Spatial Phase Spectra and Spatial-Temporal Geodynamic Filtering of Geoelectric Signals

Kuzichkin O.R.[1], Vasilyev G.S.[1], Ivashchuk O.A.[1], Su*rzhik D.I.*[1,2], *Podmasteryev K.V.*[3]

[1]1Belgorod State Research University, Belgorod, 308015, Russia
[2]Vladimir State University named after Alexander Grigoryevich and Nikolai Grigorievich Stoletovs, Vladimir, 600000, Russia
[3]Oryol state University named after I. S. Turgenev, Orel, 302026, Russia

Abstract
The article presents a method of geodynamic evaluation of control objects with multipolar geoelectric profiling by phase structure and polarization parameters, which allows to estimate distortions of current field lines by both near-surface and deep inhomogeneities. A phasometric method for geoelectric data recording is presented, which is effective for tracking the geodynamics of near-surface inhomogeneities in cases where it is necessary to provide increased sensitivity to special changes in the object of study. High efficiency is achieved by increasing the sensitivity of the measuring system, initial installation and operational positioning of the electrical installation by controlling the sources of probing signals. The general structure of the spatial phase spectra of the geoelectric vector field makes it possible to determine the distribution of secondary anomalous sources, as well as to estimate the significant heterogeneity of the medium at the points of convergence of the vectors. An approach is proposed involving the allocation of elementary components of geodynamic forms on phase images using spectral elementary geoelectric models. The data of experimental work for a two-pole geoelectric installation when creating artificial geodynamic impacts are presented.

Keywords
Geodynamic control, geoelectrics, phasometric method, adaptive filtration, polarization structure, geodynamic trend

Introduction

Geoelectric methods of geodynamic control are based on the differentiation of electrical properties of rocks and the identification of objects that cause anomalous distortions of probing geoelectric fields [1-4]. The solution of the problems of geodynamic control is based on the identification and interpretation of anomalous manifestations of geoelectric fields. Which is a broader concept than solving the inverse problem of geological exploration [5], in which it is required to determine the electrical characteristics of the studied section of the geoelectric section with known parameters of probing signals and the recorded distribution of the electromagnetic field. In geodynamic control, it is necessary to identify a relative geodynamic change in the position of near-surface inhomogeneities, in which the overall quantitative characteristics of the medium are of secondary importance. Geoelectric geodynamic control systems are based on special methods of processing geoelectric information, taking into account both the method of formation and the frequency range of probing signals, and geological conditions for collecting information [6].

The geodynamic control technique based on geoelectric methods presupposes the use of basic principles of electrical profiling when fixing the dimensions of the measuring installation, and the sensor position relative to the installation changes in accordance with the geoelectric electrical profiling technique [7]. In this case, the depth of the study does not change, and the apparent resistance determined at each installation position reflects the change in the electrical properties of rocks along the selected profile. The most well-known electroprofiling methods used in practice, such as symmetric, dipole and divergent, are characterized by the volume and reliability of the information provided about physical fields with sufficient accuracy of their registration [8]. The accuracy of measurements in these methods depends on the step of electrical profiling, which is set based on the detail of the study and depth. Therefore, an increase in accuracy and, accordingly, efficiency leads to an increase in the complexity of exploration work, and in some cases the required accuracy becomes unattainable due to industrial exploitation of the sites where research is conducted [9].

In the works [10,11], the application of a multi-pole method of electro-profiling is justified, which allows for a circular study of the areas of the karst in conditions of complex development, characteristic of most industrial facilities. It involves the registration of a two-component electric field created by a multi-pole source at a fixed position of both sources and the measuring basis. Geodynamic control is carried out by controlling the parameters of the probing signals while simultaneously regis-

Manuscript received September 5, 2022
Manuscript revised September 20, 2022
https://doi.org/10.22937/IJCSNS.2022.22.9.81

tering the phase characteristics of the field at the observation point. The registration of phase characteristics is based on the fact that the primary and secondary electric fields, the sum of which we register, are vector quantities. Due to a number of reasons, both metrological and practical, vector measurements are rarely used in electrical exploration and are preferred to areal ones with a linear installation. However, it should be noted that when carrying out work in cities, difficulties often arise with the placement of installations, and the use of vector measurements is a necessary and only possible method of research [12]. They allow to see objects that are away from the placed observation system. In addition, the registration of phase relations of the vector representation of the electric field makes it possible to eliminate the paradoxes (ambivalence) of registering an anomalous field in inhomogeneous media, since it can exceed the primary field several times and not coincide with it in sign. As a result, the apparent resistance can take a negative value.

