[
Z'_d = E'H'^T(H'H'^T)^{-1} = \begin{pmatrix} 0 & E_{x'}H_{y'}^T \\ E_{y'}H_{x'}^T & \frac{E_{y'}H_{y'}^T}{H_{x'}H_{x'}^T} \end{pmatrix}
\]  

(2.6)

and for upward biases estimates we obtain:
\[
Z_u' = E'E^T (H'E^T)^{-1} = \begin{pmatrix}
0 & \frac{E_{xt}E_{yt}^T}{H_{yt}E_{xt}^T} \\
\frac{E_{yt}E_{yt}^T}{H_{xt}E_{yt}^T} & 0
\end{pmatrix}.
\] (2.7)

Determinant of the impedance tensor is defined as:
\[
Z_{det} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}^2}.
\] (2.8)

\(Z_{det}\) is commonly used for modeling because of its rotationally invariant characteristic (Pedersen and Engels, 2005; Smirnov and Pedersen, 2009; Bastani et al., 2011). Pedersen and Engels (2005) showed that TE mode couples well with conductors and TM mode couples well with resistive features and joint TE and TM mode modeling results in superior models.

The apparent resistivity and phase of impedance corresponding to different modes described above can be obtained by the following expressions:
\[
\rho_a(\omega) = \frac{1}{\omega \mu_0} |Z(\omega)|^2,
\] (2.9)
\[
\varphi(\omega) = \arctan \frac{\text{Im}(Z(\omega))}{\text{Real}(Z(\omega))}.
\] (2.10)

### 2.2. Dimensionality analysis

The impedance tensor provides an estimate of dimensionality of the subsurface structures. Swift (1967) defined the following parameter skew as:
\[
S(\omega) = \frac{|Z_{xx}(\omega) + Z_{yy}(\omega)|}{|Z_{xy}(\omega) - Z_{yx}(\omega)|}.
\] (2.11)

The value of skew is an indicator for the dimensionality. If the skew is small and less than 0.5 then it can be assumed that the data can be expressed in a simpler model, 1D or 2D. However, this parameter does not take into account 3D effects caused by near-surface heterogeneity and it’s also sensitive to galvanic distortions. A more precise approach to estimate regional strike
was suggested by Zhang et al. (1987). It is based on least-square minimization of the Q value, which is defined as:

\[ Q_{ij} = \frac{|Z_{xx}(\omega_i) - \beta_j \text{est} Z_{yy}(\omega_i)|^2}{\sigma_{xx}^2(\omega_i)} + \frac{|Z_{yy}(\omega_i) - \gamma_j \text{est} Z_{xy}(\omega_i)|^2}{\sigma_{xy}^2(\omega_i)}, i = 1, N; j = 1, M \] (2.12)

where \( \sigma_{yy}(\omega) \) and \( \sigma_{xx}(\omega) \) are the standard deviations of \( Z_{yx} \) and \( Z_{xy} \) respectively. \( N \) is the number of frequencies used and \( M \) is the number of stations. \( \beta_j \text{est} \) and \( \gamma_j \text{est} \) are the estimated distortion parameters at station \( j \). The \( Q \) value is calculated for different rotational angles and it obtains its minimum value at the regional strike direction. This approach of estimating regional strike direction takes the galvanic distortion into account and provides more reliable estimate.
3. Data acquisition and analysis

3.1 RMT data processing

All RMT data in this thesis were acquired using the acquisition system EnviroMT (Bastani, 2001). The system is frequency-domain electromagnetic equipment designed originally for land surveys. The details of RMT data processing schemes integrated into the EnviroMT instrument can be found in Bastani (2001). The RMT frequency band of 10-250 kHz is split into nine overlapping sub-bands of one octave (Bastani, 2001). Raw RMT data at each station are the mean stacked auto and cross powers of five components of measured EM fields at selected transmitter frequencies. The number of selected transmitters depends on a predefined S/N ratio of the total horizontal magnetic field power. In the study area of Lake Mälaren (Figure 1.1) 22 to 25 transmitters were available when a threshold of 10 dB was used for transmitter selection. These raw data are often contaminated by cultural noise or may be affected by uneven distribution of available transmitter within a given band of one octave. A reliable estimate of the transfer function can be obtained by the band averaging technique (Bastani, 2001) or by using a parametric representation of each impedance tensor element combined with truncated singular value decomposition (TSVD) regularization (Bastani and Pedersen, 2001) in cases of uneven distribution of radio transmitters.

