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Physical Fields as Derivative of Deformation of Rock Massif and Technology of Their Monitoring

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***Abstract*—Conditionally the process of stress-strain development of the medium begins with dislocation in crystals; then it runs with the formation of a zone of rock fracture and ends with the collapse of the massif (fracture under natural conditions). Each stage of the stress-strain development or the change is characterized by the specific value of the amplitude-frequency vibrations of the medium caused by this change. Massif response to the action of the deforming stress is manifested by a breakdown of the electrical connections in the crystal lattice. An assessment of modern means of personnel safety control and prevention of the state of the elements of local underground space (based on electrical and radio circuit diagrams that are not protected from electromagnetic interference) has been made. Significant disadvantages include their exposure to the human factor in the form of forced shutdown. Changes in the dipole moments in a covalent bond lead to the appearance of electromagnetic pulses, and the residual deformations in the form of dislocations create acoustic wave fields. The energy characteristic of three components of intermolecular interactions (orientation, inductive and dispersed) is given in the paper.**

Considering the nature of physical fields as derivatives of the deformations of the medium, which evolve over time into mechanical irreversible changes in the structure of rocks and the structural and tectonic formation of the massif, it is possible to establish a quantitative dependence of the intensity of these fields and the safety state of the developed massif. Fiber-optic sensors based on Bragg gratings are proposed as a basic technology for monitoring natural electromagnetic pulses and sound waves.

Keywords—deformation; physical fields; amplitude-frequency characteristics; electromagnetic pulses; acoustic waves; monitoring; fiber-optic sensors

I. RELEVANCE OF THE PROBLEM

At all times production in the mining industry is conducted with a high risk. Firstly, it is still not possible to take into account the effect from the full list due to the complexity of geological situation, both in terms of structural and tectonic fragmentation and in a variety of negative factors affecting the stability of the rock massif. Secondly, this occurs due to the insufficient knowledge of the geological and structural, tectonic and geotechnical conditions of the section, both at the stage of detailed exploration and in the process of industrial development. In this work the massif is understood as the volume of rock that is of a particular interest and is prepared for industrial development and geotectonic conditions of which are subjected to the detailed study for the safe mining works.

Systems of modern means of personnel safety control and prevention of the state of the elements of local underground space, safe and uninterrupted operation of vehicles and mining equipment, as well as positioning of each employee's location in case of an emergency, are based mainly on electrical and radio circuit diagrams that are not sensitive enough and are not protected enough from electromagnetic interference. Besides, they are sensible to the human factor influence, which consists in the possibility of forced shutdown of signaling devices, arbitrary interpretation of the causes of automated signaling warnings by individual workers or entire groups of workers with supposedly false operation of control equipment and, as a result, it causes an ignoring of control system warnings. Generation of the current mine security equipment cannot block production cycles and carry out a rescue program. Innovative technologies of control and warning means should be programmed to independent blocking of production processes, positioning the locations of the sites which operate in the production cycle and each personified employee in real time. Innovative technologies should contain not only the programs of the production cycle, but also the programs of automated emergency response or mitigation of mining consequences.

II. ATOMIC AND MOLECULAR BASIS OF ROCKS AND INTERNAL LINKS

In matters relating to rock mechanics empirical conclusions, experimental evidence and theoretical vision are based on the assumption of their elastic nature, regardless of genesis, while allowing the presence of a wide range of elastic media (from soft plastic soils to almost solid mineral formations).

In the last decade, the Geophysical Institute has paid considerable attention to both the physicochemical links of the solid medium itself and the study of the behavior of a rock under intense dynamic loads based on the interaction of its nanoscale particles or the formation of the macro - physical and mechanical properties of rocks based on taking into account its micro-properties (atomic-molecular links and their changes) [1-5]. The results of such investigations can be successfully used to study the characteristics of geophysical fields and predict the behavior of rocks under strong seismic effects [6,7].

A rock is a mono- or polymineral formation cemented by intermolecular links of grains and particles of perfect crystals, due to the electromagnetic interaction of electrons and nuclei of one molecule with electrons and nuclei of another [8].

The forces of intermolecular links are manifested by dipole, electromagnetic and quantum-dispersed effects. In case of a solid body is deformed then an elastic force, aimed at restoring its original state, arises. It is always directed opposite to the deforming force caused by the violation of the natural state of the mountain massif.

The strength of rocks is determined by the intermolecular interaction of the constituent particles of the rock, arranged at the atomic-molecular level according to the equilibrium position, when the potential energy of the molecule is minimal, resulting from the equilibrium position of the Coulomb forces of attraction of the nuclei and electrons and repulsion of the nuclei and, accordingly, electrons from each other.

In turn, the stability of a molecule, crystal, or mineral as a whole is ensured by the interaction of atoms, i.e. chemical linkage, which significantly exceeds the force of intermolecular interaction (with the same mineral composition, stronger rocks that are more fine-grained).