Principles of geodynamic control based on phase parameters of geoelectric signals

The use of multi-pole electrical installations in geoelectric control systems allows for effective geodynamic monitoring of the environment in conditions of industrial and climatic interference, as well as complex buildings typical of most industrial facilities [13,14]. When using multipolar geodynamic control systems at registration points, we will deal with an elliptically polarized geoelectric field. This is due to the fact that the sources are geographically separated and initially have different parameters of probing signals. When using monochromatic probing signals , the vector of spatial parameters of the recorded field can be represented in the following form:

$$\dot{U}_x = a_x + ib_x; \quad \dot{U}_y = a_y + ib_y, \tag{1}$$

where $\mathbf{a_x = E_x \cos \varphi_x}$, $\mathbf{b_x = E_x \sin \varphi_x}$; $\mathbf{a_y = E_y \cos \varphi_y}$, $\mathbf{b_y = E_y \sin \varphi_y}$; $E_{x,y}$ and $\varphi_{x,y}$ are amplitude and phase characteristics of the recorded geoelectric field.

In general, equations (1) describe an elliptically polarized monochromatic field, and its phase structure can be estimated using polarization parameters that allow us to estimate distortions of the current field lines by both near-surface and deep inhomogeneities. Object tracking is carried out by controlling the parameters of the probing signals while simultaneously registering the phase characteristics of the field and compensating for the current trend of geoelectric signals at the observation points.

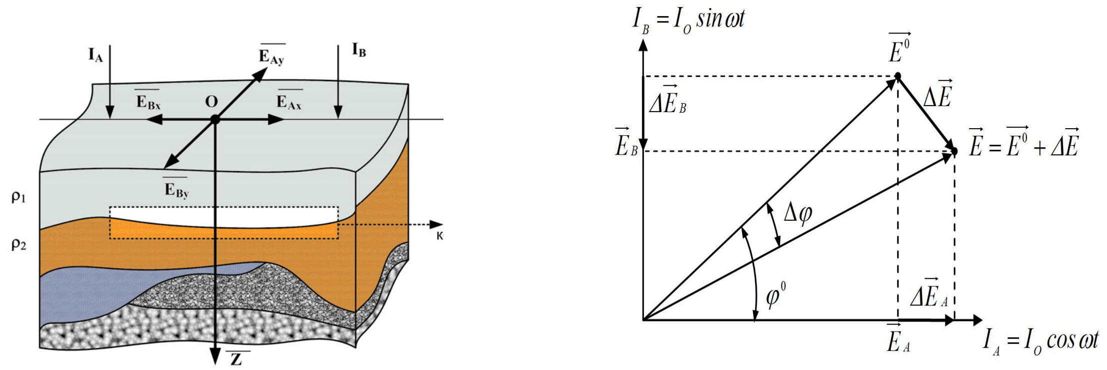


Figure 1 - The registration principle of the phase structure of the geoelectric field during geodynamic monitoring

The phasometric method of recording geoelectric data is effective for tracking the geodynamics of near-surface inhomogeneities in cases where it is necessary to provide increased sensitivity to special changes in the object of study. High efficiency is achieved by increasing the sensitivity of the measuring system, initial installation and operational positioning of the electrical installation by controlling the sources of probing signals [15]. The method of applying the phase-measuring method of geoelectric control, which consists in the fact that several sources located near the object under study and the required number of vector measuring sensors of the electric field are used as a probing signal. In the simplest case, two point sources *A, B* and one measuring sensor *O* can be used, located along the *AB* line and at equal distances from the sources (Figure 1).

