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RESONANCE IN ROCK MASS AS THE KEY REASON OF GEODYNAMIC PHENOMENA

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ABSTRACT

Purpose is to develop deformation criterion or predecessors of geodynamic phenomena within rock mass relying upon the systemized experimental data concerning rock behaviour in a volumetric field of compressive stress.

Methods. Experiments as for rock deformation and failure in a volumetric stress state were carried out with the help of a device of non-uniform volumetric compression. The device was designed by Donetsk Institute for Physics and Engineering (DonIPhE) of the NAS of Ukraine. Volumetric deformations and share deformations, elastic parameters, parameters of a type of deformation state and stress state of Lode Nadai, and Lode angles were determined separately for each load grade taking into consideration corresponding increase in deformations. Sudden arching and its characteristic features were observed in longwall 2 of inclined drift of l_1 seam in Kapitalna mine.

Findings. It has been demonstrated that rock are classic auxetics in which elastic factors change their values and signs. It has been determined that the characteristic deformations, in terms of which elastic characteristics change their values, are quantized and constant for each material. Four characteristic stages, inherent to all rocks despite their stress state type and comprehensive pressure value, have been singled out during deformation. It has been defined that jump of amplitude of linear and shear deformations, resulting from double vortex and wave resonance in terms of velocity, dimensions of structures and frequency (stage 3), is a failure predecessor. Increase in minimum relative deformations (i.e. oscillations of a working face of a seam) and in maximum relative deformations (i.e. oscillations of roof or walls of a mine working) up to several percent have been proposed as the failure criterion.

Originality. It has been determined for the first time that in the context of volumetric stress state, deformation increase is of alternative nature; elastic characteristics of rocks are not constants of a material varying in terms of a value and a sign during mechanical loading and shear deformations are of rotational nature.

Practical implications. Resonance increase in the amplitude of maximum, minimum, and shear deformation growth is a criterion of total failure and dynamic failure in particular which can be used in practice as a predecessor of a failure or its prognostic criterion.

Keywords: *geodynamic phenomena, elastic characteristics, deformation growth, resonance, failure*

1. INTRODUCTION

Deformations expand within rock mass in the form of volumetric deformation wave (Fig. 1) which can be confirmed by their alternative nature (Kurlenya, Adushkin, & Oparin, 1992; Kuksenko, Guzev, Makarov, & Rasskazov, 2011; Adushkin & Oparin, 2014).

The majority of researchers believe that reverse deformation effect is observed in the brightest way right before failure (Kurlenya, Adushkin, & Oparin, 1992; Sobolev & Ponomarev, 2003; Takahashi, Lin, & Kwasniewski, 2005). Change in the sign of growth of volumetric deformations means starting point of fissure formation also being long-term failure predecessor (Guzev & Makarov, 2007). However, as it has been shown in (Kuksenko, Guzev, Makarov, & Rasskazov, 2011; Vikulin, Bykov, & Luneva, 2000; Vikulin, 2010), sign alternation remains at each deformation stage. During the initial stage of uniaxial compression, growth of a volume decrease achieves its maximum in terms of each measurement line; then it runs down and achieves its dilatancy threshold (i.e. volumetric deformation growth is equal to zero). After that, deformation areas experience their distribution: in one direction, volume continues its decrease; in another direction, volume starts its increase. In this context, cylindrical sample in a cross section becomes of octahedral form.

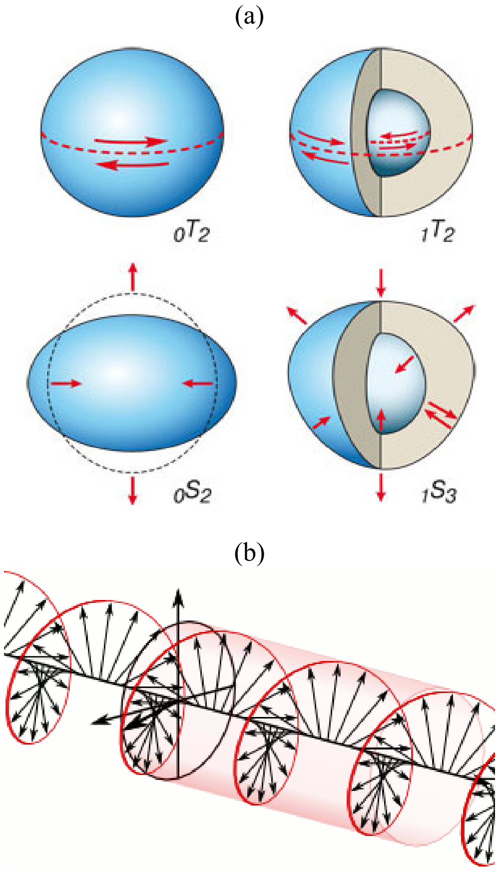

Figure 1. Volumetric deformation wave of proper Earth's oscillations: (a) T-torsional oscillations (active component); S-spheroidal oscillations (reactive component); (b) active (vortex) component represented as a superposition of two shear waves with phase difference being equal to quarter-period of oscillations

Dilatancy processes progress within the areas of relative volume increase; contraction processes progress within the areas of relative compression. Short-term stabilization process results in macrodiscontinuity preparation stage in turn factoring into jump-like increase of volume growth concerning each part of the structure. A macrofailure takes place.

It should be noted that each of the stage is interpreted expressly being registered rather accurately; thus, the authors propose to use the index as a failure predecessor.

The key disadvantage of the data is in the fact that it is impossible to measure growth of volumetric deformations; they can be only calculated. Moreover, the experiments have been carried out in terms of uniaxial compression within solid rocks; deformations, registered by tensiometers are elastic and minimal differing greatly from actual deformations within the rocks. Hence, the proposed failure predecessors cannot be used in practice.

The abovementioned means that in general, the problem of searching for reasons and predecessors of rock failure as well as in the form of geodynamic phenomena in part remains topical.

It is possible to solve the problem while analyzing both growth of volumetric deformations and all the three linear deformations as well as shear deformation in the context of non-uniform triaxial compression of sedimental rocks of Donbas carbon. Moreover, since elastic parameters are load increase-deformation growth ratio, it is expedient to analyze changes in elastic characteristics of rocks. Many studies emphasize significant nonlinearity of elastic parameters of rocks (Paterson, 1978; Stumpf, 1995; Jefferies & Shuttle, 2005), several times variation of their values during loading (Kuwahara, Yamamoto, & Hirasawa, 1990; Hakala, Kuula, & Hudson, 2007; Kodama, Goto, Fujii, & Hagan, 2013), availability of negative coefficient of lateral deformation (Lubarda & Meyers, 1999; Kimizuka, Kaburaki, & Kogure, 2000), and changes in *Q* factor of rock layers as oscillatory systems etc. (Johnson, Shankland, O'Connell, & Al-bright, 1987; Khan & McGuire, 2001; Pellet & Fabre, 2007). However, the published data are not systemized, and sometimes conflicting; conviction that elastic parameters are constants of the materials is deep in our mind.

In general, scientific sources cover insufficiently deep mining practices as well as the processes taking place during them. Only certain papers, concerning rock mechanics, petrophysics, structural geology, rock shears, and methods to measure them (Khomenko, 2012; Li et al., 2012; Bondarenko, Kharin, Antoshchenko, & Gasyuk, 2013; Lozynskyi, Saik, Petlovanyi, Sai, & Malanchuk, 2018), involve the data helping conclude the necessity to generalize materials connected with mining operations and response of geological environment to it, and necessity to develop new techniques of full-scale and laboratory studies of rock characteristics, to determine regularities of formation of geotechnical conditions, and to formulate theoretical background to forecast mining geological conditions and geodynamic phenomena in part. Moreover, very intensive geodynamic phenomena have been found out in coal mines and ore mines in Belgium, Sweden, the USA, Canada, India, South Africa, Australia, South Wales etc. (Mikhlin & Zhupiev, 1997; Pisetski et al., 2017; Khalymendyk & Baryshnikov, 2018; Starostenko, Pashkevich, Makarenko, Kuprienko, & Savchenko, 2018).

