Estimation of the anisotropy using CSRMT data in the transition zone of electric dipole

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SUMMARY

The present work focuses on the estimation of anisotropy and its influence on the interpretation. Anisotropy of the subsurface is estimated using the transition zone measurements of Controlled-Source Radiomagnetotellurics (CSRMT) field measurements. In addition, the electrical resistivity measurements were also conducted The CSRMT results are compared with the electrical resistivity tomography data. The results of our anisotropic inversions are in good agreement with the existing theory. This has been verified by substituting the resistivity values, obtained from the electromagnetic and direct current inversion, in the theoretical equations. Results of anisotropic inversions are well correlated with the borehole data, well logging data and a priori information about the geology of the study area.

Keywords: Anisotropy, Controlled-source radiomagnetotellurics, Transition zone, Horizontal electric dipole.

Introduction

The "macro-anisotropy" phenomenon is known since the pioneer studies of Schlumberger brothers. The stack of thin layers, with contrast in resistivity values, is electrically equivalent to a single layer with the anisotropic resistivity and the thickness equal to the total thickness of the stack. Vertical and horizontal resistivities of equivalent layer have simple relation with the total horizontal conductance S and vertical resistance T of the stack (Maillet, 1947):

$$\rho_h = h_\Sigma / S \qquad \rho_v = T/h_\Sigma \qquad (1)$$

Here ρ_h is horizontal resistivity, ρ_v is vertical resistivity, $S = \Sigma(h_i / \rho_i), T = \Sigma(h_i \cdot \rho_i)$, $h_\Sigma = \Sigma(h_i)$, ρ_i is the resistivity of the ith layer in the stack, h_i is the thickness of the ith layer.

This anisotropy exists on the macroscale only because of the weak resolution of ground-based (surface) soundings. However, well logging measurements are able to resolve each thin layer independently. That is why this phenomenon is called "macro-anisotropy".

Anisotropic layer has simple relations with isotropic equivalent. In the electrical resistivity measurements, conditions of equivalency are following:

$$\rho_{DC} = \sqrt{\rho_v \rho_h}, \qquad h_{DC} = \sqrt{\rho_v/\rho_h} \cdot h = \lambda \cdot h. \qquad (2)$$

Here λ is coefficient of anisotropy. In the transverse flow of electrical current, such as plane wave magnetotellurics (MT) or loop-loop transient electromagnetics (TEM), conditions of equivalency are following:

$$\rho_{MT} = \rho_h, \qquad h_{MT} = h. \qquad (3)$$

Therefore, two main conclusions can be derived: (i) in the anisotropic media we will obtain different resistivity for DC and EM methods and (ii) the thickness of anisotropic layer obtained by DC data will be λ times more than the actual thickness of the layer.

Horizontal electric dipole (HED) or grounded wire is a source of the EM field with complicated nature. In the near-field zone (Zonge, Hughes, 1991), the nature of the primary EM field is equivalent to DC case i.e. galvanic mode of the EM field. In the far-field zone, the primary EM field is the plane wave i.e. inductive mode. In the transition zone of the HED, EM field contains significant impact of both modes. Therefore, the measurements of the EM field in the transition zone of HED contain information about horizontal and vertical resistivities.

The controlled-source radiomagnetotelluric method (CSRMT) is a near surface electromagnetic frequency domain sounding, which measures the EM field of the vertical loop (Bastani, 2001) or the grounded wire (Saraev et al., 2017) in the frequency range 1-1000 kHz. In the urban regions, upper frequencies 10-1000 kHz can be covered by broadcast VLF-LF and AM radio transmitters

(McNeill, Labson, 1989; Tezkan, 2008). Usually, CSRMT surveys are conducted in the far-field zone of the controlled source for simplifying the inversion.

In this abstract, we are discussing the results of the field experiments of the CSRMT method (in the transition zone of the grounded wire) for the estimation of the macro-anisotropy. The resistivity values obtained from the CSRMT and ERT techniques are compared using equation (2).

Geology of the survey area

The survey area is located near St. Petersburg, Russia. The geology of the area is well studied during summer geological camps and it has horizontally layered structures with near to constant layer thicknesses. In the study area, the geological section contains following formations (from top to bottom):

1. Quaternary moraine loams (6-10 m);
2. Ordovician clayey limestones (11-13 m);
3. Ordovician shales (1 m).
4. Ordovician-Cambrian sandstones (10-15 m);
5. Cambrian blue clays (more than 150 m).

