Monitoring the Ore Massif State in Deep Rock Shock Mines

Olga Hachay [#1], Andrey Khachay [*2], Oleg Khachay [#3]

[#1]Institute of geophysics Ural Branch of Russian Academy of sciences, Amundsen str.100, Yekaterinburg,620016, Russia

[#2,3]Ural Federal University, Mira str.19, Yekaterinburg, 620002,Russia

Abstract

The process of mining a rock-shock array can be managed by following the recommendations of the theory of catastrophes. For this process, as the control parameters are the energy values during explosions and the location of these explosions relative to the array area being worked on. Kinematic and dynamic parameters of deformational waves and structural features of the array through which these waves pass, act as internal parameters. Combined use of qualitative recommendations of the theory of catastrophes and spatial-temporal data of changes in the internal parameters of the array will help forecast catastrophes in the mine. To correctly account for changes in internal parameters of the array, we used a new model of the array structure: a continuous medium including discrete system of blocks with hierarchical inclusions. In this work, iterative algorithms for 2-D modelling for diffraction sound and linear polarized transversal elastic waves on these inclusions are constructed.

Keywords — *mining rock shock array, recommends of theory of catastrophes, kinematic and dynamic parameters of deformational waves, structural features of the array, new hierarchical model of the array, internal parameters, algorithms of modelling.*

I. INTRODUCTION

To continue geo informational studies, a developed algorithm for processing seismological information of a detailed mine catalogue was used [1], which allows to extract additional important information for predicting hazardous phenomena in deep ore mines. [2]. In addition, attention was focused on the process of preparing a resonant emission of energy, including not only the direct effect of explosions, but also the sequential influence of weak energy responses, which in turn manifest themselves in the form of shocks, contributing to the preparation of a resonant emission. The informative features of the preparation of high-energy dynamic phenomena are used: the delay time of the response to anthropogenic influences and the volume of formation of the focus of rock bursts in the form of gradations of distances from the intended focus. The obtained complex information from seismological catalogue data is important for the prediction of hazardous phenomena in ore mines. A comparison is made of the theoretical results of the causes of the randomization of nonlinear dissipative dynamic systems and the results of the phase diagrams processing of detailed mine seismic catalogue data - seismic responses to the explosive effects of a shock-resistant rock massif. It follows from the theory that the common cause of the chaos and stochastization of the movements of a dynamic system is their loss of stability and the exponential divergence of close phase trajectories, combined with their general limitation and some of their common contraction. This result coincides with the obtained analysis of phase diagrams constructed from the seismic mine catalogue data. Changes in time types of correlation dependences by the function of the absorbed energy and the energy emitted by the array are considered in detail. The conditions for the application of the Bogolyubov's algorithm to analyse the accumulation and discharge of stored energy from explosive effects on the array had been considered. At present, the following is very significant: the interaction between physics and mathematics, the influence of the needs of physics on the development of mathematical methods and the reverse influence of mathematics on physical knowledge are becoming more and more pronounced. In a number of issues of physics and technology, a number of problems arose for which the apparatus of linear mathematics turned out to be either insufficient or even completely inapplicable [3, 4]. For a comprehensive coverage of various phenomena in acoustics and mechanics, the mathematical apparatus of linear differential equations is absolutely insufficient. It is precisely those phenomena that are most characteristic and interesting that do not fit within its framework. The fact is that the differential equations that adequately describe these phenomena are non-linear. Accordingly, we are talking about "nonlinear" systems. The foundations of a mathematical apparatus that is adequate not only to individual tasks, but also to the whole cycle of nonlinear problems, are laid down in the famous works of Poincare and Lyapunov [5, 6]. This paper is also devoted to the study of the approaches of the mathematical theory of catastrophes use for the analysis of seismological mine catalogue data, reflecting the degree of stability and its loss by the mountain massif with active influence on it.

