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Effect of inclined conductivity anisotropy on frequency induction and TEM data

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Abstract

The harmonic electromagnetic field of a vertical magnetic dipole above an anisotropic half-space has been simulated using a forward algorithm for layered conductive media with inclined anisotropy. Inclined anisotropy has been found out to change the typical behavior of frequency and transient responses. Qualitative interpretation of FD loop–loop responses of a conducting earth with inclined anisotropy requires taking into account the receiver azimuth dependence of apparent resistivities. In the case of time-domain measurements, this dependence is absent but the apparent resistivities are higher at late times.

Keywords: anisotropy; conductivity; surface resistivity survey; frequency induction sounding; TEM

Introduction

Anisotropy of rocks is almost never taken into account in processing surface induction logging data. Yet, there are many rocks to be described in terms of conductivity anisotropy. They are, for instance, fractured rocks or thinly layered gas and oil reservoirs (Rytov, 1955). Anisotropy obviously shows up in acoustic, permeability, and geoelectric properties of rocks. Thinly layered reservoirs are low permeable across the layer boundaries and can be simulated with a uniaxial conductivity tensor (Tabarovskii and Epov, 1977; Tabarovskii et al., 1977). As a consequence of various geological effects, the normal to the boundaries of anisotropic layers can deviate from the normal to the bedding planes. Then, a formation of this kind will no longer fit the layered model with a transversely-isotropic conductivity tensor. The respective problem formulation and a frequency-domain solution for logging applications were first suggested in (Tabarovskii and Epov, 1979) and the simulation results were reported in (Fedorov and Epov, 2003).

When neglected in resistivity data processing, anisotropy effects can distort the results considerably. On the other hand, progress in acquisition and processing techniques can make the resistivity survey an efficient tool to investigate the structure of formations. Eventually, studying anisotropic effects on conductivity can stimulate advance in resistivity surveys and expand the scope of their applications.

In order to highlight the effects that are associated with anisotropy of rocks, we simulate the electromagnetic field with a simple model of a vertical magnetic dipole (VMD) over an anisotropic earth. The vertical magnetic dipole is a good source model being of broad use in both frequency induction (FI) and transient electromagnetic (TEM) practice. We explore the sensitivity of the commonly measured field components (the normal and radial components of the magnetic field and the azimuthal component of the electric field) to the conductivity anisotropy of a halfspace at different receiver azimuths. This problem formulation can provide clues to the effect of conductivity anisotropy on resistivity survey data.

Forward model

Thus, we simulate the effects associated with conductivity anisotropy using a simple but appropriate geoelectirc earth model. The two halfspaces of the model space are air and an anisotropic conductive earth separated by a plane interface. The anisotropy tensor is transversely isotropic along the principal axes but its axis is inclined at an arbitrary angle (δ)

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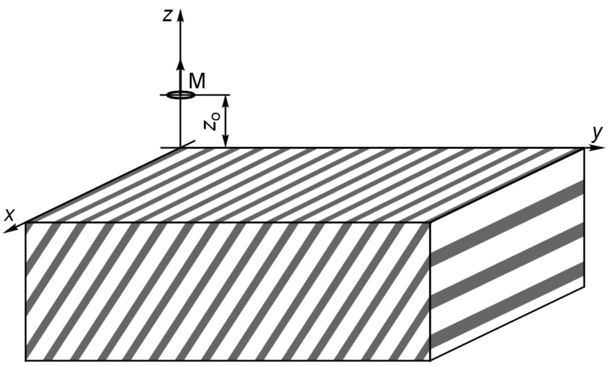

Fig. 1. Model of a conducting earth with inclined anisotropy.

