

Detectability of the resistivity anisotropy using the CSRMT method with a horizontal electric dipole

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SUMMARY

The resistivity anisotropy is an important parameter for interpretation of electromagnetic soundings data. The importance of anisotropy was demonstrated by the marine electromagnetic community. Significant anisotropy is also observed in near surface media. In this abstracts we are discussing the detectability of anisotropy using land-based controlled source radiomagnetotellurics with a horizontal electric dipole. Our field experiment was performed in an area with 1D geology and two layers with strong a priori detected anisotropy. We are comparing controlled source high frequency responses in different geometries (inline and broadside), and the dependency of anisotropy detectability taking into account a length of the source using both numerical simulation and anisotropic inversion of field data.

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

Introduction

The anisotropy of electrical resistivity is an important parameter for the correct interpretation of electromagnetic soundings data. The importance of anisotropy accounting was demonstrated using field data by the marine electromagnetic community. Marine sediments are usually anisotropic because of differing lithology and hydrocarbon reservoirs also exhibit significant anisotropy (Constable, 2010). The accounting of anisotropy is used for the correct interpretation of marine CSEM data. Also, the vertical resistivity helps to locate the reservoirs more confidently.

In near surface land-based exploration the anisotropic objects are also not exotic. For example, glacial sediments contain thin and electrically contrast layers of sand and clay. Existing experience in studying of the anisotropy for the solution of near surface tasks is limited and mostly based on modelling only (Christensen, 2000; Ivanov et al., 2011). Using of the traditional isotropic inversion of direct current (DC) data such as the electrical resistivity tomography (ERT) in significantly anisotropic media can lead to wrong results. It is known that in DC case an anisotropic layer has simple relations with its isotropic equivalent, and determined thickness h is significantly overestimated (Maillet, 1947):

$$\rho_{DC} = \sqrt{\rho_v \rho_h}, \quad h_{DC} = \sqrt{\rho_v / \rho_h} \cdot h = \lambda \cdot h$$

Here ρ_h – horizontal resistivity, ρ_v – vertical resistivity, λ - coefficient of anisotropy.

The idea of estimation of the anisotropy in land-based survey is based on the joint inversion of DC soundings data and transient electromagnetic data (TEM). The main problem of this approach is the necessity to use two different methods.

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

In this abstract we are discussing results of a field experiment for the estimation of anisotropy using data of the CSRMT method in the transition zone of the horizontal electric dipole (grounded cable). We are demonstrating the dependency of detectability of anisotropy for the relative source-receiver geometry and length of the source. Also, we are comparing obtained results with the theoretical sensitivity and a priori borehole and hydrogeological data.

Geology of the experimental area

The survey area is located near St. Petersburg, Russia. It is well studied and has horizontally layered structure. In this area the geological section contains following formations (from top to bottom):

1. Quaternary moraine loams (thickness 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 layer of Cambrian clays (basement in our case) is highly anisotropic. Photos of clay samples are presented in Figure 1. It is easy to see many thin sand lenses in the clayey matrix with thicknesses about 1 cm and less. Hydrogeological researches show that the ratio of horizontal and vertical components of the molecular diffusion coefficient for this clay is about 3-6. Ratio of horizontal and vertical hydraulic conductivity is about 5-15 (Pankina, 2010).

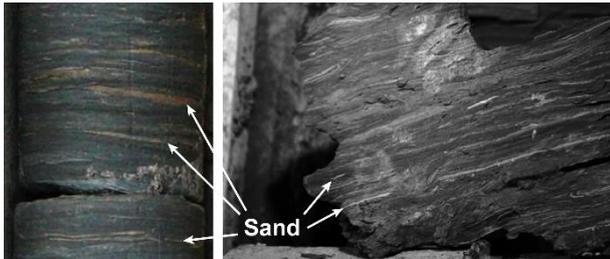


Figure 1. Thin lenses of sand in the Cambrian clays (Pankina, 2010).

The second anisotropic layer in the depth interval 10-35 m is a stack of limestones, shales and sands. Limestones contains alternation of thin more and less clayey sublayers. Between limestones and sandstones there is a thin layer of shales.

Field experiments

The field experiment using the CSRMT method for estimation of anisotropy was performed in two stages. The first stage was conducted in 2013 with relatively short (200 m length) grounded cable. Measurements were fulfilled along one profile using both inline and broadside geometries. Inline response was measured along the profile, broadside response - in perpendicular direction. The second stage of the field experiment was conducted in 2017 with the 500 m length grounded cable. In this case we used the broadside geometry only. Locations of profiles of measurements in 2013 and 2017 are not exactly the same but very close with deviation is about 10-20 m. The outline is presented in Figure 2.

