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Application of Phase-Metric Measuring Systems for Geodynamic Control of Karst Processes

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Abstract: This research is devoted to the application of the phase-metric method of geodynamic control to solving of the problems of monitoring karst processes as well as the analysis of the influence of multiplicative natural noise on the results of geodynamic control. It is noted that the applied phase-metric method of recording geoelectrical signals allows eliminating the multiplicative interference and increasing the accuracy of geoelectric control. A theoretical evaluation of the dependence of the attenuation of multiplicative interference on the basis of the model of geodynamic control of a karst suffusion cavity using a two-pole phase-metric electrical installation is presented. The developed device for recording geodynamics of near-surface inhomogeneities is described. The results of experimental studies of full-scale modeling of geodynamic control of the karst suffusion cavity development using a two-pole phase-meter electrical installation are presented. As part of the experiment, registration of geodynamic variations was carried out to obtain comparative data an equipotential geodynamic control method was used with simultaneous application of the phase-metric method.

Key words: Phase-metric method, geodynamic control, geoelectric signal, multiplicative interference, monitoring, karst processes

INTRODUCTION

The use of multi-pole electrical installations in geoelectric control systems allows for effective geodynamic monitoring of the environment in the presence of industrial and climatic interference as well as in complex buildings typical for most industrial facilities (Thunehed *et al*., 2007). The method of isolating geodynamic variations of the medium presupposes the registration and analysis of a two-component electric field created by a multipolar source of probing signals with a fixed position of sources and a measuring base. The object is monitored by controlling the parameters of the probing signals while recording the phase characteristics of the field and compensating for the current trend of geoelectrical signals at the observation points (Kuzichkin and Tsaplev, 2006.).

The application of this method showed its high sensitivity to weak geodynamic changes in the media under investigation and to external destabilizing factors, such as natural and technogenic geodeformation effects (Romanov and Kuzichkin, 2015). It should be noted that for registration of geodynamic control data, high-precision differential measuring transducers and a geoelectric signal recording device using synchronous phase detectors are required. However, the reverse side of high sensitivity when using them is low noise immunity from the influence of multiplicative interference. It is caused by the instability of the power supply voltage of the converter as well as the influence on the transmission coefficients of the branches of the measuring transducer of external disturbing factors (temperature, humidity, etc.) (Dorofeev and Kuzichkin, 2015).

When organizing the geodynamic control of karst processes, these noise-producing factors are conditions that significantly complicate the monitoring work given the long-term nature of the measurements. However, the use of the phase method for recording geoelectric signals in multi-pole electrical installations is justified because of the possibility of revealing the initial stage of changes in the geological environment (Tsaplev and Kuzichkin, 2007). Therefore, the need to adapt the phase method to the conditions of strong multiplicative interference in the organization of geodynamic control of karst processes is an urgent task. This implies both the creation of specialized phase-metric systems and the development of specialized algorithmic support adapted to the tasks of geodynamic control of karst processes.

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The purpose of this study is to analyze the influence of multiplicative natural disturbances on the results of geodynamic control as well as a description of the application of the phase-metric method of geodynamic control in monitoring karst processes.

MATERIALS AND METHODS

The phase metric method of recording geoelectric data of geodynamic control: The phase-metric method for recording geoelectrical data is used to track the geodynamics of near-surface inhomogeneities in cases where it is necessary to provide increased sensitivity to special changes in the object of investigation. High efficiency is achieved by increasing the sensitivity of the measuring system initial installation and operational positioning by controlling the sources of sounding signals (Kuzichkin, 2007; Sharapov and Kuzichkin, 2013). By Leonov *et al.* (2006), Kuzichkin and Dorofeev (2015), Kuzichkin *et al.* (2004), the applying of the phase-metric method of geoelectrical control is substantiated, consisting in the fact that several sources located near the object under investigation and the necessary 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 located along the line AB and at equal distances from the sources can be used (Fig. 1a).