Point sources *A* and *B* form probing signals shifted in phase by $\pi/2$ relative to each other. It should be noted that with a different location of the sources relative to the sensor, as well as with multi-pole sensing, the phase shifts between the test signals may be different. Each of the point sources generates at point O an electric field signal of the following type:

$$\vec{E}_{Ax} = \vec{E}^0_{Ax} + \Delta\bar{E}_{Ax}, \quad \vec{E}_{Ay} = \Delta\bar{E}_{Ay}$$
$$\vec{E}_{Bx} = \vec{E}^0_{Bx} + \Delta\bar{E}_{Bx}, \quad \vec{E}_{By} = \Delta\bar{E}_{By} \qquad (2)$$

where $\vec{E}^0$ is a normal signal in the absence of inhomogeneity; $\Delta\bar{E}$ is an anomalous component of the electric field caused by the presence and geodynamics of inhomogeneity, determined by secondary sources of the field.

The basic recorded phase characteristics include the values of the main semi-axes of the polarization ellipse or the maximum and minimum values of the geoelectric field vector in the plane of the polarization ellipse, which can be expressed from the Stokes relations [16]. At the same time, they are the initial ones for estimating the intensity of secondary field sources, and their position and features can be estimated based on the dependences of phase characteristics on the parameters of probing signals. As phase characteristics, the phase of the field, independent of the selected coordinate system, and the azimuth of the field vector, which binds to the position of the measuring basis, can be used. As an independent phase, special points of the ellipse and the time points of their appearance can be used. These include the phase that determines the coincidence of the full vector of the electric field E with the semi-axes of the ellipse, which can be written from the orthogonality condition of the conjugate half-diameters

$$\boldsymbol{tg2\phi} = \frac{2(a_x b_x + a_y b_y)}{(a_x^2 + a_y^2) - (b_x^2 + b_y^2)}. \qquad (3)$$

It can be seen from the relation (3) that although it is possible to obtain four values of phases that differ from each other by a quarter of the period, however, the phase of origin of the larger axis ϕ_a and the phase of passage of the minor axis ϕ_b is determined unambiguously

$$\boldsymbol{\phi_a = arctg\left(\frac{a_x b_x + a_y b_y}{A^2 - (b_x^2 + b_y^2)}\right), \ \phi_b = arctg\left(\frac{a_x b_x + a_y b_y}{B^2 - (b_x^2 + b_y^2)}\right)}. \qquad (4)$$

The azimuth of the complex vector of the geoelectric field can be found similarly to the real vectors (Figure 2)

$$\frac{\dot{u}_y}{\dot{u}_x} = \frac{a_y + ib_y}{a_x + ib_x} = \frac{\sin\psi + ik\cos\psi}{\cos\psi - ik\sin\psi}.$$

Representing the azimuth by a complex number $\theta = \psi + i\chi = \psi + arctg\ ik$, the real part is equal to the azimuth of the major axis of the ellipse of polarization, and the imaginary part is the azimuth of the asymptotes of this ellipse [17]

$$\boldsymbol{tg(\psi + i\chi) = \frac{tg\psi + tg\ i\chi}{1 - tg\psi \cdot tg\ i\chi}}. \qquad (5)$$

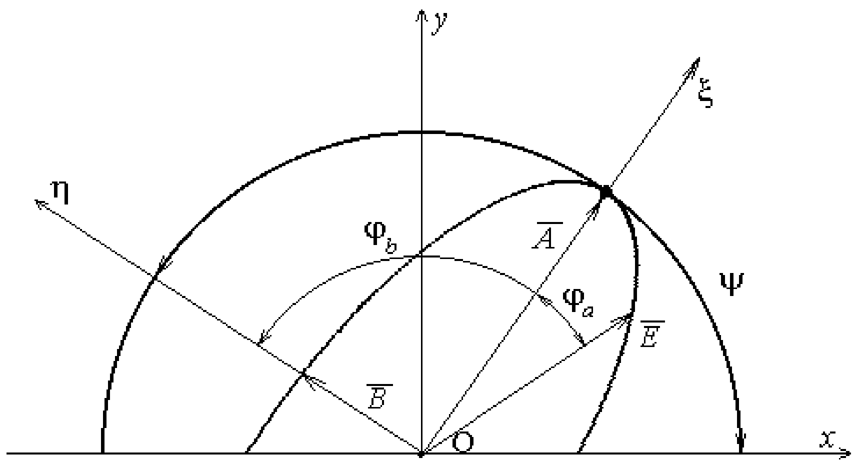


Figure 2. Azimuth of the complex vector of the geoelectric field under geodynamic control

