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# Modeling and interpretation of azimuthal resistivity sounding over two-layered model with arbitrary - oriented anisotropy in each layer.

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The basic moment for creation of new algorithm was clear aware of half-space model limitation. Two-layered model with isotropic first layer (Bolshakov et al., 1997) and anisotropic basement has allowed to receive many new peculiarities of azimuthal soundings. The practice has shown that further development of model is required. Therefore an algorithm and program of modeling and interpretation of azimuthal resistivity sounding (ARS) data over two-layered model with arbitrary - oriented anisotropy in each layer has been developed. The decisions for such model were known earlier (Gurevich, Sagina, 1977; Ping Li et al., 1997). Our purpose was in receiving fast and effective computing algorithm, which would give precise results.

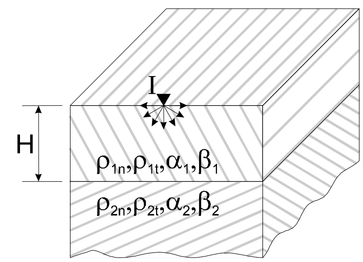


Fig.1. Two-layered anisotropic model

The basis of the decision is spectral approach. The potential value is calculated as a sum of spectral harmonics $C_{2n}$. At estimation of potential for various azimuths, its harmonics are calculated only once, that increases effectiveness of algorithm. The final expressions for an electrical field potential look like:

$$U(r,\varphi,z) = \sum_{n=-\infty}^{\infty} C_{2n}(r,z)\exp(-i\cdot 2n\varphi)$$

$$C_n(r) = \frac{I\rho_{1,l}}{4\pi^2 r}\,\frac{1}{2\pi}\int_{-\pi}^{\pi} E_n(r,k_\varphi)\exp(i\cdot nk_\varphi)\;dk_\varphi, \quad E_n(r,k_\varphi) = \frac{1}{b_1(k_\varphi)}\left[D_{n,0}(r,k_\varphi) + 2\sum_{m=1}^{\infty} K^m(k_\varphi)\cdot D_{n,m}(r,k_\varphi)\right]$$

$$D_{n,m}(r,k_\varphi) = \frac{1}{\sqrt{1+\left(ms(r,k_\varphi)\right)^2}\cdot\left(\sqrt{1+\left(ms(r,k_\varphi)\right)^2}+ms(r,k_\varphi)\right)^n}$$

$$\lambda = \sqrt{\rho_n/\rho_t}, \quad g = \sin^2(\alpha) + \frac{1}{\lambda^2}\cos^2(\alpha), \quad b(k_\varphi) = \sqrt{g\sin^2(k_\varphi-\beta) + \frac{1}{\lambda^2}\cos^2(k_\varphi-\beta)}, \quad s(r,k_\varphi) = \frac{2b_1(k_\varphi)H}{g_1 r}$$

The final formulas are similar to the formulas for two-layered isotropic model and just as these allow to fulfill calculations with high accuracy. On the basis of harmonics for potential it is possible to receive harmonics for any component of electrical field and $\rho_a$ for any array. The same formulas allow to fulfill transformation of azimuthal data for dipole equatorial array to linear one (D.K. Bolshakov et al., 1997), that is very useful for reduction of deep and near-surface inhomogeneities' influence, for comparison of results for different arrays and their interpretation.

To study equivalence problem for the given model, two new parameters $\lambda_{ef}$ and $H_{ef}$ were entered.

$$\lambda_{ef} = \sqrt{\lambda^2\sin^2(\alpha) + \cos^2(\alpha)}, \quad H_{ef} = \frac{\lambda_1}{\lambda_{1ef}}H,$$

Thus, instead of three parameters (α, λ, H) there is the influence of only two effective parameters ($\lambda_{ef}$, $H_{ef}$) or theoretical equivalence. At measurements on the earth surface it is impossible the estimate these three parameters separately.

We calculated a series of two-layered models with an anisotropy in first or in the second layer. We reasoned that the task with anisotropy in both layers makes the model too complex. To study a large series of data the program was supplied with the system of visualization. It allows to see all data for any azimuth depending on spacing or to see all data for any spacing depending on azimuth. Except these the program shows diagrams $\lambda_a$ = f(r), harmonics of spectrum $C_{2n}$ = f(r), and values $\rho_l$, $\rho_m$, $\rho_n$ for sounding curves, transformed to a uniform half-space. These transformations are estimated on azimuthal diagrams' spectra and their introduction is similar to introduction of apparent resistivity for isotropic media.

The examples of accounts for two models are shown on fig.2. A number of anomalous or unusual phenomena were found out here. The most complicated forms of sounding curves are found for dipole array at its orientation near 45° from strike direction. The visible number of layers on fig.2, B, D differs from true. The right and left asymptotes fall outside the limits of $\rho_l$, $\rho_m$ values.