3.2 CSAMT data processing

The concept of controlled sources in magnetotellurics (MT) was originally developed to improve the signal strength (Goldstein and Strangway, 1975). The AMT signal from natural sources in the frequency range of 1 to 10 kHz is primarily generated by lightning storms that propagate within the earth-ionosphere waveguide (Smith and Jenkins, 1998; Garcia and Jones, 2002). This waveguide is affected by temporal fluctuations that cause significant attenuation of signal strength (Szarka, 1987; Qian and Pedersen, 1991; Chave and Jones, 2012). Goldstein and Strangway (1975) proposed the use of controlled-source audio-magnetotelluric (CSAMT) method to improve the S/N. For the plane wave approximation to be valid, the source should be sufficiently far enough from the measuring station. The rule of thumb is that
the transmitter and receiver distance should be at least five times more than the skin depth (Sasaki et al., 1992; Wannamaker, 1997).

The controlled-source tensor magnetotelluric (CSTMT) method was proposed by Li and Pedersen (1991). The CSTMT data used in this thesis was also collected by the EnviroMT system in the frequency range of 1 to 10 kHz. The source for CSTMT measurements consists of two orthogonal horizontal magnetic dipoles and is remotely controlled from the measuring site. When the source is triggered, a signal at the selected frequency from one of the dipole is transmitted and scalar estimates are recorded. The second dipole is activated and the process is repeated. Eventually, the tensor transfer functions and their corresponding errors are estimated with a method suggested by Li and Pedersen (1991). The use of magnetic dipole is advantageous as they are easier to install and their range is sufficient to cover large distances up to 1 km. The EnviroMT system is integrated with phase-lock technique that helps in estimating reasonably stable transfer functions for CSAMT measurements. They also have little coupling to nearby conductive structures compared to electric dipoles and they are therefore generally expected to provide better plane-wave conditions and have smaller galvanic distortion effects than electric dipoles (Bastani, 2001). Pedersen et al. (2005) and Bastani et al. (2011) presented the results of tensor controlled-source RMT (CSRMT) measurements for different near-surface investigations. The estimated transfer function in case of CSRMT measurements must be carefully analyzed to check if there is any signature of near-field effect. 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 increases above 45 degrees and apparent resistivity decreases (Li and Pedersen, 1991).
4. Inverse theory and modeling

4.1. 2D inversion

In estimating the earth’s model, representing the subsurface structures form the observed geophysical data, mathematical inversion methods have played a vital role. In this thesis, for 2D modeling of RMT data, a modified version of REBOCC program (Siripunvaraporn and Egbert 2000; Kalscheuer et al., 2008) has been used. The advantage of this modified inversion module is that it accounts for displacement currents and also allows inversion of determinant mode (Kalscheuer et al., 2008). Further, the inversion algorithm performs in data space which helps to significantly cut down the computational cost and makes it a portable inversion module for personal computers.

Mathematically, we can consider earth as a discretized \( M \) number of blocks of constant resistivity, \( m = [m_1, m_2, \ldots, m_M] \), \( N \) observed data \( d = [d_1, d_2, \ldots, d_N] \). The fitness of the model response \( F[m] \) to the observational data can be expressed as:

\[
X_d^2 = (d - F[m])^T C_d^{-1} (d - F[m]), \tag{4.1}
\]

where, the superscript \( T \) denotes matrix transpose and \( C_d^{-1} \) is the inverse of data covariance matrix. The inversion problem is ill poised and thus the model norm \( X_m \) is minimized towards prior information. General model norm is expressed as:

\[
X_m^2 = (m - m_0)^T C_m^{-1} (m - m_0), \tag{4.2}
\]

where \( m_0 \) is a priori model and \( C_m^{-1} \) is an inverse of a model covariance matrix which acts as a smoothness operator. The objective function defined for minimization of the problem is a combination of equations (4.1) and (4.2) and can be expressed as

\[
\Phi = (m - m_0)^T C_m^{-1} (m - m_0) + \lambda^{-1} \{(d - F[m])^T C_d^{-1} (d - F[m]) - X^*_d^2\}. \tag{4.3}
\]

Here \( \lambda \) is a Lagrange multiplier that acts as a tradeoff between minimizing the norm of data misfit and the norm of the model (Tikhonov and Arsenin, 1977; Parker, 1994). \( X^*_d^2 \) is the desired level of misfit.
The inversion algorithm uses finite difference approach to discretize the model space with rectangular cells. In Papers I and II, the shallowest layer was 1 m thick and an increasing vertical cell size with geometrical progression of ratio 1.12, the deepest cell of 1200 m was considered. The horizontal blocks were variable and defined by the station spacing. The modified REBOCC module allows employing different inversion scheme like Occam, mean-square error (MSE) inversion and Marquardt-Levenberg inversion. Models in this thesis were generated using Occam type regularization to obtain smooth models.