The elements of the polarization ellipse of the harmonic vector can be expressed in terms of the azimuth tangent of the corresponding complex vector. For the azimuth of the larger axis of the polarization ellipse

$$\boldsymbol{tg\psi = \frac{2\,Re\,T}{(1-|T|^2)+\sqrt{(1-|T|^2)^2+(2\,Re\,T)^2}}}. \qquad (6)$$

Equations (5) and (6) allow us to determine the curvature of current lines due to inhomogeneities of the medium and evaluate their characteristics.

For example, in the study of karst phenomena, where the lithological composition of rocks and fracture zones play a significant role, contributing to the formation of various inhomogeneities, the behavior of phase characteristics can cause ambiguity in the interpretation of the data obtained. This may occur due to significant anomalies of resistance in cases of unequal intensity of crack development in different directions and implicit layering. In this case, a more complete picture can additionally be given by the data of the orthogonal-linear decomposition of the recorded electric field at the observation point.

$$\boldsymbol{\dot{u}_y/\dot{u}_x = u \cdot exp(\,i\Delta\phi),\ \ \Delta\phi = \phi_y - \phi_x}. \qquad (7)$$

They can be determined by the known phase parameters k and based on the following expressions

$$\boldsymbol{u^2 = \frac{k^2+tg^2\psi}{1+k^2tg^2\psi}}, \qquad \boldsymbol{\Delta\phi = arctg\left(\frac{2k}{1-k^2\,sin\,2\psi}\right)}, \qquad (8)$$

which are easily obtained from the relations (4) and (5).

It is known from the practice of vector measurements and their processing that the anomalous influence of inhomogeneities on the vector field during geodynamic control occurs in accordance with the structure of the anomalous electric field. Vectors converge to negative sources and diverge from positive ones. The general picture of the vector field construction makes it possible to determine the distribution of secondary anomalous sources, which makes it possible to estimate the significant heterogeneity of the medium at the points of convergence of the vectors.

Selection of geodynamic variations based on spectral processing of phase data

One of the most effective approaches to the analysis of anomalous components of the geoelectric field in geodynamic monitoring is the use of adaptive filtering algorithms for recorded spatio-temporal data. At the same time, this approach assumes the allocation of elementary components of geodynamic forms on phase images, using spectral elementary geoelectric models (EGM). In accordance with the fundamentals of the spectral method of analysis and synthesis of systems, this problem can be reduced to optimal non-stationary filtration for a known useful component that describes the corresponding EGM. This method assumes spectral optimal estimation of the dynamic characteristics of filters in the form of spectral representations, based on the Wiener-Hopf vector matrix equation in accordance with the minimum of the mean quadratic error [17]. Assuming the limitation of the geodynamic control area $x = [0, x_n], y = [0, y_m]$, it can be reduced to the Fredholm equation of the first order

$$\int_0^{x_n} \int^{y_m} \bar{\boldsymbol{G}}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\tau}_x, \boldsymbol{\tau}_y) \, \boldsymbol{R}_{ss}(\boldsymbol{\tau}_x, \boldsymbol{\tau}_y, \boldsymbol{\xi}) \boldsymbol{d\tau}_x \boldsymbol{\tau}_y = \boldsymbol{R}_{ms}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\xi}) \tag{9}$$

where $G(r, \tau)$ is the matrix of pulse transient functions of the optimal filter, $R_{ss}(\tau, \xi), R_{ms}(r, \xi)$ are the specified correlation matrices of the phase image and EGM.

Assuming the criterion of the minimum of the mean square of the error

$$\boldsymbol{M}\{[\boldsymbol{F}(\boldsymbol{x}, \boldsymbol{y}) - \boldsymbol{H}^*\{\boldsymbol{L}(\boldsymbol{x}, \boldsymbol{y})\}]^2\} = \boldsymbol{min}, \tag{10}$$

where is the expectation operator, $F(x, y) = H\{L(x, y)\}$ is the true operator of a real object, $H^*\{L(x, y)\}$ is an operator that characterizes a certain type of EGM in accordance with equation (9).