relative to the normal to the air-earth interface. Let the z and x axes in the Cartesian coordinates coincide, respectively, with the normal to the air-earth interface and with one principal axis of the conductance tensor (Fig. 1). The azimuth is counted in the positive direction from the x axis. Let a point source of the electromagnetic field in the form of a harmonic vertical magnetic dipole, with its moment $\mathbf{M} = M\mathbf{e}_z\, e^{-i\omega t}$ where $\mathbf{e}_z$ is the unit vector along z, be located on the z axis at the height z_0 above the earth surface. For the TEM field solution, one has to obtain the frequency dependence of the moment and to apply the time-domain Fourier transformation. The conductance tensor in the selected coordinates is

$$\hat{\sigma} = \begin{pmatrix} \gamma_x & 0 & 0 \\ 0 & \gamma_x \cos^2\delta + \gamma_z \sin^2\delta & (\gamma_x - \gamma_z)\cos\delta\sin\delta \\ 0 & (\gamma_x - \gamma_z)\cos\delta\sin\delta & \gamma_x \sin^2\delta = \gamma_z \cos^2\delta \end{pmatrix}, \qquad (1)$$

where γ_x, γ_z are the longitudinal and transversal conductances, respectively, and δ is the angle between the tensor axis and the normal to the air-earth interface (Tabarovskii and Epov, 1979). Hereafter we employ the conductivity tensor which is derived by simple inversion from the conductance tensor. This is convenient for comparing apparent resistivities with the tensor parameters in the two different methods.

The FI problem is solved on the basis of Maxwell's equations for an anisotropic medium in a quasi-stationary approximation:

$$\mathrm{rot}\,\mathbf{H} = \mathbf{j},$$

$$\mathrm{rot}\,\mathbf{E} = i\omega\mu_0\mathbf{H}, \qquad (2)$$

$$\mathrm{div}\,\mathbf{H} = 0,\ \ \mathrm{div}\,\mathbf{j} = 0.$$

where the current density is related to the electric field through the Ohm law:

$$j_i = \sigma_{ij} E_j.$$

The boundary conditions at the air-earth interface imply continuity of the tangential components of the electric and magnetic fields (brackets mean a jump):

$$[E_x]_{z=0} = 0,\ \ [E_y]_{z=0} = 0,$$
$$[H_x]_{z=0} = 0,\ \ [H_y]_{z=0} = 0. \qquad (3)$$

Having applied the 2D Fourier transform along x and y and some algebraic transformation, we reduce the Maxwell equations to the linear system of ordinary differential equations (Tabarovskii and Epov, 1979) for each layer

$$\hat{\beta}_2 \frac{\partial^2 \mathbf{W}}{\partial z^2} + \hat{\beta}_1 \frac{\partial \mathbf{W}}{\partial z} + \hat{\beta}_0 \mathbf{W} = \mathbf{Q}, \qquad (4)$$

where

$$\mathbf{W} = \begin{pmatrix} E^+ \\ E^- \end{pmatrix} = \begin{pmatrix} i\xi & i\eta \\ i\eta & -i\xi \end{pmatrix} \begin{pmatrix} E_x^* \\ E_y^* \end{pmatrix},$$

$$\hat{\beta}_2 = \begin{pmatrix} -\dfrac{k_{zz}^2}{\lambda^2 + k_{zz}^2} & 0 \\ 0 & -1 \end{pmatrix},\ \ \hat{\beta}_1 = \frac{k_{yz}^2}{\lambda^2 + k_{zz}^2} \begin{pmatrix} -2i\eta & i\xi \\ i\xi & 0 \end{pmatrix}, \qquad (5)$$

$$\hat{\beta}_0 = \begin{pmatrix} k_{xx}^2 - \dfrac{\eta^2}{\lambda^2}A & \dfrac{\xi\eta}{\lambda^2}A \\ \dfrac{\xi\eta}{\lambda^2}A & \lambda^2 + k_{xx}^2 - \dfrac{\xi^2}{\lambda^2}A \end{pmatrix}.$$

In these equations, $\lambda^2 = \xi^2 + \eta^2$, $A = \dfrac{\lambda^2 + k_{xx}^2}{\lambda^2 + k_{zz}^2}(k_{xx}^2 - k_{yy}^2)$, $k_{ij}^2 - i\omega\mu_0\sigma_{ij}$, ξ and η are the Fourier variables and E_x^*, E_y^* are the 2D Fourier images (asterisked hereafter) of the respective components of the electric field. The vector $\mathbf{Q}$ is defined by the source configuration.