It should be noted that lack of the systemized experimental data for the rock behaviour within volumetric field of compressive stresses, being typical for rock mass, is the key obstacle preventing from solving many geomechanical problems (Shashenko, Gapieiev, Solodyankin, 2009; Menshov & Sukhorada, 2017; Sukhov, Chuyenko, & Suyarko, 2017).

It is hoped that numerous laboratory experiments, carried out by the authors with the help of non-uniform device of volumetric compression designed in DonIPhE of the NAS of Ukraine (Ryazantsev, 2012) using cube samples of coal, argillite, aleurite, and sandstones, help fill the information gap.

2. METHODS

Type of experimental equipment, the number of indices, being registered during the experiment, methods of data processing, methods of the data representation and analysis determine considerably informativeness of experiments.

Dominantly, rocks under non-uniform compression ($\sigma_1 > \sigma_2 > \sigma_3$) have been tested in Ukraine and Russia with the help of the device of non-uniform triaxial compression designed by DonIPhE of the NAS of Ukraine (Fig. 2).

Figure 2. Device of non-uniform compression (DNUC) designed by DonIPhE of the NAS of Ukraine

Despite the fact that the device is unique, a form of representation of research results for the period of its operation and their interpretation kept from complete understanding physics of failure process.

Traditionally, rock behaviour research results are represented in the form of following diagrams: spherical tensor of stresses – relative volumetric deformation; octahedral tangent stress – relative octahedral tangent (shear) deformation; maximum stress – maximum deformation etc. The diagrams make it possible to determine elastic parameters (i.e. modulus of volumetric compression, shear modulus, and coefficient of lateral deformation), characteristic deformations in the context of which elastic parameters vary in the form of jump, regularities of changes in strength and energy intensity of rock failure depending upon a type of stress state and deformation state etc. However, in the context of a general case, neither absolute loading value nor a value of relative deformation can be the failure criterion for one and the same type of a stress state or one and the same spherical tensor of stresses. Strength boundary and boundary relative deformation depend upon numerous factors which effect is not even often understood.

Taking into consideration the fact that traditional approach to experimental data interpretation has already run its course, the paper proposes somewhat different technique to represent them. First of all, it concerns the analysis of growth of the three deformations during loading, their variations, and effect on elastic parameters of rocks since by definition elastic moduli are load increase-deformation growth ratio.

In the process of rock sample tests, deformations are registered with the help of tensor resistant sensors or mechanical ones. Registration of displacements by means of tensor resistant sensors with data output to a personal computer is automated; however, since destructive deformations within the rocks achieve 10 – 20%, and they cannot be registered by the sensors as they operate in a linear zone, mechanical clock-type sensors with 10^{-6} m accuracy should be preferable. It is also more expedient to register pressure according to manometer data. Maximum external load, being formed using 50×50×50 mm sample, is almost 400 MPa when the manometer operates within a safe area. 2 MPa loading degree is taken for adequate and synchronous registration of deformations.

During the experiments, DNUC registers pressure within the hydraulic system using manometers with hydraulic cylinders along axes 1, 2, and 3 as well as displacement of the sample planes with the help of clock-type Δl_1, Δl_2, and Δl_3 indicators. Other parameters are calculated with the help of apparatus of a theory of elastic and plastic behaviour with the difference that stress-deformation dependence is interpreted like piecewise-linear dependence (i.e. when elastic moduli varies during loading) rather than like linear dependence (elasticity theory).

Analysis of the growth of deformations and elastic moduli during loading is the key idea of the paper. The current relative linear deformation of ribs of the samples was determined using $\varepsilon_j = \Delta l_{ij}/l_{io}$ formula where l_{io} is initial value of the dimensions of the sample ribs and Δl_{ij} is current displacement of the sample ribs. Growth of relative linear deformation of the sample ribs is $\Delta\varepsilon_{jn} = \varepsilon_{jn} - \varepsilon_{j(n-1)}$ where ε_{jn}, $\varepsilon_{j(n-1)}$ is current relative linear deformation of ribs of n^{th} and previous loading degree respectively. Volumetric deformations and shear deformations, stresses, elastic parameters, type of deformation state and stress state of Lode Nadai, and Lode angles were determined separately for each load grade taking into consideration corresponding increase in deformations. It should be noted that such studies, concerning changes in parameters during loading, were carried for the first time.

3. RESULTS AND DISCUSSIONS

Figure 3 represents traditional spherical stress tensor-relative volumetric deformation diagrams for samples of coal, argillites, and sandstones with the difference that the diagrams are not smooth; they are piecewise-linear (i.e. polygonal).

The diagrams demonstrate variation of a modulus of volumetric compression of rocks as the diagram slope ratio. Similarly, Figure 4 demonstrates shear modulus variation as a slope ratio of octahedral shearing stress-octahedral tangential (shear) deformation. The diagrams mirror clearly changes in relative deformations during loading. They show breaks with jump-like changes in elasticity moduli meaning that electronic as well as structural and phase transitions are available within the minerals being a part of the rocks.

Figure 3 explains clearly structural and phase transitions of type one and type three. Transitions of type one follow with volume decrease under constant pressure; transitions of type three (so called critical transitions) follow with volume increase under growing pressure. In Figure 3a, behaviour of certain coal samples is interesting when dilatancy (i.e. volume increase in the context of structural and phase transition of type three) is not available. Actually, alternating volumetric deformation under constant pressure is observed within the areas which cannot be represented in terms of such a diagram; after that, pore becomes flatter and volume decreases. Jump-like changes in comprehensive compression in Figure 3, and shear modulus in Figure 4 are indicative of structural and phase transitions of type two.

Figures 5 and 6 demonstrate dependence of strength as well as boundary deformation, and complete deformation upon side pressure and a type of deformation state.

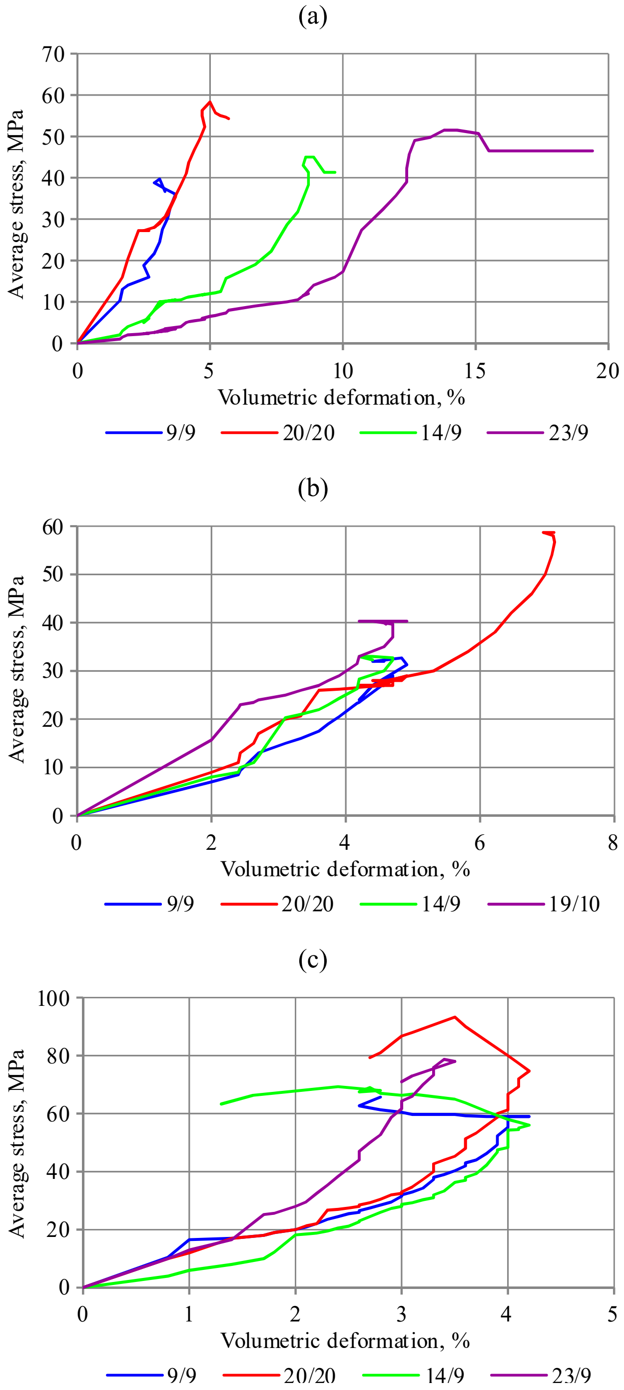

Figure 3. Octahedral normal stress (spherical tensor)-volumetric deformation dependence for the volumetric stress state (slashes separate values of intermediate stress and minimum stress):(a) for coal; (b) for argillites; (c) for sandstones