In this case, control signals for the initial installation and positioning of measuring geoelectric systems by the phase method are formed in accordance with:

$$\bar{\phi}_i(t_0) = F_U(\boldsymbol{M}_{Si}, \bar{\phi}^*(t_0)), \tag{11}$$

where F_U is the forming functional of the initial positioning according to the phase vector of control $\bar{\phi}^*(t)$ by the system of spatio-temporal processing of control data at the initial time $t = t_0$, and $\boldsymbol{M}_{Si}$ is the vector of model parameters.

Then the geoelectric measuring system operates directly in semi-automatic mode according to the following algorithm:

$$\bar{\phi}_i(t) = \bar{\phi}_i(t_0) + \Delta\phi(\boldsymbol{M}_{Si}, \bar{\alpha}) + F_U(\Delta\boldsymbol{M}_{Si}, \bar{\phi}^*(t)), \tag{12}$$

where $\Delta\phi(\boldsymbol{M}_{Si}, \bar{\alpha})$ is the current positioning control of the electrical installation according to the geodynamic variation vector; $\Delta\boldsymbol{M}_{Si}$ is model correction.

Equation (10) allows spatial dynamic filtering of the phase image of an object according to a certain class of EGM. The resulting matrix equation establishes a correspondence between the spatial spectral form of the description of a geodynamic object and its spectral phase image.

$$\boldsymbol{H}^{\boldsymbol{Y}} = \left(\boldsymbol{S}_{\boldsymbol{F}}^{\boldsymbol{Y}}\right)^{-1} \boldsymbol{S}_{\boldsymbol{F}}^{\boldsymbol{X}} \boldsymbol{H}^{\boldsymbol{X}} = \boldsymbol{S}_{\boldsymbol{F}} \boldsymbol{H}^{\boldsymbol{X}}, \tag{13}$$

where S_F is the spectral phase characteristic of the object.

Equation (13) can be solved by reducing it to a linear system of equations with respect to the basic decomposition coefficients for the current geodynamic trend using the regression analysis method

$$\boldsymbol{R}_{\mathrm{XY}} = \boldsymbol{\Phi}^{\boldsymbol{T}}(\boldsymbol{x}_1, \mathrm{Y}_1) \boldsymbol{S}_{\boldsymbol{F}} \boldsymbol{H}^{\mathrm{YY}} \boldsymbol{\Phi}(\boldsymbol{x}_2, \mathrm{Y}_2), \tag{14}$$

where $H^{\mathrm{YY}} = M\{H^Y H^{\mathrm{YT}}\} = M\{h_{\mathrm{ij}}^Y\}$.

Equation (14) is a classical linear regression model that allows an optimal estimation of the regression parameters of the basic decomposition coefficients [18]. To detect an EGM of a certain class in the phase image, it is necessary to conduct an independent regression analysis using the spectral estimation method for each type of EGM. When assessing the adequacy of models, various statistical methods can be used, such as estimating variance ratios or estimating the correlation coefficient of experimental data with EGM characteristics.

Experimental data

For experimental verification of the algorithms discussed above, studies were conducted within the framework of the FZWG -2020-0029 project "Development of theoretical foundations for building information and analytical support for telecommunication systems for geo-ecological monitoring of natural resources in agriculture" on the territory of the Svyato karst Lake of the Nizhny Novgorod region [19].

Figure 3 shows a diagram of the installation of elements of the information technology complex on the reference section of geodynamic control.

