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Modeling of the Geodynamic Event Detection in the Near-Surface Subsoil Area Based on the Phase-Measuring Geoelectric Control Method

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ABSTRACT

The near-surface subsoil area undergoes active changes as a result of antropogenic impact and natural factors. Effective use of geological environment necessitates control of the area, which is complicated by high noise level. The idea of phase-measuring geoelectric control method is based on tracking the phase changes of geoelectric signals and allows to detect low-level signals indistinguishable by well-known amplitude methods. Block diagram of the two-threshold phasometric control system of the geological environment was shown, as well as its operation principles and mathematic expressions. Matlab Simulink model of the geodynamic event detector circuit was developed. Dynamic mode simulation of the model was done, and the influence of the filter's parameters on the probability of successful geodynamic detection was estimated. The obtained results confirmed the effectiveness of the proposed approach.

Keywords: geodynamic control, geoelectrics, phasometric method, detector.

INTRODUCTION

The geological environment [1-4] is a fragment of the lithosphere and the underground hydrosphere, forming the upper part of the earth's crust, which is used in human economic activity. It is a multi-level system that develops under the influence of various factors and influences the development of living organisms, their living conditions and environment. At the same time, there are both direct and inverse connections of various ecosystems (biosphere, hydrosphere and atmosphere) and technosphere with objects of the geological environment in various manifestations.

The upper boundary of the geological environment is considered to be the Earth's surface, and the lower one is determined by the depth of man-made penetration into the lithosphere (as a rule, up to 1-1.5 km in mining areas, up to 3-5 km in oil and gas production areas and up to 1.5 km below the seabed level when drilling wells in the oceans). At the same time, it is traditionally accepted to allocate a special near-surface part of the geological environment (the "upper part of the section") with a capacity of tens (less often hundreds) meters, corresponding to the zone of its most active transformation under the influence of various types of technical activity (technogenesis) and having a significant impact on ground and underground structures, agro-industrial and other conditions of human economic activity.

The most important characteristic of the geological environment is its stress–strain state. All parts of the environment are under natural stress of various magnitudes, resisting the acting deforming force. When a certain critical value of stresses exceeding the limiting resistance of the geological environment is reached, a sharp change in its structure and properties can occur – deformations occur, manifested in the form of certain dynamic geological processes that can cause adverse, dangerous and even catastrophic consequences. The concepts of its stability and stability are associated with the stress–strain state of the geological environment [2]. The first term refers to the ability of the environment to actively maintain its structure and in space and time under dynamically changing conditions, the second term refers to the performance under constant external conditions.

The loss of stability and stability of the geological environment inextricably leads to a number of environmental problems. In general, the violation of the ecological functions of the geological environment is understood as its negative change, which has a direct or indirect impact on the comfort of human existence, flora and fauna. The reason for this is the numerous complex interrelations of the geological environment with the outer layers of the Earth (atmosphere, hydrosphere and biosphere), as well as with human economic activity – technogenesis.

Dynamic processes manifested as a result of deformations of the geological environment are usually divided into endogenous (occurring inside the Earth) and exogenous (representing the interaction of the Earth's crust with the outer shells of the planet). At the same time, it is known that the manifestations of the second group of these processes are most characteristic of the geological environment. In this regard, from the point of view of geoecology, exogenous dynamic geological processes are of the greatest interest, and the subject of geoecological research are those whose manifestations fall into the category of catastrophic and pose an immediate threat to the existence of living organisms (they are dangerous to humans, flora and fauna).

Thus, it is obvious that effective and environmentally safe human use of the geological environment in economic activity in modern conditions is possible only if there is a complete picture of the processes occurring on the surface and in the bowels of the Earth, as well as an understanding of the causes of their occurrence and key features.

PHASOMETRIC GEOELECTRIC METHOD OF MONITORING THE GEOLOGICAL ENVIRONMENT

Obtaining reliable and complete information about the state of the geological environment is complicated by a number of factors of various nature.

Firstly, the geological environment, as part of the lithosphere, is characterized by non-linearity and variability of parameters over time depends on physical and chemical properties, geometric parameters of the solid phase and fluids, as well as on variations of natural and man-made physical fields. This is manifested, for example, in its strain sensitivity (the dependence of elastic parameters of rocks on pressure) and fluid sensitivity (the dependence of elastic parameters of rocks on the composition, displacements and characteristics of the contained fluids (water, oil, gas)), deterministic and random changes in the parameters of natural and artificial physical fields of the Earth and their accompanying processes with variations in cosmic fields in time.