II. REVIEW OF CATASTROPHE THEORY METHODS FOR STUDYING LOSS STABILITY OF NONLIBEAR DYNAMICS

Major advances in applied mechanics are often the result of the application of new mathematical ideas and methods. It is possible to hope that the applied mathematical theory-theory of catastrophes, which is actively developing in recent years, in combination with modern methods of system analysis will become a useful and effective means of qualitative analysis of various real processes [7].

The first information about the theory of catastrophes appeared in the press around 1979, where it was testified that this theory provides a universal method for studying all jump transitions, discontinuities and sudden qualitative changes [3]. Following V.I. Arnold [8], the sources of the theory of catastrophes are the theory of singularities of the Whitney smooth maps and the theory of bifurcations of the dynamic systems of Poincare and Andronov. The concept of "bifurcation" means a split and is used to denote the qualitative rearrangements of various objects when the parameters on which they depend change.

Disasters are called catastrophes, occurring as a sudden system response to a smooth change in external conditions. An evolutionary process that reflects the response of a system to an applied action is mathematically described by a vector field in the phase space [9]. The phase space point specifies the state of the system, and the vector attached at this point indicates the rate of the state change. At the points where the vector vanishes, they are called equilibrium positions. Over time, oscillations can be established in the system, and the equilibrium state becomes unstable. The evolutionary process is mathematically described by a vector field in the phase space, and the point of the phase space specifies the state of the system, and the vector attached at this point indicates the rate of state change. On the phase plane, steady-state oscillations are represented by a closed curve, called the limit cycle. In the paper [8], the study of the evolution of a dynamical system is associated with the time variation of the internal and control parameters. The scheme of most applications of the theory of catastrophes is as follows: it is assumed that the process under study is described with the help of a certain number of controllers and internal parameters. The equilibrium states of a process form the surface of one or another number of dimensions in this space. The projection of the equilibrium surface onto the plane of control parameters may have features. These features are called general features, and the theory associated with these features predicts the geometry of "catastrophes," that is, hops from one state to another when the control parameters change. One of the most famous features is the Whitney assembly. In this regard, after the loss of equilibrium stability, two types of steady-state regimes can be observed. One of them is oscillatory periodic mode. This kind of loss of stability is called soft loss of stability, since the established oscillatory mode at low super criticality differs little from the state of equilibrium. The second type is associated with the following features: before the steady state loses stability, the region of attraction of this mode becomes very small, and random perturbations eject the system from this region before the region of attraction completely disappears. This kind of buckling is called hard buckling, and the system leaves the stationary mode abruptly and switches to another driving mode. This mode may be another stable stationary mode, or stable oscillations, or more complex motion. Established modes of motion are called attractors. Those of them, which differ from equilibrium states and strictly periodic oscillations, are called strange attractors and are associated with the problem of turbulence [4].

The subject of catastrophe theory is the study of the dependence of the qualitative nature of the solutions of equations on the values of parameters present in the described equations [7]. In order to clarify what specifically studies the theory of catastrophes, we can consider the solution $\psi_1(t,x;c_\alpha),\psi_2(t,x;c_\alpha),....$ of a system of n equations defined in the space $\Re^N$ with coordinates $x=(x_1,x_2,...,x_N)$,

$$F_i(\psi_j;c_\alpha;t,\frac{d\psi_j}{dt},\frac{d^2\psi_j}{dt^2},...;x_l;\frac{\partial\psi_j}{\partial x_l},\frac{\partial^2\psi_j}{\partial x_l\partial x_m},...;\int dx_l,...)=0;$$
$$1\le i\le N;1\le l;1\le m;1\le\alpha\le k \quad (1)$$

xl and t-spatial and temporal variables, solutions Fi- describe the state of some system, we will call them state variables, they depend on k parameters cα, which are called control parameters. The problem of studying the solutions of a system of equations, even if it is only a question of how these solutions depend on the control parameters, is very complex. However, it can be simplified by making a series of consistent assumptions.

