Seismological and Well-Acoustic Monitoring of Nonlinear Manifestations in a Layered-Block Environment with Hierarchical Inclusions

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Abstract Problem statement : *The geological environ-ment is an open system on which external and internal factors act. They can lead it to an unstable state, which, as a rule, manifests itself locally in the form of zones called dynamically active elements, by which potential catastrophic sources can be identified. These objects differ from the host geological environment in their structural forms, which are often hierarchical types.* ***Applied method and design.*** *The process of their nonlinear activation can be observed using borehole monitoring of acoustic fields, for the mathematical support of which new modeling algorithms have been developed using the method of integral and integro-differential equations with the inclusion of nonlinear terms in the dependence of the wave parameter on frequency.* ***Typical results.*** *When interpreting the results of acoustic monitoring, it is necessary to use the data of such observation systems that are configured to study the hierarchical structure of the medium. A new algorithm has been developed for processing the seismological information of a detailed mine catalogue taking into account the kinematic and dynamic characteristics of deformation waves propagating at different speeds in a rock mass, which is under intense external influence in the form of mass or technological explosions.* ***Concluding note.*** *It was established that waves propagating with velocities from 1 to 10 m / h are the predominant carrier of energy in the array and contribute to its release. The responses of an array with energy of less than 10^4 joules contribute to the crypto rearrangement of the array and with energy of release greater than 10^5 joules, can be considered as precursors of destructive dynamic phenomena.*

Keywords: *slow deformation waves, seismic mine catalogue, seismological information processing algorithm, hierarchical environment, acoustic field, iterative modeling algorithm, nonlinear manifestations.*

I. INTRODUCTION

The most important result of geomechanical - geodynamic studies of the past century was the discovery of a close relationship between global geodynamic and local geomechanical processes due to mining operations, especially in tectonically active zones. An equally significant result of the research was the conclusion about the fundamental role of the block-hierarchical structure of rocks and massifs to explain the existence of a wide range of nonlinear geomechanical effects and the emergence of complex self-organizing geosystems. The hierarchical structure is typical for many systems, especially for the Earth's lithosphere, where more than 30 hierarchical levels were distinguished from geophysical studies, from tectonic plates thousands of kilometres long to individual millimetre-sized mineral grains [1]. Distribution and redistribution of energy of the deformation process in block media is associated with slow movements [2, see bibliography], which coincides with the results of the analysis of data from the seismological shaft catalogue [3]. To implement the study of the state of the array using the approaches of the theory of dynamic systems [4], the data of the seismic catalogue of the Tashtagol underground mine were used for two years of observations from June 2006 to June 2008. The data used are the spatial-temporal coordinates of all dynamic phenomena — the array responses that occurred during this period inside the mine field and the explosions produced to mine the array, as well as the energy of the explosions and array responses recorded by the seismic station [5].

II. SEISMOLOGICAL INFORMATION PROCESSING ALGORITHM

The entire mine field was divided into two halves: the workings of the north-western section, the areas of the Western and Novo-Kapitalnaya shafts and the workings from 0 to 13 were designated by us as the northern section. Excavations from 14 to 31, the southern ventilation and field drifts, the shaft of the Southern mine, the excavations of the south eastern section are designated as the southern section. All response events from horizons with marks of 140 m, 210 m, 280 m, and 350 m were analysed. Explosions were carried out in the southern, south eastern, north western and northern sections. The seismological catalogue was also divided into two parts: northern and southern, according to events: responses and explosions that occurred in the northern and southern parts of the mine field. We consider each explosion point as a source of seismic and deformation waves. Using the kinematic approach to processing seismic information, we use each response point of the array as the spatial-temporal point of the first arrival of the deformation wave to calculate the wave velocity. We introduce the following two groups of gradations of velocities (Vs) from 1-6 in each group. The first group - from 1000 m / h to 500 m / h (1), from 500 m / h to 100 m / h (2), from 100 m / h to 50 m / h (3), from 50 m / h up to 10 m / h (4), from 10 m / h to 1 m / h (5), from 1 m / h to 0. 01 m / h (6). The second group - from 1000 m / s to 500 m / s, from 500 m / s to 100 m / s, from 100 m / s to 50 m / s, from 50 m / s to 10 m / s, from 10 m / s to 1 m / s, from 1 m / s to 0. 01 m / s. All the responses of the array, together with their spatial-temporal, velocity and energy characteristics, are distributed according to these gradations. Then we calculate the average values of the velocities of the deformation waves participating in the dynamic phenomena of the array for each gradation from explosion to explosion.