4.2. Constrained inversion

A priori knowledge derived from other independent studies of geology or other geophysical methods can be of great use to constrain the interpretation and overcome the problem of non-uniqueness to a great extent. This a priori knowledge can also be introduced in the inversion process that guides the algorithm to better resolve structural units. The modified REBOCC program (Kalscheuer et al., 2008) allows the introduction of a priori model that helps to obtain better geological model and a better fit. In Paper II, the known bathymetry data were used as a priori model to constrain RMT models.

4.3. Synthetic modeling

MT inversion is a nonlinear problem. The inversion results are also non-unique. Thus to validate and investigate the important features interpreted in RMT model, synthetic data modelling can be carried out. This can be done by analyzing the sensitivity of the data with respect to changes in model parameters. In Paper II of this thesis, a set of synthetic analysis was carried out to investigate the sensitivity of the RMT method in detecting fracture zones in the crystalline bedrock that lies under the lake. Synthetic analysis also helped in the design of optimum frequencies for control-source measurements to provide the desired depth of penetration.
5. Summary of papers

5.1. Paper I: Boat-towed radio-magnetotellurics — A new technique and case study from the city of Stockholm

5.1.1 Summary
The main objective of the paper was to demonstrate the development of an acquisition system that has the capacity to carry out tensor radio-magnetotelluric measurements on lakes and other shallow fresh water bodies. The waterborne resistivity survey is not new and several reports have been published to demonstrate DC resistivity survey (Day-Lewis et al., 2006; Chang Ping-Yu et al., 2015; Danielsen and Dahlin, 2009; Tassis et al., 2015). Application of transient EM technique on shallow water bodies have also been demonstrated by Mollidor et al. (2013), Goldman et al. (1996) and (2005) and Hatch et al. (2010). For the first time in this paper, set up for tensor RMT measurement on lake is introduced and named as boat-towed RMT. The paper gives detailed information about the setup, field procedures and data processing. It also illustrates the feasibility of the system by showing some results of boat-towed RMT measurements from the Lake Mälaren, located near the city of Stockholm, Sweden.

The motivation for developing such an acquisition system emerged when an attempt to carry out geophysical investigation for the Stockholm Bypass project was planned. The new planned motorway will be underground in the form of bedrock tunnel for 18 km and the tunnel will pass under Lake Mälaren at three water passages. Thus an effort was made to develop the already existing RMT acquisition system EnviroMT (Bastani 2001), so that it could be used for waterborne RMT surveys. The boat towed RMT setup is nearly the same as EnviroMT (Bastani, 2001) system that is used for RMT survey on land. The EnviroMT system can be divided into two parts: the analog part and the digital part. In the boat-towed RMT system, the analog part is made to float on a platform made of wood and foam. The analog part consists of a 3C magnetometer field sensor, analog filter, electrodes and other electronics. Two pairs of steel electrodes are fixed on the floating platform at a distance of 5 m with the help of wooden arms. These floating analog components are towed by a boat, where the digital part of the system is
located. The analog signal is transferred from the analog part with a cable of 10 m. Figure 5.2 shows the boat-towed RMT system in an operational mode.

Figure 5.1. Detailed location map of the boat-towed RMT profiles (see the areas marked by 1, 2, and 3) in the study area over three water passages (WPs). The dashed line indicates the route of the planned tunnel with a maximum depth of approximately 60 m below the surface. Also see Figure 1.1.

The measurements using boat-towed RMT system was highly efficient. With 5 hours of data acquisition per day, all three water passages were covered (Figure 5.1). A total length of 15 km which includes 54 RMT profiles was surveyed. The speed of the boat was maintained at about 0.5 m/s and the average spacing between the stations was approximately 15 m. The initial tests showed that the EM signals from a total number of 20 to 27 transmitters with S/N >10 dB could be used for the RMT measurements on the Lake Mälaren at the three selected sites. The city related cultural noise was reduced using the procedure described by Bastani and Pedersen (2001) to obtain reliable estimate of impedance tensor. The boat-towed RMT system lacks inbuilt GPS system and position was registered using a handheld GPS which was in the boat at an offset of 10 m from the central measuring point. Thus this error in positioning was overcome by the estimating boat heading using two consecutive measuring points with known offset.
Figure 5.2. A photo showing the boat-towed RMT setup while measuring on the Lake Mälaren close to Stockholm, Sweden. Modified from Bastani et al. (2015).

