Estimations of the macro-anisotropy of geological sections using data of the controlled source radiomagnetotellurics

Shlykov A.[1], Saraev A.[2]
[1] St. Petersburg State University, St. Petersburg, Russia, shlykovarseny@gmail.com
[2] St. Petersburg State University, St. Petersburg, Russia, a.saraev@spbu.ru

SUMMARY

Joint data inversion of galvanic (DC) and inductive (TEM or MT) soundings allows us to determine the coefficient of macro-anisotropy horizon, composed by the sequence of thin conductive and resistive layers, and to determine horizons thickness more correctly. A horizontal electric dipole excites the electromagnetic field with both galvanic and inductive modes. In the transition zone the contribution of galvanic and inductive modes in the total field are comparable. The possibility of implementation of a horizontal electric dipole as a source in the controlled source radiomagnetotellurics for the study of macro-anisotropic horizons is discussed in this paper. An algorithm of the anisotropic 1D inversion and results of its testing on synthetic data are described.

Keywords: macro-anisotropy, radiomagnetotellurics, controlled source, anisotropic inversion

INTRODUCTION

The sequence of thin conductive and resistive layers is equivalent to a single macro-anisotropic layer with following parameters (Maillet, 1947):

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

where h_Σ - total thickness of the sequence, $S=\Sigma h_i/\rho_i$ - total horizontal conductance of the sequence, $T=\Sigma h_i \cdot \rho_i$ - total vertical resistance of the sequence, h_i – thickness of a thin layer, ρ_i – resistivity of a thin layer, i - index of a thin layer in the sequence.

For DC methods (e.g. vertical electric soundings - VES) the source current has a large vertical component. Thus the DC response depends on both horizontal ρ_h and vertical ρ_v resistivities of a macro-anisotropic layer. For inductive methods (e.g. transient electromagnetics - TEM or magnetotellurics – MT) the current has only horizontal components and EM response only depends on horizontal resistivity ρ_h. Therefore in the significant macro-anisotropic ground results of inversion of data galvanic and inductive methods can be different. Using the joint data inversion of galvanic and inductive methods it is possible to determine the coefficient of macro-anisotropy λ ($\lambda^2=\rho_v/\rho_h$) and to minimize of the equivalence influence on the inversion results (Jupp, Vozoff, 1977; Christensen, 2000).

A horizontal electric dipole – HED (grounded cable) has a complex structure of EM field. In the near-field zone the primary EM field mostly contains the galvanic mode, similar to DC sounding methods. In the far-field zone the primary field as a plane wave contains only inductive mode. Primary field of HED in the transition zone is the combination of galvanic and inductive modes. Thus the vertical component of magnetic field has only inductive origin.

Measurements of EM field components in the transition zone of HED (cable) can be used for the study of macro-anisotropic layers, as the joint application of galvanic and inductive methods VES and TEM.

The radiomagnetotelluric (RMT) method is based on the use of EM fields of widely broadcasting radio transmitters in frequency range from 10 to 250-1000 kHz (Tezkan, 2008). Efficiency of this method in remote areas is limited by the possibility to measure signals of very low frequency - VLF (10-30 kHz) radio transmitters with great long-range action. In this case profiling investigations only are possible and the informative value of the method is considerably reduced. For these conditions the RMT method with own (controlled) source (CSRMT) has been developed. In the CSRMT method a vertical loop (horizontal magnetic dipole) (Bastani, 2001) or HED (Simakov et al., 2010) as sources are used. Using the controlled source allows us to extend the frequency range up to 1 kHz. In the CSRMT method measurements are usually fulfilled in the far-field zone and MT techniques and software tools for the inversion are applicable.

In this paper the CSRMT measurements in transition zone of HED and technique of anisotropic 1D inversion are discussed.

FORWARD PROBLEM

Expressions for EM field components generated by HED in 1D anisotropic media are presented in some papers, for example, in (Løseth and Ursin, 2007). The Hankel transforms are used in these expressions.

In the CSRMT method high frequencies (up to 1 MHz) are used and measurements at large distances (up to several kilometers) are carried out. In this case the quasi-stationary assumption can not be applicable because of the EM wavelength in the air λ_0 is comparable or less than source-receiver separation r (λ_0/r~1 or $|k_0|$r~1, where k_0 - air wavenumber). In this case kernels of the Hankel transform are not smooth functions and standard Fast Hankel Transform (FHT) method can not be applied. Two different approaches for solving of this problem are considered by Siemon (2012) and Shlykov and Saraev (2014).

