Acta Technica *62* No. 4B/2017, 1–8

Development and research of the geoelectric model of the local zone of geodynamic control[1]

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Abstract. The article deals with the question of constructing a geoelectrical model used in geotechnical control systems on the local areas of geodynamic observations. An equivalent scheme for replacing the geological medium at a local point of geodynamic control was developed. This scheme makes it possible to obtain the basic relations for the tensor of electrical resistances of a particle in the medium in state of geodynamic rest, taking into account the anisotropy and macro-voidness of media in the construction of geoelectrical transfer geoelectric functions. A model of near-surface inhomogeneities in the zone of local geodynamic control was developed, and a graph of the relationships of this model was constructed. The approach proposed in this paper makes it possible to describe any structure of a geoelectric section by a fractional function and to operate with arrays of real numbers under geodynamic control, which facilitates the automation of the processes of using theoretical results of modeling and interpreting experimental data.

Key words. Geoelectric model, geodynamic control, bias current, grid method.

1. Introduction

When organizing of geodynamic control in the systems of geotechnical monitoring of technical and life-supporting facilities, the choice of the environment model is of great importance. It must fully and accurately reflect the main regularities of possible geodynamic variations of the geological environment and the monitoring

[1]The work was carried out as part of the research on the project, supported by the Ministry of Education and Science of the Russian Federation No. 5.3606.2017/PCH.

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object [1–3]. When using geoelectric methods of geodynamic control, the parameters of the transfer function are the main parameters of the environment models. The parameters of the transfer function depend on the spatio-temporal distribution of the electromagnetic properties of the geological medium [4, 5]. The role of modeling when installing a control system of geodynamic objects is crucial, since the construction of data processing modules and the subsequent evaluation of geodynamic changes of the object is carried out based on the selected class of geoelectric models [6]. Real geodynamic objects have a structure exactly described by combinations of simple elementary models. Therefore, geoelectric modeling is based on the division of the geodynamic object into separate elementary geoelectric models (EGMs), which make it possible to estimate the geodynamics of the entire object on the basis of an analysis of the geodynamics of separately distinguished EGMs [7]. Based on this, a number of problems arise in the construction and investigation of geoelectrical models for application in geotechnical control systems of local zones of geodynamic observations.

2. The equivalent scheme for replacing the geological environment at a local point of geodynamic control

There are many equivalent circuits that can be used as the initial electrical model of the medium that serves to construct the transfer functions of the geoelectric section. The choice of model is determined by the conditions of the control, the main of which are the frequencies of the sounding effect. But under all conditions the construction of an equivalent circuit is based on the assertion that the electrical model of the media under study is represented in the form of an equivalent circuit consisting of parallel or series-connected frequency-independent active and capacitive resistances [6]. Suppose that the sedimentary-type medium in question is an isotropic matter, shown in Fig. 1. It consists of conductive particles 1 with a specific conductivity σ_1 and a host medium 2 with conductivity σ_2, which depends on the saturation of the medium and is an imperfect dielectric.

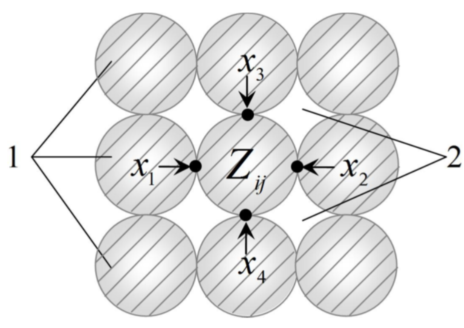

Fig. 1. Block diagram of the arrangement of medium particles

Each particle of the geoelectric section interacts with eight neighboring particles, which allows us to reduce the model to a four-pole interaction, which is completely described by a fourth-order tensor. The proposed model of the geoelectric section (Fig. 1) allows to take into account these conditions, which is especially important in studying the effects of induced anisotropy in the joint use of seismoacoustic and electromagnetic methods of geodynamic control. Figure 2, left part, shows the proposed equivalent circuit of a particle of the medium, where $\dot{Z}_1$ is the reactance describing the dielectric properties of medium 1. Quantity $\dot{Z}_2$ is the resistance, which is a parallel connection of the active resistances of two media r_1 and r_2 (Figure 2, right part). As a result of the analysis of the equivalent circuit, it is possible to obtain the basic relations for the electric resistance tensor.