2D inversion of tensor RMT data of all the profiles in Kungshatt-Lovön water passage was carried out using the modified REBOCC program (Siripunvaraporn and Egbert, 2000; Kalscheuer et al., 2008). The determinant RMT data were used because of their rotationally invariant property. Occam type regularization was used for inversion and 4% error floor on apparent resistivity and 1.2 degree on phase were used to avoid data overweighting. 2D models of some selected lines are shown in Figure 5.3. The distinct features that can be observed are the water column (w), conductive lake sediments (LS), highly resistive crystalline bedrock (B) and possibility of fracture zones (FB?).

5.1.2 Conclusions
The experiment of boat-towed RMT measurement has been illustrated, and its capability was proved by the Lake Mälaren case study. It was observed that the floating platform was stable in still to moderately wavy water. The data acquired using this newly developed system were of reasonably good quality and acquired at a very efficient rate of 1 km/hr with an average spacing of 15 m. 2D resistivity models obtained from the acquired dataset showed consistent results that were in good correlation with the existing geological field observations. Distinct features in the models, like highly resistive bedrock, conductive lake sediments, resistive water layer and a possible fracture zone were identified. The system should be of great use in
bedrock mapping for other near-surface applications since Scandinavia has approximately 7% of its land covered by fresh water bodies.

**Figure 5.3.** Selected 2D resistivity models along four lines located on the WP between Lovön and Kungshatt: (a) line 1, (b) line 9, (c) line 16, and (d) line 24 (Figure 5.1). The resistive bedrock is marked by B, possible low-resistivity-fractured bedrock by FB, water by W, and lake sediments by LS.
5.2. Paper II: Resolution and sensitivity of boat-towed RMT data to delineate fracture zones – Example of the Stockholm bypass multi-lane tunnel

5.2.1 Summary

The previous paper (Paper I) explained in detail about the logistics, field procedures and practicalities of the data acquisition using the boat-towed RMT system. However, the detailed examination of the data acquired in terms of its resolution power, its sensitivity and detailed interpretation of the resistivity models were left for further studies. The objective of this paper was to securitize the boat-towed RMT data to a greater extent and address a few unanswered issues with the help of other geophysical information from drill hole and available seismic refraction results.

The boat-towed RMT data were processed to remove the cultural noise associated with city related environment using a parametric representation of each impedance tensor element combined with a truncated singular-value decomposition (TSVD) regularization (Bastani and Pedersen, 2001). After strike analysis by several different approaches, it was quite evident that data could be expressed by 2D models. 2D inversion of determinant and joint TE+TM mode of all the profiles (38 in number) from two water passages were carried out (Figure 5.4).

![Figure 5.4](image.png)

*Figure 5.4* The location of the study area and two water passages (WP2 and WP3) in the Lake Mälaren, Sweden, where the boat-towed RMT survey was conducted. All the RMT stations are marked with red points and the profiles selected for detailed presentations in this summary are marked by green dots. The locations of available boreholes are marked with B1, B2, B3 and B4.
Distinct structural features in 2D RMT models in Paper 1 were also clearly observed in other water passage (Kungshatt-Sätra). The water layer thickness from bathymetry data corresponds well in all the RMT models. The depth to the crystalline bedrock can be interpreted with confidence at both ends of all the profiles where the conductive sediment thickness is less than 10 m. At the middle of all the profiles a conductive zone is observed and interpreted as a fracture system. To examine this fractured bedrock zone, the interpreted layers from existing seismic refraction data were superimposed on the RMT models (Figure 5.5). A low-velocity zone is observed in seismic refraction section that corresponds with the low-resistivity zones on RMT models. Also, the data available form inclined drill holes suggests that a system of fractures is present that have infillings of conductive minerals like graphite, chlorite and calcite. Drill cores showed occurrences of both ductile and brittle deformations (Ignea, 2015) from the zone. The average fracture frequency for the whole drill core is reported to be 6 fractures per meter. These additional data confirm that a fracture zone runs perpendicular to all the profiles and can be considered as weakness zone.

