Introduction

Based on how the depth of investigations is regulated, electroprospecting methods could be divided into two groups – geometrical and induction soundings. In geometrical soundings, the depth of the investigation is determined by the array spacing (R) which is the distance between the power dipole electrodes A and B (Schlumberger array) or by the distance between centres of power (AB) and receiving (MN) dipoles (Dipole array). All induction soundings methods are based on the skin-effect phenomenon, where the depth of the investigation is defined by the frequency of the electromagnetic (EM) field (MT, AMT, CSAMT, FDEMS and TEM).

The geometrical soundings group of methods consists of VES, DES, Electrotomography and Electrical Profiling (EP). The first two methods are effective for mapping close to horizontally layered sections. Application of Electrotomography is expedient for largely inhomogeneous sections, whereas EP is commonly used for detailed mapping of particular boundary topologies and localization of inhomoginieties. Advantages of geometrical soundings are relative simplicity and low equipment cost, well-developed over time technologies and capability to investigate IP effect. The disadvantages include weak sensitivity to A, AA, etc. type of sections, large array sizes and limitations when investigating geoelectric sections deeper than 50m. The induction soundings group of methods could be divided into two large subgroups according to the source of the EM field being used. The first one, uses Earth's alternating natural EM field as the source of energy Magnetotellurics (AMT, MT), Magnetotelluric and Magnetovariational Profiling (MTP and MVP), whereas the second, uses artificial alternating EM field created in electric (P_x (A, B)) or magnetic (M_z (Q)) dipoles with specialized geophysical current sources (transmitters). The second group is further separated into two segments (subgroups). The first one uses EM field's frequency domain (CSAMT, FDEMS-IP, FDIP, VLF and SIP methods), and the second one works in the time domain (TDEM, TEM and TDIP methods).

Induction soundings methods were actively developed in the former USSR in the 50s of previous century after publication by A.N. Tikhonov (1950). Three groups of methods were being developed simultaneously - MT (Berdichevsky, 2009), FDEMS (Enenstein, 1967) and TDEM (Vanyan, 1965). Since 60s of the previous century, they have been actively used for oil and gas, groundwater and geothermal exploration, and from 80s - for mining exploration. The advancements which were made in the development of multifunction EM equipment (generation 5 and 5+) have balanced the cost of one measuring channel for geometrical and induction soundings, and for a number of cases, matched the field productivity as well. From this point of view, the application of induction soundings methods for solving geological engineering problems becomes an important topic. Hence, there are several questions, but the fundamental one is the sensitivity of methods to the changes in geoelectric section parameters as well as the accuracy of mapping the boundaries.

Response functions of geometrical and induction soundings methods for typical geoelectric sections

In the present paper, theoretical modelling was applied for investigation of geoelectric methods sensitivity using the horizontally layered model with 60m depth to a high-resistivity basement with 1000Ohm resistance (Figure 1). Typical for geological engineering investigations two (2), three (3), and four (4) layer models have been considered. For all models, the resistivity of the first layer is 10 Ohm. Calculations were performed for the DES method (geometrical soundings), AMT (induction soundings with natural EM field), TDEM (loop-loop) and FDEMS. In the latter case, results were calculated for the parallel electric (E_x) and vertical magnetic components (H_z) of the equatorial array. Resulting curves of apparent resistivity and, in addition, phase curves for the frequency domain induction methods are shown in Figure 2.

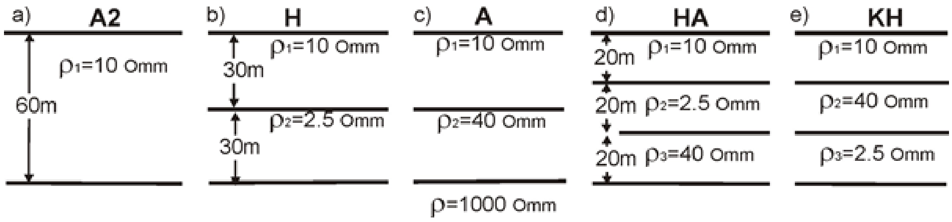

Figure 1 *Horizontally layered models with high-resistivity basement typical for geological engineering investigations: (a) two-layer model, (b) three-layer model type H, (c) three-layer model type A, (d) four-layer model type HA, (e) four-layer model type KH.*

