Results of FDEM-(CS)AMT test studies on the Alexandrovka area

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SUMMARY

The article presents the results of electrical surveying acquisition tests carried out in the winter of 2021 in the area of the educational and geophysical base of the Faculty of Geology of the Lomonosov Moscow State University "Alexandrovka" in the Kaluga region. The purpose of the experimental and methodological work was to obtain data in the "dead" frequency range of the audio magnetotelluric sounding (AMT) range. The paper describes the methodological features of the work performed by the method of frequency domain electromagnetic sounding (FDEM) and AMT with a controlled source (CSAMT). The obtained result is compared with a priori geological information, with geophysical studies of previous years. Some methodical features of test studies have been described in this paper.

Keywords: audio-magnetotelluric method, frequency-domain electromagnetics, skin-effect, resistivity

INTRODUCTION

The authors of this article performed test surveys of AMT and FDEM. The main purpose and objectives of these studies are as follows:

- combining the AMT technique with the method of frequency domain electromagnetic sounding (FDEM) and AMT with a controlled source (CSAMT) with the possibility of using the same set of equipment to record data from all methods;
- obtaining CSAMT data in areas complicated by cultural noise, as well as in the "dead" frequency range of AMT;
- obtaining data on the transverse resistance parameters of insulator layers based on the interpretation of the individual components frequency characteristics (curves) of frequency sounding.

Methods

Frequency domain electromagnetic sounding method providing information about changes in the resistance of the medium with depth by studying the frequency dependencies of the components of the electromagnetic field created by the artificial source.

In this paper, a horizontal electric dipole was used as a source. In a medium with resistivity ρ, the components of electric and magnetic fields in the far zone ($\omega\mu_0 r/\rho \gg 1$) of a source of HED type with dipole moment $P_{AB} = I_{AB} \cdot AB$, oriented along the x-axis, are expressed as follows (Modin et al. 2018):

$$E_x = \frac{P_{AB}(3\cos^2\varphi - 2)}{\pi r^3} \cdot \rho,$$

$$H_y = \frac{1}{\sqrt{-i\omega\mu_0}} \frac{P_{AB}(3\cos^2\varphi - 2)}{\pi r^3} \cdot \sqrt{\rho},$$

$$H_z = \frac{1}{-i\omega\mu_0} \frac{3P_{AB}\sin\varphi}{2\pi r^4} \cdot \rho, \qquad (1)$$

$$Z_{xy} = \frac{E_x}{H_y} = \sqrt{-i\omega\mu_0\rho},$$

r – distance from source, φ – azimuth of the measurement point. Since the method works in the far zone, it is necessary to use a maximum spacing and a maximum current to perform measurements, which in turn leads to the need to use power generators and good grounding (<30 Ohm · m).

To achieve the objectives, the authors made an assessment of the parameters of the installation and practical measurements. Experimental and methodical works were performed on the territory of the scientific and educational geophysical base of the Lomonosov Moscow State University geological faculty "Alexandrovka" in Kaluga region.

AMT field measurements were performed with measurement of five components of the electromagnetic field. NORD stations (Nord-West LTD) were used as measuring devices, IMS 5 sensors (Vega LTD, Nord-West LTD) were used to register the magnetic field components, providing operation in the frequency interval from 1 Hz to 20 kHz. The electrical components of the field were recorded using nonpolarizing graphite electrodes NW-4 (LTD "Nord-West"). The works was performed using a cross-shaped system with a central electrode Figure 1. The length of each electrical line was 100 m (2 legs of 50 m). Azimuths of system of electrical lines and horizontal magnetic sensors: x – 73°, y – 163°. The x-axis is directed parallel to the HED. Induction sensors (two

horizontals, one vertical) were buried in the ground. The electrodes were grounded in pits 0.2–0.3 m deep in a mud mixture moistened with salt water.

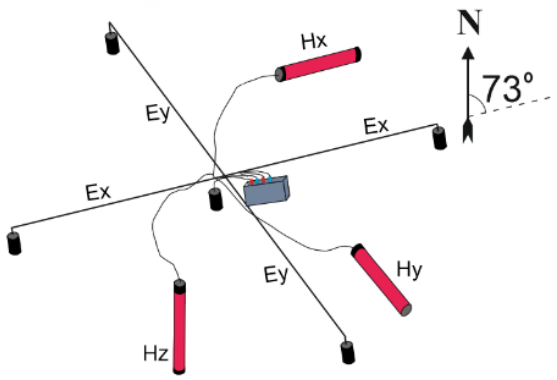

Figure 1. Measuring system for AMT, FDEM и CSAMT.