The sought solution can be written using the general solution for the electromagnetic field of a harmonic vertical magnetic dipole for each halfspace after applying boundary conditions (3).

Not going far into derivation details, we present only the final solution for a source located in the upper nonconducting halfspace (air). For the sake of convenience, we separate the variables that contain the angle of the inclined anisotropy axis:

$$E^+ = \lambda^2 \frac{f_2 F_4 - F_2}{D} M e^{\lambda(z+z_0)},$$

$$E^- = \frac{\lambda}{2}\frac{\lambda - \nu_1}{\lambda + \nu_1} M e^{\lambda(z+z_0)} \left(1 - 2\lambda \frac{F_2 f_4}{D}\frac{\nu_4 + \nu_1}{\lambda - \nu_1}\right), \qquad (6)$$

$$H^+ = \frac{\lambda^2}{2}\frac{\lambda - \nu_1}{\lambda + \nu_1} M e^{\lambda(z+z_0)} \left(1 - 2\lambda \frac{F_2 f_4}{D}\frac{\nu_4 + \nu_1}{\lambda - \nu_1}\right),\quad H^- = 0,$$

where

$$D = (\lambda + \nu_1) F_4 + (\nu_4 - \lambda) F_2 f_4,$$

$$f_{1,2} = \frac{\xi\sqrt{\lambda^2 + k_{xx}^2}}{\eta\sqrt{\lambda^2 + k_{xx}^2} \pm i\lambda^2 \cot\delta},$$