The most important characteristic of the geological section is alternation of thin more or less clayey sub-layers in the limestones. Between limestones and sandstones there is a thin layer of shales. It is illustrated by electrical well logging data obtained in the borehole drilled directly on the test area (Figure 1).This features will produce the macro-anisotropic response. The layer of clay was not reached by well but the top boundary of the clay is clearly observable on the nearby riverbed's slopes.
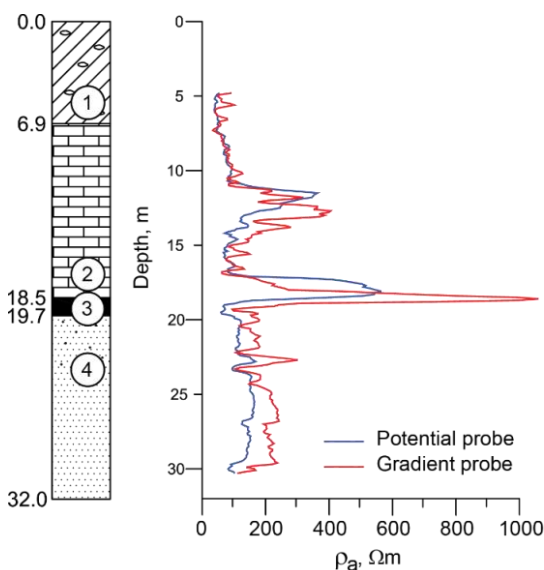

Figure 1. Geological column and electrical well logging data for the study area. 1 – moraine loams, 2 - clayey limestones, 3 - shales, 4 – sands.

Equipment

For CSRMT soundings, a digital EM receiver RMT-5 and portable AC transmitter GTS-1 was used (Saraev et al., 2017). The receiver was developed in St. Petersburg State University, and has five channels (two electric and three magnetic), total frequency band 1-1000 kHz and the 16 bit ADC. The RMT-5 receiver allows to use ungrounded (capacitive) electric antennas which significantly increase usability of the method. The GTS-1 transmitter has 1 kW output power, up to 300 V output voltage, 0.1-7.5 A output current and frequency band 0.1 Hz – 1 MHz. The transmitter is powered by portable gasoline generator. The squared wave output signal allows to use main harmonic of the signal and its higher odd subharmonics which increase the performance of the soundings.

For ERT measurements, the geophysical transmitter Astra-100 (Nord-West LLC, Moscow), receiver Medusa (SibGeophysPribor, Novosibirst) and digital commutator ComDD-2 (Geodevice LLC, St. Petersburg) were used.

Field experiment

The experimental survey layout is presented in Figure 2. For CSRMT measurements, two transmitters were placed orthogonal and independent to each other. The measurements were conducted along four lines of 200 m length each. The inter station spacing was selected 10 m and therefore 21 stations were measured along each profile line. The distance between the neighboring lines was about 50-70 m.
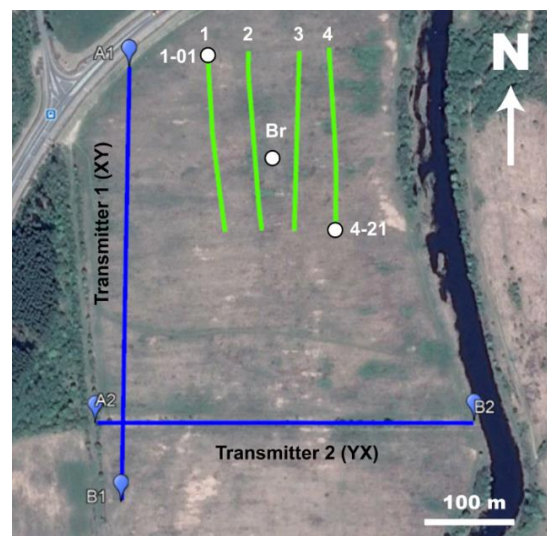

Figure 2. Survey layout. Green lines are the lines of measurements for CSRMT and ERT. Br – is borehole.