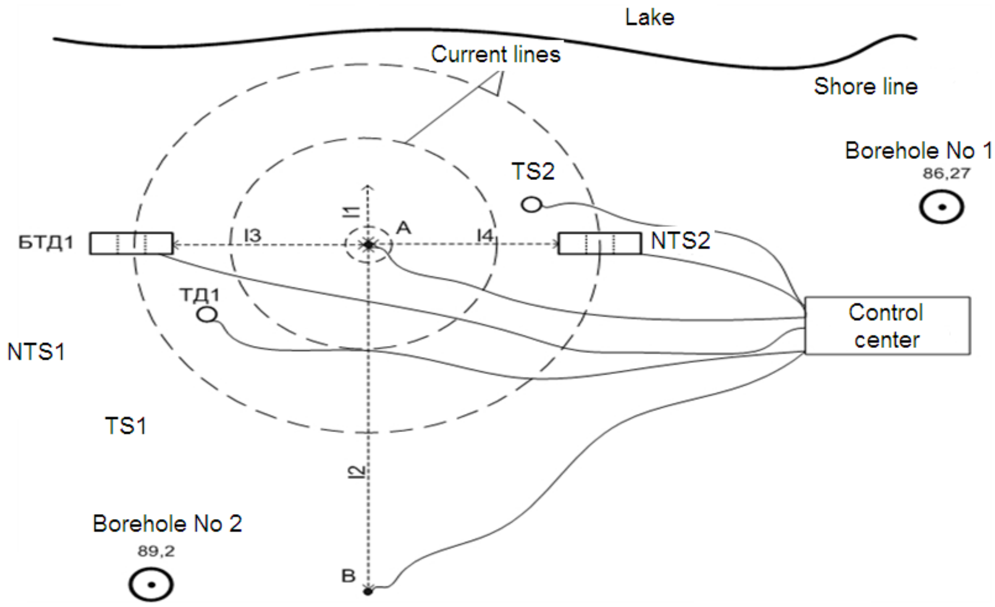
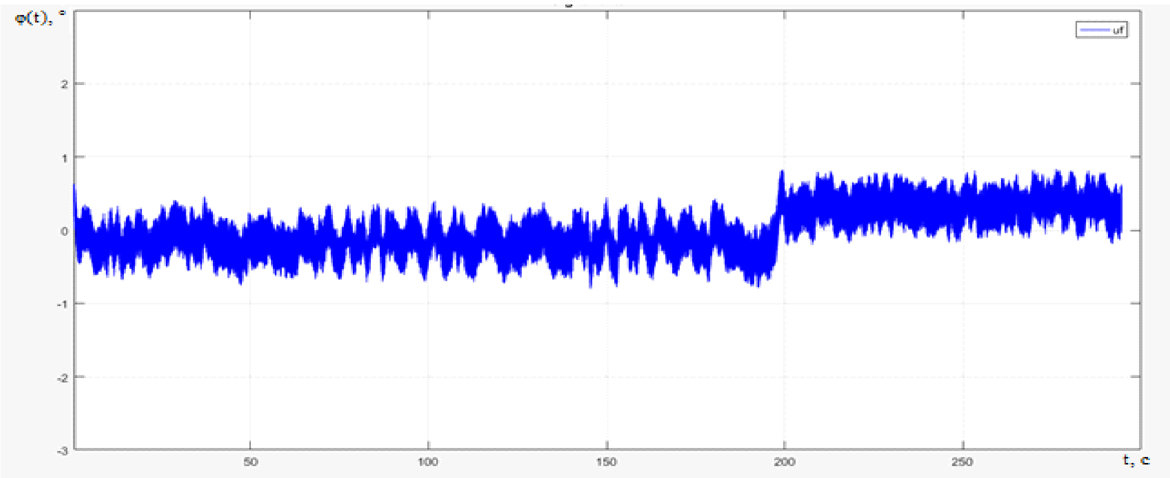
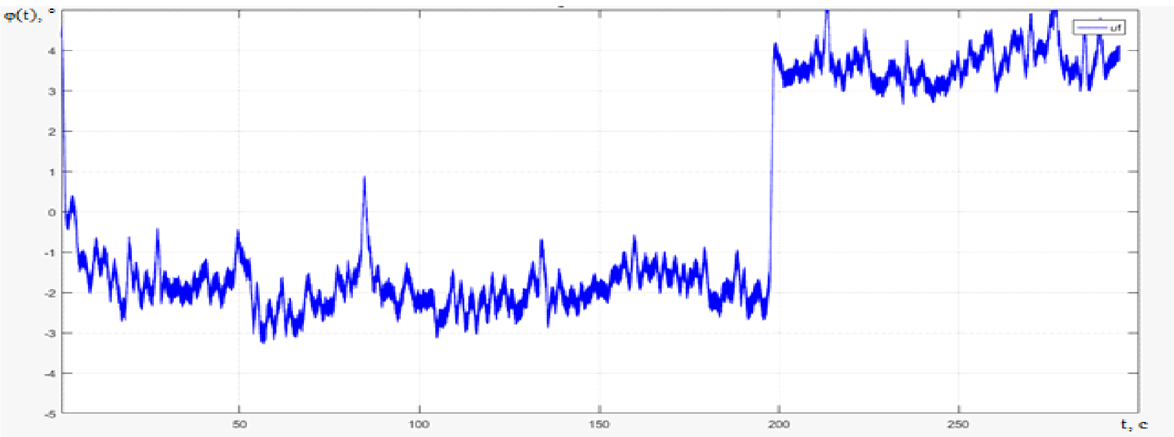