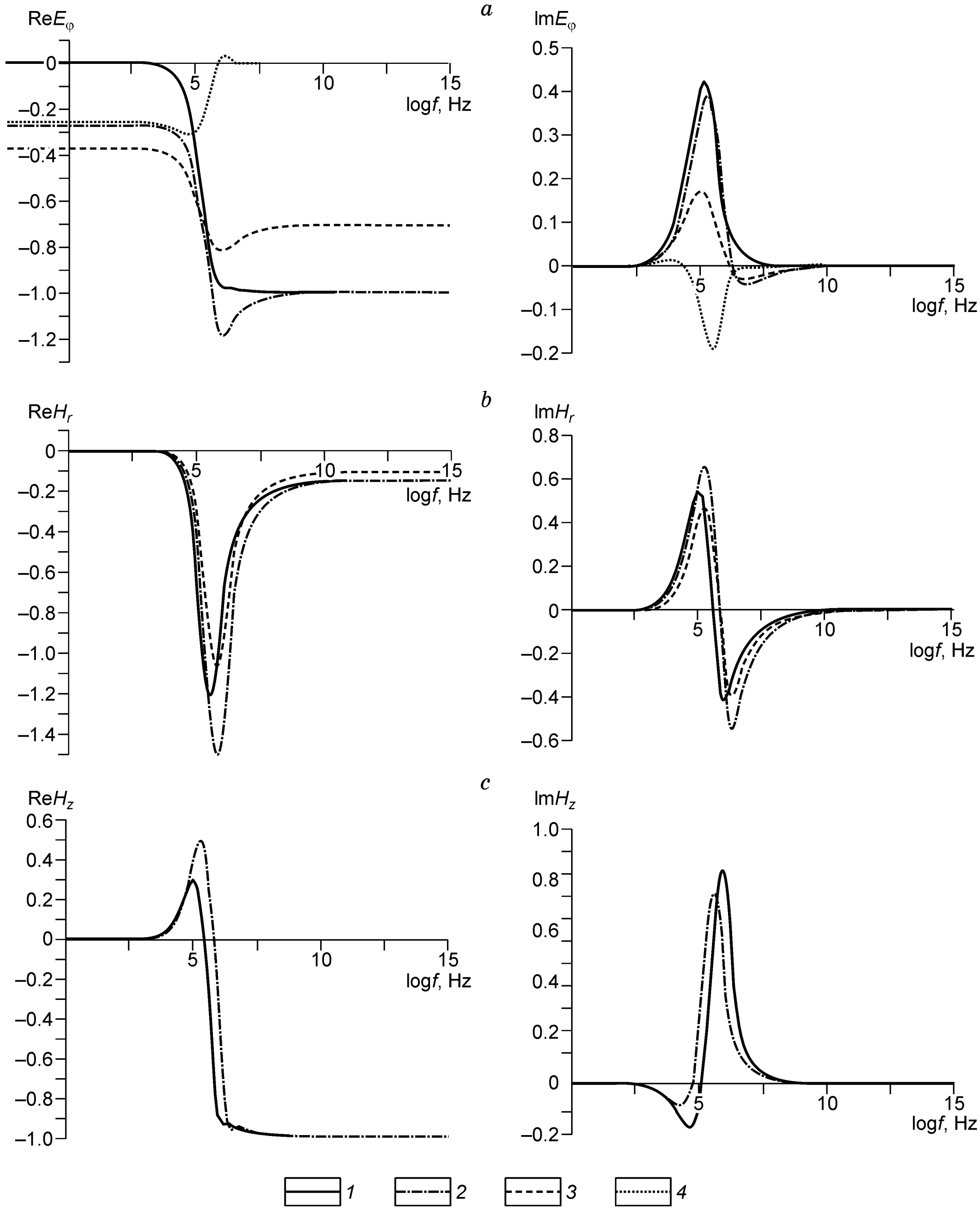

Fig. 2. FI responses of transversely isotropic and anisotropic halfspaces for commonly measured electric components. *1*, transversely isotropic earth; *2–4*, anisotropic earth, with inclined anisotropy at δ = 40°, for receiver azimuths of 0°, 45°, and 90°, respectively. See text for explanation.

$$f_{3,4}=\frac{-\xi\, k_{xx}^2}{\eta(\lambda^2+k_{xx}^2)+i\lambda^2\,\nu_{3,4}\cot\delta},$$

$$F_{1,2}=(\lambda^2+k_{zz}^2)^{-1}((\nu_{1,2}\,\sigma_{zz}+i\eta\sigma_{yz})\,f_{1,2}-i\xi\sigma_{yz}), \qquad (7)$$

$$F_{3,4}=(\lambda^2+k_{zz}^2)^{-1}(\nu_{3,4}\,\sigma_{zz}+i\eta\sigma_{yz}-i\xi\, f_{3,4}\,\sigma_{yz}),$$

$$\nu_{1,2}=\pm\sqrt{\lambda^2+k_{xx}^2}\ ,$$

$$\nu_{3,4}=-\,i\eta\frac{\sigma_{yz}}{\sigma_{zz}}\pm\sqrt{\frac{\gamma_x}{\sigma_{zz}}}\sqrt{\xi^2+k\frac{\gamma_z}{\sigma_{zz}}\left(\eta^2+k_{xx}^2\right)}\ .$$

The parameters of the magnetic field $H^{\pm}$ are found in the same way as $E^{\pm}$ with equation (5) by the simple substitution $E^{\pm}\to H^{\pm}$, $E^{*}_{x,y}\to H_{x,y}$. Thus one can find all field components in the space of Fourier images using (3), (4) and (5)–(7).

The frequency-domain coordinate dependences are derived by means of 2D Fourier inversion along ξ, η with exact quadratures with the specified weight function (exponent of an imaginary argument).

In the same way, the solution for quick turn-off TEM responses is obtained, having the computed frequency dependence, with a numerical algorithm of frequency-domain 1D Fourier inversion (Tabarovskii and Sokolov, 1982).

Modeling frequency responses

The frequency responses of an anisotropic earth with inclined anisotropy are compared with those of a transversely isotropic earth using the following model. The conductivity tensor in both cases is the same in the principal axes and its eignevalues are $\rho_x = 50$ Ohm m and $\rho_z = 150$ Ohm m (longitudinal and transverse resistivities, respectively). The principal tensor axis is inclined at $\delta = 40°$. The model configuration consists of a vertical magnetic dipole raised at the height $z_0 = 1$ m above the earth's surface and a receiver which measures any wanted component of the electromagnetic field, the transmitter and the receiver being spaced at $r_0 = 20$ m.