1. Let the expression (1) does not contain integrals, i.e. the system (1) is a set of nonlinear partial differential equations.
2. Let the system of equations (1) does not contain spatial derivatives of any order.
3. Now suppose the system (1) is completely independent of spatial coordinates.
4. Suppose that the system (1) does not contain time derivatives above the first, then the simplified function will be:

$$F_i=\frac{d\psi_i}{dt}-f_i(\psi_j;c_\alpha;t)=0;1\le i\le N;1\le\alpha\le k \quad (2)$$

A system of this type is called a dynamical system, but it is also difficult to solve it.

5. To simplify the dynamical system, we will assume that f_i does not depend on time, then system (2) is transformed to an autonomous dynamic system and if $c_\alpha \le 4$, then there are several important statements.

6.If:

$$f_i = -\frac{\partial V(\psi_j;c_\alpha)}{\partial \psi_i},\ F_i = \frac{d\psi_i}{dt} + \frac{\partial V(\psi_j;c_\alpha)}{\partial \psi_i} = 0$$

such system is called a gradient system, against which many important theorems are proved. Of particular interest is the study of the equilibrium state of gradient dynamic systems, which is described by the following system of equations: $\frac{\partial V(\psi_j;c_\alpha)}{\partial \psi_i} = 0$.

Thus it can be said that the elementary theory of catastrophes is the science of how the equilibrium states of the potential function *V* change as the control parameters change.

III. ANALYSIS OF MINE SEISMOLOGICAL DATA OF ACTIVE MONITORING OF THE MINE AREA, BASED ON THE OF CATASTROPHES

The main purpose of this monitoring is to determine the precritical state of the mountain area under development by explosive effects [10]. It is determined by the magnitude of the response energy, not exceeding 10^4 joules. If this value exceeds this value within 10^5–10^7 joules, then the state of the array is considered critical. For response energies of 10^8–10^9 or more, the array state is considered supercritical or catastrophic. On November 25, 2007, a mining rock shock with an energy of 8.14 10^8 joule occurred in the Tashtagol mine at ort 29 and at a depth of 714 m, figure 1. We will try to follow up the preparation of this event in terms of the loss of stability of the array and the connection of this effect with the energy impact of the explosions and their location. The investigated volume is enclosed in the OX axis: 25–31 orts (≈240 m), in the OY axis: (the length of the orts between the field and ventilation drift is average ≈240 m), in the OZ axis: (horizons –140, –425, (≈ 590–875 m)).

Let us analyse the morphology of the temporary process of the energy responses of the array, using the results obtained.

The first interval: June 4, 2006 – 13 August 2006. The loss of stability of equilibrium manifests itself for four effects in the form of an oscillatory process, with the first explosion occurring within the investigated volume, however the impact energy is the smallest of the four analysed, therefore the maximum energy response is within the precritical.

The second interval: August 20, 2006 - September 17, 2006. The loss of stability of equilibrium for two effects manifests itself in the classical way. There is a response in the form of an almost constant distribution of energy over time, which turns into an oscillatory process, with the explosion energy on September 3 exceeding 10^8 J, and the explosion energy on September 17, 2006 — 10^6 J within the studied volume; however, the overall level of energy emitted by the responses has decreased and does not exceed 10^3 J.

The third interval: September 24, 2006 – 14 October 2006. On September 24, 2006, the response to an explosion within the studied volume has a different morphology; the oscillatory process is interleaved by an abrupt release, after which the system returns to an oscillatory process, the background level of which corresponds to a soft loss of stability. Subsequent responses to explosions outside the study area are of a low-amplitude vibration character in energy. On October 14, 2006, the morphology of the process for an explosion in the studied area has a classic character of soft loss of stability with attenuation of the oscillatory energy release process.

The fourth interval: October 21, 2006 – 12 November 2006. From October 21 to November 12, 2006, explosions occur in the studied area, however, the morphology of the soft loss of stability of the massif is more pronounced after the explosion on November 12. Almost immediately after the explosion, the oscillating process of energy release begins then a jump, then again a return to the oscillatory state and a jump again with amplitude higher than 10^4 J. The background level of energy fluctuations rises above 10^2 J.