The point sources A and B form the probing signals, shifted in phase by π/2 relative to each other. It should be noted that for a different arrangement of the sources relative to the sensor as well as for multi-pole sounding, the phase shifts between the test signals may be different. Each of the point sources generates at the point O the signal of the electric field of the following form:

$$\begin{aligned} \vec{E}_{Ax} &= \vec{E}^0_{Ax} + \Delta\bar{E}_{Ax} = \vec{E}_{Ay} = \Delta\bar{E}_{Ax} \\ \vec{E}_{Bx} &= \vec{E}^0_{Bx} + \Delta\bar{E}_{Bx} = \vec{E}_{By} = \bar{E}_{Bx} \end{aligned} \quad (1)$$

Where:

$\bar{E}^0$ = The normal signal in the absence of inhomogeneity

$\Delta\bar{E}$ = An anomalous component of the electric field, caused by the presence and geodynamics of the inhomogeneity

As a result of the principle of superposition of source fields I_A and I_B, the resulting normalized signal at point O in accordance with Fig. 1b has the form:

$$\begin{aligned} H_x &= E_x/I_0 = (E^0_{Ax}/I_0 + \Delta E_{Ax}/I_0)\sin\omega t + \\ &(E^0_{Bx}/I_0 + \Delta E_{Bx}/I_0)\cos\omega t \\ H_y &= E_y/I_0 = \Delta E_{Ay}\sin\omega t/I_0 + \Delta E_{Bx}\cos\omega t/I_0 \end{aligned} \quad (2)$$

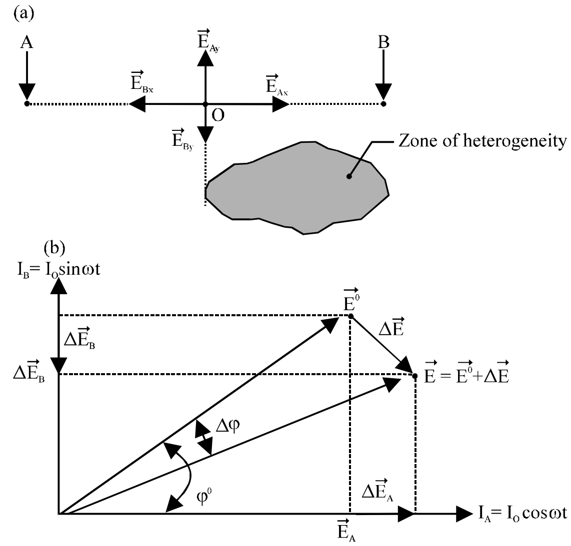

Fig. 1: a, b) Phase-metric method of geodynamic control

A distinctive feature of this method is the information parameter being recorded is not the amplitude but the phase φ of the resulting signal, determined in accordance with the following relations:

$$\varphi_x = \text{arctg}\left(\frac{E^0_{Ax} + \Delta E_{Ax}}{E^0_{Bx} + \Delta E_{Bx}}\right), \varphi_y = \text{arctg}\left(\frac{\Delta E_{Ay}}{\Delta E_{By}}\right) \quad (3)$$

The geodynamic variations of the investigated object are determined by the displacement of fictitious sources which leads to imbalance of the measuring system. The offset signal of fictitious sources after preliminary processing can be represented by the additive-multiplicative class model (Eq. 4):

$$\begin{aligned} E_x(t) &= \Delta E_x(t,T)(1+\xi_x(t)) + E^0_x(t) \\ E_y(t) &= \Delta E_y(t,T)(1+\xi_y(t)) + E^0_y(t) \end{aligned} \quad (4)$$

Where:

ΔE_x (t, T) and ΔE_Y (t, T) = The signals of fictitious sources offset taking into account the temperature dependence of the contrast ratio

E_x^0 (t) = E_y^0 (t) = The trend of the bias signal are the multiplicative interference characterizing the effect of planetary and climatic factors

T = The generalized temperature

Elimination of multiplicative noise in phase-metric systems of geoelectric control: The applied phase-metric method of recording geoelectrical signals allows to eliminate the multiplicative interference and to increase the accuracy of geoelectrical control due to the phase principle of the formation of probing signals. The research of the phase-measurement systems of geoelectric control (Fig. 1) is based on the direct transformation of the useful signal into the harmonic oscillation phase (Leonov *et al*., 2012).