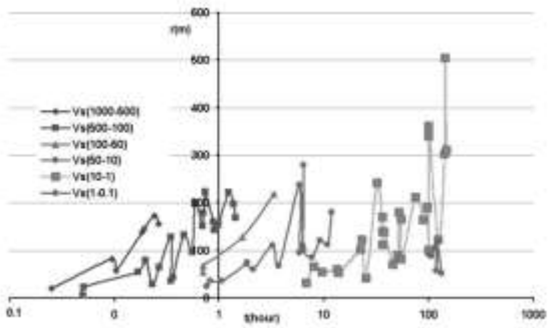

Figure 1a

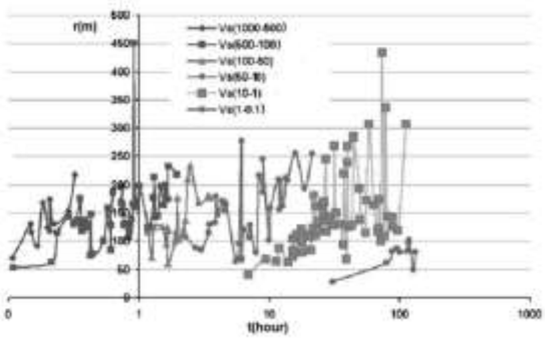

Figure 1b

Figure. 1 Dependence of the arrival time of the deformation wave on the distance between the response point of the array and the source of the explosion: 1a - 11/19/2006. Mass explosion, block 18, horizon (-350) - (- 280), collapse, 167.8t, E = 1.21 10^9 j., 1b - 12.24.2006. Mass explosion, block 26, horizon (-350) - (- 280), collapse, 200.2t, E = 9.5 10^7 j. [6]. Velocities Vs are expressed in units of m / hour.

Thus, using the developed algorithm for processing the seismological information of a detailed mine catalogue, taking into account the kinematic and dynamic characteristics of deformation waves propagating at different speeds in a rock mass, which is under intense external influence in the form of mass or technological explosions, it was possible to trace the scenario of preparing mountain impacts with energy greater than 10^5 joules. It has been established that waves propagating with velocities from 10 to 1 m / h are the predominant carrier of energy in the array and contributing to its release. Events occurring in the array with these velocities and having release energy of less than 10^4 joules contribute to creep rearrangement of the array. Events occurring in an array with these velocities and having release energy greater than 10^5 joules can be used as precursors and which are recommended to be taken into account when adjusting the product of explosions in one or another part of the array. The complete absence of these events indicates an increase in the stress state in the mine array as a whole. The obtained complex information from the data of the seismological catalogue is important for modeling and interpreting the propagation of seismic and deformation waves in hierarchical structures.

III. ALGORITHM FOR 2D PROPAGATION OF ACOUSTIC LONGITUDINAL WAVES IN A LAYERED BLOCK MEDIUM WITH HIERARCHICAL INCLUSIONS, TAKING INTO ACCOUNT NONLINEAR MANIFESTATIONS IN THEM.

To consider the behaviour of an elastic rock massif within the framework of a model of a hierarchical medium of arbitrary rank, an algorithm for solving the direct two-dimensional problem for a seismic field in a dynamic version is developed. Moreover, the model of local hierarchical heterogeneity of the L-th rank seems to be a crack-like inclusion. The inclusions of the hierarchical structure of the remaining ranks in the form of elastic heterogeneity in the approximation when the Lame parameter $\mu = 0$, both in the inclusions and in the medium enclosing them. In this case, the dynamic seismic problem can be considered independently for the propagation of a longitudinal and a transverse wave. In the present paper, we will consider the first case for the proposed model. The idea presented in [7] for solving the direct problem for the two-dimensional case of propagation of a longitudinal wave through a local elastic heterogeneity with a hierarchical structure located in the J-th layer of an N-layer medium is extended to the case when a crack-like state appears in the L-th hierarchical level with some nonlinear features.