Stable atomic-electron pairs (chemical element) in strictly appropriate quantities through a certain type of linkage forms molecules, which, in its turn, in combination with another atomic-electron pair or another molecule, form crystals and minerals, the combination of which is rock.

In rocks, the covalent (homeopolar) linkage prevails, i.e. the electron cloud of one atom is simultaneously under the influence of another atom, and the electron cloud of the second atom is also under the influence of the first atom, while the electron cloud is drawn out between the atoms.

The physics of intermolecular interaction is caused by the electromagnetic interaction of an electron and the nuclei of one molecule with electrons and nuclei of another, like an atomic interaction. The energy of intermolecular interactions consists of three types of interactions: orientational, inductive and dispersed [9].

The interaction of orientational molecules occurs due to the presence of a dipole moment. The force of attraction between molecules depends on their orientation relative to each other. The maximum interaction force of molecules is observed in the case when their dipole moments are oriented in one direction, along the same line. The attraction energy of an orientational view for two molecules can be approximately expressed by the formula:

$$E_{or}=k(m_1^2 * m_2^2)/r^6 \qquad (1)$$

where k is a coefficient depending on temperature; m_1, m_2 are dipole moments of molecules and r is the distance between molecules.

The induction interaction is caused by the interaction of the electron dipole moment of one molecule with the dipole moment of another polar or non-polar molecule induced by it. The energy of the induced interaction can be approximately expressed by the formula:

$$E_{ind}= - k(\alpha 1 m12 * \alpha_2 m_2^2)/r^6, \qquad (2)$$

where α_1 and α_2 are the polarizability of molecules.

When quantum-mechanical fluctuations of the electron density occurs, the dispersion interaction of molecules occurs due to charge displacement when electrons move around nuclei and the formation of instantaneous dipoles, which induce instantaneous dipoles in the neighboring molecule, which leads to their interaction. The energy of the dispersed interaction is determined by the formula:

$$E_{dis}= - \frac{3}{2} (\alpha 1 \alpha 2 I1 I2) / I_1 I_2 r^6 \qquad (3)$$

here I_1 and I_2 are the ionization potentials of molecules.

Dispersion interaction is weakly screened, and therefore the interaction between the particles can be easily determined by summing the interactions between molecules and atoms in both particles, for example, by integrating under the assumption of additivity of intermolecular (interatomic) interactions. The increment of the energy of molecular attraction per unit area of particles can be calculated on the basis of the formula of Boore and Hamaker [10].

To obtain the equation of the energy of molecular attraction between particles, we use the equation of the energy of attraction of one molecule [11]:

$$U=\pi Cn/6x^3 \tag{4}$$

where x is the distance between the atoms of one particle and the surface of another; C is a constant; n is the number of atoms. If we denote the distance between an atom of one particle and the surface of another particle x = r + h, where h is the distance between particles; r is the distance of the atom from the surface of the particles, and n is the number of interacting atoms, then the increment of the energy of molecular attraction per unit area of the particles will be:

$$dU=-\pi n^2Cdr/6(r+h)^3 \tag{5}$$

After integration we get:

$$U=-\pi n^2C/12h=A/12\pi h^2 \tag{6}$$

where A is the Hamaker constant, having a value of the order of 10-19 Joul.

Based on the formula of Boore and Hamaker, it is possible to determine (approximately) the strength of the molecular links between the grains.

The specific force of interaction between the grains (strength of intermolecular bonds), based on the previous equation, will be:

$$f=A/6\pi h^3 \tag{7}$$

The minimum distance between the rock grains is equal to the sum of the radii of the atoms in contact. Taking h = 3 × 10-10 m, we get:

$$f=10^{-19}/6*3.14*(3*10^{-10})^3=3.7*10^9 \text{ Pa}, \tag{8}$$

which is higher than the strength of the most durable rocks, such as quartz.

III. GEOPHYSICAL FIELDS AS INDICATORS OF MECHANICAL PROCESSES

The physical and chemical bases of intermolecular links of rocks are at the same time precursors of the occurring disturbances of these links, the cause of which is an increase in stresses in the rocks and subsequent elastic or residual deformations. On the assumption of the basics of intermolecular links, it is obvious that electromagnetic fields are an indicator, since crystal lattice deformations cause a change in the distances between atoms and quantum-mechanical fluctuations of the electron density of particles (molecules, atoms) [12-24]. The instantaneous distribution of the electric charge of the molecule, which corresponds to the instantaneous dipole moment of the molecule (or a higher order multipole moment), induces an electric multipole moment in another molecule. The avalanche effect of instantaneous multipole moments creates the energy of dispersion interaction, which manifests itself in the form of electromagnetic pulses (EMP) of the field E_{dis}

The frequency spectrum of electromagnetic oscillations lies in the range of 1KHz-50 MHz, and in the initial stage of development of the deformation process, the spectrum shifts towards higher frequencies, and with the onset of residual deformations, gradually shifts to low frequencies. For the initial stage of loading, the occurrence of dislocations is characteristic, i.e. local displacements of individual atoms of the crystal lattice. A dislocation is able to propagate in a crystal due to less additional external energy than is required for the formation of a defect with a perfect lattice [25, 26].