The receiver-transmitter distances were 80-220 m for Tx-1 oriented from South to North (XY direction) and 210-400 m for Tx-2 oriented from West to East (YX direction). Therefore, data from Tx-1 contains significant transition zone responses but the data from Tx-2 are mostly in the far-field zone (Figure 3). At each of the stations, we had three simultaneous measurements for frequencies 0.5, 5 and 50 kHz for Tx-1 and 0.45, 4.5 and 45 kHz for Tx-2. In the processing stage, we used up to 19th subharmonic for each main frequency. As a result, we have 27 points on the sounding curve from 1.5 to 950 kHz.
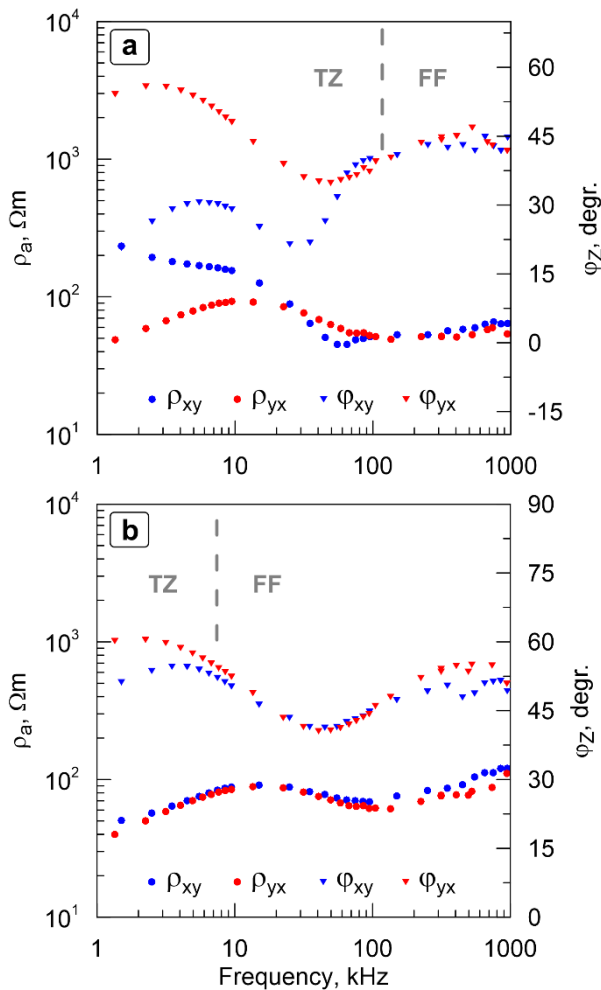

Figure 3. Example of the CSRMT data. **a** – line 1, station 5, **b** – line 4, station 5. TZ and FF stands for the transition zone and far-field zone of the source for φ_{XY} data, respectively.

Examples of the sounding curves for CSRMT stations 1-5 (line 1, station 5) and 4-5 (line 4, station 5) are presented in Figure 3. In both cases, the XY data contains transition zone response because of the closer distance to the source (80 and 220 m respectively). The YX data are totally in the far-field zone of the Tx-2 (distance 350 m). Very close data in the far-field for XY and YX direction prove the

assumption of 1D geology. Certainly, the shallowest horizons are little bit more inhomogeneous and provide higher difference in XY and YX data at high frequencies. Small scattering of points along the sounding curve indicates high quality of measurements.

For electrical resistivity tomography, the pole-dipole array (forward and reverse) was applied. Distance between potential electrodes was equal to five meters. Maximum distance between current and potential electrodes was 120 m. This provides depth of investigation about 60 m.

Inversion and results

The 2D isotropic inversion of the ERT data is done by using the ZondRes2D software with smoothness-constrained stabilization functional by keeping uniform X-Z smoothing because of good density of data. The ERT inversion results are presented in Figure 4. Three-layer structure is clearly indicated: top layer with medium resistivity about 60 Ωm and thickness about 10 m (Quaternary loams), second layer with resistivity about 300-400 Ωm and thickness about 40 m (limestones and sands) and conductive basements (clay). Line 2 has interesting detail: the thickness of the resistive layer increases up to 50 m from South to North.

For anisotropic inversion of CSRMT data, we used the code described in Shlykov and Saraev, 2015. For this purpose, only XY impedance (ρ_{XY} and φ_{XY}) data along the Tx-1 is used because of strong transition zone response close to the source. We used 4-layer model based on the sounding curves. Results of the anisotropic 1D inversion are presented in Figure 5. We can see that only the third layer is anisotropic and this layer has thickness 22-27 m as expected by a priori geological information. Thickness of the anisotropic layer obtained from CSRMT data has little changes along the lines of measurement. The coefficient of anisotropy is $\lambda = 1.3$-1.7.