The 5th interval: November 19, 2006 - December 17, 2006. On 19 November 2006 outside the area under investigation, an explosion occurs with energy of more than 10^9 J, while the array under study responds with two abrupt outbursts of energy with a value corresponding to the jumps on November 12. The subsequent explosion in the study area on November 26, 2006, causes an array response characteristic of a soft loss of stability against the energy background corresponding to the second interval. The next explosion on December 3, 2006, again causes a more excited response with fluctuations and jumps, similar to the above-considered response of the third interval.

The 6th interval: December 24, 2006 - 21 January 2007. On December 24, 2006, an explosion in the studied area (near the place of the future rock shock) with an energy of 10^8 J causes a sharp, but still critical, loss of stability of the array, two jumps with energy slightly less 10^5 J, three jumps with an energy of 10^4–10^3 J. The oscillatory process is more intense. The remaining explosions, which occur at a sufficient distance from the studied area from December 30, 2006 to January 14, 2007, continue to support the oscillatory process caused by the explosion on December 24, and the explosion on January 21 with energy less than 10^5 J, which also occurs at a long distance from the studied area, did not prevent the jump-like release of energy, reflecting the process of tightening the relaxation of the system.

The 7th interval: February 18, 2007 - April 1, 2007. The explosions from March 25 to April 8, 2007 occur outside the studied area mainly at a sufficiently large distance. Therefore, the array response is randomly non-oscillating in nature, and most of its energy does not exceed 10^4 J, except for the response to the explosion of April 8, 2007, when there was a jump in energy slightly more than 10^4 J.

The 8th interval: April 15, 2007–27 May, 2007. On May 6, 2007, an explosion occurred in the northern part of the massif, then on May 13, occurred simultaneously in the northern part and in the studied part of the massif (in the orts, where rock shock will be) explosions, the response of the array has an energy jump of 10^5 j.

The 9th and 10th intervals are: June 3, 2007–September 23, 2007. There is an interaction between the response of the studied array and the effect of explosions located mainly outside the area under study, and in the presence of an explosion inside it there were energy jumps up to 10^5 J (9th interval) without preliminary oscillatory process (as it was in the 9th interval).

The 11th interval: September 30, 2007– October 21, 2007. From September 30 to October 21, explosions occur exclusively in the studied area near the ort, where a catastrophic rock shock will occur. The morphology of the distribution of the energy of the responses is such that: there is a low-energy time dependence and a very short oscillatory process.

The 12th interval: October 28, 2007– November 25, 2007. The explosions from October 28 to November 10 do not bring the area of the array under study to the stage of the oscillatory process of energy release. With the repeated explosion in the block 27 on November 25, 2007, a complex dynamic catastrophic process took place. Three foreshocks, one aftershock, four precritical and one supercritical energy jump occur. All these manifestations were accompanied by a low-energy vibration process.

IV. DISCUSSION AND RESULTS

As results of the analysis we can draw the following conclusions. The mining process is a dynamic process, which can be managed by following recommendations provided by the theory of catastrophes. In this process, the energy values for explosions and the location of these explosions relative to the studied or developed area of the array are the control parameters. The internal parameters are the kinematic and dynamic parameters of deformation waves [2, 10-12], as well as the structural features of the array through which these waves pass [13-15]. The use of analysis methods for short-term and medium-term forecasts of the state of a mountain range only when using control parameters is not enough in the presence of a sharp heterogeneity. However, the joint use of qualitative recommendations of the theory of catastrophes and the spatial-temporal data of changes in the internal parameters of the array will help prevent catastrophes when mining shaft arrays. At present, theoretical results on modelling the electromagnetic and seismic field in a layered medium with inclusions of a hierarchical structure are in demand. Algorithms for modelling in the electromagnetic case are constructed for the 3D heterogeneity, in the seismic case for 2D heterogeneity [13, 16, 17]. It is shown that with an increase in the degree of hierarchy of the environment, the degree of spatial nonlinearity of the distribution of the components of the seismic and electromagnetic fields increases, which corresponds to the detailed monitoring experiments conducted in shock-rock mines of the Tashtagol mine and SUBR. The constructed theory demonstrates the degree of the complicated process of integration of methods using an electromagnetic and seismic field to study the response of a medium with hierarchical structure. This problem is closely linked with the formulation and solution of the inverse problem for the propagation of electromagnetic and seismic fields in such complex environments. In the works [18, 19] the problem of constructing an algorithm for solving the inverse problem using the equation of the theoretical inverse problem for the 2D Helmholtz equation is considered. Explicit equations of the theoretical inverse problem are written for cases of electromagnetic field scattering (E and H polarization) and scattering of a linearly polarized elastic wave in a layered conducting and elastic medium with a hierarchical conducting or elastic inclusion, which are the basis for determining the contours of non-coaxial inclusions of the l-th rank hierarchical structure. Obviously, when solving the inverse problem, it is necessary to use observation systems set up to study the hierarchical structure of the environment as the initial monitoring data. On the other hand, the more complex the environment, the each wave field introduces its information about its internal structure, therefore, the interpretation of the seismic and electromagnetic fields must be conducted separately, without mixing these databases. In this paper, we will study the question of the integration of different types of geophysical fields that are distributed in hierarchical structural environments.