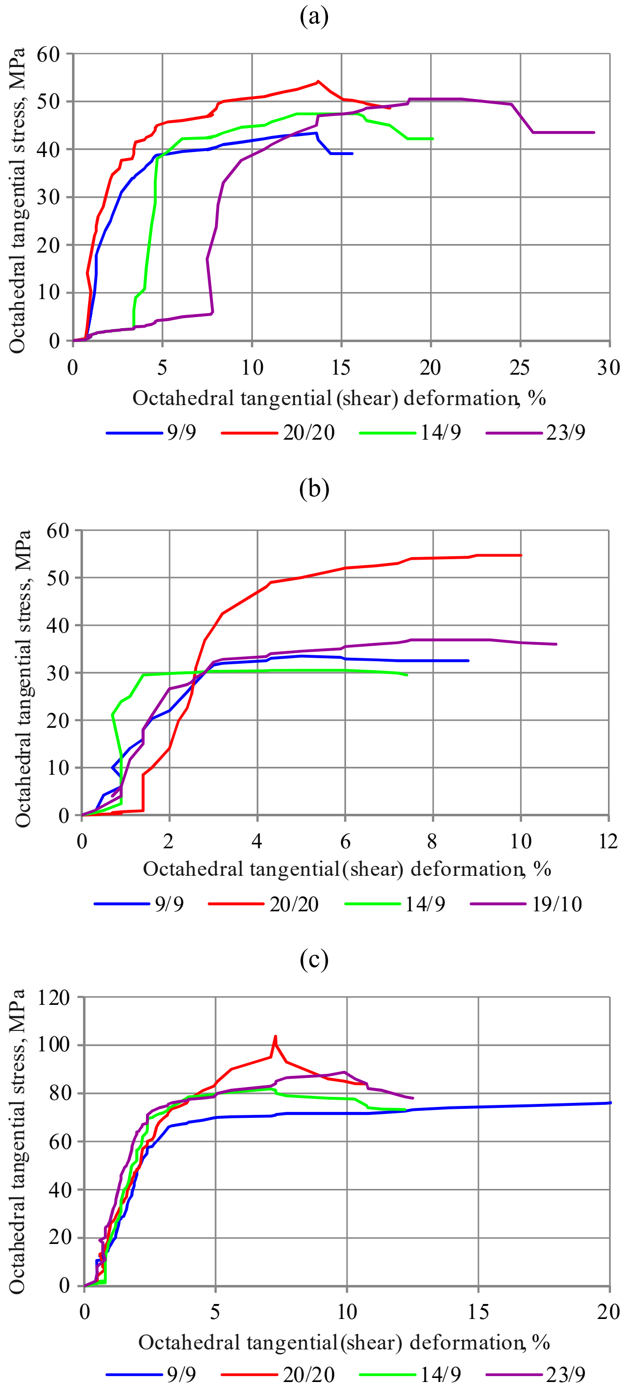

Figure 4. Octahedral tangential stress-octahedral shear deformation dependence (slashes separate values of intermediate stress and minimum stress): (a) for coal; (b) for argillites; (c) for sandstones

As it has been shown in (Ryazantsev, 2012), characteristic deformations, in terms of which changes in elasticity moduli for coal, sandstones, aleurites, and argillites are of jump-like nature, have certain discrete values: 0.64; 1.0; 1.5; 1.8; 2.25; 2.6; 3.0; 3.7; 4.6; 5.8; 6.3; 7.0; 8.3; 9.7; 11.2; 12.7; 13.7; 14.5 and 16.3% which means that structural and phase transitions are of type two. It is characteristic that the same range of discrete deformations is observed in the context of metals and alloys.

However, it is impossible to argue unambiguously and previously what deformations or stresses will result in failure in terms of one or another stress state since dependences are very complex and vary from sample to sample.

As for the changes in deformation growth in the process of deformation and failure, the dependences are practically similar in the context of all rocks, types of stress state, and spherical tensor values. Hence, it is expedient to search for failure predecessors while analyzing changes in deformation growth during loading.

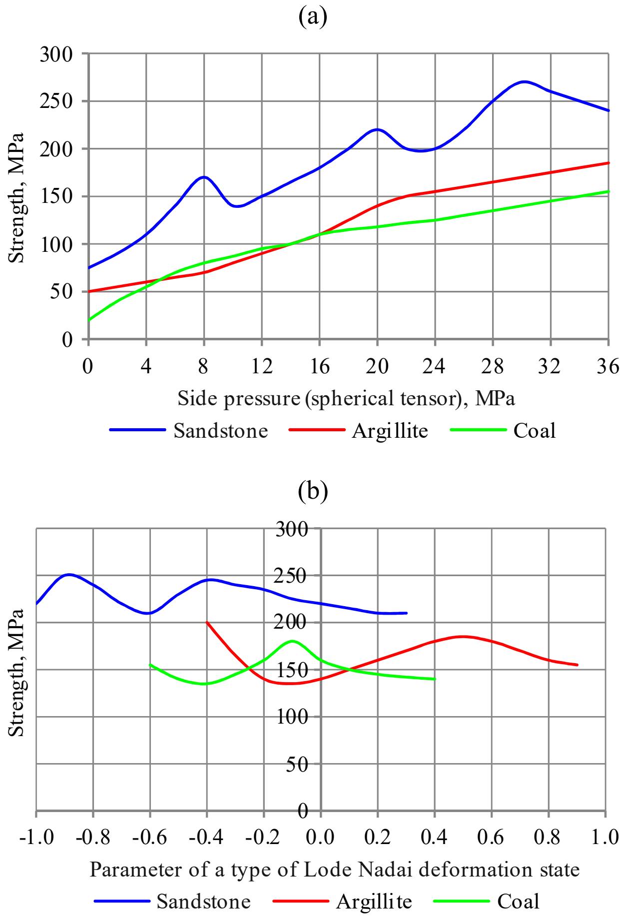

Figure 5. Octahedral normal stress (spherical tensor)-volumetric deformation dependence for the volumetric stress state (slashes separate values of intermediate stress and minimum stress):(a) for coal; (b) for argillites; (c) for sandstones

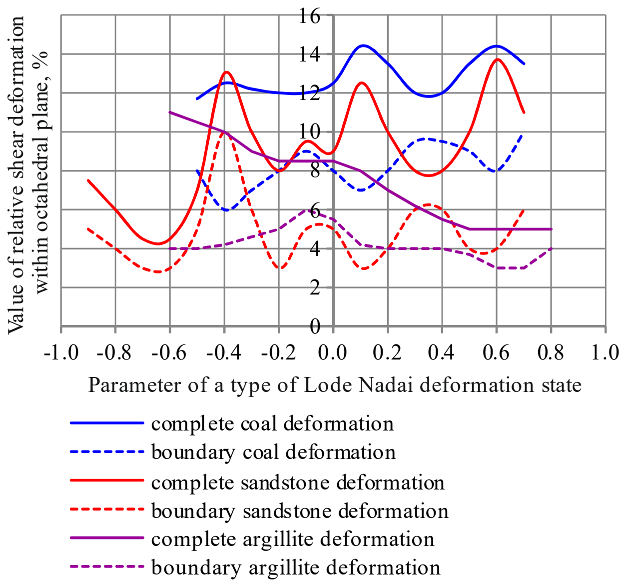

Figure 6. Dependence of tangential (shear) deformation of coal and enclosing rocks upon a type of deformation state, if $\sigma_3 = 20$ MPa

Figures 7 and 8 demonstrate changes in growth of volumetric, shear, and linear relative deformation during coal sample loading in terms of different types of stress state.