Figure 3 - Layout of the complex at the reference point of hydrogeological control

The measuring geoelectric system was placed as follows: - the emitting electrode A was removed from the lake shore at a distance of $l1$ = 5m; the first and second blocks of the non-contact transformer sensor (NTS1 and NTS2) are located at a distance of $l3$ and $l4$ from the emitting electrode (provided that $l3$=$l4$= 30m); electrode B is installed at the highest possible distance $l2$= 250 m from the emitting electrode A. At the same time, phase data were recorded with long-range filtration and isolation of an artificial geodynamic event in the form of near-surface drilling with a diameter of 40 cm to a depth of 0.5 meters at various distances from the measuring installation. Figure 4a shows the initial phase data of registration under geodynamic artificial influence at a distance of 60 meters from the center of the measuring system. Figures 4b show the results of processing using the considered approach to isolate the geodynamic phase trend.



a)



b)

Figure 4 – Experimental data – geodynamic impact at a distance of 60 m from the center of the system. Recording time: 5 minutes

Conclusions

The technique of geodynamic evaluation of control objects presented in this paper using geoelectric multipolar electrical profiling by phase structure and polarization parameters, allows us to evaluate the distortion of current field lines by both near-surface and deep inhomogeneities. It is based on the application of the phasometric method of recording geo-electrical data and allows to see objects that are far away from the distributed observation system. In addition, the registration of phase relations of the vector representation of the electric field makes it possible to eliminate the paradoxes of registering an anomalous field in inhomogeneous media, since it can exceed the primary field several times and not coincide with it in sign. As a result, the apparent resistance can take a negative value. High efficiency is achieved by increasing the sensitivity of the measuring system, initial installation and operational positioning of the electrical installation by controlling the sources of probing signals.

The general structure of the spatial phase spectra of the geoelectric vector field makes it possible to determine the distribution of secondary anomalous sources, which makes it possible to estimate the significant heterogeneity of the medium at the points of convergence of the vectors. The basic recorded phase characteristics include the values of the main semi-axes of the polarization ellipse or the maximum and minimum values of the geoelectric field vector in the plane of the polarization ellipse. At the same time, they are the initial ones for estimating the intensity of secondary field sources, and their position and features can be estimated based on the dependences of phase characteristics on the parameters of probing signals. As phase characteristics, the phase of the field, independent of the selected coordinate system, and the azimuth of the field vector, which binds to the position of the measuring basis, can be used. As an independent phase, special points of the ellipse and the time points of their appearance can be used.

An approach is proposed involving the allocation of elementary components of geodynamic forms on phase images using spectral elementary geoelectric models. The data of experimental work for a two-pole geoelectric installation when creating artificial geodynamic impacts are presented. As can be seen from the experimental data obtained, the system based on the phasometric method has significant sensitivity. This allows us to conclude that the developed method allows for the directions of changing the phases of the recorded signals relative to the stationary state of the system by using a network of multiple receiving electrodes to effectively isolate the place of occurrence of geodynamic effects.

Acknowledgements

The work was supported by the grant Russian Federation FZWG-2020-0029 "Development of theoretical foundations for building information and analytical support for telecommunications systems for geoecological monitoring of natural resources in agriculture".