On fig.3 the values of apparent anisotropy $\lambda_a$ appear more than true greatest and smallest ones. The values $\lambda_a$ for D - array on fig.3 were recalculated to equivalent linear array (D.K. Bolshakov et al., 1997) to compare with linear array's data (E).

| Model | 1st layer | | 2nd layer | |
|---|---|---|---|---|
| | $\rho_M$ | $\lambda$ | $\rho_M$ | $\lambda$ |
| 1 | 50 | 1 | 10 | 1.8 |
| 2 | 50 | 1.8 | 10 | 1 |

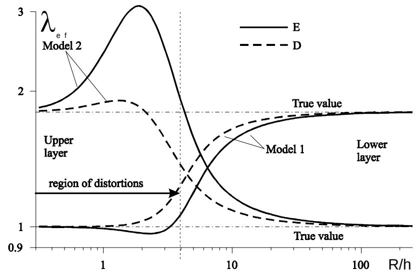


Fig.3. $\lambda_a$ graphs for two models from fig.2

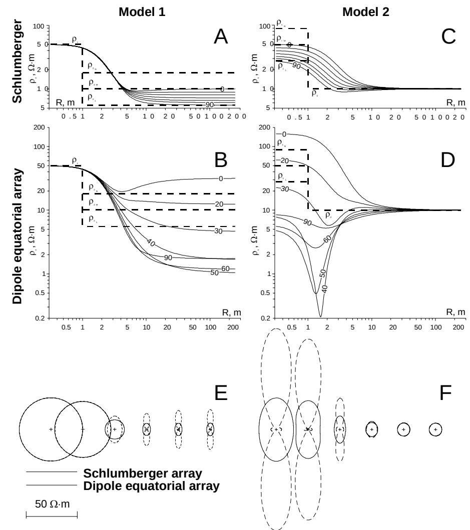


Fig.2. Sounding curves and azimuthal diagrams for two anisotropic models

From comparison of $\lambda_a$ graphs for two models with an anisotropy in the first or in second layer, it is visible, that phenomena of amplification (for model 2) and decrease of anisotropy (for model 1) are similar. Case 1 gives the change of ellipse orientation for E-array (disappearance of anisotropy paradox). D-array for both models gives smaller deviations of apparent and true parameters and has no change in ellipse orientation.

On fig.4 an example of interpretation of azimuthal resistivity soundings, received in a place Patil (Ukraine, Crimea) above two-layered earth with anisotropy in both layers (A), is presented. In the first layer the bedding (and anisotropy) orientation is close to horizontal, while in the second layer these are close to vertical. Due to inclined earth surface cut the first layer, its bedding plane appears inclined to the earth surface. Interpretation or fitting experimental and theoretical data fulfills and checks on all types of diagrams; that is on azimuthal diagrams for any spacing (B), on sounding curves for any azimuth (along and across the strike on example D) and on spectral characteristics, in particular on harmonics, $\lambda_a$ graphs and $\rho_l$, $\rho_m$, $\rho_n$ diagrams (C). The best fitting is achieved when $\lambda$ of the first layer equals 4 and dip angle of its bedding $\alpha$=5°. These results are close to geological estimations.

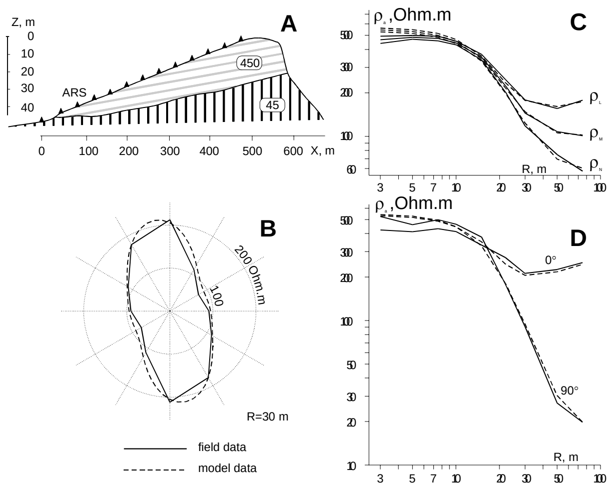


Fig.4. Example of practical data interpretation.

## Conclusions

The decision for $\rho_a$, potential and electric field's calculation for many arrays above two-layered model with arbitrary oriented anisotropy in each layer has been received.

Principles of theoretical equivalence of ($\alpha$, $\lambda$, H) parameters for such model are formulated.

Some anomalous and unusual effects on sounding curves and $\lambda$=f (r) diagrams were revealed for two-layered anisotropic models.

This program is suitable for interpretation of experimental azimuthal resistivity sounding data.

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