$$\frac{(k_{1jil}^2 - k_{1j}^2)}{2\pi}\iint_{S_{Cl}} \varphi_l(M) G_{Sp,j}(M,M^0)\,d\tau_M + \frac{\sigma_{ja}}{\sigma_{jil}}\varphi_{l-1}^0(M^0) -$$
$$-\frac{(\sigma_{ja}-\sigma_{jil})}{\sigma_{jil}2\pi}\oint_{Cl} G_{Sp,j}\frac{\partial\varphi_l}{\partial n}dc = \varphi_l(M^0),\ M^0\in S_{Cl} \qquad (1)$$
$$\frac{\sigma_{jil}(k_{1jil}^2-k_{1j}^2)}{\sigma(M^0)2\pi}\iint_{S_{Cl}}\varphi_l(M)G_{Sp,j}(M,M^0)\,d\tau_M + \varphi_{l-1}^0(M^0) -$$
$$-\frac{(\sigma_{ja}-\sigma_{jil})}{\sigma(M^0)2\pi}\oint_{Cl}G_{Sp,j}\frac{\partial \varphi_l}{\partial n}dc = \varphi_l(M^0),\ M^0\notin S_{Cl}$$

Where $G_{Sp,i}(M,M^0)$ is the source function of the seismic field, it coincides with the expression function [7], $k_{1jil}^2 = \omega^2(\sigma_{jil}/\lambda_{jil})$ - is the wave number for the longitudinal wave, in the given expression, the index ji means properties of the medium are inside the heterogeneity, ja means that the properties are outside the heterogeneity, l = 1 ... L-1 is the number of level, $\vec{u}_l = grad\,\varphi_l$, φ_l^0 is the potential of a normal seismic field in a layered medium without the lack of heterogeneity of the previous rank if l = 2 ... L, if l = 1, which coincides with the corresponding expression from [7]. If during the transition to the next hierarchical level the two-dimensional axis does not change, and only the cross-sectional geometry of the embedded structures changes, then, similarly to [7], iterative process of modeling the seismic field can be written (the case of the formation of only a longitudinal wave). An iterative process refers to modeling a displacement vector when moving from a previous hierarchical level to a subsequent level. Within each hierarchical level, the integro-differential equation and integro-differential representation are calculated using algorithms (1). If at a certain hierarchical level the structure of a local heterogeneity splits into several heterogeneities, then the double and contour integrals in expressions (1) are taken over all heterogeneities. If l = L, then inside the heterogeneities of this hierarchical level there is a fractured heterogeneity. In this case, system (1) taking into account [8] is rewritten in the form, taking into account the propagation of the main wave from an acting source and two envelope waves:

$$\frac{(k_{1jiL}^2 - k_{1j}^2)}{2\pi}\iint_{S_{0L}} \varphi_L(M) G_{Sp,j}(M,M^0)\,d\tau_M + \frac{\sigma_{ja}}{\sigma_{jiL}}\varphi_{L-1}^0(M^0) -$$
$$-\frac{(\sigma_{ja}-\sigma_{jiL})}{\sigma_{jiL}2\pi}\oint_{CL} G_{Sp,j}\frac{\partial\varphi_L}{\partial n}dc = \varphi_L(M^0),\ M^0\in S_{0L} \qquad (2)$$
$$\frac{\sigma_{jiL}(k_{1jiL}^2-k_{1j}^2)}{\sigma(M^0)2\pi}\iint_{S_{0L}}\varphi_L(M)G_{Sp,j}(M,M^0)\,d\tau_M + \varphi_{L-1}^0(M^0) -$$
$$-\frac{(\sigma_{ja}-\sigma_{jiL})}{\sigma(M^0)2\pi}\oint_{CL}G_{Sp,j}\frac{\partial \varphi_L}{\partial n}dc = \varphi_L(M^0),\ M^0\notin S_{0L}$$

$$k_{1jiL}^2 = \omega^2(\sigma_{jiL}/\lambda_{jiL}) +$$
$$+\frac{-b_{1jL}\pm\sqrt{b_{1jL}^2+4b_{2jL}\left(\omega_{1jL}+\gamma_{jL}a_{jL}^2\right)}}{2b_{2jL}} \qquad (3)$$