Figure 5.5 (a, c and e) 2D resistivity models (determinant data) of lines 2, 12 and 24 (WP2), respectively from Kungshatt-Lovön region. (b, d and f) 2D resistivity models of the same lines but obtained using joint inversion of TE and TE mode data. The interpreted layers from refraction seismic data are superimposed on the RMT models for comparison (shown in black lines). The interpreted structural features of two data sets correlated well. Velocities obtained, for example 1480 and 1750 m/s, well match those obtained for water and post-glacial sediments (e.g., Salas-Romero et al., 2015). W stands for water, LS glacial sediments, FZ fracture bedrock and B fresh bedrock. From Mehta et al. (2017).

The synthetic analysis was then carried out to validate the structural features that were expressed by the RMT dataset in the 2D models. Furthermore, the
sensitivity of the RMT method with respect to changes in model parameters was studied. The synthetic model considered closely mimics the RMT models obtained from observed data. Overall, it is a three layered electrical resistivity model with a top layer of resistivity 300 ohm-m that mimics the water followed by a layer of lake-sediments of 10 ohm-m and then the crystalline bedrock of 1000 ohm-m with a thin fracture zone. The data generated by forward modeling were contaminated by 4% Gaussian noise and inverted using an initial model of half space with different frequency ranges. Later, an a priori model was introduced to the inversion with an additional fracture zone located at some distance from the one in forward model. The synthetic data were inverted for both determinant and joint TE+TM modes (Figure 5.6). It was evident from the analysis that RMT method is capable of resolving fracture zone but lower frequencies are required to achieve desired depth of penetration for more conclusive results. Also, the analysis showed that joint TE+TM mode inversion provides better model of the conductive fracture zone as compared with the determinant mode.

Figure 5.6 (a) Synthetic model (with one major fracture zone in the bedrock) used to generate synthetic RMT data; it replicates the general features observed in real RMT models. (b) An a priori model (with two major fracture systems in the model), which was introduced in the inversion process later. The idea with this model was to study the sensitivity of the RMT data to arbitrary a priori information in the inversion.
5.2.2 Conclusions

The data acquired by using the boat-towed RMT method by itself has the resolution power and sensitivity to detect the presence of thin conductive fracture zone in resistive crystalline bedrock. The drawback is that due to its limited frequency band, a limited depth of penetration can be achieved thus cannot give conclusive results. RMT is an inductive method and presence of conductive lake sediments acts as a shield that further hampers the penetration depth. Synthetic analysis showed that using lower frequencies this problem can be overcome. Thus, it was suggested that future surveys should use controlled-source boat-towed RMT method to provide greater penetration depth for more conclusive interpretation. The study also shows the advantage of having a water layer that acts as a near homogeneous medium, which eliminates near surface static shift effects. Figure 5.7 shows the 3D visualization of all the 2D RMT models in the two water passages and it shows the consistent fracture zone in all profiles, but certainly more penetration depth is required for resolving deep structures.

*Figure 5.7.* 3D visualization of all the 2D resistivity profiles; (a) the two water passages and the locations of all the RMT line and (b) the planned Stockholm Bypass tunnel model (in green) visualized with the RMT resistivity models.
5.3. Paper III: Enhanced model resolution from inversion of RMT data by preserving the identity of radio transmitters

5.3.1 Summary

Traditionally, RMT data were acquired using analog systems that collected one frequency at a time (Tuberg et al., 1994; Tezkan et al., 1996 and Tezkan et al., 2000). For this technique, the strike direction is assumed and the profile direction is planned perpendicular to the strike. Thus, the RMT data are modelled in 2D taking into account the direction of the transmitters with respect to profile direction. The transmitter stations lying approximately parallel with the survey line are assumed to produce only TM mode data and those lying approximately orthogonal produce only TE mode data. The major disadvantage of this technique is that the data do not allow for an analysis of strike direction and the recognition of 3D effects in the data. Also, some transmitters have to be rejected because they do not satisfy the conditions of lying parallel or orthogonal to the profile direction. However, the advantage of this technique is that the identity of the individual transmitter frequencies is preserved.

The tensor RMT technique (Bastani et al., 2011; Bastani, 2001) made it possible to estimate the strike direction and dimensionality. In this technique two horizontal electric field components and three magnetic field components are measured simultaneously for each radio transmitter signal. Thus a full 2x2 impedance matrix can be estimated in a certain frequency band. This allows for decomposition of the tensor into TE and TM modes and moreover the full impedance tensor can even be modelled in 3D. The standard way of estimating the impedance elements is the band averaging technique. However, the issue with this technique is that it is adversely affected in cases where there is no transmitter available in a certain frequency band. The uneven distribution of transmitters is also an issue that leads to unreliable estimates.