V. SOUND DIFRACTION SIMULATION ON A TWO DIMENSIONAL ANOMALOUS DENSITY HIERARCHICAL HETEROGENEITY, LOCATED IN A N-LAYERED ELASTIC MEDIUM

In the paper [17], an algorithm for simulating the diffraction of sound on a two-dimensional elastic hierarchical inclusion located in the J-th layer of the N-layer medium is described. $G_{Sp,j}(M,M^0)$ - the source function of the seismic field, the boundary problem for which was formulated in [16]; $k_{1ji}^2 = \omega^2(\sigma_{ji}/\lambda_{ji})$ - wave number for the longitudinal wave; in the above expression, the index ji denotes the belonging of the properties of the medium inside the heterogeneity, ja - outside the heterogeneity; λ is the Lame constant; σ is the density of the medium; ω is the circular frequency; $\vec{u} = \text{grad}\,\varphi$ - displacement vector; φ^0 is the potential of a normal seismic field in a layered medium in the absence of heterogeneity: $\varphi^0_{ji} = \varphi^0_{ja}$. We assume that the elastic parameters of the hierarchical inclusion for all ranks l and the containing layer are the same, and the density of the hierarchical inclusion for all ranks differs from the density of the containing medium, then the system of equations [17] is rewritten in the form:

$$\frac{(k_{1ji}^2 - k_{1j}^2)}{2\pi} \iint\limits_{Scl} \varphi_l(M) G_{Sp,j}(M, M^0) d\tau_M + \frac{\sigma_{ja}}{\sigma_{ji}} \varphi^0_{l-1}(M^0) -$$

$$-\frac{(\sigma_{ja} - \sigma_{jil})}{\sigma_{jil} 2\pi} \oint\limits_{Cl} G_{Sp,j} \frac{\partial \varphi_l}{\partial n} dc = \varphi(M^0), M^0 \in S_{Cl},$$

$$\frac{\sigma_{jil}(k_{1jil}^2 - k_{1j}^2)}{\sigma(M^0) 2\pi} \iint\limits_{Scl} \varphi_l(M) G_{Sp,j}(M, M^0) d\tau_M + \varphi^0_{l-1}(M^0) -$$

$$-\frac{(\sigma_{ja} - \sigma_{jil})}{\sigma(M^0) 2\pi} \oint\limits_{Cl} G_{Sp,j} \frac{\partial \varphi_l}{\partial n} dc = \varphi_l(M^0), M^0 \notin S_{Cl}. \quad (3)$$