Secondly, unlike the atmosphere, where any disturbances are rather short-term with a rapid restoration of the background state, the geological environment is characterized by a high inertia of the disturbing factor, critical and supercritical states are formed in it, which affect the environment for long periods of time.

Thirdly, the geological environment is characterized by both slow and fast dynamic processes. Fourth, it should be borne in mind that any natural and man-made disturbances in the geological environment trigger chains of processes that can develop over time with increasing intensity. At the same time, it is known that the upper near-surface part of the geological environment is characterized by extreme manifestations of both natural (sharp geological, petrophysical and physical heterogeneity in space and time) and man-made (maximum manifestation of all kinds of artificial physical fields) processes.

In this regard, at the moment there is a group of methods of geodynamic control [5-10] of the geological environment based on various physical principles. One of the most promising of them is phasometry [11-13], which belongs to the class of geoelectric methods and has increased sensitivity to small geodynamic events (compared to traditional amplitude methods) and the ability to solve monitoring tasks in the presence of regular interference effects, changes in climatic factors and variations in the parameters of a specific geoelectric installation. The idea of this method is based on tracking the dynamics of phase changes of recorded geoelectric signals relative to the phase of a reference highly stable oscillation. At the same time, several radiating point sources located in a controlled area are used to form a geoelectric field of a given configuration and with specified parameters, and the required number of pairs of point

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meters are used for reception. Point sources form probing signals shifted in phase by a given angle relative to each other, and geodynamic variations of the geological environment are determined by the displacement of fictitious sources, which lead to an imbalance of the measuring system and registration of the corresponding signal vector in it.

In general, the principle of phasometric control of the geological environment can be represented by a structural diagram shown in Figure 1, where the following designations are adopted: PCD – a phase comparison device, ICD – an information component detector, PDD – a phase detection device.

Figure 1. Generalized block diagram of the phasometric control system of the geological environment

GEODYNAMIC EVENT DETECTOR BASED ON THE PHASOMETRIC GEOELECTRIC CONTROL METHOD

As a result of processing by the geoelectric control system based on the phase–measuring method of the recorded signals from the receiving pairs of point meters, a phase image of dynamic processes in the geological environment is formed, defined as

$$s_{phase}(t) = \varphi_{trend} + \Delta\varphi_{dynam}(t),$$

where φ_{trend} is the trend component of the phase image, $\Delta\varphi_{dynam}(t)$ is the dynamic component of the phase image.

The task of detecting geodynamic events based on the phase-measuring method of geoelectric control is to register deviations of the dynamic component of the phase image relative to the zero phase (obtained after preliminary compensation of the trend component) by a given value and it can be considered as a special case of the classical problem of detecting a deterministic signal based on a correlation receiver. Using the basic principles of this method, a block diagram of the dynamic event detector in the upper part of the geological environment section has been developed – Figure 2. The following designations are adopted on the block diagram: DAmp – differential amplifier, VGA – variable gain amplifier, SubD – subtracting device, PD – phase detector, LPF - low-pass filter, Amp – amplifier, CD – conversion device, HPF - high-pass filter, RG – reference generator, TD - threshold device.

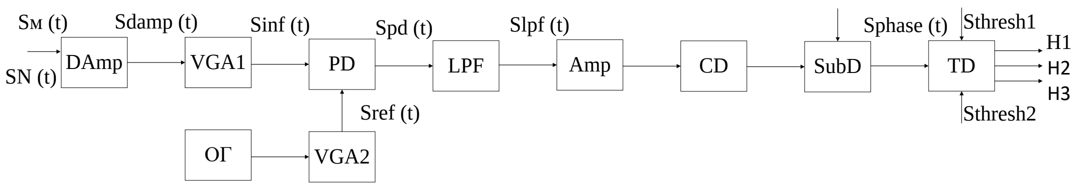

Figure 2. Block diagram of a dynamic event detector in the upper part of a section of the geological environment based on the phasometric geoelectric control method

The threshold device of this detector has three alternative hypotheses (Figure 3):

– hypothesis *H1* about the presence of geodynamic events and a change in the trend component of the phase image "up", which corresponds to the upper detection threshold G_1;

– hypothesis *H3* about the presence of geodynamic events and a change in the trend component of the phase image "down", which corresponds to the lower detection threshold $G_2 = -G_1$;

– hypothesis *H2* about the absence of geodynamic events, which corresponds to the range between the detection thresholds $G_2 < G < G_1$.