In the case of using a bipolar electrical installation and the phase method of equipotential registration of geodynamic variations and taking into account multiplicative interference, Eq. 2 take the form:

$$\begin{aligned} H_x &= (E^0_{Ax}/I_0 + \Delta E_{Ax}(1+\xi_x)/I_0)\sin\omega t + \\ &(E^0_{Bx}/I_0 + \Delta E_{Bx}(1+\xi_x)/I_0)\cos\omega t\, 0 \\ H_y &= (1+\xi_y)(\Delta E_{Ay}\sin\omega t/I_0 + \Delta E_{Bx}\cos\omega t/I_0) \end{aligned} \quad (5)$$

In this case, the senstivity of the recorded phase signals to the multiplicative interference can be determined from the relationships:

$$\begin{aligned} &\frac{\Delta\varphi_y}{\Delta\xi_y} = 0 \\ &\frac{\Delta\varphi_x}{\Delta\xi_x} = \max\left\{\frac{\Delta E_{Ax}}{E^0_{Ax}}, \frac{\Delta E_{Bx}}{E^0_{Bx}}\right\}, E^0 \neq 0. \end{aligned} \quad (6)$$

As can be seen from the Eq. 6, the multiplicatie noise does not effect the detected phase φ_y and in the phase φ_x the multiplicative noise is weakned by n-times:

$$n = \min\left\{\frac{E^0{}_{Ax}}{\Delta E_{AX}}, \frac{E^0{}_{Ay}}{\Delta E_{Ay}}\right\}, \Delta E \neq 0 \quad (7)$$

To estimate the attenuation of the multiplicative noise, the well-known solution about the field of a point electrode in the presence of a karst-suffosive cavity is used Eq. 8 and 9:

$$\begin{aligned} &\dot{U}(r,\theta) = \frac{\dot{I}\rho_1}{4\pi d}\sum_{n=0}^{\infty}\left(\frac{R}{d}\right)^n P_n(\cos\theta) + \sum_{n=0}^{\infty} A_n R^n P_n(\cos\theta) \\ &A_n = \frac{\dot{I}\rho_1}{4\pi}\frac{(\rho_2-\rho_1)n}{(\rho_1 n + \rho_2(n+1))d^{n+1}} \end{aligned} \quad (8)$$

Where:

$P_n(\cos\theta)$ = The Legendre polynomial
R = The radius of the cavity
d = The distance from the sounding point to the center of the inhomogeneity
θ = The angle between the direction from the center of the heterogeneity to the point of phase control; the coefficient

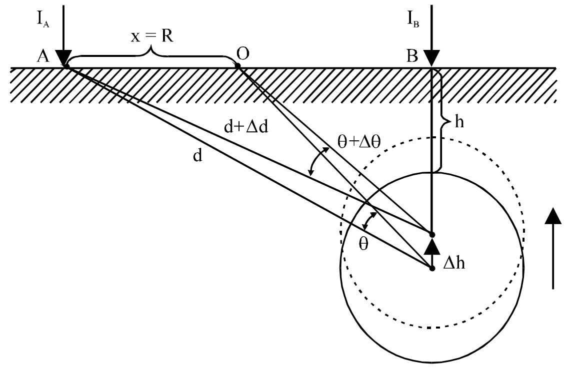

Fig. 2: The calculation model of karst-suffosion process

A_n = Determined by the boundary conditions and spatial parameters of the near-surface inhomogeneity

The theoretical estimation of the dependence of attenuation of multiplicative interference will be carried out on the basis of the model of geodynamic control of the karst suffusion cavity using a two-pole phase-metric electrical installation with a base L = 2R equal to twice the radius of the cavity displaced in relation Δx = R to the center of the electrical installation for different depths of the upper arch of the cavity h (Fig. 2).