Evaluation of system parameters

Works by the FDEM are performed in a far zone condition corresponding to ($\omega\mu_0 r/\rho \gg 1$). In practice, in order to achieve the far-zone conditions, so that the distance from source exceeds the effective depth of the skin layer by several tens of times, using the very low frequency (Modin et al. 2018). The depth of the skin layer is calculated using the formula:

$$h_\delta \approx \frac{\sqrt{\rho T}}{2}\ (\mathrm{km}) \qquad (2)$$

Let's estimate the distance satisfying the far zone condition for a structure with an average electrical resistivity of the order of 150 Ohm·m. This resistivity was determined by the results of acquisition tests performed by the authors in 2019 (Ermolin et al. 2020). The final stack according to the results of acquisition tests in 2019 is shown in Figure 2. The curve in Figure 1 is measured in the same area. A minimum at a frequency of 50 to 100 Hz corresponds to a conductor at an altitude of 0 to -100 meters in Figure 3. Thus, to study the "dead" frequency range, information is needed on the average electrical resistivity of rocks located above the altitude of 0 m. The average level of resistance in the depth range is an average of 150 Ohm · m.

In order to close the "dead" range of AMT, it is necessary to obtain high-quality data for the frequency of 800 Hz and above. The depht of the skin layer at 800 Hz can be estimated as:

$$h_\delta \approx \frac{\sqrt{\rho T}}{2} = \frac{\sqrt{\frac{150}{800}}}{2} \approx 0.2\ (\mathrm{km}) \qquad (3)$$

As a result, a distance from the source of 6 km was used for work by the FDEM, providing the realization of the far zone condition ($\omega\mu_0 r/\rho \gg 1$).

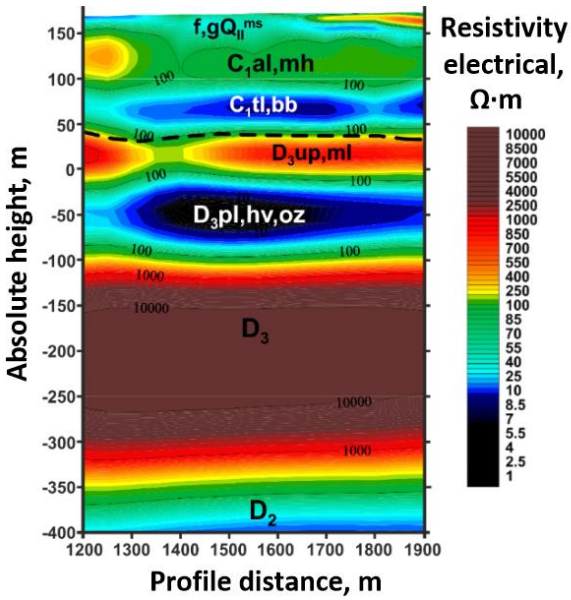

Figure 2. Electrical model from 2D inversion data AMT and ERT-IP (Ermolin et al. 2020).

The length of the transmitter line is 1150 m. The grounding resistance of the AB line is 30 Ohms, which made it possible to use a current of up to 7 A. The configuration is shown in Figure 3. The same figure shows the position of the profile along which the electrical model is built, shown in Figure 2. When performing the work of the FDEM, the most time-consuming is the organization of the HED (work shift of 4 operators), while the installation time of the measuring device is from 15 to 45 minutes (by two operators).

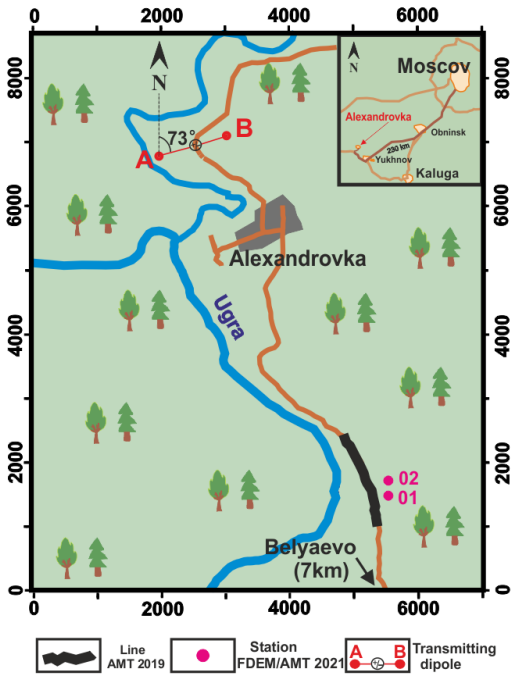

Figure 3. Scheme of acquisition tests perfomed

Due to the absence of time limits, all possible

frequencies of the transmitter GER-1000 from 1.22 Hz to 5000 Hz were used. The total time to use all frequencies (1.22, 2.44, 4.88, 9.77, 19.53, 39.06, 78.13, 156.25, 312.5, 625, 1250, 2500, 5000 Hz) was 15 minutes. A problem occurred while working with the transmitter. Due to the complex character of the transmitter line resistance at high frequencies, the output current had to be reduced to 3-4 A and the signal lost its rectangular shape, characteristic of a stabilized meander at low frequencies. An example of an unstabilized current is shown in Figure 4.