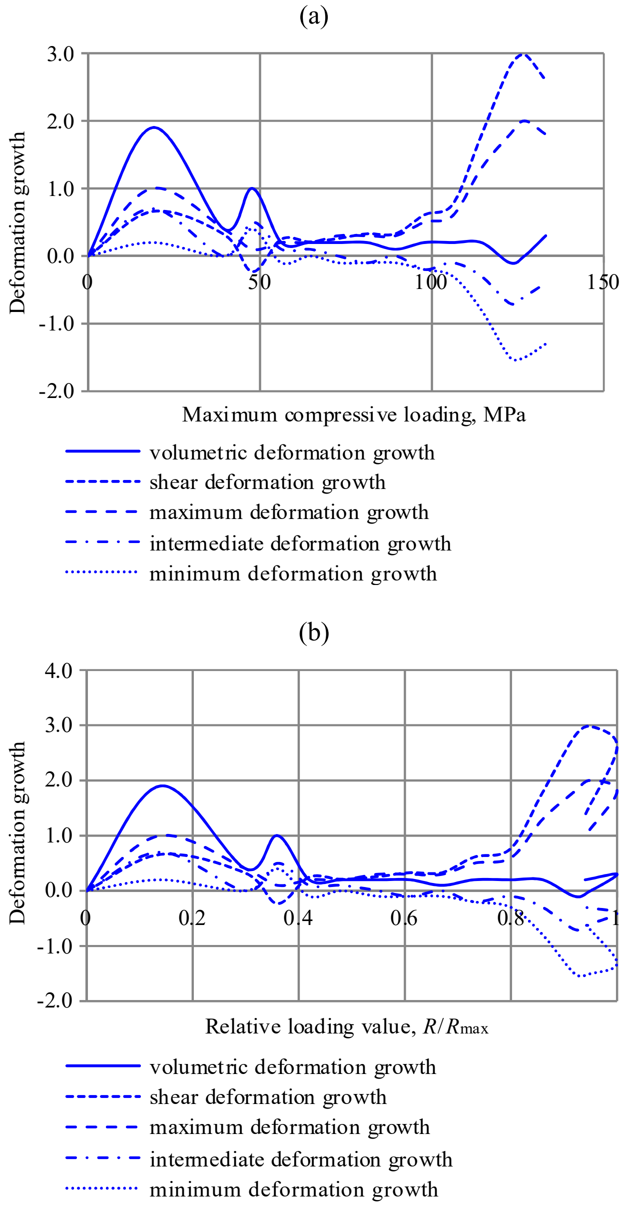

Figure 7. Changes in volumetric, shear, and linear deformation growth during coal sample loading, if $\sigma_1 > \sigma_2 = \sigma_3 = 20$ MPa of absolute value of maximum compressive stress (a); and relative value of maximum loading (classified as a failure one) (b)

Figures 9 and 10 demonstrate similar dependences for sandstone; and Figure 11 – for argillite.

In the following, the explanatory legend will be shortened. Since deformation growth is the question, only specific deformation will be meant in the explanatory legend.

Analysis of the data should involve such a fact that rocks deformation in terms of mechanical loading under the conditions of non-uniform triaxial compression can be divided into four stages:

1. Intensive volume decrease at the initial deformation stage with no change of a form (if loads are up to 0.3 – 0.4 of breaking ones).

2. Decrease in volumetric deformation down to zero (i.e. achievement of dilatancy threshold or more precisely, compressive boundary); and growth variation of other deformations where amplitude is not more than 0.5% (if loads are up to 0.6 – 0.75 of breaking ones).

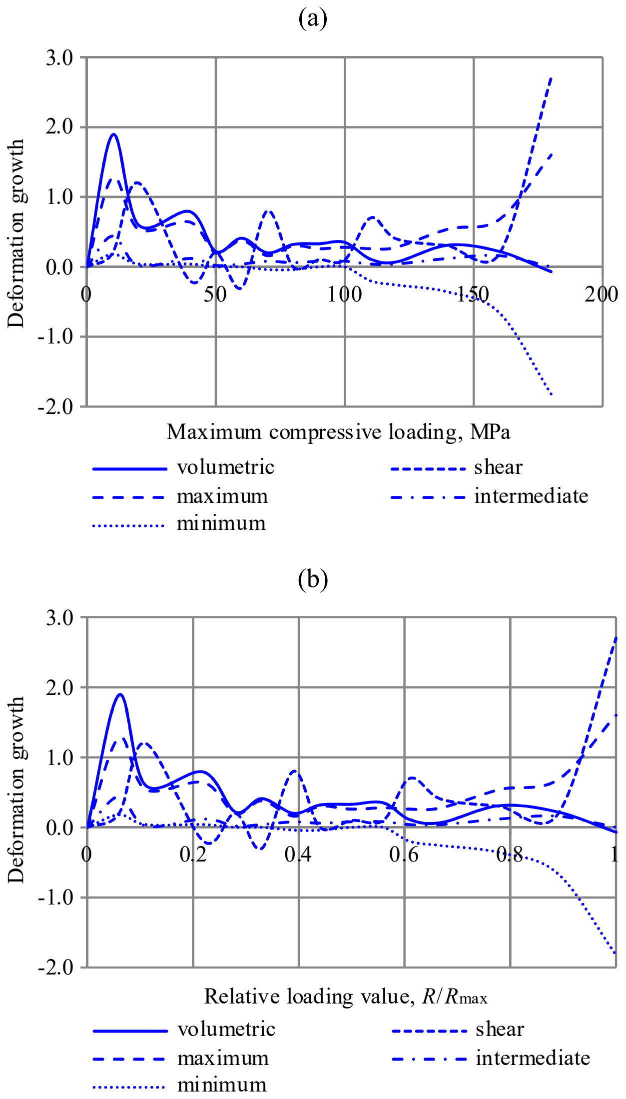

Figure 8. ***Changes in volumetric, shear, and linear deformation growth during coal sample leading, if $\sigma_1 = \sigma_2 > \sigma_3 = 22$ MPa of absolute value of maximum compressive stress (a); and relative value of maximum loading (classified as a failure one) (b)***

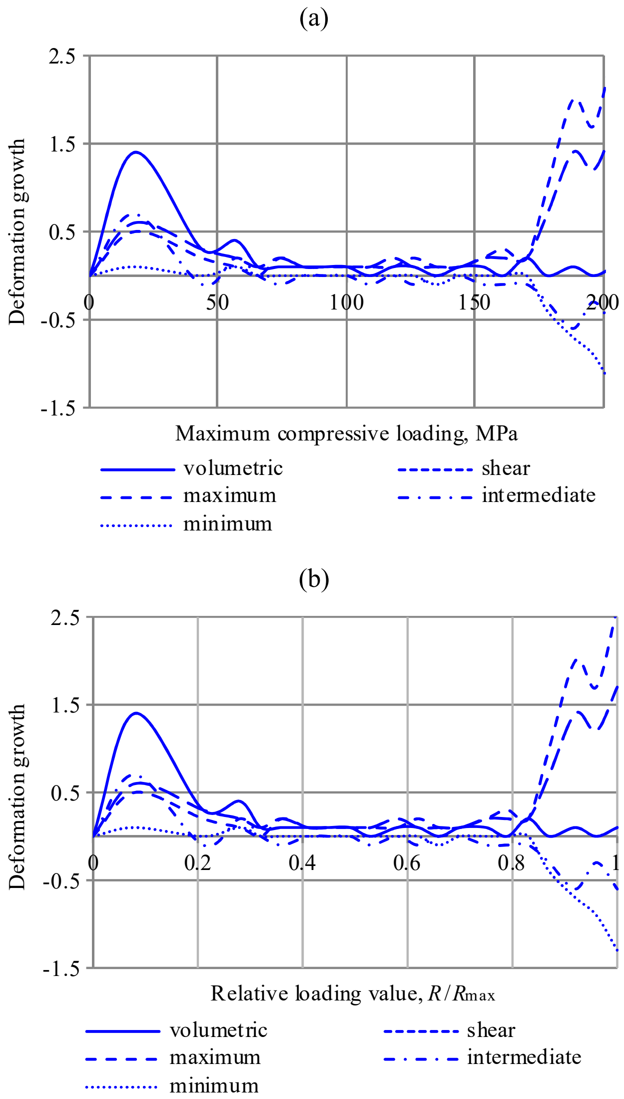

Figure 9. ***Changes in growth of volumetric, shear, and linear deformations during sandstone sample loading, if $\sigma_1 > \sigma_2 > \sigma_3$ ($\sigma_2 = 23$ MPa; and $\sigma_3 = 9$ MPa)***