In accordance with the accepted assumptions, provided that the geodynamic changes in the cavity Δh are small, we can write:

$$\Delta d \approx \frac{h}{\sqrt{4R^2+(R+h)^2}}\Delta h, \Delta\theta \approx 0 \quad (9)$$

Based on the Eq. 8 for the registered geoelectrical signals in the additive-multiplicative form Eq. 4, the equation for the phase sensitivity will take the following form:

$$\frac{\Delta\varphi_x}{\Delta\xi_x}(h,R,\Delta h) = \frac{\Delta E_{Ax}}{E^0_{Ax}} = \frac{h\sum_{n=0}^{\infty}\frac{P_n(\cos\theta)R^n(2n+1)}{d^{n+2}}\Delta h}{\sqrt{(4R^2+(R+h)^2}\sum_{n=0}^{\infty}\frac{P_n(\cos\theta)R^n(2n+1)}{d^{n+1}(n+1)}} \quad (10)$$

Figure 3 shows the theoretical dependences of the magnitude of attenuation of multiplicative interference as a function of the relative change in the roofing of the cavity Δh/h at different values of the spatial parameter of the placement of the measuring installation R/h performed using the MATLAB Software package.

As can be seen from Fig. 3, the use of the phase-metric method made, it possible to significantly reduce the influence of multiplicative noise on the results of geodynamic measurements. However, the presence of a karst cavity has a negative effect on the

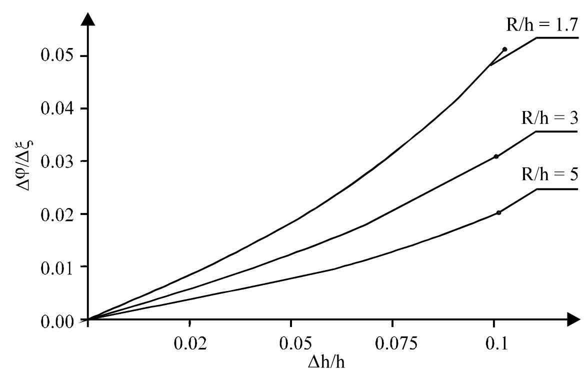

Fig. 3: The theoretical dependence of the attenuation of multiplicative interference

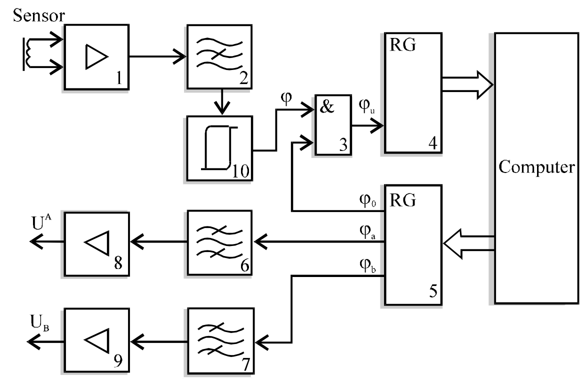

Fig. 4: The block diagram of the device for recording the geodynamics of karst processes by the phase-metric method

noise immunity of geoelectric measurements which should be taken into account when conducting of the longer karst observations.

RESULTS AND DISCUSSION

For experimental work with full-scale modeling of geodynamic control of the karst suffusion cavity using a two-pole phase-meter electrical installation, a device for recording the geodynamics of near-surface inhomogeneities was developed, shows in Fig. 4. In this device, a signal proportional to the detected electric field from the Sensor S through the built-in amplifier 1 goes to the notch filter 2, suppressing interference of the industrial frequency. The comparator 10 serves to form a rectangular signal with a measured phase φ. On the "AND" element, a phase detector circuit is constructed that generates a signal proportional to the phase shift φ_u introduced through the register 4 in the computer. The generator part of the device consists of two identical parts U_A and U_B including amplifiers 8 and 9 as well as bandpass filters 6 and 7, tuned to the fundamental harmonic of the electric field test signal. Register 5 serves to output the reference clock sequences φ_0, φ_a and φ_b generated by the computer.