The lack of current stabilization is not a problem for the CSAMT method, as well as the classical FDEM, provided that the factual waveform in the transmitter line is registered witch a Hall sensor and taken into account during processing.

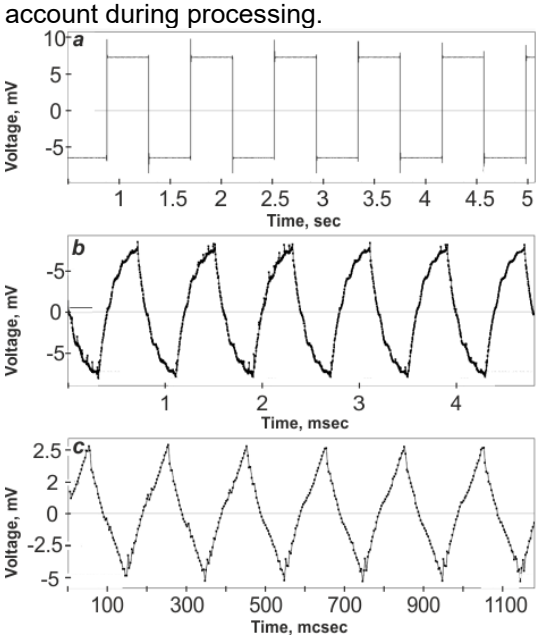

Figure 4. Example of transmitter line current record for frequencies: a) 1.22 Hz b) 1250 Hz c) 5000 Hz

Results

The result of processing of the FDEM field data are the curves of the electrical (Ex), magnetic components (Hy, Hz) and impedance (Zxy), shown in Figures 6-9.