3. Increase in shear, minimum, and maximum linear deformations (if loads are 0.85 – 0.9 of breaking ones being very sharp, i.e. up to several per cent); increase in rock volume.

4. Growth inversion of each deformation type and dynamic rock failure with sharp loading decrease (is considered right before failure in terms of 0.99 of breaking loading).

Plastic oscillation shear process (i.e. flow) takes place when loading decrease is not available.

Availability of stage three, when growth amplitude of linear deformation and shear deformation experiences several times increase (i.e. tenths of a percent to more than one per cent), confirms availability of resonance phenomena. Failure transition to dynamic or a flow depends upon resonance type. In this connection, it is expedient to consider the idea of vortex-wave resonance developed in many papers starting from (Panin & Grinyaev, 2003; Panin, Panin, & Moiseenko, 2007).

According to the idea (Basin, 2000; Basina & Basin, 2006), separation boundary of three-dimensional environments (i.e. boundaries of certain layers or blocks within the rock mass) is considered as two-dimensional surface. If three environments with different characteristics neighbour (for instance, coal seam, roof, and face space atmosphere), their common border is considered as a one-dimensional line. Origination of blast waves within continuous environment is the mechanism to form the boundaries. That makes it possible to classify phase separation boundaries and similar as nonlinear blast waves; consider solid body as a wave body, and its boundaries – as nonlinear blast waves.

Near-boundary layer with resonance jump of density is being formed in the neighbourhood. In the context of mechanical loading of rocks, energy is redistributed within the stress state with actua-lization of both translation and return modes being observed within the boundaries of distribution of structural components (i.e. within the boundaries of grains, blocks, tectonic plates etc.).

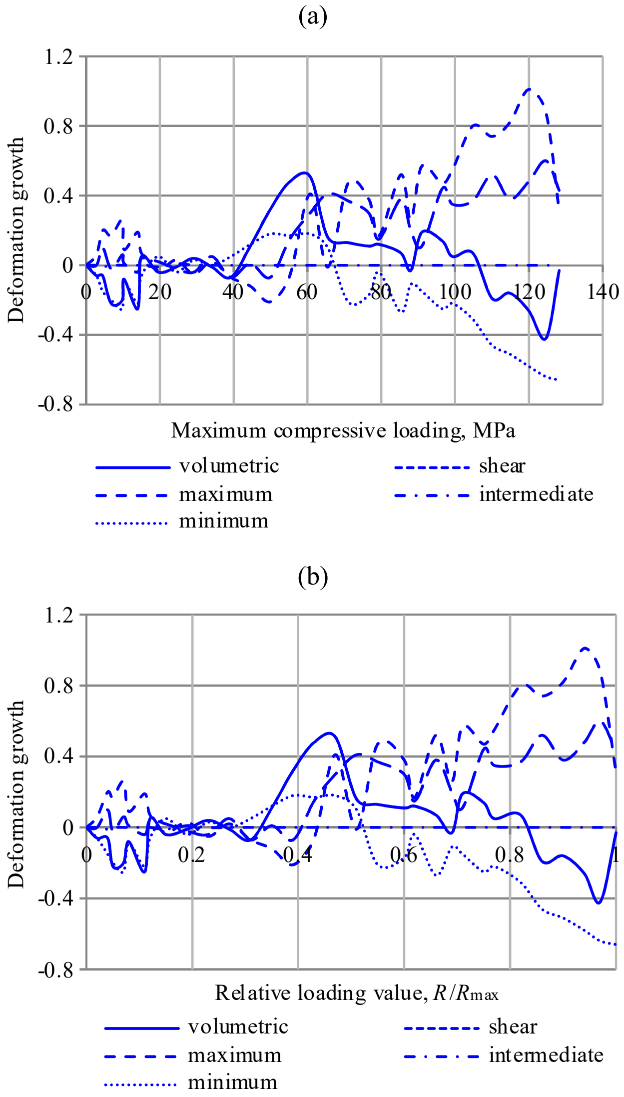

Figure 10. Changes in growth of volumetric, shear, and linear deformation during sandstone sample loading, if $\sigma_1 > \sigma_2 = \sigma_3 = 13$ MPa

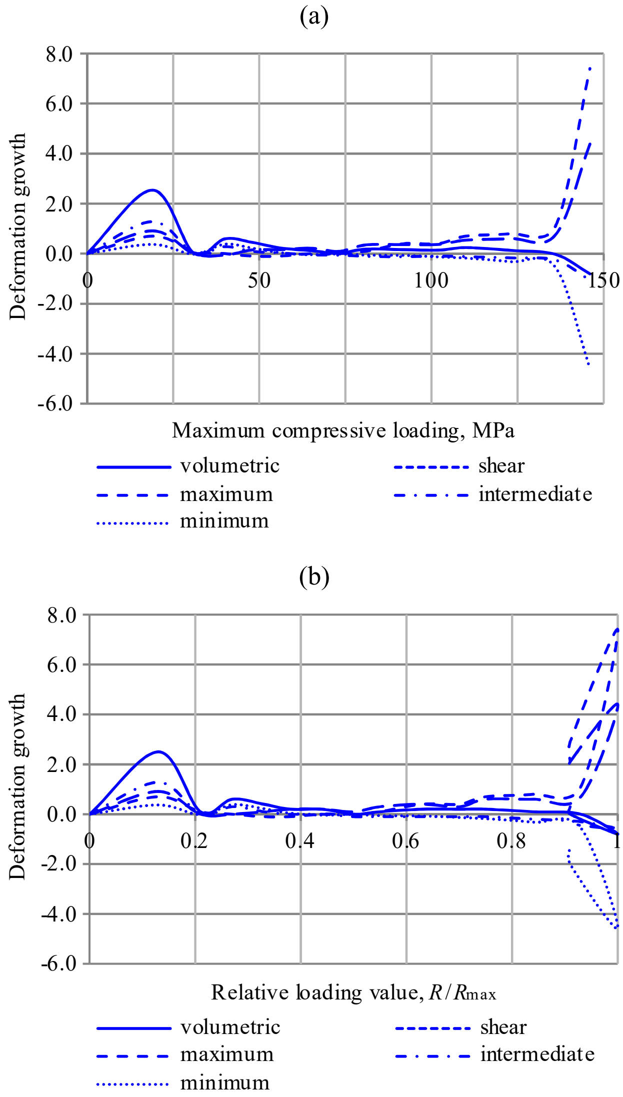

Figure 11. Changes in growth of volumetric, share, and linear deformation during argillite sample loading, if $\sigma_1 > \sigma_2 > \sigma_3$ ($\sigma_2 = 20$ MPa; and $\sigma_3 = 16$ MPa)

Rotational and vortex mechanism of rock failure is as follows: it takes place within the areas of return and shear modes generating by block boundaries. In this context, both left- and right hand rotations of corresponding rock masses; transition of right hand polarization to left hand polarization is possible. During the transition at the moment of polarization sign alternation (i.e. linear polarization) "discharge" of wave energy, accumulated within the rock mass, takes place. The energy is consumed by failure. Breaking mechanisms are similar at microlevel and at mesolevel. Paper (Ryazantsev & Starikov, 2013) confirms rotational nature of shear deformations within the volumetric field of compressive stresses. As an example, Figure 12 demonstrates the change in deformation vector rotation before breaking in coal.