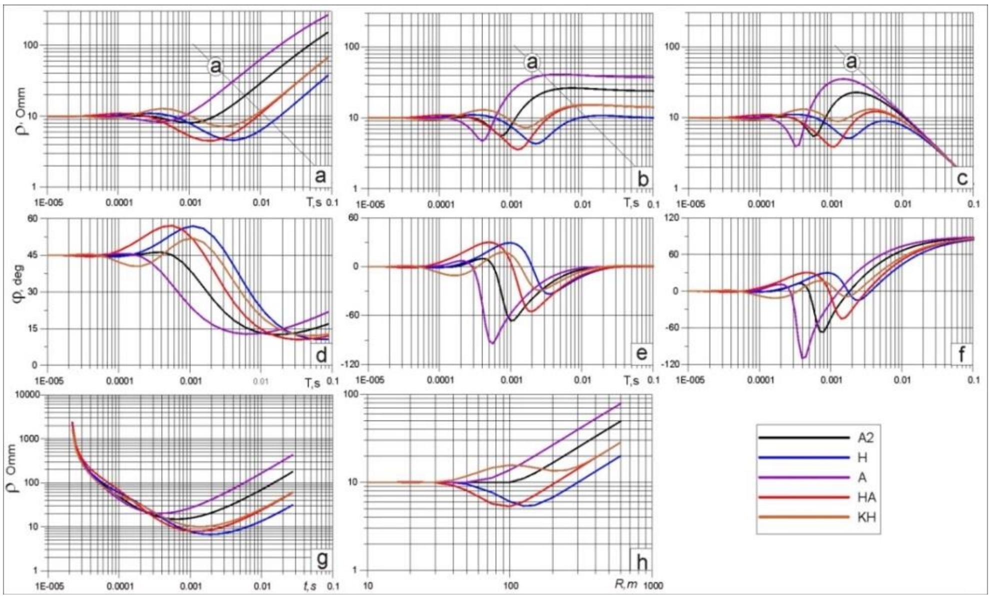

Figure 2 *AMT, FDEMS, TDEM and DES 1D modelling results for models from Figure 1: apparent resistivity curves (a, b, c) and phase curves (d, e, f) for AMT (a, d), electrical E_x (b, e) and magnetic H_z (c, f) components for FDEMS, TDEM apparent resistivity curves (g) and DES (h), a - is the asymptote of the far zone.*

As can be seen from the Figure 2, sounding curves for all methods clearly reflect parameters of the geoelectric section. For DES, required spacing interval is 20-400m for these types of geoelectric sections. The frequency range for AMT and FDEMS is 50,000 - 50 Hz, the time interval for TDEM is 0.02 - 10ms (Figure 2). As it can be visually noted, when parameters of the geoelectric section are varied, the most significant changes of both amplitude and phase curve's shape are observed in the FDEMS method (Figure 2). Thus, for the phase curves, changes in the ordinate of the minima reach 60 degrees for the electrical component and 90 degrees for the vertical magnetic component. It is important to note that the accuracy of modern equipment allows to achieve the phase error calculation of less than 0.01º.

	Model H, S2=12 Sm							**Model A, S2=0.75 Sm**						
Ro2, Omm	1	1.5	2	**2.5**	3	3.5	4	10	20	30	**40**	50	60	70
H2,m	12	18	24	**30**	36	42	48	7.5	15	23	**30**	38	45	53
							Err,%							
FDEMS	8	5.1	2.5	**0**	2.4	4.6	6.6	2.5	1.6	0.7	**0**	0.6	1.1	1.4
AMTS	3.2	2.4	1.2	**0**	1.1	2.1	3	1.3	0.9	0.4	**0**	0.4	0.8	1.2
TDEM	6	3.9	1.9	**0**	1.8	3.7	4.9	2	1.3	0.6	**0**	0.6	1.1	1.6
DES	1.2	0.9	0.5	**0**	0.6	1.2	1.9	0.9	0.7	0.4	**0**	0.4	0.8	1.2

Table 1 *Estimation of 2^{nd} layer equivalence for three-layer models (A and H types).*

Further, in order to evaluate the sensitivity of the soundings curves to the variation of the geoelectric section's parameters and to estimate the limits of the equivalence principle, conductivity of the section S was kept constant, and resistivity and thickness of individual layers were varied. The parameters of the changes are provided in Tables 1 and 2.

Model HA, S3=0.5 Sm							
Ro3, Ohm	10	20	30	**40**	50	60	70
H3, m	5	10	15	**20**	25	30	35
Err,%							
FDEMS	0.5	0.4	0.3	**0**	0.3	0.3	0.4
AMT	0.2	0.07	0.06	**0**	0.06	0.1	0.2
TDEM	0.4	0.2	0.1	**0**	0.1	0.2	0.3
DES	0.08	0.07	0.05	**0**	0.06	0.1	0.18
Model KH, S3=8 Sm							
Ro3, Ohm	1	1.5	2	**2.5**	3	3.5	4
H3, m	8	12	16	**20**	24	28	40
Err,%							
FDEMS	4	2.6	1.3	**0**	1.4	2.5	3.7
AMT	2.6	1.3	0.8	**0**	0.8	1.2	2.3
TDEM	3.4	2.2	1.1	**0**	1.1	2.1	3
DES	0.2	0.2	0.1	**0**	0.1	0.2	0.4

Table 2 *Sensitivity of the 3rd layer parameters variation for different types of EM sounding methods (HA and KH types of geoelectric sections).*

The average changes at all frequencies (times) or arrays size are shown in the table. However, as it was already noted in the present and earlier papers, the most noteworthy are variations that occur at significant points of the curves (Lozovoy, 2011). It also important to note that the FDEMS method has a significant reserve for increasing its sensitivity and accuracy of determining boundaries, such as measurement of two components (E_x и B_z) and conducting measurements with several spacings (R_1-R_n) (Enenstein, 1967, Gorunov et al., 1987, Ingerov et al., 1990, Ingerov et al., 1998, Lozovoy et al., 2011, Ingerov et al., 2012, Ingerov et al., 2015). Another advantage of the FDEMS-IP method is the fact that the summed parameters of geoelectric section can be quickly determined using significant points of the frequency domain induction soundings (summed longitudinal conductivity S and total thickness of overburden H) (Enenstein, 1967, Gorunov et al., 1987, Ingerov et al., 1990, Ingerov et al., 1998, Lozovoy et al., 2011, Ingerov et al., 2012, Ingerov et al., 2015).