Consider frequency responses in the case of different receiver azimuths. Figure 2 presents frequency responses for the classical set of measured components of the electromagnetic field: E_φ, H_r, H_z (Fig. 2, *a*, *b*, *c*, respectively). There are plots for both real and imaginary parts of the total field components (labeled Re and Im, respectively). In order to highlight the anomalous behavior of the field, the respective transversely isotropic and anisotropic earth responses are given together. Hereafter the field components are normalized in a way which (unlike the standard normalization) has turned out to be the most convenient for the simulation:

$$(E) \to \left(\frac{i\omega\mu_0 M}{4\pi r_0^2}\right)^{-1} E, \quad (H) \to \left(\frac{M}{4\pi r_0^3}\right)^{-1} H.$$

The magnetic field curves remain almost unaffected by the presence of inclined anisotropy: they are similar qualitatively being different only in maximum amplitudes and in the position of their extremes. The vertical component H_z shows no difference for different azimuths, like the radial component H_r for the receiver azimuths 0° and 90°. The receiver azimuth of 45° (as well as any other angle from 0° to 90°) is intermediate because the current lines are in this case nonorthogonal to the radial direction of the receiver (Fig. 2, *b*).

The azimuthal component of the electric field (Fig. 2, *a*) is the most sensitive to both inclined anisotropy and receiver azimuth. The most striking feature is the presence of a nonzero component of the normalized electric field in the low-frequency bandwidth (beginning with direct current). This is actually a consequence of an induced surface electric charge that acts as a secondary galvanic source. The change being qualitative, this curve is impossible to process with the classical techniques.

One can calculate low-frequency apparent resistivities for different field components as functions of the receiver position and of the conductance tensor angle using known asymptotic formulas. Figure 3 shows azimuth-dependent apparent resistivities derived from the imaginary part of the vertical magnetic component at a point of the *x* axis, for different angles of the inclined conductance tensor axis. The source

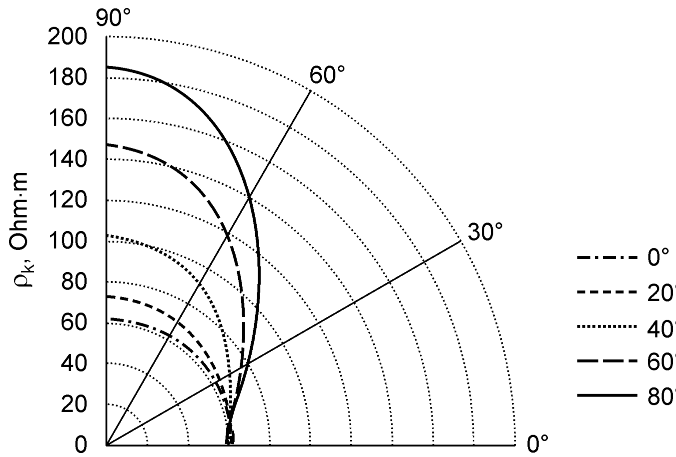

Fig. 3. Apparent resistivity in a VMD–VMD system as a function of receiver azimuth at different angles (δ) of inclined conductor tensor axis.

frequency is $f = 1$ kHz. The conductance tensor in principal axes is the same as in the previous model.

Note that the apparent resistivity decreases slightly as the dip of the conductor tensor increases when the receiver is located on the *x* axis and reaches its maximum when the receiver is on the *y* axis. In the model with the anisotropy coefficient $\Lambda^2 = \rho_z / \rho_x = 3$, the maximum apparent resistivity is more than three times the minimum value.

Modeling transient responses

Transient responses of an anisotropic earth with an inclined conductance tensor appear to have virtually no literature. We report simulation results for the TEM field of a vertical magnetic dipole above an anisotropic earth, with the parame-