In all cases we have the strong transition field effect – significant impact of the galvanic mode of EM field. We will use following numbering: case 1 – inline geometry and 200 m length of the source, case 2 – broadside geometry and 200 m length of the source, case 3 – broadside geometry and 500 m length of the source. Inversion was performed using an 1D anisotropic code described in (Shlykov, Saraev, 2015). For the inversion we used scalar apparent resistivity and impedance phase along the corresponding source only. Figure 3 illustrates cross-section for obtained horizontal resistivity, Figure 4 - for the coefficient of anisotropy λ .

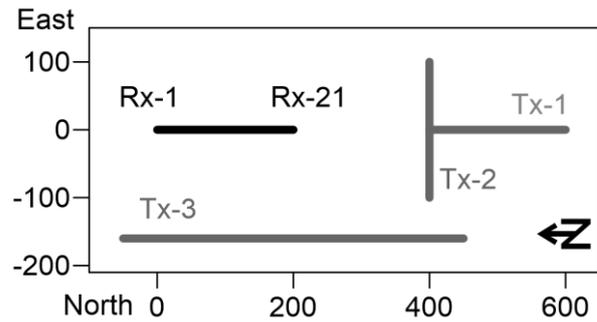


Figure 2. The outline of survey.

Four-layer structure is seen in Figure 3. Two upper layers are soil and moraine loams. The third layer is composed with limestones, shales and sandstones. The fourth layer is represented by clays.

Top layers of Quaternary moraine loams is isotropic one because of no impact of galvanic mode at high frequencies (far-field zone). It has resistivity about 30-60 Ωm . The third resistive layer of limestones and sandstones is obviously anisotropic. In the first and second cases coefficient of anisotropy estimated by the inversion of CSRMT data was relatively similar, about 1.6-1.8. In the third case (broadside area of long source) $\lambda = 1.3-1.6$. In the area near to a grounding the coefficient of anisotropy was not resolved. In all cases the horizontal resistivity is near to 100 Ωm .

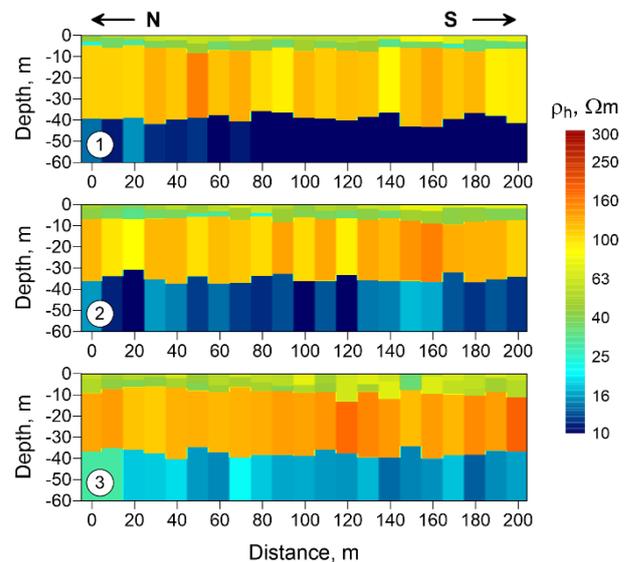


Figure 3. Cross-sections of the horizontal resistivity for different source-receiver geometries.

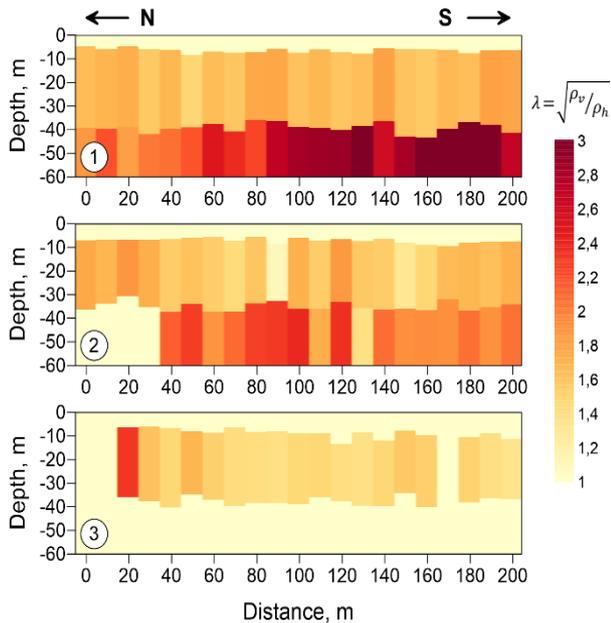


Figure 4. Cross-sections of anisotropy coefficient for different source-receiver geometries.