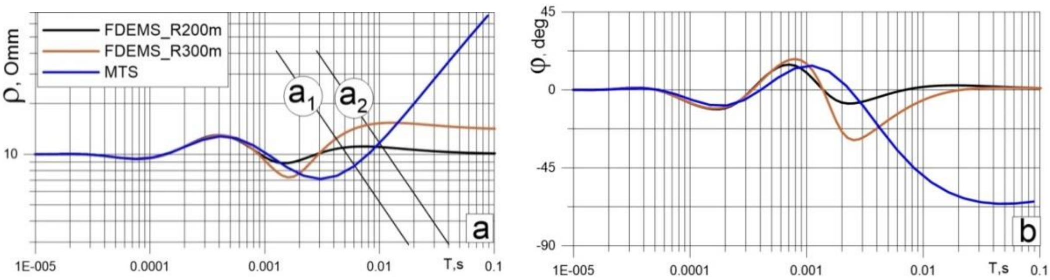

Figure 3 *AMT apparent resistivity (left) and phase (right) curves (blue), FDEMS with 300m (brown) and 200m (black) spacing for KH model, a_1 - the asymptote of the far zone at 200m spacing, a_2 - the asymptote of the far zone at 300m spacing.*

Figure 3 shows FDEMS amplitude and phase curves for the four-layer section type KH for 200m and 300m sounding spacing and AMT amplitude and phase (apparent resistivity phase) curves. In the far zone of the control EM field source (frequency range 100 000 – 3 000Hz) all three curves are noticeably different, and in transition and near zones, the form of FDEMS-IP curves is determined by the spacing and relation of the sounding spacing (R) to the total thickness of the host medium above the reference basement (H).

Conclusions

- Induction soundings in contrast to geometrical methods have narrow window of equivalency principle, higher sensitivity to the changes of geoelectric section's parameters and more accurate inversion results.
- According to the listed above characteristics, the EM methods are listed in the following order:
  - FDEMS-IP
  - TDEM
  - AMT, CSAMT
  - VES, DES
- The FDEMS-IP method with its accuracy of mapping boundaries and ability to register IP is considered to be the most suitable for geological engineering investigations.
- The cost and productivity of FDEMS field surveys is comparable to similar factors of geometrical soundings methods whereas more compact FDEMS-IP array is deployed in the field.

References

Berdichevsky, M.N., and Dmitriev, V.I. [2009] Models and Methods of Magnetotellurics. *Scientific World*, Moscow.

Enenstein, B.S. [1967] Ways to interpret two-layer frequency sounding curves. *Reports of USSR Academy of Science - Physics of the Earth*, **9**.

Gorunov, A.S., Ingerov A.I., and Kulikov, A.V. [1987] Equipment EVA-203 application for Frequency Electromagnetic sounding. *Application Geophysics*, **117**, 62-69.

Ingerov, A.I., and Soldatenko, V.P. [1998] About accuracy of the depth of high resistive reference horizon estimation by methods of frequency electromagnetic sounding. *The reports of National Academy of Science of Ukraine*, **12**, 123-128.

Ingerov, A.I., Ingerov, I.A., Lozovoy A.L., and Mendriy Y.V. [2012] Application of amplitude and phase curves received by induction sounding with natural sources for the purpose of mapping. *Scientific Bulletin of National Mining University*, Scientific and technical journal, **2**, 5-10.

Ingerov, A.I., Ingerov, I.A., Lozovoy A.L., and Mendriy, Y.V. [2015] Differential curves of induction electromagnetic soundings with natural sources for structural mapping in oil and gas geology. *Scientific Bulletin of National Mining University*, Scientific and technical journal, **1**, 42-48.

Lozovoy, A.L., Ingerov, A.I., and Soldatenko, V.P. [2011] The method of significant points FDEMS data interpretation in conditions of Ukrainian Shield. *Materials of the Fifth all-Russian workshop-seminar in the name of M.N. Berdichevsky and L.L. Vanyan on electromagnetic soundings of the Earth - EMS-2011*, Abstract Book, **2**, 194-196.

Tikhonov, A.N. [1950] About determining the electrical properties of deep layers of Earth crust and mantle. *Abstracts of USSR Academy of Science*, series 1950, Vol. **73**(2), 295-297.

Vanyan, L.L. [1965] The basis of electromagnetic soundings. *Nedra*, Moscow.