The most high-frequency part of the EMP spectrum corresponds to the occurrence of such dislocations, many of which lead to the formation of fracture zones and tectonic disturbances. Each rank of tectonic manifestation is accompanied by a certain spectrum of electromagnetic impulses, while low-frequency impulses are characteristic violations of relatively low orders and vice versa. Of course, this applies to any single complex, whether magmatic, metamorphic or sedimentary, with the only difference that the deformation spectra of each complex will be individual.

Since the electromagnetic pulse is a vector, and its amplitude-frequency characteristics and spatial directionality are the most important parameters for determining the nature of the impact, it is advisable to measure the EMP in the 3-component recording mode. In combination with the geotechnical, lithological and structural-tectonic conditions of the field, the data of 3 component observations of electromagnetic pulses allow you to set intervals of the developed massif with the active dynamics of mechanical stress development, to give a qualitative characteristic of the deforming factor, to predict the development of hazardous processes.

The use of the EMP method in solving the detection problems, monitoring of the development of an event in the form of intense deformation of the environment, preventing catastrophic consequences and forecasting such major geodynamic events as rock blows at diggings and mines covered at great depths, as well as earthquakes, is promising for ensuring the safety of underground mining works.

The ore-containing massifs of the Central Caucasus mainly consist of metamorphic, igneous, volcanogenic-sedimentary complexes belonging to the category, in general, hard rocks. Residual deformations in such rocks in the form of microcracks, rock bursts, rebounds of rock elements, deformational cracks, flaking, etc. are accompanied by a sound effect.

Plastic deformations associated with the appearance and development of defects at the level of structural and textural features of the material in the form of micro- and macro-cracks and allotropic changes in the crystal lattice appear as separate acoustic impulses that serve as a universal sign of the detection of multi-scale cracks in the frequency spectrum of radiation. Such impulses manifest themselves in the crystal lattice even in the elastic region, and arise from the fact that the medium is heterogeneous at the level of textural and structural packaging, unevenly loaded, and plastic deformation occurs in some areas, although the process remains elastic in general. Excitation of high-frequency acoustic waves favors the use of seismoacoustic studies in the acoustic and ultrasonic frequency range.

The cycle of acoustic emission of rock from the beginning of loading to complete destruction will be differentiated by characteristic amplitude-frequency spectra reflecting the stages of deformation at the levels of the crystal lattice, the structural-textural and lithological structure of the medium.

Increased stress occurs due to the redistribution of the pressure of lateral or overlying rocks, changes in the textural characteristics of the rock, and then inter-element links at the level of structural changes. At the pressures which exceed the ultimate strength of the rock the phase of elastic deformations is replaced by non-linear changes in the structure of the medium (plastic deformations) and aperture of discontinuity. Then the collapse of the rock or discharge in the form of a rock blow occurs.

Shifts at the intermolecular level of structural-tectonic bagging of rock generate high-frequency elastic longitudinal and transverse waves, the frequency spectrum of which will shift to the left with the preparation, appearance and development of residual deformation. The frequency range at an early stage of development of a stress-strain process can be recorded by ultra-high frequency sensors, the introduction of which will provide a complete cycle of preparation, development and occurrence of stress-strain processes in the hazardous areas of mine workings. The stress corresponding to the initial stage of deformation in the form of a microcrack will have a short duration (of the order of microseconds or fractions of microseconds) [27].

With ever-increasing pressure, longitudinal shear displacements cease to be elastic, elastic deformation becomes plastic, and part of the energy begins to be spent on dissipative losses, including residual deformation, which is used in the practice of photoelastic recording of the stresses experienced by a mountain massif and determined by the ratio of principal optical axes, for which optical composite materials are used [28].

IV. MONITORING OF THE STRESS-STRAIN STATE OF THE MASSIF UNDER DEVELOPMENT BY PHYSICAL FIELDS

Research and analysis of the nature of the origin of electromagnetic pulses and acoustic waves are aimed at the determination of reliable and effective indicators characterizing the state of the developed rock massif using equally reliable technological means of observation.