If positive pressure gradient is available, double spiral vortex originates within the near-boundary layer. Numerous reclosing processes take place within the vortex, and vortex bubble is formed. If there is a fissure or a channel from which gas-coal mixture flows out, circular bubble is shaped in terms of certain ratio between its dimensions and the channel radius.

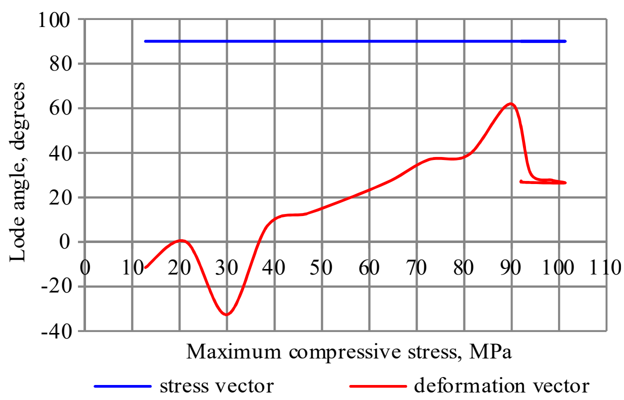

Figure 12. Change in deformation vector turn direction during coal loading, if $\sigma_1 > \sigma_2 = \sigma_3 = 9$ MPa

The bubble separates away from a stope leaving behind it a vortex flow, and so-called mushroom-shaped structure is formed. Similar structures arise within the borders of the near-boundary layer between seam and enclosing rocks, separate coal benches, between seam and face space during sudden outbursts, sudden archings, explosions of dust-gas-air mixture, atomic explosions etc.

Minimally, the three types of the related nonlinear wave processes, involving mushroom-like structures are singled out:

1. Displacement of the structure boundary relative to the environment – mushroom-like structure as a wave body.

2. The structure-environment exchange with material resources and information resources.

3. Circulation of substance, energy, and information inside the mushroom-like structure.

Free vortex motion is resonance variant of the forced motion. In this context, equality between a velocity of vortex pair motion and central vector of the environment velocity is a resonance condition. The condition is an individual case of the vortex-wave and structural resonance. It is characteristic that in the context of the concept, velocity of elementary wave propagation within the environment is determined by means of a length of an exciting wave (i.e. velocity resonance). The waves, differing in their length, are either of higher velocity or lower velocity respectively; thus, resonance is not available. If motion of the environment particles becomes equal to sonic velocity, resonance takes place with each wave of the spectrum. Resonance increase in amplitude of waves, being of different lengths, originates nonlinear impact wave, vortex structures, and mushroom-like structures. Following types of vortex-wave and structural resonances are singled out:

1. Velocity and frequency resonance – resonance excitation by a vibrating system, i.e. only one wave of the potential wave spectrum within the environment.

2. Velocity and geometry resonance – resonance excitation of waves by means of a vibrating system or by means of a vortex system when characteristic geometry of the system or its structural component are either close to the vibrating system geometry or divisible by it.

3. Double vortex-wave resonance in terms of velocity, geometry, and parameters of vortex structures. It factors into sharp change in the flow circulation within the environment, wave-environment interaction, origination of dispersive waves as well as new vortex structures.

4. Structural resonance – resonance interaction between several nonsymmetrical systems with distribution boundaries or vortex structures.

Coincidence or multiplicity of lengths, velocities, and frequencies of nonlinear interacting periodical or separate waves is the criterion to forecast and predict geo- and gasodynamic phenomena. If any of the located nearby structures (i.e. layers or blocks), placed within certain common field through which they can effect each other irrespective of their displacement relative to the field, condition two (i.e. approximate velocity of nonlinear wave structures) is performed automatically. As it is demonstrated in (Kurlenya, Oparin, & Eremenko, 1993; Glikman, 2003; Glikman, 2005a; Glikman, 2005b), each structural component of the Earth is resonator for all geomaterials and the Earth on the whole; velocity of shear waves is similar being 2500 m/s ± 10%. Condition one is fulfilled at the expense of relatively similar geometry of blocks within rock mass as well as one multiplicity modulus during transition from one scale level to another one (Kurlenya, Oparin, & Eremenko, 1993; Makarov, 2004; Oparin & Tanaylo, 2009). However, it is expedient to search for resonance interacting objects as well as for their resonance parameters.

According to (Kumchenko, 2002a; Kumchenko, 2002b; Kumchenko, 2009). World source of wave energy (WSWE) with $T = 160$ min period is external loading for each space object. WSWE is a self-gravitation source of each planet and the Sun itself; planets of the Solar system are within WSWE antinodes. The excitating zero oscillation frequency effects all structural planetary objects being resonators. According to a resonator theory, total energy of oscillator-resonator system depends upon oscillating amplitudes and phases as well as mutual arrangement of the both oscillators since resonator is considered as secondary oscillator which amplitude and phase are functions of deformation field, resonator parameters, and exciting frequency. Source-resonator system is a system with a single degree of freedom and one antiresonance frequency. In the immediate vicinity of resonance frequency, resonator initiates increase in the intensity of the source oscillation; in the neighbourhood of antiresonance, source oscillation decreases. However, substantial growth of the amplitude of proper resonator oscillations is observed. Increase in impedance (i.e. wave resistance) is $Z = \rho V_p = (\rho K)^{0.5} = \pm \infty$, and $Z = \rho V_s = (\rho G)^{0.5} = 0.5Z_{ap}$ is for antiresonance where ρ is rock density, V_p is primary wave velocity, K is volumetric compression modulus, V_s is shear wave velocity, G is shear modulus, and Z_{ap} is wave resistance of antiresonance.

As it has been shown in (Glikman, 2003; Glikman, 2005a; Glikman, 2005b), in the context of normal wave fall on the distribution layer-resonator border on a resonance frequency (i.e. monochromator frequency), wave dissipation is not available and complete wave transmission is observed. In this context, connection between frequency, characteristic size of resonator, and wave velocity is:

$$f_{mx} = \frac{V_p}{2l} \cdot k \,, \tag{1}$$

where:

V_p – a velocity of longitudinal component of volumetric wave;

l – a characteristic geometry of layer, block (thickness for a layer);

k – harmonic order.

Monochromator effect is observed in any material, and on each harmonic; it moves over longitudinal waves and is half-wave for parallel-plane layers. Since mass-transfer and energy-transfer are not available in the mode of stationary waves and longitudinal wave velocity is phase velocity.

Adverse effect, i.e. so called acoustic resonance absorption (ARA), arises at antiresonance frequency. In this context, connection between frequency and characteristic resonator size is:

$$f_0 = \frac{V_s}{l} \cdot k \,, \tag{2}$$

where:

V_s – a velocity of longitudinal component of volumetric wave.

Partial wave attenuation is observed, if ARA effect takes place; all the rest is absorbed by resonator layer turning into its proper oscillations which do not leave the layer boundaries but propagate along its borders without attenuation of falling down orthogonal wave. ARA effect is observed within unpaired harmonics, it moves over longitudinal waves. It is harmonic for plane-parallel layer and trajectory of particles is of rotational (i.e. vortex) nature.

Hence, wave interaction is divided into two motions: active vortex motion at the frequency of proper oscillations of structural component of rock mass and reactive pulsating motion as a response for external component of volumetric wave entering the Earth from all directions (Kumchenko, 2002a; Kumchenko, 2002b; Kumchenko, 2009). Thus, two way types propagate within a matter of each rock layer or block: compression-expansion waves, connected with volume variations and distortion waves, connected with vortex motion and shape variation. Under the external pulsating pressure, volumetric plastic wave is formed with following velocity:

$$V_p = \sqrt{\frac{K}{\rho}}, \quad (3)$$

where:

K – a volumetric compression module;

ρ – a rock density.