$$\dot{Z}_{12} = \dot{Z}_{34} = \frac{\dot{Z}_1\dot{Z}_2}{\dot{Z}_1 + \dot{Z}_2}, \ \dot{Z}_{13} = \dot{Z}_{14} = \dot{Z}_{32} = \dot{Z}_{42} = \frac{\dot{Z}_2(3\dot{Z}_1 + \dot{Z}_2)}{4(\dot{Z}_1 + \dot{Z}_2)}\,. \quad (1)$$

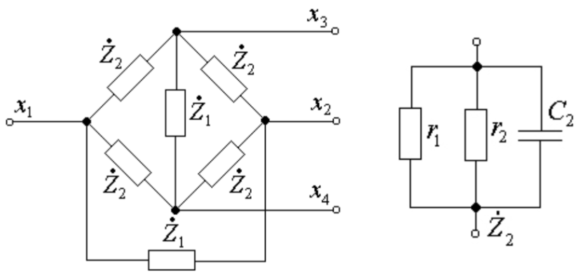

Fig. 2. Equivalent circuits for replacing a particle of the medium

3. The transfer function of the geoelectric section

In this case, it is permissible to use the approximation of the transfer functions of the geoelectric section by equivalent fractional-rational functions of the complex variable $p = \mathrm{j}\omega$. The physical realization of these functions is a discrete electrical circuit, taking into account equivalent replacement circuits (1). The equivalence of the functions of the geoelectric section should ensure that the characteristics do not coincide on the entire infinite range of frequencies and spatial coordinates, but only on a limited interval. In accordance with these assumptions, the transfer function of the geoelectric section for the fixed position of the field source $X(\mathrm{j}\omega, x, y, z)$ and the point of registration of the geodynamics of the object $Y(\mathrm{j}\omega, x, y, z)$ with respect to the day surface have the form

$$H(p, x, y, z) = \frac{W(p, x, y, z)}{V(p, x, y, z)} =$$

$$= \frac{b_0(x, y, z) + b_1(x, y, z)p + ... + b_n(x, y, z)p^n}{a_0(x, y, z) + a_1(x, y, z)p + ... + a_m(x, y, z)p^m}\,, \quad (2)$$

where $n \leq m$ and $V(p, x, y, z)$ is the Hurwitz polynomial. When electromagnetic methods are used to control media in the low-frequency range of waves, the geodynamics of individual selected objects is well described in the representation of the transfer function in the form

$$\frac{Y(\mathrm{j}\omega, x, y, z)}{X(\mathrm{j}\omega, x, y, z)} = H^*(\mathrm{j}\omega, x, y, z) = \sum_{i=1}^{\mathrm{n}} \prod_{j=1}^{m} \frac{A_{ij}\bar{\alpha}}{B_i(\bar{\alpha}) + \mathrm{j}\omega}, \tag{3}$$

where the coefficients $A_{ij}(\bar{\alpha})$ and $B_i(\bar{\alpha})$ are functional dependences on the spatial parameters of the rocks composing the geological section, as well as the vectors of the geodynamic variations. The accuracy of the approximation can be estimated by the Chebyshev criterion

$$\frac{\int_S \int_{\Delta\omega} \lambda(S) \left((\mathrm{Re}H(\mathrm{j}\omega) - \mathrm{Re}H^*(\mathrm{j}\omega))^2 + (\mathrm{Im}H(\mathrm{j}\omega) - \mathrm{Im}H^*(\mathrm{j}\omega))^2 \right) \partial S \partial\omega}{\int_S \int_{\Delta\omega} (\mathrm{Re}H^2(\mathrm{j}\omega) + \mathrm{Im}H^2(\mathrm{j}\omega)) \partial S \partial\omega} \leq \delta. \tag{4}$$

The weight factor $\lambda(S)$ is determined by the geoelectric method used to extract spatial geodynamic variations for the object of investigation in the control zone S and the frequency range $\Delta\omega$. Within the framework of the 2-D model under consideration, the structure of the inhomogeneity can be represented by a combination of media sets along the layering.