According to the nonlinear dispersion relation for the nonlinear Schrödinger equation, this describes the propagation of the envelope of a wave moving over a carrier wave [8]. The coefficients $b_{1jL}, b_{2jL}, \gamma_{jL}$ (3) in the layer j are constant, real quantities, the first two correspond to the dispersion terms, the third corresponds to the nonlinear term, a-is the maximum amplitude of the envelope wave. If this wave process propagates into the j-1 layer at l = L. expressions (2) - (3) can be rewritten in the form:

$$\frac{(k_{1(j-1)iL}^2 - k_{1(j-1)}^2)}{2\pi}\iint_{S_{0L}} \varphi_L(M) G_{Sp,j-1}(M,M^0)\,d\tau_M + \frac{\sigma_{(j-1)a}}{\sigma_{(j-1)iL}}\varphi_{L-1}^0(M^0) -$$
$$-\frac{(\sigma_{(j-1)a}-\sigma_{(j-1)iL})}{\sigma_{(j-1)iL}2\pi}\oint_{CL} G_{Sp,j-1}\frac{\partial\varphi_L}{\partial n}dc = \varphi_L(M^0),\ M^0\in S_{0L} \qquad (4)$$
$$\frac{\sigma_{(j-1)iL}(k_{1(j-1)iL}^2-k_{1(j-1)}^2)}{\sigma(M^0)2\pi}\iint_{S_{0L}}\varphi_L(M)G_{Sp,(j-1)}(M,M^0)\,d\tau_M + \varphi_{L-1}^0(M^0) -$$
$$-\frac{(\sigma_{(j-1)a}-\sigma_{(j-1)iL})}{\sigma(M^0)2\pi}\oint_{CL}G_{Sp,(j-1)}\frac{\partial \varphi_L}{\partial n}dc = \varphi_L(M^0),\ M^0\notin S_{0L}$$

$$k_{1(j-1)iL}^2 = \omega^2(\sigma_{(j-1)iL}/\lambda_{(j-1)iL}) +$$
$$+\frac{-b_{1(j-1)L}\pm\sqrt{b_{1(j-1)L}^2+4b_{2(j-1)L}\left(\omega_{1(j-1)L}+\gamma_{(j-1)L}a_{(j-1)L}^2\right)}}{2b_{2(j-1)L}} \qquad (5)$$

That process can be continued and the hierarchical inclusions with nonlinear features can go nearer to the boundary of the block layered system, then a catastrophic event can happen.

IV. DISCUSSION AND RESULTS

In most cases, in specific geological systems, oscillatory processes are non-linear. Therefore, the theory of such processes and modeling methods have important practical value [2, 9]. Especially for the formulation of stability criteria for mountain ranges that are in the process of mining. In the book [10], from a unified point of view, the theory and methods of studying the nature of the instability of physical systems of various natures, described by partial differential equations, are presented. The theory of wave processes in linear systems is used to justify these methods, since the development of instability at the initial stage can be described using the concept of small perturbations of the state under study. It turned out that in order to establish the instability threshold and its nature, it is sufficient to know only the dispersion equation that relates the wave vector and the frequency of this wave process. This made it possible to develop a unified approach to the study of instabilities in various systems, regardless of their nature and frequency range. By their nature, all types of instability can be divided into two types: absolute and convective [11]. Therefore, the study of the conditions under which the system under consideration is unstable, and the determination of the nature of this instability are the starting points of theoretical and experimental studies of the generation and amplification of waves of any type. As is known from the theory of stability of systems with a finite number of degrees of freedom [12], the problem of the stability of some of its states reduces to solving systems of linear differential equations, while solving the question of the nature of the steady state in the general case requires solving a system of nonlinear differential equations. Moreover, in the general case, an implicit dependence between ω and k is obtained, which is determined from the dispersion equation D (ω, k) = 0. In this paper, we propose one of the possible nonlinear modeling algorithms for acoustic 2D modeling of a layered block medium with hierarchical inclusions. From the results it follows that the seismological monitoring data must be supplemented by borehole acoustic monitoring data tuned to a model with hierarchical inclusions, since it is in them that the fluctuation process originates, which leads to instability of the layered block array. In further work, we will investigate the question of practical methods for maintaining the stability of a mountain range using integrated geophysical monitoring.

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