In this paper, a new technique referred to as TE-TM processing technique is illustrated that preserves the identity of each transmitter. The new technique is based on the assumption that the profile direction is perpendicular to the known strike. Under this assumption, the idea is now to assume that the measured RMT data represent responses of a 2D structure with a given strike direction. Under this assumption a given transmitter may excite both TE and TM modes. If the angle between strike direction and transmitter direction is less than a certain threshold, say 23 degrees, only TE mode will be excited (see Figure 5.8). If the angle between profile direction (assumed to be orthogonal to strike direction) and transmitter direction is less than this threshold, then only TM mode will be excited. In all other cases both TE and TM modes will be excited and measurement of the two horizontal magnetic and
two horizontal electric fields will be sufficient to recover the TE and TM impedance elements. Figure 5.8 shows the schematic representation of the TE-TM processing method described.

*Figure 5.8. A schematic diagram of the TE-TM processing method. At a measurement point in the strike coordinate system a threshold angle, $\alpha$, is defined. In each quadrant the transmitters making an angle less than $\alpha$ to the strike direction will excite dominant TE mode. Similarly for the dominant TM mode the same angle is used for the direction perpendicular to the strike. The corresponding regions are shown for quadrants 1 and 2.*

Once the transmitters are classified, the spectra of individual transmitters can be estimated. To estimate the spectra of individual transmitters, adjacent frequencies in the spectra with similar transmitter direction where stacked over narrow bands. The impedance tensor elements $Z_{xy}$ and $Z_{yx}$ are then estimated and corresponding upward (equation 2.7) and downward bias (equation 2.6) resistivity and phases are calculated to be used for 2D inversion.

For test and demonstration, this new TE-TM processing technique was applied on the RMT data collected over one of the water passages (Kungshatt-Lövon). Also, a different dataset from Volvi basin, Greece was used to test the effectiveness of this technique. For the purpose of this summary, results from Lake Mälaren are presented. The estimated phase of the impedance tensor element $Z_{xy}$ (TE mode) is plotted for all frequencies in Figure 5.9. The apparent resistivity for TE and TM modes along the profile for selected frequencies are plotted for both upward and downward biased estimates (Figure 5.10)
Figure 5.9. (a) Phase for all frequencies at all stations for profile 2 calculated from the estimated downward bias impedance tensor $Z_{xy}$ (TE mode). (b) Phase for 3 selected frequencies are shown for all stations along profile 2.

Figure 5.10. Apparent resistivity for (a) downward bias and (b) upward bias of impedance tensor $Z_{xy}$ (TE mode). The absolute difference between the upward and downward bias estimates is shown in (c). Similarly for TM mode (d) and (e) corresponds to downward bias and upward biases respectively. The absolute difference between (e) and (d) is shown in (f) which appears to have higher values.

The stability of the impedance tensor element provides a confidence about data quality. The ratio between the estimated upward and downward bias data using the proposed technique is in general close to one. The 2D model obtained from these estimate is shown in Figure 5.11. The new 2D resistivity models are in general consistent with the band averaging-based models although there are clear indications of improvement in sensitivity and resolutions especially at greater depths.
5.3.2 Conclusions

A new RMT data processing technique for the estimation of transfer functions has been introduced. The proposed method to estimate impedance tensor elements based on transmitter identity preservation and its classification clearly shows that the resolution and sensitivity of RMT data can be improved when maximum possible information can be preserved. The application of this approach to a data set from Lake Mälaren, Stockholm showed that the apparent resistivity and phase are smooth and the calculated error bars are small. The improvement is also evident in the 2D models obtained that reflect greater details in the subsurface that are confirmed by other available data. To implement this approach, knowledge of strike direction is important, which can be estimated with full tensor analysis in the VLF band and some prior information can also be useful in estimating the strike for appropriate survey planning. This approach can remarkably improve the 2D modelling of RMT data.
5.4. Paper IV: CSRMT survey on frozen lakes: opportunities for urban applications

5.4.1 Summary

The application of frequency-domain EM methods for near-surface studies is rapidly increasing worldwide. Papers I and II in this thesis elucidate the effectiveness and applicability of RMT method in challenging environment over shallow water bodies in urban settings. However, our experiences suggest that presence of a conductive overburden hinders the effectiveness of the method. The penetration depth of RMT method is limited as it operates in the frequency range of 10-250 kHz. The lack of penetration depth was one of the drawbacks highlighted (see also Bastani et al., 2015; Mehta et al., 2017) in the experiment of the boat-towed RMT at Lake Mälaren. In case of a conductive cover (e.g., water column or sediments), the boat-towed RMT method suffers penetration depth. In case of the Lake Mälaren site, the synthetic modelling suggested that if low frequency signals in the range from 1-10 kHz are used sufficient penetration depth could be achieved.