4. The geoelectric modeling of geodynamic control of near-surface inhomogeneities

To test the adequacy of the developed empirical models, a series of experiments was carried out on the field model. These experiments simulated the geodynamic control of near-surface inhomogeneities using a two-phase geoelectric installation.

The experimental installation is a rectangular electrically insulated container filled with moistened soil with specific conductivity $\rho = 370\,\Omega\mathrm{m}$ and size $L \times D = 150 \times 80\,\mathrm{m}^2$. The scheme is in Fig. 3. Electrodes of the electrical installation are placed in the middle of the container along one line (Fig. 4), and $l = 2r + d$.

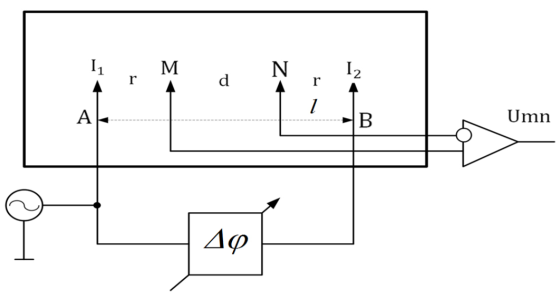

Fig. 3. The diagram of the experimental installation

In accordance with the adopted layout of the installation in the absence of inho-

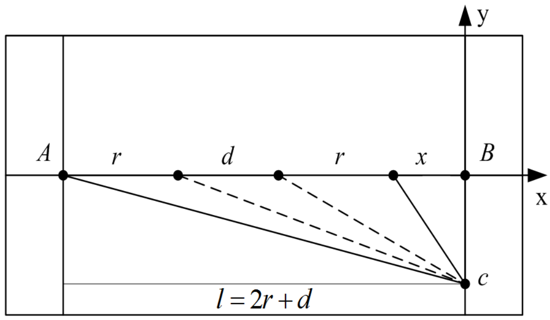

Fig. 4. The calculation scheme for the location of heterogeneity

mogeneity in the medium, the potential is determined with the following relationships:

$$U_{\mathrm{mn}} = U_{\mathrm{m}} - U_{\mathrm{n}},\ U_{\mathrm{m}} = \frac{I_1\rho}{2\pi r} + \frac{I_2\rho}{2\pi(r+d)},\ U_{\mathrm{n}} = \frac{I_1\rho}{2\pi(r+d)} + \frac{I_2\rho}{2\pi r}\,. \tag{5}$$

It describes the normal field of a two-phase electrical installation in a homogeneous half-space.

If the inhomogeneity is located at point C (Fig. 4), in accordance with the calculated scheme for the geoelectric field being recorded:

$$U_{\mathrm{m}} = \frac{I_1\rho}{2\pi r} + \frac{I_2\rho}{2\pi(r+d)} - \frac{(I_1 - I_2)\rho}{2\pi\sqrt{y^2 + (x+d+r)^2}}\,,$$

$$U_{\mathrm{n}} = \frac{I_1\rho}{2\pi(r+d)} + \frac{I_2\rho}{2\pi r} - \frac{(I_1 - I_2)\rho}{2\pi\sqrt{y^2 + (x+r)^2}}\,. \tag{6}$$

On the basis of relations (5) and (6) for the anomalous component of the geoelectric field, determined by the presence and, accordingly, possible geodynamics

$$\Delta U_{\mathrm{mn}} = -\frac{(I_1 + I_2)\rho}{2\pi}\left(\frac{1}{\sqrt{y^2 + (x+d+r)^2}} - \frac{1}{\sqrt{y^2 + (x+r)^2}}\right). \tag{7}$$