As we mentioned in the introduction, in the DC case the anisotropic layer has electrically equivalent and isotropic layer with thickness λ times bigger than thickness of the original anisotropic layer. In Figure 5, a comparison of the actual boundaries of the resistive layer obtained from the field ERT measurements (thick white dashed lines), the theoretical position of the bottom boundary of the resistive layer obtained from equation (2), and the anisotropic inversion results (thin pink lines) from the CSRMT method.
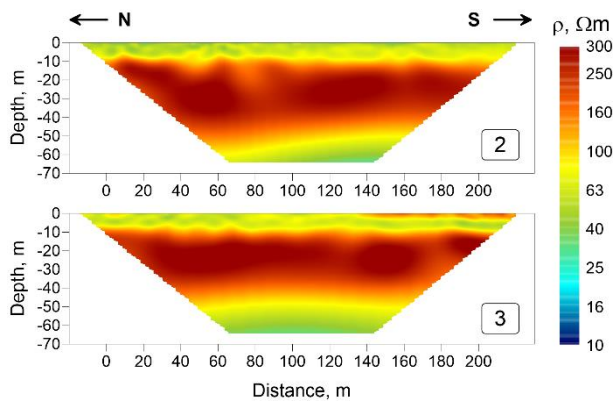
Figure 4. Results of the 2D inversion of ERT data for lines 2 and 3.

In general, the correlation between the thickness of the resistive layer obtained by ERT method and the theoretical thickness obtained by anisotropic inversion is very good. For line 2, the anisotropic layer has λ increase in thickness towards North. The same increment in the thickness is noticed in ERT results for the resistive layer. Here, we can conclude that the observed increase in the thickness in ERT result is an apparent increase. However, in reality only the vertical resistivity increases. This leads us to two possible geological interpretations. The increase in thickness might be attributed to either the lateral variation in the concentration of the clay particles in limestones or the lateral variation in the horizontal fracturing of the limestones.
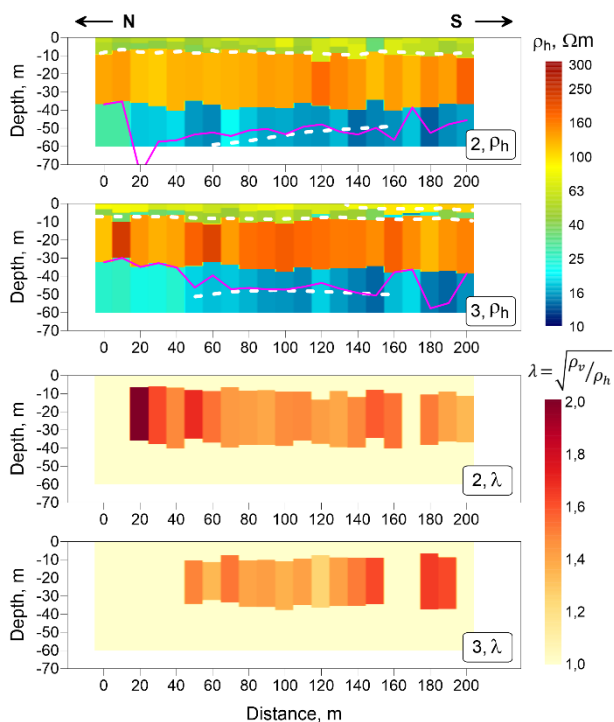

Figure 5. Results of the 1D anisotropic inversion of CSRMT XY data for lines 2 and 3. For details, refer to the text.

Conclusions

The results of the field experiment for estimation of the anisotropy of rocks using CSRMT method are presented and discussed. Anisotropic inversion algorithm is applied to the CSRMT data measured in the transition zone of the grounded wire. Inversion results for ERT and CSRMT data are significantly different in the thickness of the resistive macro anisotropic layer. The thickness obtained by ERT is 1.3-1.7 times larger than the CSRMT result. This mismatch has good agreement with the theoretical relations of the equivalent anisotropic and isotropic layers and partially proves the correctness of anisotropy obtained by CSRMT measurements.

Acknowledgements

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