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) suggests perquisites for source–receiver separation to be 5 times the skin depth limit in order to avoid near-field effects (Bastani et al., 2009). Pedersen et al. (2005) and Bastani et al. (2011) present the results of tensor-controlled-source RMT (CSRMT) measurements for different near-surface investigations. However, the logistics requirement to carry out CSRMT measurements on shallow water bodies using the boat-towed RMT setup (Bastani et al., 2015) is rather challenging. For example, to record a single RMT measurement at a station 10-15 seconds of time is required whereas for a CSRMT measurement with five target frequencies about 5 minutes is required. To keep the slow moving boat and a floating platform stable for long duration is difficult especially in windy conditions. 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. This paper reports the experiment and our findings.

The CSRMT data were collected along four profiles (Figure 5.12) on the frozen lake of Mälaren. All the four profiles are nearly parallel to each other and run in a SW-NE direction (parallel to the water passage). The profiles are separated from each other with a distance of ca. 50 m with station interval of 25 m. The EnviroMT system acquires data in two modes, namely RMT and CSTMT. At each station, first the data corresponding to the radio frequencies (15-250 KHz) are recorded and then the controlled-source sig-
nals generated in the frequency range of 1-10 KHz are recorded (see Bastani 2001 for more details).

Figure 5.12. Location of the existing RMT profiles marked from L1 to L24 on a resistivity slice at 38 m depth (Bastani et al., 2015). 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 black arrow) along with the four controlled-source stations that lie along it.

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. Figure 5.13 shows the field setup used for the CSRMT measurement over the frozen lake. At each station five holes were drilled in the ice (about 10 cm) to make analog electrical sensors in contact with water below the ice crust. Thus the efficiency of CSRMT measurement was significantly reduced when compared to boat-towed RMT.
Figure 5.13. (a) Photo showing the CSRMT field setup using the EnviroMT system while measuring on the frozen 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 horizontal magnetic dipole transmitter (source).

2D inversion of the CSRMT data was carried out using the modified RE-BOCC 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. For more details about the inversion scheme and parameters refer to chapters 3 and 4 of this thesis. The TM mode gives a better fit than the TE mode in the TE+TM mode inversion. Figure 5.14 a,b shows the 2D resistivity models of profile L4, using the boat-towed RMT data collected by Bastani et al. (2015) and data included from the four CSRMT points that collocate the same profile. Both datasets with only boat-towed RMT and with controlled-source stations effectively resolve the shallow features of the subsurface. The topmost layer (300 Ω·m) is well resolved and presents the resistive lake water, which has known thickness of 10-12 m. The water covers low resistivity lake sediments with a very well-defined upper boundary. Models from 2D inversion of only RMT dataset (Figure 5.14a) resolves the depth to the resistive crystalline bedrock at both ends of the profile as it is relatively shallow. Inclusion of the four CSRMT stations that lie in the middle of the profile in the inversion provides better penetration depth in that part of the model and consequently improves the resolution.
at greater depths (Figure 5.14b) when compared with the model from the inversion of only RMT data set (Figure 5.14a). Previous results (Bastani et al., 2015; 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. Using the CSRMT data bedrock level can now be resolved in the middle of the profile where the sediments are thickest. Moreover, the borehole data (Ignea, 2015) indicates that a fracture system is present within the bedrock and has infilling of conductive minerals such as graphite and chlorite. We can therefore image the fractured bedrock, as a relatively low resistivity feature, in the middle of the profile with more confidence. The depth to bedrock in the middle of the profile is also predicted by existing seismic reflection (Figure 5.14c) available along L4 (Nilsson, 2008). For comparison with the CSRMT model and conducting an integrated interpretation the CSRMT model is superimposed on the seismic section (Figure 5.14d). One notices that the depth to the bedrock resolved by the CSRMT model is well estimated except for the region where the near field effect in the most southeastern CSRMT station may have dominated.

We observed the near-field effect (NFE) dominantly at three frequencies at the station closest to the source, which is located towards the SE side of the profile. The typical signature of the NFE for a magnetic dipole source in case of homogeneous half space is that with decreasing frequency the phase increases above 45 degrees and apparent resistivity decreases. The NFE is more dominant on lower frequencies; hence we removed three lowest frequencies at the last controlled-source station.