The phase shift $\Delta\varphi_{\mathrm{mn}}$ determined by the inhomogeneity can be determined from eqs. (5)–(7). In accordance with the calculation scheme shown in Fig. 4 we obtain

$$U_0^* = \frac{I_0\rho}{2\pi}\left(\frac{1}{r} - \frac{1}{r+d}\right),\ U_1^* = \frac{I_0\rho}{2\pi}\left(\frac{1}{\sqrt{y^2 + (x+d+r)^2}} - \frac{1}{\sqrt{y^2 + (x+r)^2}}\right). \tag{8}$$

In accordance with relations (5), one can determine the phase shift from the relation

$$\tan \Delta\varphi_{\mathrm{mn}} = \frac{U_0^*}{U_1^*} = \frac{\frac{1}{\sqrt{y^2+(x+d+r)^2}} - \frac{1}{\sqrt{y^2+(x+r)^2}}}{\frac{1}{r} - \frac{1}{r+d}}. \tag{9}$$

Figure 5 shows the theoretical dependences of the transmission coefficient on the phase shift $\Delta\varphi_{\mathrm{mn}}(x, y)$ obtained for different coordinates of the location of the inhomogeneity in accordance with the condition of minimization by the Chebyshev criterion (2) $\lambda(x, y, z) = 1$ for the relations (8), (9) in the form of a geoelectric 2-D model (see Fig. 5).

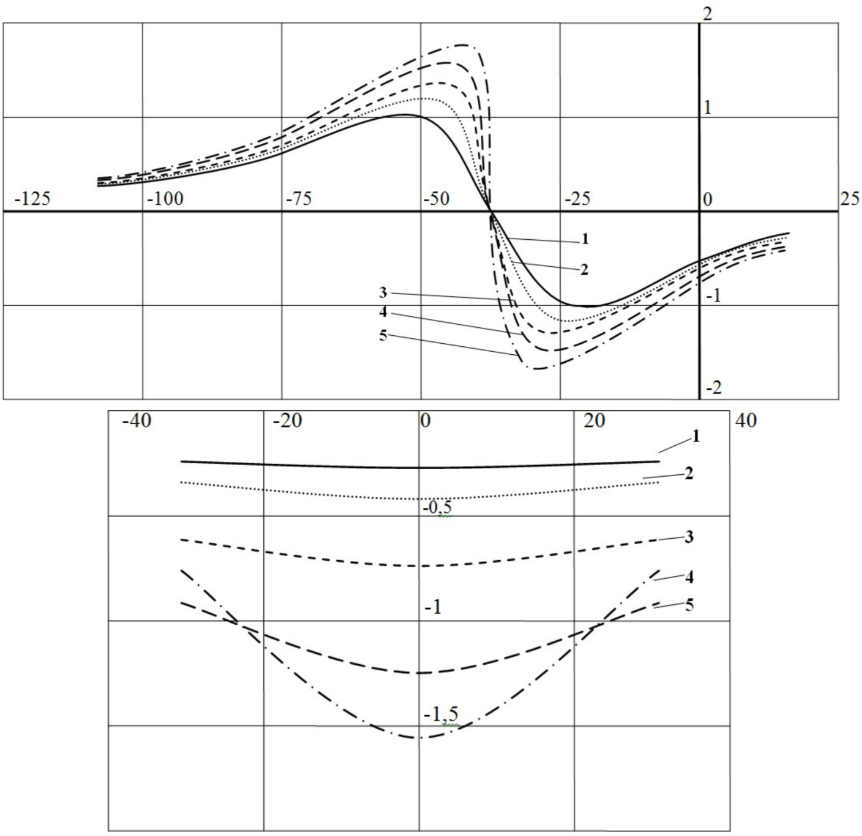

Fig. 5. Results of geoelectric modeling: left–dependence of the transmission factor on the phase shift along the coordinate $x \subset [-0.8L; 0.2L]$ for fixed values of the coordinate$y = [0.4D; 0.3D; 0.25D; 0.2D; 0.1D]$, right–coordinate $x = [-0.2L; -0.1L; 0; 0.1L; 0.2L]$ is already fixed