In the simplest scalar case of the CSRMT method for estimating of the coefficient of macro-anisotropy we should measure the surface impedance $Z_{xy}=E_x/H_y$ and the tipper $T_{zy}=H_z/H_y$. As shown in (Shlykov, Saraev, 2014) even at source-receiver separations more than 160 m in the HED equatorial area the EM field components are not quasi-stationary at frequencies 100 kHz and higher. For CSRMT frequencies the surface impedance is not affected by displacement currents in the air but tipper has such dependence (Figure 1). Thus CSRMT anisotropic inversion algorithm has to be based on forward problem with taking to account the displacement currents in the air.

INVERSION STRATEGY

In this case Marquardt inversion with damping factor optimization is implemented:

$$\Delta \mathbf{m} = (\mathbf{J}^T\mathbf{J} + \alpha \mathbf{I})^{-1}\mathbf{J}^T\Delta \mathbf{d}, \qquad (1)$$

where $\Delta \mathbf{m}$ – target increment of model parameters, $\Delta \mathbf{d} = \mathbf{d}^o - \mathbf{d}^c$, $\mathbf{d}^o$ – observed data, $\mathbf{d}^c$ – calculated data, $\mathbf{J}$ – sensitivity matrix (derivatives of the calculated data with respect to the model parameters), $\mathbf{I}$ – identity matrix, α – damping parameter and ^{T} means transpose operation.

From analytical analysis is seen that $\partial H_z/\partial \rho_V=0$, and numerical analysis showed that $\partial H_y/\partial \rho_V$ has order about 10^{-12}-10^{-14} and can be negligible. Therefore only E_x and Z_{xy} out of the far-field zone are affected by ρ_V. In the far-field zone (at higher frequencies) neither impedance nor tipper are not affected by ρ_V. Therefore ρ_V of the upper layers can be unresolvable. These layers can be assumed isotropic. To highline layers with resolvable ρ_V any kind of the resolution analysis can be used, e.g. introduced by Jupp and Vozoff (1975) or by Stoyer (2010). We can choose some threshold level for ρ_V resolution. If corresponding resolution value is less or equal to chosen threshold level, this layer can be assumed as isotropic.

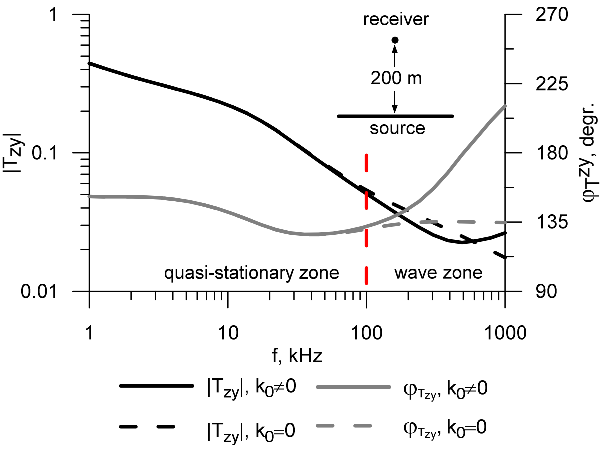

Figure 1. Comparison of tipper calculated with (solid lines) and without (dashed lines) accounting of the displacement currents in the air. Model is shown in Figure 2.

RESULTS

Simple model

Three-layer model for conditions of St. Petersburg region is presented in Figure 2a. The upper (first) layer is represented by sandy loam (ρ_1=50 Ωm, h_1=10 m). The second layer is represented by the clayey limestone and contains a sequence of resistive thin layers (ρ=400 Ωm, h=2 m) and conductive thin layers (ρ=40 Ωm, h=1 m). Total thickness of the sequence $h_{\Sigma 2}$=20 m. Bottom (third) layer is represented by clay (ρ_3=30 Ωm). In this case the second layer can be represented by an equivalent horizon with the following parameters: $h_{\Sigma 2}$=20 m, ρ_{h2}=108 Ωm, ρ_{v2}=292 Ωm (Figure 2b). Here and below the relative permittivity ε=6.

A sounding station is located in the equatorial area of a grounded cable of 200 m length with source-receiver separation r = 200 m. Synthetic sounding curves have 20 frequencies linearly spaced in log scale for 1-1000 kHz range. Comparison of the CSRMT apparent resistivity ρ_a and impedance phase φ_z^{xy} with corresponding plane wave values allows allocating the transition – far-field zones boundary. The far-field zone condition is the identity of CSRMT and RMT data with small difference (5% for ρ_a and 2° for φ_z^{xy}). In this case the far-field conditions are ensured for ρ_a^{xy} and φ_Z^{xy} at 8 kHz and 25 kHz respectively.