5.4.2 Conclusions

For the first time CSRMT data over a frozen-water body were acquired successfully in an area close to Stockholm and in an area within the planned bypass multi-lane underground tunnel project. The main motivation for this study was to map the depth to bedrock and study the presence of any fracture system within the crystalline bedrock particularly in the middle of the profiles where the collected boat-towed RMT dataset was incapable of resolving such details. Variation of the modelled resistivity well correlates with the results reported in the previous studies, available boreholes and seismic data in modeling depth to the top of the bedrock and the fracture systems within it. Quality of the collected CSRMT data were in general good although at some stations closer to the transmitter near-field effect was experienced. In a broader perspective, the idea of conducting CSRMT study on frozen lakes can be of practical value on water bodies in similar climatic conditions especially where only RMT dataset does not provide the desired depth penetration.
Figure 5.14. 2D inversion results of (a) RMT and (b) RMT + CSRMT datasets. The location of the controlled-source stations along the profile is marked by ‘*’ (c) Seismic reflection section along the same profile. (d) The CSRMT model in (b) superimposed on the seismic section in (c) for a comparison as.
6. Conclusions and outlook

The work in this thesis explores and expands the tensor RMT technique to new dimensions. For the first time tensor RMT survey was conducted on shallow water condition using a slowly moving boat and a floating platform. This acquisition setup was termed ‘boat-towed RMT’ technique. The development, measurement procedures, capability and its adaptability are reported in Paper I. The study area selected for testing the boat-towed RMT setup was challenging in itself as it consisted of three water passages of the Lake Mälaren, in the city of Stockholm. The urban setting is not an ideal condition for EM surveys. The prime objective was to map bedrock surface in the area and identify if there is any presence of weakness zone. This was required since the planned tunnel path of the new motorway project Stockholm Bypass is supposed to pass under the Lake Mälaren. In Paper II the RMT data set acquired using boat-towed RMT setup over the Lake Mälaren were scrutinized and detailed analysis about its resolution power and sensitivity was done. The resistivity models obtained from RMT data had reliable resolution at the shallower part of the models. Basic resistivity features like water column, sediment thickness and depth to bedrock close to shores could easily be interpreted. However, in the mid zone of all profiles, where the thickness of the sediments was more than 10 m, RMT dataset did not have sufficient penetration to delineate bedrock level. Information from drill cores and seismic refraction data suggested the presence of a fracture system. These results led to further motivation to seek and develop new techniques and methods to improve the resolution and penetration depth of the RMT method.

In the second half of the thesis different solutions were proposed to further improve RMT method that could help in mapping the fracture system in the bedrock. In Paper III a new technique to estimate the transfer functions is proposed that preserves the identity of VLF and LF transmitters. The idea is based on the assumption that measured RMT data represent the response of 2D structures with a given strike direction along a profile. Under this assumption a given transmitter may excite both TE and TM modes or may excite them individually. If the angle between strike direction and transmitter direction is less than a certain threshold (say 23 degrees) then only TE mode will be excited. Similarly if the angle is greater than 67 degrees than only TM mode will be excited and in all the other cases both TE and TM mode. The 2D resistivity models obtained using this new technique showed remarkable improvement and more details could be resolved in the deeper part
of models. In **Paper IV**, controlled-source frequencies in the range of 1-10 kHz were used to have a better penetration depth to resolve the fracture system in the bedrock. The unique aspect of this controlled-source tensor MT survey was that, it was, for the first time, carried out on frozen lake. This survey lacked efficiency when compared to the boat-towed RMT survey but gave useful insight of the deeper features in the resistivity model. The CSRMT method provided sufficient resolution and depth to bedrock as well as the indication of fracture system could be interpreted.

These new techniques of RMT data acquisition over shallow water bodies could be used for many near surface investigations especially in Scandinavian conditions where 7% of the land mass is covered by fresh water bodies. It would be interesting to test these techniques on water bodies in different conditions. In case of contaminated water bodies, which would act like a conductive layer, controlled-sourced RMT survey could be helpful. More sophisticated techniques or systems should be developed in future to routinely carry out CSRMT measurements even on water so that dependency on extreme winter can be eliminated. The new processing technique introduced in this thesis helps in improving the resolution power of RMT method.
7. Summary in Swedish


användbar insikt om de djupare funktionerna i resistivitetsmodellen. CSRMT-metoden gav tillräcklig upplösning och djup till berggrunden såväl som indikationer för hur spricksystemen kan tolkas.

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