$G_{Sp,j}(M, M^0)$ - function of the source of the acoustic field, it coincides with the function [17]; $k_{1jil}^2 = \omega^2(\sigma_{jil}/(\lambda_{jil});\ \lambda_{jil} = \lambda_{ja}$ - the wave number for the longitudinal wave, in the above expression, the index ji means that the properties of the medium are inside the heterogeneity, ja is outside the heterogeneity; l = 1 ... L is the number of the hierarchical level; φ^0_l - potential of the normal acoustic field in a layered medium in the absence of heterogeneity of the previous rank, if l = 2 ... L, $\varphi^0_l = \varphi_{l-1}$, if l = 1 $\varphi^0_l = \varphi^0$, that coincides with the corresponding expression. If, on going to the next hierarchical level, the axis of two-dimensionality does not change, but only the geometry of sections of nested structures change, an iterative process of modelling an acoustic field can be described (the case of a longitudinal wave only). The iteration process refers to the modelling of the displacement vector during the transition from the previous hierarchical level to the next level. Within each hierarchical level, the integral-differential equation and the integral-differential representation are calculated using the algorithms (3). If at a certain hierarchical level the structure of a local heterogeneity splits into several heterogeneities, then the double and contour integrals in expressions (3) are taken over all heterogeneities. This algorithm considers the case when the physical properties of heterogeneities of the same level are the same, only the boundaries of the areas differ.

VI. MODELLING THE DIFFRACTION OF ELASTIC TRANSVERSAL WAVE ON ABNORMALLY DENSITY HIERARCHICAL HETEROGENEITY,LOCATED IN AN-LAYERED ELASTIC MEDIUM

Similarly to (3), the same process is written to simulate the propagation of an elastic transversal wave in an N-layer medium with a two-dimensional hierarchical structure inclusion of arbitrary section morphology using integral relations written in [17].

$$\frac{(k_{2jil}^2 - k_{2j}^2)}{2\pi} \iint\limits_{SCl} u_{xl}(M) G_{Ss,j}(M, M^0) d\tau_M + u^0_{x(l-1)}(M^0) = \quad (4)$$

$$= u_{xl}(M^0), M^0 \in S_{Cl},$$

$$\frac{\mu_{jil}(k_{2jil}^2 - k_{2j}^2)}{\mu(M^0) 2\pi} \iint\limits_{SCl} u_{xl}(M) G_{Ss,j}(M, M^0) d\tau_M + u^0_{x(l-1)}(M^0) =$$

$$= u_{xl}(M^0), M^0 \notin S_{Cl}$$

where $G_{Ss,j}(M, M^0)$ is the source function of the seismic field of the problem under consideration, it coincides with the Green function, written in [17] for the corresponding task; $k_{2jil}^2 = \omega^2(\sigma_{jil}/(\mu_{jil});\ \ \mu_{jil} = \mu_{ja}$ - wave number for the transversal wave; μ is the Lame constant; u_{xl} is the component of the displacement vector; l = 1 ... L is the number of the hierarchical level; u^0_{xl} - component of the displacement vector of the seismic field in a layered medium in the absence of heterogeneity of the previous rank, if l = 2 ... L $u^0_{xl} = u_{x(l-1)}$, if l = 1 $u^0_{xl} = u^0_x$, that coincides with the corresponding expression for the normal field in [17]. It should be noted that the structure of equations (1) coincides with the general case, when the hierarchical heterogeneity has not only dense parameters other than the parameters of the surrounding medium, but also elastic parameters at all ranks differ from the elastic parameters of the containing layer. The difference of this task lies only in the values of the wave number. Thus, the response of the medium associated with the transverse wave is more sensitive to the region of density heterogeneities in the array. This should be taken into account when assessing the state of a complex geological environment.

VII. SOUND DIFRACTION SIMULATION ON A TWO DIMENSIONAL ANOMALOUS STRESSED HIERARCHICAL HETEROGENEITY, LOCATED IN A N-LAYERED ELASTIC MEDIUM