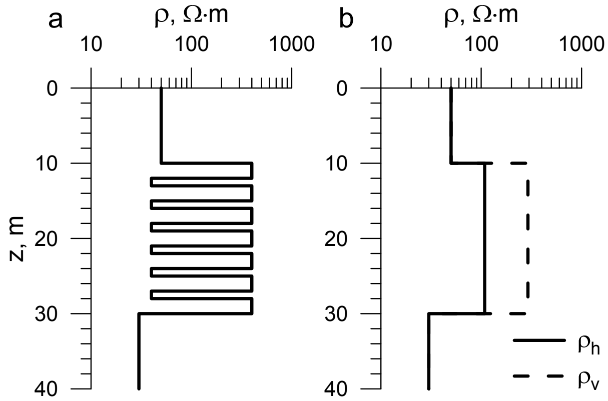

Figure 2. Base multilayer isotropic model (a) and equivalent anisotropic model (b).

A start model is chosen as isotropic half-space with ρ=300 Ωm. Results of applications of different inversions procedures are shown in Figure 3: isotropic inversion of scalar CSRMT data ρ_a^{xy} and φ_Z^{xy} (1), anisotropic inversion of ρ_a^{xy}, $|T_{zy}|$, φ_Z^{xy} and φ_T^{zy} (2) and anisotropic inversion of ρ_a^{xy}, $|T_{zy}|$, φ_Z^{xy} and φ_T^{zy} (3) with resolution analysis.

Application of the isotropic inversion of ρ_a^{xy} and φ_Z^{xy} shows that the only the 1st layer is determined correctly because of reached high frequency asymptote. Resistivity of 2nd layer is equals to ρ_{h2} in the base model. Thickness of 2nd layer is less than real one (16 m instead of 20 m in the base model). Resistivity of 3th layer is also determined incorrectly (37 Ωm instead of 30 Ωm in the base model).

In the DC case the second anisotropic layer can be represented as an equivalent isotropic layer with thickness in λ times more than in the model, where λ is a coefficient of macro-anisotropy, and resistivity equals to geometric mean of ρ_h and ρ_v (Maillet, 1947). In the inductive case (TEM or RMT) the second anisotropic layer can be represented as an equivalent isotropic layer with the same thickness and resistivity equals to ρ_h (Christensen, 2000). The EM field of a grounded cable in the transition zone is complicated combination of galvanic and inductive modes of EM field and properties of equivalent layer are depend on frequency and distance.

Anisotropic joint inversion of the impedance and tipper from CSRMT data (four curves of ρ_a^{xy}, $|T_{zy}|$, φ_Z^{xy} and φ_T^{zy}) gives much better results. But ρ_{v1} is resolved highly incorrect (125 Ωm instead 50 Ωm in the base model) because of correspondence of the far-field zone condition for high frequencies. Impedance is not sensitive parameter to ρ_v in the far-field zone and inversion result strongly depends on start model parameters.

To solve this problem the resolution analysis is implemented. At the end of each iteration value of resolution corresponding to ρ_v in the vector **m** is analyzed. Values of resolution are changed from 0 to 1. If one of them is less than some threshold level (in this case 0.1), corresponding layer is assumed as isotropic. As shown in Figure 3 this approach gives the most accurate result.

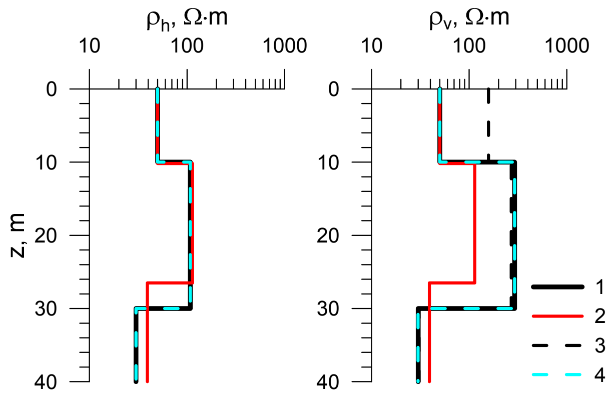

Figure 3. Results of different inversion procedures applications. 1 – base model, 2 – result of isotropic inversion of ρ_a^{xy} and φ_Z^{xy}, 3 – anisotropic inversion of ρ_a^{xy}, $|T_{zy}|$, φ_Z^{xy} and φ_T^{zy}, 4 – anisotropic inversion of ρ_a^{xy}, $|T_{zy}|$, φ_Z^{xy} and φ_T^{zy} with ρ_v resolution analysis.

Model from real electric logging data

The next model based on real electric logging data was used by Christensen (2000) for joint anisotropic inversion of synthetic DC and TEM data. The model has about 140 thin layers and can be approximated as 7-layers section where 2nd, 3th and 5th layers are apparently anisotropic (Figure 4). To have appropriate resolution of ρ_v for upper layers (to have more data in transition zone) an observation station is moved to the source (y=100 m). Far-field zone conditions are fulfilled for ρ_a^{xy} and φ_Z^{xy} from 43 kHz and 67 kHz respectively.