The bottom layer of clay is highly anisotropic. In the first case (inline measurements) $\lambda = 1.8-3.0$. The coefficient of anisotropy is decreased toward the North (Figure 4, 1). In this case the horizontal resistivity of clay is about 5-12 Ωm . In the second case the clays have $\lambda = 1.9-2.3$, but at the northern stations the coefficient of anisotropy was not resolved. Horizontal resistivity in this case is a little bit higher and varies from 9 to 17 Ωm . In the third case with long source the clays are shown as totally isotropic with horizontal resistivity near to 15-20 Ωm .

Modelling and discussion of results

Let's consider averaged 1D anisotropic model (Table 1) and integral sensitivity of apparent resistivity and impedance phase along the source for vertical resistivity of two anisotropic layers.

Table 1. Averaged model for numerical simulation.

Layer's #	$\rho_h, \Omega\text{m}$	$\rho_v, \Omega\text{m}$	h, m
1	60	60	3
2	30	30	7
3	100	300	25
4	5	50	∞

Integral sensitivity has following expression (Zhdanov, 2002):

$$S_{int} = \left\{ \sum_f \left[\frac{\partial \ln(\rho_a)}{\partial \ln(\rho_v)} \right]^2 + \sum_f \left[\frac{\partial \ln(|\varphi_z| + 45^\circ)}{\partial \ln(\rho_v)} \right]^2 \right\}^{\frac{1}{2}}$$

Here f – index of frequency.

We use the transformation of ρ_a and φ_z for making their dynamic range compatible. Integral sensitivity was calculated for three sources with lengths 200, 500 and 1000 m. Results are presented in Figure 5. Maps of the integral sensitivity explain all mismatches in the discussed results.

The inline data have the strongest sensitivity for ρ_v because of strong impact of the vertical electric field. It is also known from the marine CSEM (Constable, 2010). That is why the inline data show the most significant anisotropy including anisotropy of the conductive clays below the resistive and anisotropic limestones and sandstones. Moreover, the anisotropy of clays obtained from inline measurements is in good agreements with the hydrogeological data.

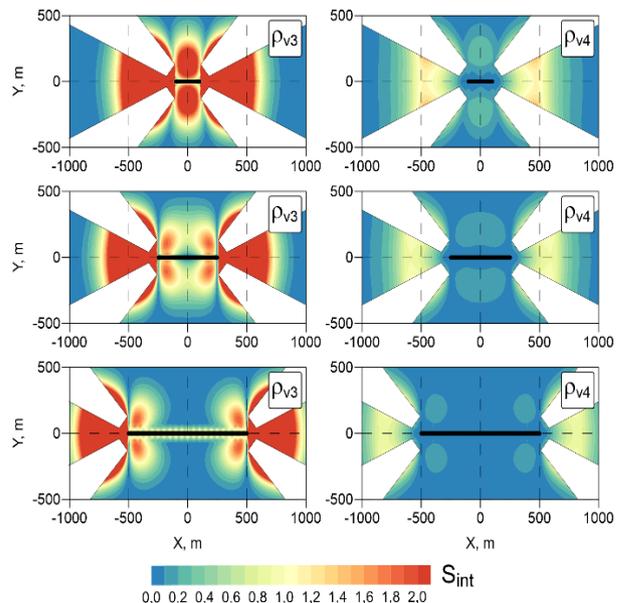


Figure 5. Integra sensitivity of Z_{xy} for vertical resistivity of third and fourth layers. Black solid line in the center is a source. White polygons mask areas of numerical instabilities because of the structure of normal field.

For our model the sensitivity to ρ_v in the broadside area of the long source is near to zero and is increased with decreasing of the length of source. It has simple physical explanation: in the near-field zone EM field is mostly galvanic and injected current goes sub vertically from groundings. In the broadside area the current is sub horizontal. When we use a short source the broadside response still contains the significant impact of vertical component of the electric field. That is why the anisotropy obtained with 500 m length of source is weaker. The anisotropy for broadside

measurements with 200 m length of source is compatible with the inline results. Resistivity of clays in the third case is close to geometrical mean of ρ_h and ρ_v obtained by inline data according to the theoretical equivalency (Maillet, 1947).

The sensitivity has minimum in the area exactly in front of the grounding. That is why the anisotropy is totally unresolved in the third case near to the northern end of the profile.

Conclusions

Controlled source radiomagnetotellurics measurements in the transition zone of the grounded cable allow us to determine the anisotropy of resistivity. Detectability of the anisotropy is well controlled by the numerical simulations and theory. It is enough to use scalar impedance only for anisotropic inversion if the sensitivity is significant. Sensitivity to the vertical resistivity in the broadside area of the grounded cable depends on the length of the source and becomes zero with increasing of the length. Short source allows us to determine anisotropy in the broadside area even below the relatively resistive layer. Good agreement of results obtained in different years indicates the reliability of measurements. Anisotropy of the electrical resistivity obtained by CSRMT method is compatible with the hydrogeological data obtained in laboratory, but this relation have to be studied more carefully and is the subject of further research.

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