The traditional electrical and radio circuits used are, on the one hand, not adequately protected from a wide range of electrical interference going from underground equipment and natural ones, and on the other hand, technological control lines are accessible to anyone interested. The first disadvantage leads to frequent false warnings, and the second one leads to shutdowns for unconfirmed state or intentional adjustments to the response threshold of the device, i.e. to the possible underestimation of the device sensitivity. The statistics shows that the number of accidents in underground workings associated with the deterioration of the massif due to anthropogenic disruption of stable geostatic stability of rocks and the impact of deforming natural events on the already unstable rocks of the mine area being developed does not decrease [29].

Among the many areas that require the safety of mining production, here we consider only the massif under development, the stress-strain state of which is generated by the emptiness of workings, technological explosions, seismotectonic unloadings in the area of large-scale dislocations (random developments), and random seismic dislocation focused on the territory of the massif etc.

Based on the physics of lattice deformation and subsequent physicochemical interactions at the atomic-molecular level, the result of which electromagnetic pulses and acoustic waves are, diagrams of these characteristics can fully contain information about the dynamics of deformation changes in a massif.

When choosing a technological line for monitoring the electromagnetic and acoustic derivatives of the residual deformation of the massif, the disadvantages of traditional radio and electrical systems (regarding their sensitivity to interference) are taken into account, which predetermines the use of fiber optic lines and sensors. It is necessary to use sound sensors (for acoustic waves) and magnetic and electric fields (for electromagnetic pulses) as the sensors.

For the spatial-temporal association of events, it is necessary to stipulate for the possibility of amplitude-frequency differentiation of the useful signal, which is available when using a quasi-distributed sensor [30], which is an array of point sensor elements, usually based on intrafiber gratings, united by one common fiber i.e. single-mode fiber-optic cable with Bragg gratings recorded in the fiber. Bragg gratings are sections of a fiber with alternating refractive index along its axis due to the transformation of the fiber structure by ultraviolet irradiation. The FBG (fiber Bragg gratings) of each sensor reflects light of a certain wavelength with a spectrum width of about 1 nm. During mechanical action (deformation, displacement, vibration) the period and the refractive index of the lattice change, as a result of which the wavelength of the reflected light is shifted. Processing the results of measurements of the magnitude of this displacement determines the relative deformation, temperature, inclination, acceleration, vibration, pressure and displacement (depending on the sensor design). Each element has its own unique characteristics, which allows one analyzing its state independently of other sensory elements.

The locations of the fiber-optic sensors and the network of their location are determined on the basis on the maximum safety of personnel and mining equipment, the degree of importance of the object in the technological cycle of the development of the massif, taking into account the structural-tectonic and geotechnical conditions of operation of the massif, the hydrogeological regime of ground and stratal waters, seismicity of the territory, possible organizational disruptions, infrastructure inconsistencies, etc. For a confident interpretation of the results of observations and a reasonable conclusion about the onset of an emergency, there should be two production observation lines duplicating each other with Bragg gratings, one of which records electromagnetic pulses and the other records the acoustic waves.

The communication line should also consist of fiber-optic cable. Installation of sensors and communication lines is carried out in the inaccessibility of mine personnel who are not directly involved in the monitoring process.

The management of the technological monitoring line is displayed on the day surface in the control room.

At the stage of experimental methodological development and production observations, it seems advisable to establish criteria for determining an emergency by perturbation parameters, to which the recording equipment is subsequently calibrated for operation in an autonomous mode without operator intervention.

The final scheme of the technological line, the type of fiber-optic cable, the spectral width of the source signal, periods of Bragg gratings, sensor installation technology and other technical details of starting the fiber-optical technological monitoring line can design, execute and run fiber-optic communication lines with which The age of innovation technology requires miners to establish close contacts.

V. CONCLUSIONS

Indicators of the stress-strain state and the degree of development of residual deformations in the rock massif and elements of technological workings, the threat of rock bump and methane emissions, collapses and landfalls and prolonged seismological effects resulting from external deforming stresses are natural electromagnetic pulses and acoustic waves.

The mechanics of the stress-strain state at the level of the crystal lattice and the physicochemical processes at the atomic-molecular level are described.

The physicochemical principles of detection and development of the stress-strain state of a rock are shown, based on the anomalous manifestations of such physical parameters as impulses of electromagnetic and sound waves.

The early stage of plastic deformation in the rock is theoretically associated with changes at the level of the crystal lattice, texture and structural bagging of the rock, accompanied by an avalanche-like manifestation of microcracks in particular focal points and generation of electromagnetic and acoustic vibrations in a wide range of the frequency spectrum.

The authors assumed the possibility of differentiation of the signals of both characteristics according to the amplitude-frequency spectra and the possibility of determination of the degree of deformation process development.

The current state of the control of the stress-strain state of the massif is estimated on the basis of interference-free electrical and radio circuits.

The prospect of using fiber-optic sensors of a closed type with the removal of recording equipment on the surface in the control room as a technological line and sensors for monitoring the state of a rock massif is substantiated.

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