References

[1] Dorofeev, N. V. Spatio-temporal data processing of automated geodynamic monitoring system / N. V. Dorofeev, O .R. Kuzichkin, R .V. Romanov, A .V. Koskin //Proceedings of the 2017 IEEE 9th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2017. Volume 1, P 231–237.

[2] Electrospecting by the method of resistances. / Edited by V.K.Khmelevsky: Textbook. - Moscow: Publishing House of Moscow State University, 1994. 160 p.

[3] Zhdanov M.S. Electrical exploration: Textbook for universities. – Moscow: Nedra, 1986.

[4] Dorofeev, N.V., Kuzichkin, O.R. Processing of heterogeneous data in GIAS of geodynamic monitoring // Proceedings of the 2015 IEEE 8th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2015 Volume 1, 30 November 2015, Pages 33-37

[5] Bogolyubova N.P. Geoelectric karst models and typical anomalies of electro-profiling and vertical electrical sounding above them. – Moscow: Nauka, 1987.

[6] A.K. Smirnov, Underground gas storage in aquifers («Kompanija Sputnik+», Moscow, 2003).

[7] Kuzichkin, O., Grecheneva, A., Bykov, A., Dorofeev, N., Romanov, R. Optimization of an equipotential method of electroinvestigation for a research of karst processes // International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, Volume 17, Issue 52, 2017, Pages 681-688

[8] Chigin M.M., Kovalenko V.A. On the quantitative assessment of the effectiveness of methods of electrical exploration geophysics. Izv. VUZov No. 3, 1973.

[9] Bogolyubov, A.N. On the relationship between geophysical and engineering-geological parameters of soils/ A.N. Bogolyubov, Yu.D. Zykov, Yu.D. Baulin, R.I. Korkina. "Proceedings of PNIIIS", 1976, issue 51, p51-62.

[10] Kuzichkin, O.R. Development and research of the geoelectric model of the local zone of geodynamic control/ O.R. Kuzichkin, A.V. Grecheneva,R.P. Gakhov et al // Journal of Advanced Research in Dynamical and Control Systems. - Vol.10(Issue 13). - 2018. -P. 620-625

[11] Kuzichkin, Oleg Application of phase-metric measuring system for geodynamic control of karst processes/ Oleg Kuzichkin, Anastasia Grecheneva, Ekaterina Mikhaleva et al. // Journal of Engineering and Applied Science. - 12 (Spesial Issue 4). - 2017. – P. 6858-6863.

[12] Bogolyubov, A.N. Guide to the interpretation of the curves of the VEZ MDS / A.N. Bogolyubov, N.P. Bogolyubova, E.Ya. Mozganova. -Moscow: Stroyizdat, 1984, p. 200.

[13] Kuzichkin, O. Monitoring of karst-suffusion formation in area of nuclear power plant / O. Kuzichkin, R. Sharapov // Journal of Politics. 2013. T. 2. C. 810-814.

[14] Vasilyev, G.S. Compensation method of geodynamic trend in the systems of geoelectric control/ G.S. Vasilyev, O.R. Kuzichkin, A.V. Grecheneva et al // International Journal of Engineering and Technology(UAE). - Vol.7(Issue 4). -2018. -P.3697-3701

[15] Kuzichkin, O.R. Method of increasing geodynamic sensitivity in the system of geoelectric control of karst processes./ O.R. Kuzichkin, S.A. Finogenov// Algorithms of data processing in multipolar electrolocation systems.- Radio engineering. – No. 6. – 2007. – pp. 60-63

[16] Dmitriev, V.I. Computational mathematics and technology in exploration geophysics. Handbook of Geophysics/ V.I. Dmitriev.– Moscow: Nedra, 1990.

[17] Perov V.P. Applied spectral theory of estimation. – Moscow: Nauka, 1982. 432 p.

[18] Kuzichkin, O. Regression algorithms eliminate interference with the endogenous character geoecological monitoring of water resources/ O. Kuzichkin, N. Dorofeev, A. Bykov et al. // International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM. - Volume 17. - Issue 52. – 2017. – P. 749-754

[19] Kuzichkin O et al, Hydrogeological Monitoring of Karst Activity Based on Regime Observations in the Territory of Karst Lakes. // Journal of Water and Land Development 2021 No 48 pp. 130-140