Velocity of shear wave of proper oscillations is:

$$V_s = \sqrt{\frac{G}{\rho}}, \quad (4)$$

where:

G – a share modulus.

As it has been shown above, resonance origination should involve equality of the velocities which is possible when volumetric compression modulus and share modulus are equal.

It has been mentioned above that in the process of rock sample test when non-uniform compression takes place, elastic parameters vary during loading. As an example, Figures 13 – 16 demonstrate changes in elastic parameters of coal and sandstone in terms of different stress states.

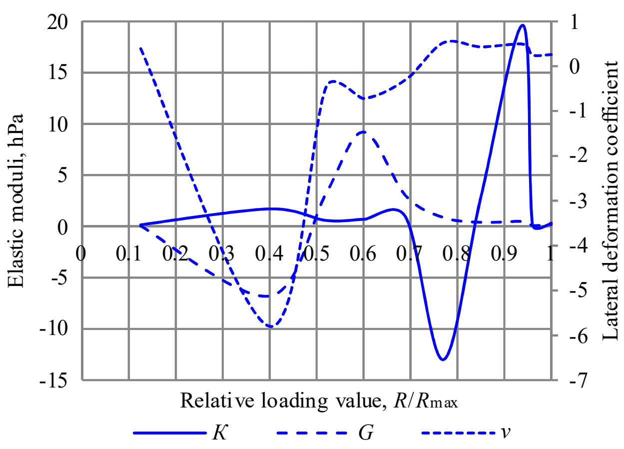

Figure 13. Change in elastic parameters of coal during loading if $\sigma_1 > \sigma_2 > \sigma_3$ (σ_2 = 23 MPa; σ_3 = 9 MPa)

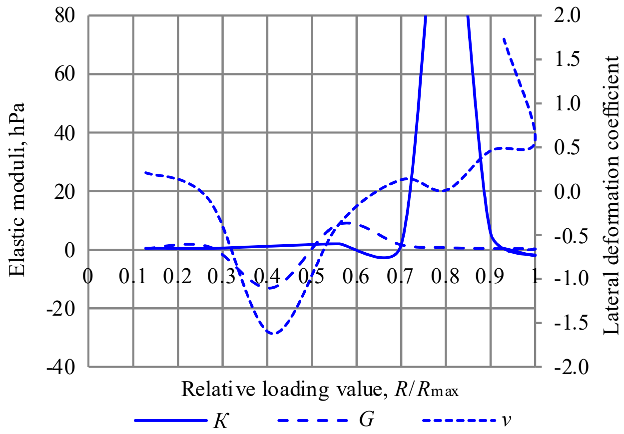

Figure 14. Change in elastic parameters during coal loading if $\sigma_1 > \sigma_2 > \sigma_3$ (σ_2 = 30 MPa; σ_3 = 20 MPa)

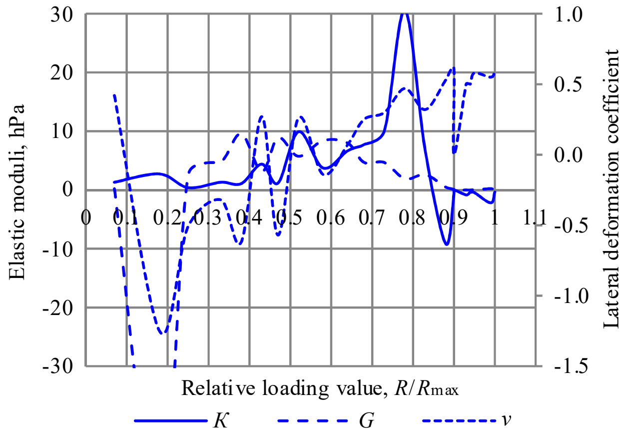

Figure 15. Change in elastic parameters of sandstone during loading, if $\sigma_1 > \sigma_2 = \sigma_3$ = 9 MPa

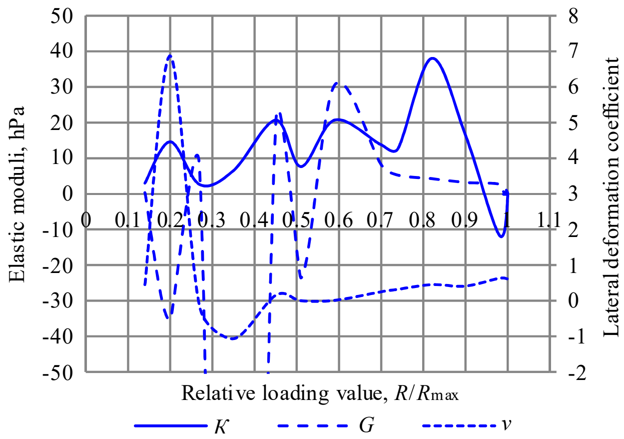

Figure 16. Change in elastic parameters of sandstone during loading, if $\sigma_1 > \sigma_2 > \sigma_3$ (σ_2 = 35 MPa; σ_3 = 20 MPa)

The data mean that coal and sandstone are classic auxetics and have negative coefficient of lateral deformation (coal as a classic poroplast, and sandstone as a classic rock with minerals having polymorphic transformations).

Up to the compression border, shear modulus varies periodically passing in sandstones through bifurcation point (–∞); after achieving the compression border it decreases gradually down to a half of antiresonance value.

Volumetric compression modulus varies to the compression border; within it, the modulus increases sharply often passing through bifurcation point (+∞). After the bifurcation point it changes its sign either taking negative values or decreasing significantly.

Moduli become equal several times during the loading process (i.e. velocity resonance occur); however, up to the compression border it takes place in the context of antiphase variation of moduli and parallel resonance in a monochromator mode takes place (i.e. current). Only after bifurcation of comprehensive compression modulus, the moduli become equal in the context of in-phase decrease; series resonance starts in ARA mode with the sharp growth of deformation amplitude (by an energy factor achieving 100 in rocks). Shear modulus becomes more than volumetric compression modulus (i.e. velocity of the substance particles is more than sonic velocity) and impact wave originates.

In the context of parallel resonance (monochromator effect), solid body flows like a fluid. If radial and axial symmetric flows are available then slide curves form two orthogonal series logarithmic vortex-like spirals within the environment. If the substance flows, deformation vector rotates which results in residual displacement accumulation as well as in the directed substance transfer inside the flowing area. Later that factors into the infinite growth of internal deformations while external deformations are remaining minor. Current area becomes spiroid. Despite the increased viscosity, the current kinetics does not experience even quantitative changes; thus, effect of differential rotation or the directed mass transfer will be similar for gas, liquid, and solid body.

Series resonance (i.e. ARA effect) originates in the process of the deformation development and the current velocity increases by an order or two. At a certain stage, velocity of the substance particles becomes equal to sonic velocity within the environment as a result of origination of impact wave and explosive fracture. The phenomenon is the most probable in the context of gas saturated disintegrated rocks when sonic velocity within the environment is decreased. This very process can explain origination of earthquakes, various geodynamic phenomena etc.

Preparation period for "discharge" of other energy types, period of the "discharge" during earthquakes, volcanic activities, rock bursts, sudden outbursts etc., and period to come back to the stable state is always equal to the period of proper oscillations of one or another structural component of the Earths lasting from several seconds to 10 – 240 minutes. For instance, in O.O. Skochynsky mine, when outbursts of sandstone and gas take place, weak second pulse and methane release always follows after 4 hours (i.e. 240 minutes).

As an example of one of geodynamic phenomena as a result of vortex-wave resonance is a series of sudden outbursts in longwall 2 of Central inclined drift of seam l_1 in Stakhanov mine (Kapitalna mine now). Characteristic features of the occurrence are:

1. Impact within the rock mass with wedge-like fissure between roof sandstone and coal seam; depth of the fissure is down to 4 m.

2. 0.8 – 1.0 m displacement of the seam in block towards the mined-out area within 20 m area.