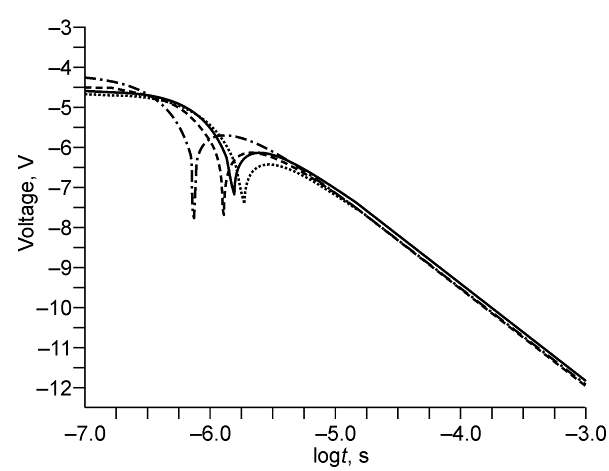

Fig. 4. Loop–loop (dipole approximation) transient responses of transversely isotropic and anisotropic halfspaces for different receiver azimuths. Curve symbols same as in Fig. 2.

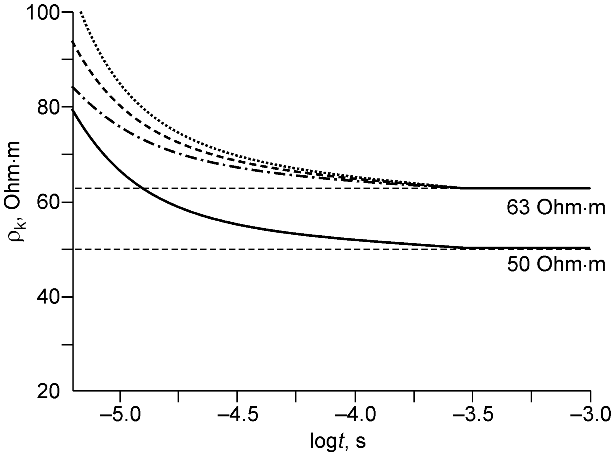

Fig. 5. Voltage-derived apparent resistivities for different receiver azimuths. Curve symbols same as in Fig. 2.

ters same as in the FI problem. As in the previous case, the field is measured at three points of different azimuths but at the same distances from the source. Measured is the voltage induced in the receiver loop by the vertical component of magnetic flux.

Figure 4 shows time dependences of the transient responses of an anisotropic earth for three receiver azimuths and a response of a transversely isotropic earth.

At late times all anisotropy-affected responses show asymptotic behavior which differs from that of the transversely isotropic case. Conversion of voltage into apparent resistivity, with the known asymptotic formula, gives a pattern as in Fig. 5. Apparent resistivities derived from all responses tend to the 63 Ohm m asymptote being more than 25% in excess of the exact resistivity of 50 Ohm m.

In this respect two features of the transient responses of an anisotropic earth are worthy of note. First, they show no qualitative difference from the responses of an isotropic earth: they likewise pass once through zero and decay in the same way at late times. Second, the obtained resistivity is azimuth independent. Thus, this source configuration cannot ensure discriminating between anisotropic and isotropic media at late times. On the other hand, such a possibility does exist in a large time range if the responses are measured at different receiver azimuths, because the signals differ significantly at early times. The difference is, namely, in the time of the passage through zero.

Conclusions

Simulation of the VMD responses of an anisotropic earth shows that inclined anisotropy causes little effect on the qualitative behavior of FI and TEM curves. However, processed data of surface resistivity surveys can differ strongly from the expected results in the case of an isotropic-earth reference model, and this discrepancy is not always cancelled in measurements at varied receiver azimuths. Processing near-field TEM data without due regard for anisotropy can lead to wrong resistivities which are virtually independent of the receiver azimuth.

The reported results can make basis for a low-frequency acquisition technique to measure the total anisotropy tensor. The required loop configuration is the same as in the classical method and consists of a VMD transmitter and a receiver laid at a varied azimuth, the latter being the only specific modification. Thus obtained responses bear evidence for the presence of conductance anisotropy. The use of the TEM method for this purpose is inefficient at late times but is informative at early times. To correct for the ambiguity, one can apply additional measurements of the vertical component of the electric field which appears uniquely in the presence of an induced surface charge and reflects the field symmetry. The latter fact rules out data distortion from finite- size anomalies.

Thus, the study highlights the importance of multi-component electromagnetic surveys, especially in areas with potential conductance anisotropy of rocks.

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