In the paper [17], an algorithm for simulating the diffraction of sound on a two-dimensional elastic hierarchical inclusion located in the J-th layer of the N-layer medium is described. $G_{Sp,j}(M, M^0)$ - the source function of the seismic field, the boundary problem for which was formulated in [16]; $k_{1ji}^2 = \omega^2(\sigma_{ji}/\lambda_{ji})$ - wave number for the longitudinal wave; in the above expression, the index ji denotes the belonging of the properties of the medium inside the heterogeneity, ja - outside the heterogeneity; λ is the Lame constant; σ is the density of the medium; ω is the circular frequency; $\vec{u} = \mathrm{grad}\,\varphi$ - displacement vector; φ^0 is the potential of a normal seismic field in a layered medium in the absence of heterogeneity: $\varphi_{ji}^0 = \varphi_{ja}^0$. We assume that the density of the hierarchical inclusion for all ranks l and the containing layer is the same, and the elastic parameters of the hierarchical inclusion for all ranks differ from the elastic parameters of the containing medium, then the system of equations (5) will be rewritten as:

$$\frac{(k_{1jil}^2 - k_{1j}^2)}{2\pi} \iint_{SCl} \varphi_l(M) G_{Sp,j}(M, M^0) d\tau_M + \varphi_{l-1}^0(M^0) = \tag{5}$$

$$= \varphi_l(M^0), M^0 \in S_{Cl},$$

$$\frac{\sigma_{jil}(k_{1jil}^2 - k_{1j}^2)}{\sigma(M^0) 2\pi} \iint_{SCl} \varphi_l(M) G_{Sp,j}(M, M^0) d\tau_M + \varphi_{l-1}^0(M^0) ==$$

$$= \varphi_l(M^0), M^0 \notin S_{Cl}$$

Designations are the same as for the system of equations (3).

VIII. MODELLING THE DIFFRACTION OF ELASTIC TRANSVERSAL WAVE ON ABNORMALLY STRESSED HIERARCHICALLY HETEROGENEITY,LOCATED IN AN-LAYERED ELASTIC MEDIUM

Similarly to (5), the same process is written to simulate the propagation of an elastic transversal wave in an N-layer medium with a two-dimensional hierarchical structure inclusion of arbitrary section morphology using integral relations written in [17].

$$\frac{(k_{2jil}^2 - k_{2j}^2)}{2\pi} \iint_{SCl} u_{xl}(M) G_{Ss,j}(M, M^0) d\tau_M + \frac{\mu_{ja}}{\mu_{jil}} u_{x(l-1)}^0(M^0) +$$

$$+ \frac{(\mu_{ja} - \mu_{jil})}{\mu_{jil} 2\pi} \int_{Cl} u_{xl}(M) \frac{\partial G_{Ss,j}}{\partial n} dc = u_{xl}(M^0), M^0 \in S_{Cl},$$

$$\frac{\mu_{jil}(k_{2jil}^2 - k_{2j}^2)}{\mu(M^0) 2\pi} \iint_{SCl} u_{xl}(M) G_{Ss,j}(M, M^0) d\tau_M + u_{x(l-1)}^0(M^0) +$$

$$+ \frac{(\mu_{ja} - \mu_{jil})}{\mu(M^0) 2\pi} \int_{Cl} u_{xl}(M) \frac{\partial G_{Ss,j}}{\partial n} dc = u_{xl}(M^0), M^0 \in S_{Cl}. \tag{6}$$

where $G_{Ss,j}(M, M^0)$ is the source function of the seismic field of the problem under consideration, it coincides with the Green function, written in [17] for the corresponding task;

$k_{2jil}^2 = \omega^2(\sigma_{jil}/(\mu_{jil}))$; $\mu_{jil} \neq \mu_{ja}, \sigma_{jil} = \sigma_{ja}$ - wave number for the transversal wave; μ is the Lame constant; u_{xl} is the component of the displacement vector; $l = 1 \ldots L$ is the number of the hierarchical level; u_{xl}^0 - component of the displacement vector of the seismic field in a layered medium in the absence of heterogeneity of the previous rank, if $l = 2 \ldots L$ $u_{xl}^0 = u_{x(l-1)}$, if $l = 1$ $u_{xl}^0 = u_x^0$, that coincides with the corresponding expression for the normal field in [17]. It should be noted that the structure of equations (6) coincides with the general case, when the hierarchical heterogeneity has not only elastic parameters different from the parameters of the containing medium, but density parameters on all ranks differ from the density parameters of the containing layer. The difference of this task lies only in the values of the wave number. Thus, the response of the medium associated with the longitudinal wave is more sensitive to the region of elastic heterogeneities in the array. This should be taken into account when assessing the state of a complex geological environment.