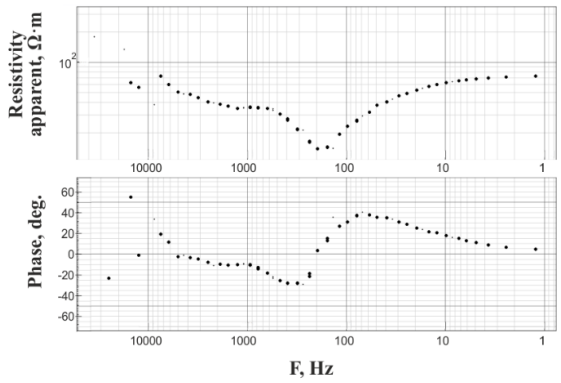

Figure 5. Component Ex, PK 01

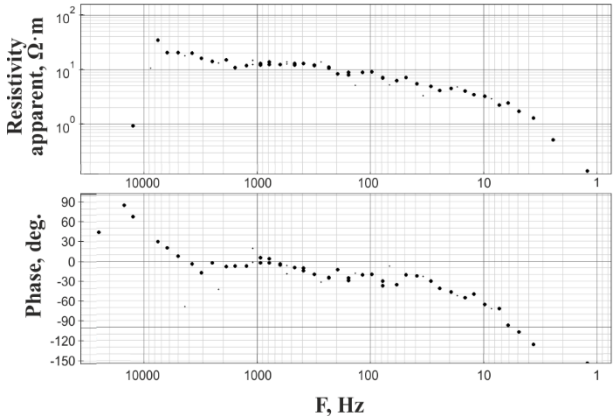

Figure 6. Component H_y, PK 01

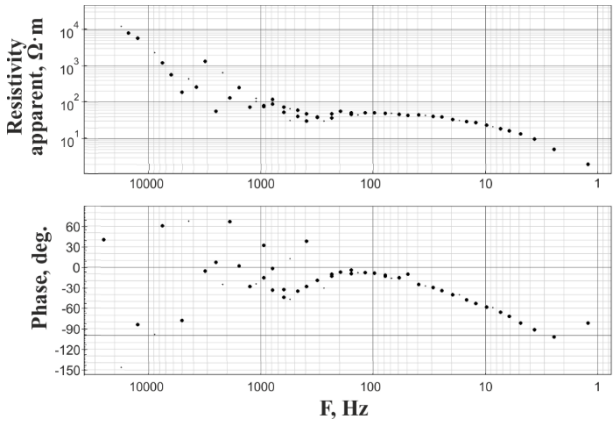

Figure 7. Component H_z, PK 01

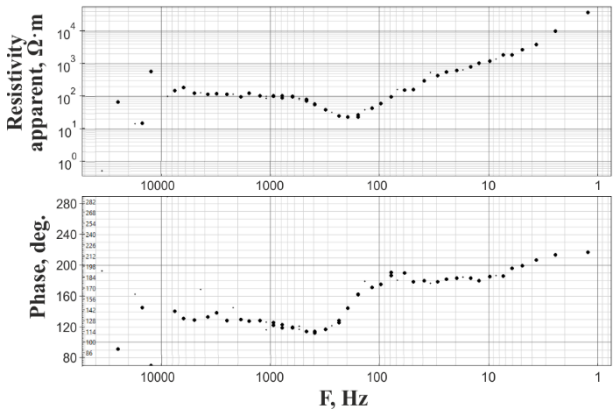

Figure 8. Component *Z*xy, PK 01

To interpretation the data of FDEM and CSAMT, selection was applied within the framework of 1D models, using the program CsmtSolver (author Dmitry Epishkin). An example of the selection performed for the CSAMT of the Zxy impedance component is shown in Figure 10.

Using a priori geological information the following geological interpretation of the model can be carried out at measurement point 01. The first three layers are interbedding of sands and loams. Next, a more conductive layer is clay with inclusion of coals of the Tula formation and Bobrikovian horizon of the Lower Carboniferous.

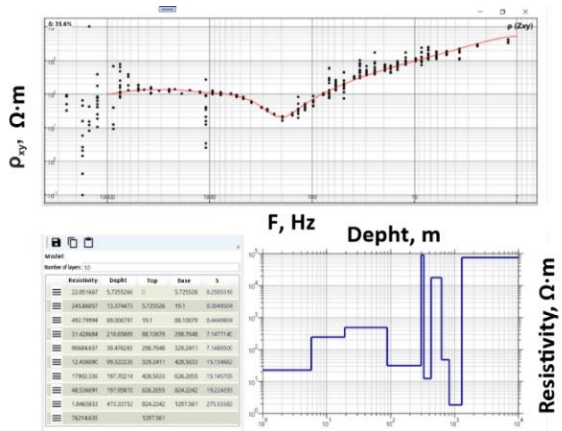

Figure 9. Selection of the geoelectric model by the Zxy impedance of frequency sounding in the CsmtSolver program window. PK 01.

Below is a high-resistivity layer represented by limestones, dolomites and marls of the Upper Devonian. This formation in the model is represented by the fifth, sixth and seventh layers. This range of resistances was selected to account for vertical anisotropy. The conductive layer is connected to the aquifer, the layers with high resistivity correlate with gypsified limestones, marls and dolomites. The eighth layer is terrigenous sediments, represented by clays, mudstones and sands of the Middle Devonian. The ninth layer is a conductive layer of Vendian sandstones with interbedded clays in which high-salt water is present. The tenth layer is a crystalline basement with high resistivity, composed of crystalline shists and gneisses of Lower Proterozoic and Archean age.

The result of AMT field data processing are splines. Figure 10 (left). At the next stage, a 1D inversion was performed using the AMT invariant curve Figure 10 (right). The results in Figure 10 (right) do not contradict the results of 2019 (Ermolin et al. 2020).

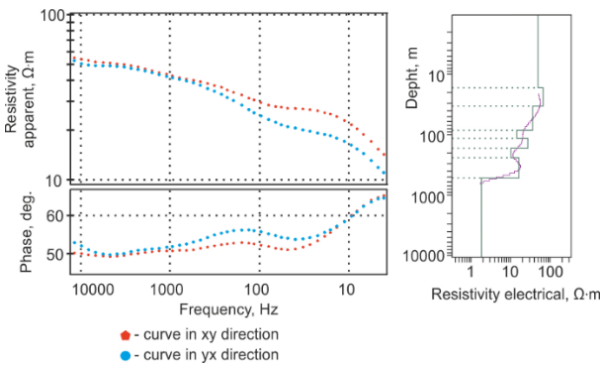

Figure 10. Example spline (left) and 1D inversion (left) smooth Occam inversion (model marked in pink) and eight-layer model (in green).

Conclusion

As a result of the acquisition tests, it was shown that the application of the FDEM allows obtaining data in the "dead" range of AMT for a component parallel to the direction of HED. In this experiment, the levels of the AMT and CSAMT curves did not coincide according to the measurement results.

In this test studies, it was not possible to perform an appropriate selection of the 1D resistivity model for the Ex component of the FDEM. But the results of the 1D interpretation of the AMT and CSAMT data are comparable. According to CSAMT data insulator layers (dolomites with interbedded gypsum) have a higher resistance value than according to the results of the interpretation of the AMT curve. Thus, the CSAMT results most correctly reflect the high resistances of gypsified dolomites, the resistivity of which exceeds tens of thousands of Ohm·m.

Importantly, it is necessary to register the transmitter line current when performing FDEM, because the signal at frequencies above 1000 Hz is not a correct meander.

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