5. The simulation results

Full-scale modeling was carried out in a manner similar to the computational method. In the first series of experiments, the coordinate x was fixed, and the inhomogeneity model moved along the coordinate y. Starting with the 20 seconds of the experiment, the grounded electrode was moved. The measurement was carried out for the selected point for 10 seconds with 10 second interruptions for permutation of the electrodes. Similarly, a series of experiments was conducted to fix the coordinate y and move the model along the coordinate$x$. Figure 6, left and right parts, show the results of experimental studies and theoretical geoelectric modeling curves based on the methodology outlined in this article.

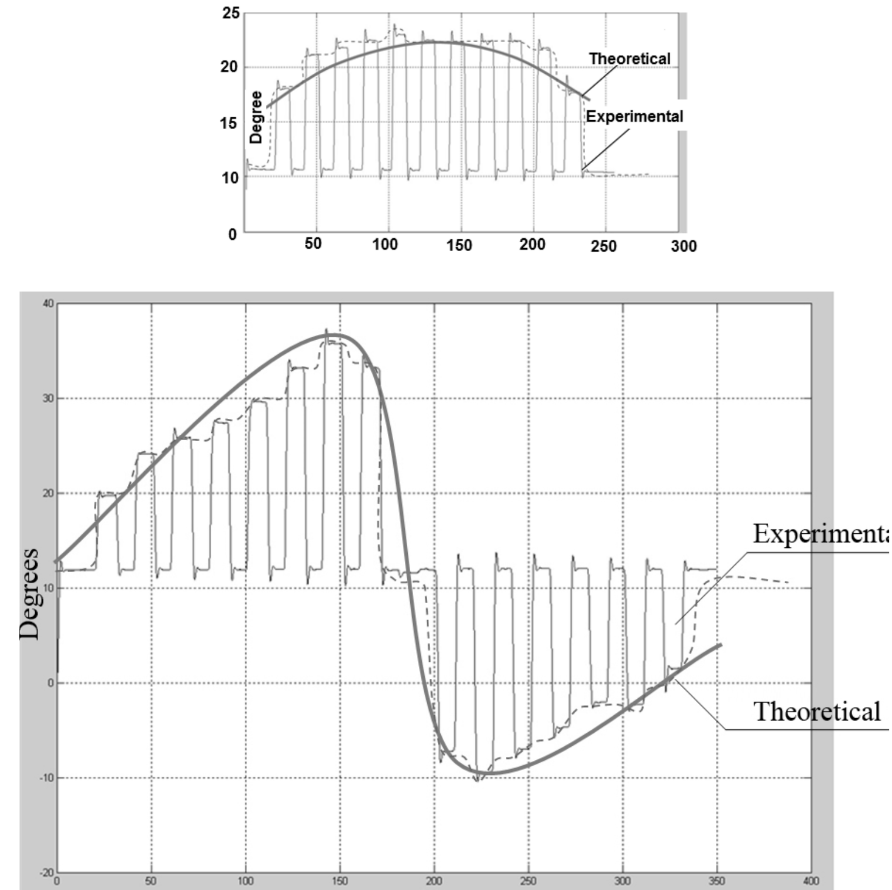

Fig. 6. Results of experimental studies

6. Conclusion

The data presented in this article confirm the fact that the result of the numerical simulation adequately describes the characteristics of the real control object, represented as a ground model, investigated for near-surface inhomogeneities using a two-phase geoelectric installation. Based on the above, it can be concluded that the approach proposed in this paper allows us to describe any structure of the geoelectric section by a fractional function and to operate under geodynamic control by arrays of real numbers. This facilitates the automation of the processes of using the theoretical results of modeling and interpreting experimental data. In addition, the use of the relations obtained simplifies the geodynamic estimation of the variations of individual isolated research objects on the basis of an analysis of model changes of the transfer function coefficient of the geoelectric section.

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Received October 12, 2017