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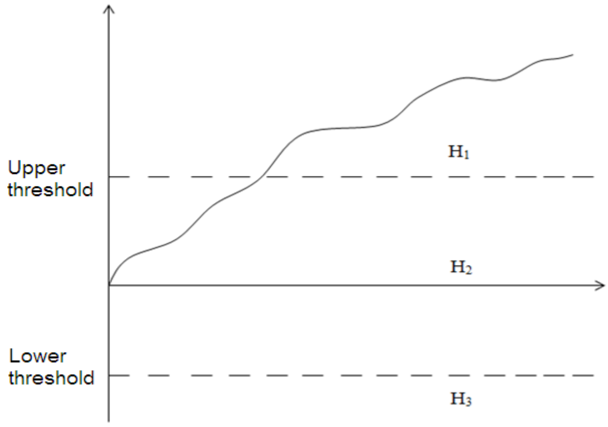

Figure 3. Limits of detection thresholds

Based on the block diagram, the upper detection threshold, depending on the type of oscillation used during detection, is calculated as

$$G_1 = \arccos[GK_{conv}]\frac{180}{\pi} - \varphi_{trend} \text{ or } G_1 = \arcsin[GK_{conv}]\frac{180}{\pi} - \varphi_{trend},$$

where K_{conv}– conversion coefficient, depending on the characteristics of the phase detector; G – detection threshold of the standard correlation receiver, defined as

$$G = \frac{Э}{2} + \frac{N_0}{2}\ln(\Lambda_0),$$

where $Э = \int_0^T s^2\,(t)\,dt$ is the energy of the useful signal, $N_0 = \frac{\sigma^2}{B}$ is quasi–white noise with dispersion σ^2 and a Gaussian probability distribution density having a uniform two-sided energy spectrum of width B, Λ_0 is a threshold likelihood ratio chosen in accordance with one or another criterion (Bayesian likelihood ratio, a posteriori probability maximum, and others). In particular, it was found that the distribution density of these signals over a long observation interval can be considered quasi–normal - Figure 3.

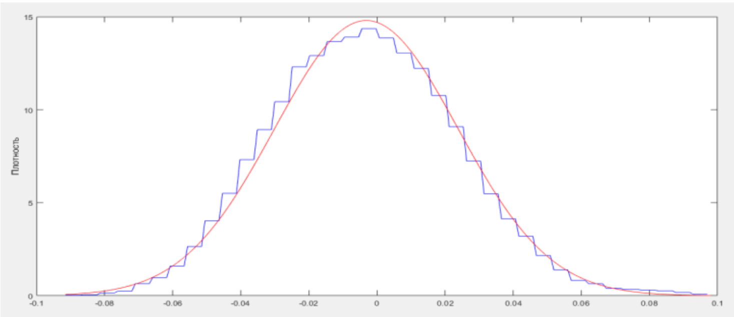

Figure 3. Theoretical (red) and experimental (blue) probability distribution density of phase images, expressed as a percentage

Based on this, when calculating detection thresholds, it is possible to focus on the value of the dispersion σ_φ^2 or the RMS value σ_φ of phase images. Then

$$G_1 = k\sqrt{\sigma^2} = k\sigma,$$

where k is a weighting factor depending on the conditions of geodynamic monitoring of the geological environment and the events expected in it.

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SIMULATION OF THE GEODYNAMIC EVENT DETECTOR OPERATION BASED ON THE PHASE-MEASURING GEOELECTRIC CONTROL METHOD

Based on the block diagram of the geodynamic event detector in the upper part of the section of the geological environment, a corresponding functional model has been developed, implemented in the Matlab Simulink environment – Figure 4.