This device allows to provide the maximum possible gain of the measurement path when registering the 0o.bject's geodynamics $K_u = 10^5 K_{AMP}$ (where K_{AMP} is the amplification factor of the amplifier built into the sensor) due to the direct conversion of information into the duration of the signal (Kuzichkin, 2006) (Fig. 4).

The object of the study was a karst lake of the Nizhny Novgorod Region. The choice of this object for research of the possibility of applying the phase-metric method for geodynamic control of karst phenomena was due to the fact that the lake and its environs are characterized by intensive development of karst and suffosion processes (Waltham *et al*., 2005). The electric field sensors were located at a distance of 12 m from the coastal line of the lake and the equipment for recording and controlling the electrical installation at a distance of 30 m from the location of the sensors when the supply electrodes are spaced 120 m apart (Fig. 5). During the

(a)

(b)

Fig. 5: Experimental work on the karst lake of the Nizhny Novgorod Region

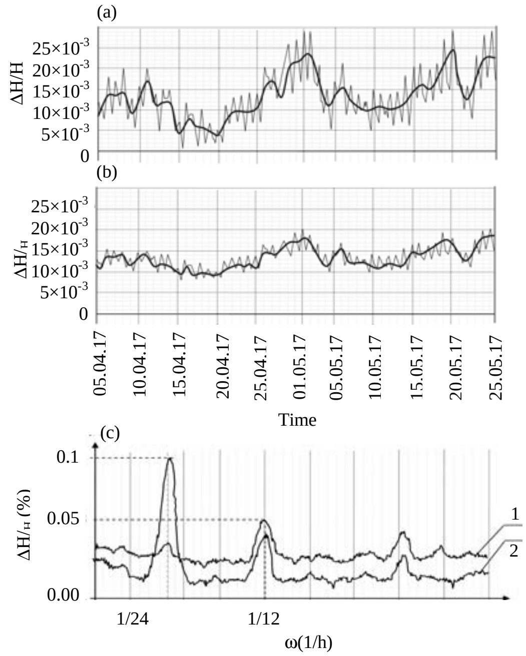

Fig. 6: Results of expermental studies

experiment, the registration of geodynamic variations was carried out by the phase-metric method and simultaneously to obtain comparative data, the already known equipotential method of geodynamic control (Bykov *et al.*, 2015) was applied with the direction of registration along the normal to the shoreline of the lake. 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 in the period between 5.04.2017 and 25.05.2017.

Figure 6 shows the results of experimental studies using the phase-metric method of geodynamic control (Fig. 6a) and by using an equipotential control method with the use a single compensation source (Fig. 6b). Figure 6c shows the spectra of recorded geoelectric signals.

As can be seen from the presented graphs, when using the phase-metric method of geodynamic control, there is a compensatory suppression of multiplicative interference over the entire frequency range (curve 1) with respect to the equipotential method (curve 2). Moreover, the attenuation at the main frequency of climatic interference $\omega = 1/24\ h^{-1}$ is $\delta = 38$ DB.

CONCLUSION

A distinctive feature of the application of the phase-metric geoelectric monitoring method considered in this study is the use of the phase φ of the resulting signal as an informative parameter which makes it possible to ensure the metrological stability of geodynamic measurements.

The multiplicative interference does not affect the detected phase φ_y and in the phase φ_x the multiplicative noise is attenuated a factor by n-times. The theoretical dependences of the magnitude of attenuation of multiplicative noise as a function of the relative change in the roofing of the karst cavity $\Delta h/h$ at different values of the spatial parameter of the placement of the measuring installation R/h are confirmed by the metrological possibilities of the phase-metric method.

To test the theoretical positions on the applicability of the method in karstological studies an original device for registering the geodynamics of near-surface inhomogeneities was developed using the phase-metric method for experimental work of geodynamic control of karst processes.

The results of experimental full-scale studies confirmed the advantage of the phase-metric method, characterized by compensatory suppression of multiplicative interference over the entire frequency range, compared with the equipotential method. So, in the course of experimental work, it has been established that when using the phase-metric method of geodynamic control, the interference at the fundamental frequency is $\omega = 1/24\ h^{-1}$ reduced by 38 dB.

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