Start model for the inversion was chosen as uniform isotropic halfspace (ρ=60 Ωm - geometric mean of ρ_a^{xy}) divided into 7 layers (minimum number of layers for good data fitting).

Result of the inversion is shown in Figure 4. It has good agreement with the base logging diagram, especially in the bottom part. Second layer is resolved as isotropic because the pure resolution of ρ_V in the fare-field zone. Other anisotropic layers (3^{th} and 5^{th}) are resolved well: λ_3=1.67 (1.57 in the base model), λ_5=1.85 (1.76 in the base model).

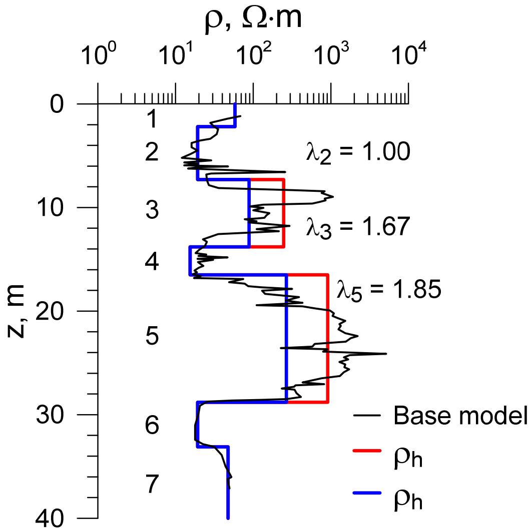

Figure 4. Result of the anisotropic inversion of synthetic CSRMT data compared with base electric logging diagram.

Using HED as a source in the controlled source radiomagnetotelluric method at measurements in the transition zone allows us to allocate macro-anisotropic horizons in a section and to estimate of their coefficients of macro-anisotropy. Impedance in the transition zone of HED contains significant component of galvanic mode of EM field and information about vertical resistivity. Tipper is connected with inductive mode and unaffected by vertical resistivity.

CONCLUSION

Results of joint inversion of synthetic impedance and tipper data measured in the transition zone of HED are presented. Data at high frequencies are usually connected with the far-field zone. Therefore vertical resistivities of upper layers can be unresolvable by CSRMT data inversion. Using the resolution analysis in the inversion process helps us to solve this problem. It can be assumed that any layer with resolution of vertical resistivity less than some threshold level can be considered as an isotropic one.

Presented examples of the synthetic data inversion show that anisotropic inversion procedures give more accurate results in complicated geoelectric conditions and the CSRMT method with HED as a source can be used for the estimation of parameters of macro-anisotropic horizons.

ACKNOWLEDGEMENTS

The works were fulfilled at the support of the Foundation for Assistance to Small Innovative Enterprises (FASIE).

REFERENCES

Bastani M (2001) EnviroMT – a new controlled source/radiomagnetotelluric system. PhD thesis, university of Uppsala.

Christensen NB (2000) Difficulties in determining electrical anisotropy in subsurface investigations. Geophysical Prospecting 48: 1-19

Jupp DLB, Vozoff K (1975) Stable iterative methods for the inversion of geophysical data. Geophysical Journal of Royal and Astronomical Society 42: 957–976.

Jupp DLB, Vozoff K (1977) Resolving anisotropy in layered media by joint inversion. Geophysical Prospecting 25: 460-470

Løseth LO, Ursin B (2007) Electromagnetic fields in planarly layered anisotropic media. Geophysical Journal International 170: 44–80.

Maillet R (1947) The fundamental equations of electrical prospecting. Geophysics 12: 529–556

Shlykov A, Saraev A (2014) Wave effects in the field of a high-frequency horizontal electric dipole. Physics of Solid Earth 50: 249-262

Siemon B (2012) Accurate 1D forward and inverse modeling of high-frequency helicopter-borne electromagnetic data. Geophysics 77: WB71–WB87.

Simakov A, Saraev A, Antonov N, Shlykov A, Tezkan B (2010) Mobile and controlled source modifications of the radiomagnetotelluric method and prospects of their application in the near-surface geophysics. 20th EM Workshop, Giza, Egypt: S5−P9.

Stoyer C (2010) Equivalence analysis of DC and EM data for layered models using the resolution matrix. Symposium on the application of geophysics to engineering and environmental problems: 173-182.

Tezkan B (2008). Radiomagnetotellurics. Groundwater geophysics: a tool for hydrogeology. Reinhard Kirsch (ed.), Berlin, Heidelberg. Springer, pp. 295-318.