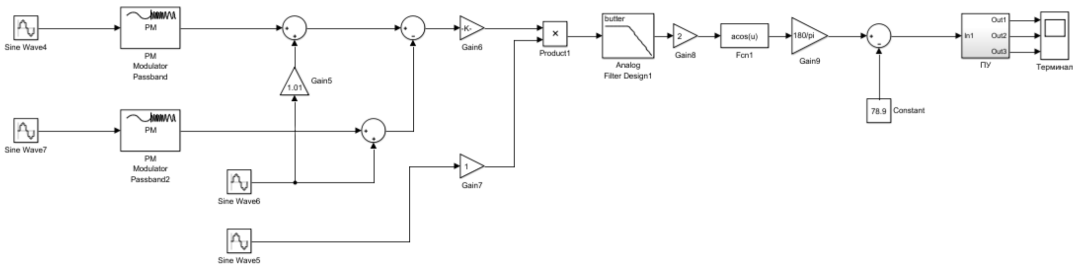

Figure 4. Matlab Simulink model of the geodynamic event detector circuit in the upper part of the geological environment section

Based on this model, a step-by-step study of the detector's operation in the time domain was carried out. So in Figure 5, an orange color shows a useful signal simulating a dynamic event in the geological environment, and blue is the result of its selection by the system taking into account the transient process. The results of the threshold device operation within several useful signal periods are shown in Figure 6.

Here, the blue color corresponds to the operation of the device "above" the upper detection threshold, orange in the range between the thresholds and turquoise – "below" the lower detection threshold.

The following simulation parameters were used for both figures:

- input signal model: additive signal-noise mixture;

- type of useful components of input signals: phase-modulated oscillations;

- type of interference components of input signals: harmonic oscillations;

- phase shift between the useful components of the input signals: 40 degrees;

- phase shift between the interference components of the input signals: 0 degrees;

- amplitudes of useful and interfering components of the input signal: 1 V;

- frequencies of useful components of the input signal: 170 Hz;

- frequencies of the interference components of the input signal: 50 Hz.

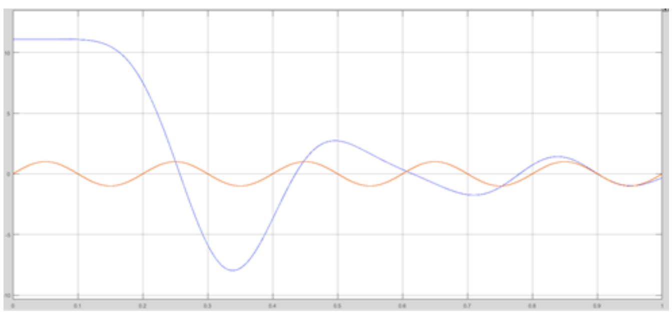

Figure 5. A useful signal simulating a dynamic event in a geological environment and the result of its isolation

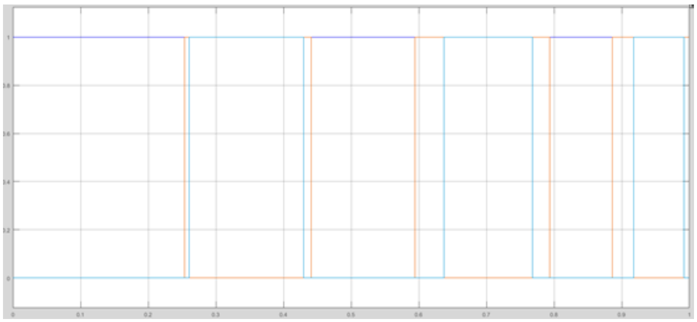

Figure 6. The result of the threshold device operation (blue color – "above" the upper detection threshold, orange – between the thresholds, and turquoise – "below" the lower threshold)

CONCLUSION

Comparison of the initial signal simulating a dynamic event in the geological environment and the result of its isolation from the noisy input phase-modulated signals of the geodynamic control system based on the phasometric method allows us to conclude that the received signal at the end of the transition process is almost completely identical with the initial one in phase and amplitude. The differences that arise in this case are associated with errors in the normalization of the input signals of the phase detector and the inconsistency of the analog filter allocated to the frequency spectrum band of the useful signal.

From the obtained graphical dependence of the results of the threshold device operation, it can be seen that at each moment of time one of the values of its output signal takes a single value, and the rest are zero. This result can be used to further determine the type of geodynamic event and its localization in space.

In addition, the detector operation was simulated when the cutoff frequency and the order of the analog low-pass filter were changed. It is established that an increase in the filter order leads to a significant decrease in the undesirable high-frequency component, but is accompanied by an increase in the duration of the transient process; and with an increase in the filter cutoff frequency, the level of the phase signal increases and its distortions appear associated with the penetration of high-frequency components into the filter bandwidth.

The obtained dependences and conclusions based on them confirm the effectiveness of the approach proposed in the work and can be used in the further practical implementation of the geodynamic event detector based on the phasometric method of monitoring the geological environment.

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