3. Formation of a pipe-like vortex cavity with 300 mm diameter at 45º angle within the rock mass depth opposite to 224 section at the distance of 4.0 – 4.5 m from a working face inclined towards the mined-out area as well as thin 10 mm vortex near-boundary areas at roof and floor. They are filled with red ash left after coal substance sublimation resulting from structural and phase transition of type one, i.e. solid matter-gas.

4. Local formation of 120 mm diameter channel opposite to section 226. It discharged small amount of wet coal dust and gas (up to 15 – 20 t of coal and 15 – 20 m^3 of methane) as well as powerful energy flow with the growth of characteristic gas-dust cloud, and impact wave which resulted in broken coal shearer, conveyor, and support sections. Moreover, workers were injured within a radius of 20 m (included those injured fatally).

5. Water condensation on the roof and equipment as a result of opposite structural and phase crystallohydrate water – free water transition in coal.

6. Crystobalite emersion within enclosing rocks resulting from structural and phase transition of type two α-quartz → β-crystobalite with 12.7% volume increase.

4. CONCLUSIONS

Hence, during loading process within volumetric field, rocks behave like classic auxetics when elastic parameters experience value variations up to ± infinity as a result of electronic transitions and structural and phase transitions. Shear deformations in rocks are of rotational (vortex) nature.

Deformation growth is alternating which is stipulated by wave character of their expansion. Four strict stages are singled out during rock loading:

1 – intensive volume increase at the initial deformation stages with minor shape variation when the loads are up to 0.3 – 0.4 of breaking ones;

2 – decrease in volumetric deformation growth down to zero (i.e. achievement of compression boundary), variations of residual deformation growth with no more than 0.5% amplitude (when loads are up to 0.6 – 0.75 of breaking ones);

3 – resonance increase in shear, minimum, and maximum linear deformations up to several per cent in terms of loads being 0.85 – 0.99 of breaking ones, increase in rock volume;

4 – inversion of growth of all deformation types, and dynamic rock failure with sharp decrease in load or current in terms of constant pressure (it is observed right before failure in terms of 0.99 of breaking load).

From the viewpoint of breaking forecast, stage three is the most interesting – resonance deformation growth when both stope and boundary of a mine working start "breathing" with more than 2% amplitude (i.e. 10 – 20 mm). Increase in deformation growth amplitude is connected with double resonance in terms of velocity, dimensions, and frequency. In the context of resonance (i.e. monochromator effect), current is observed with complete transmittance of deformation wave with no reflection, dissipation, and absorption. In the context of antiresonance (i.e. effect of resonance acoustic absorption), exciting wave experiences its partial reflection; the other part transforms into proper oscillation process on the shear (vortex) vertical waves. Oscillation amplitude increases by an order of energy factor and rock falls in a dynamic mode with the discharge of seismic energy, electromagnetic energy, and acoustic energy. Since the difference between frequencies of resonance and anti-resonance is 15% only, sudden transition from current to dynamic failure (so called lagged dynamic phenomenon) is possible.

Resonance increase in amplitude growth of minimum deformation (working face) and maximum deformation (roof) which can be registered by means of distance meter or scanner with ±3 mm accuracy has been proposed as a predecessor of geodynamic phenomena.

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РЕЗОНАНС У ГІРСЬКОМУ МАСИВІ ЯК ОСНОВНА ПРИЧИНА ГЕОДИНАМІЧНИХ ЯВИЩ

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Мета. Розробка деформаційного критерію або передвісника геодинамічних явищ у гірському масиві на основі систематизованих експериментальних даних з поведінки порід в об'ємному полі стискаючих напружень.

Методика. Експериментальні дослідження з деформування і руйнування гірських порід в об'ємному напруженому стані виконувались на установці нерівнокомпонентного об'ємного стискання конструкції ДонФТІ НАН України. Об'ємні та зсувні деформації, напруження, пружні параметри, параметри виду деформаційного і напруженого стану Надаі-Лоде, кути Лоде визначались окремо для кожного ступеня навантаження, враховуючи відповідний приріст деформацій. Шахтні спостереження раптових видавлювань вугільного пласта та їх характерні ознаки проводились у 2-й лаві центрального бремсбергу пласта l_1 шахти "Капітальна".

Результати. Показано, що гірські породи є класичними ауксетиками, в яких пружні показники у процесі механічного навантаження змінюють величину і знак. Встановлено, що характерні деформації, при яких пружні характеристики змінюють свою величину, є квантованими і постійними для всіх матеріалів. В процесі деформації виділено чотири характерних етапи, притаманних всім породам незалежно від виду напруженого стану і величини всестороннього тиску. Виявлено, що передвісником руйнування є різке зростання амплітуди приросту лінійних і зсувних деформацій внаслідок подвійного вихро-хвильового резонансу по швидкості, розмірах структур та частоті (третій етап). Запропоновано в якості критерію руйнування зростання приросту мінімальної (коливання груді вибою пласта) і максимальної (коливання покрівлі або боків виробки) відносних деформацій до кількох відсотків.

Наукова новизна. Вперше виявлено, що в об'ємному напруженому стані приріст деформацій має знакопемінний характер, пружні характеристики гірських порід не є константами матеріалу, а змінюються за величиною і за знаком у процесі механічного навантаження, зсувні деформації мають ротаційний характер.

Практична значимість. Резонансне зростання амплітуди приросту максимальної, мінімальної і зсувної деформацій є критерієм руйнування взагалі, та динамічного руйнування зокрема, що на практиці може використовуватись як передвісник або прогнозний критерій руйнування.

Ключові слова: *геодинамічні явища, пружні характеристики, приріст деформації, резонанс, руйнування*

РЕЗОНАНС В ГОРНОМ МАССИВЕ КАК ОСНОВНАЯ ПРИЧИНА ГЕОДИНАМИЧЕСКИХ ЯВЛЕНИЙ

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Цель. Разработка деформационного критерия или предвестника геодинамических явлений в горном массиве на основе систематизированных экспериментальных данных по поведению пород в объемном поле сжимающих напряжений.

Методика. Экспериментальные исследования по деформированию и разрушению горных пород в объемном напряженном состоянии выполнялись на установке неравнокомпонентного объемного сжатия конструкции ДонФТИ НАН Украины. Объемные и сдвиговые деформации, напряжения, упругие параметры, параметры вида деформационного и напряженного состояния Надаи-Лоде, углы Лоде определялись отдельно для каждой степени нагрузки, учитывая соответствующий прирост деформаций. Шахтные наблюдения внезапных выдавливаний угольного пласта и их характерные признаки проводились во 2-й лаве центрального бремсберга пласта l_1 шахты "Капитальная".

Результаты. Показано, что горные породы являются классическими ауксетиками, в которых упругие показатели в процессе механического нагружения изменяют величину и знак. Установлено, что характерные деформации, при которых упругие характеристики изменяют свою величину, являются квантованными и постоянными для всех материалов. В процессе деформации выделено четыре характерных этапа, присущих всем породам независимо от вида напряженного состояния и величины всестороннего давления. Выявлено, что предвестником разрушения является резкий рост амплитуды прироста линейных и смещенных деформаций в результате двойного вихре-волнового резонанса по скорости, размерах структур и частоте (третий этап). Предложено в качестве критерия разрушения роста прироста минимальной (колебания груди забоя пласта) и максимальной (колебания кровли или боков выработки) относительных деформаций до нескольких процентов.

Научная новизна. Впервые выявлено, что в объемном напряженном состоянии прирост деформаций имеет знакопеременный характер, упругие характеристики горных пород не являются константами материала, а изменяются по величине и по знаку в процессе механической нагрузки, сдвижные деформации имеют ротационный характер.

Практическая значимость. Резонансный рост амплитуды прироста максимальной, минимальной и смещенной деформаций является критерием разрушения вообще, и динамического разрушения в частности, что на практике может использоваться как предвестник или прогнозный критерий разрушения.

Ключевые слова: *геодинамические явления, упругие характеристики, прирост деформации, резонанс, разрушение*

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