IX.DISCUSSION OF RESULTS

Comparing expressions (3) and (4), (5) and (6), we can draw the following conclusions. When building a complex seismic-gravitational model without taking into account the anomalous influence of the stress-strain state inside the inclusion, an analysis of the anomalous acoustic effect using longitudinal wave propagation data shows that it is also more sensitive to the form of the inclusion, compared to the acoustic effect of transverse wave propagation. However, from these expressions it follows that the influence of elastic parameters in the seismic model in the surrounding medium cannot be neglected, and they affect the interpretation of the values of the required anomalous densities. If these values are used in the construction of the density gravitational model, then these density values will not reflect the material composition of the analyzed medium. When constructing an abnormally stressed geomechanical model without taking into account the anomalous influence of density heterogeneities within the inclusion, an analysis of the anomalous acoustic effect using data on the propagation of the transversal wave shows that it is also more sensitive to the form of inclusion than the acoustic effect on the propagation of a longitudinal wave. However, it follows from these expressions that the influence of density parameters in the seismic model in the host medium cannot be neglected, and they affect the interpretation of the values of the sought-for anomalous elastic parameters that cause the anomalous stress state. If these values are used when building a geomechanical model, then these values of the elastic parameters will not reflect the stress state of the analyzed medium.

CONCLUSIONS

For the first time the phenomenon of zone disintegration of rocks around underground workings was described in [20-24]. The formation of structures during irreversible processes is associated with a qualitative leap upon reaching the threshold (critical) parameters. Self-organization is a supercritical phenomenon when system parameters exceed their critical values. When a system deviates strongly from a state of equilibrium, its variables satisfy non-linear equations. Non-linearity is an important and common feature of pro- cesses proceeding far from equilibrium. In this case, the supercritical return of entropy is possible only if there is an unusual, special internal structure of the system [22]. This means that self-organization is not a universal property of matter, it exists under certain internal and external conditions, and it is not associated with a particular class of substances. So, there are two classes of irreversible processes: 1. destruction of the structure near the equilibrium position, this is a universal property of systems under arbitrary conditions; 2. the emergence of structures far from the equilibrium position under the conditions that the system is open and has non-linear internal dynamics, and its external parameters have supercritical values. I. Prigogine called them dissipative structures [25, 26]. The study of the morphology and dynamics of the migration of these zones is of particular importance in the development of deep-seated deposits, complicated by dynamic phenomena in the form of rock bursts. At the same time, geomechanics requires a new model to be adopted, namely, a layered-block model with inclusions of a hierarchical type. In this regard, for the analysis of mechanical fields propagating in such an environment, it is necessary to apply not kinematic, but dynamic methods based on modeling their propagation through a multi-range environment. An important tool for this study is geophysical research. As shown in [27], to describe the geological environment in the form of an array of rocks with its natural and technogenic heterogeneity, it is necessary to use its more adequate description, which is a discrete model of the environment in the form of a piecewise-inhomogeneous block environment with nested heterogeneities of lower rank than the block size. This investment can be traced several times, i.e., by changing the scale of the study; we see that heterogeneities of a lower rank now appear as blocks for heterogeneities of the next rank. A simple averaging of measured geophysical parameters can lead to distorted ideas about the structure of the environment and its evolution. The Institute of Geophysics of the Ural Branch of the Russian Academy of Sciences has developed an instrumental, methodical and interpretative complex for studying the structure and state of a complex geological environment, which has potential instability and the ability to rearrange the hierarchy of the structure with significant external influence. This complex is based on the developed 3D method of electromagnetic induction research in frequency-geometric variant, based on the one hand on the software-implemented system for interpreting 3D variable electromagnetic fields [24,28,29], and on the other hand, for the developed Ph.D. A.I. Chelovechkov instrument series for induction research. Currently, the developed methodology is used for mapping and monitoring of complex geological environments in the surface and underground (mine) variants.

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