Rock Failure Mechanism / Механизмы разрушения горных пород

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Makarov V., Golosov A., Ksendzenko L., Opanasiuk N.

VLADIMIR V. MAKAROV, Doctor of Technical Sciences, Professor, Department of Mining Engineering, School of Engineering, Far Eastern Federal University, Vladivostok, Russia. 8 Sukhanova St., Vladivostok, Russia, 690950, e-mail: vlmvv@mail.ru
ANDREI M. GOLOSOV, Engineer, Department of Mining and Complex Developing of Georesources, School of Engineering, Far Eastern Federal University, Vladivostok. 8 Sukhanova St., Vladivostok, Russia, 690950, e-mail: a-dune@mail.ru
LUDMILA S. KSENDZENKO, PhD, Assistant-Professor, Department of Algebra, Geometry and Analysis, School of Natural Sciences, Far Eastern Federal University, Vladivostok. 8 Sukhanova St., Vladivostok, Russia, 690950, e-mail: ksendzenko@mail.ru
NICOLAI A. OPANASIUK, Assistant-Professor, Department of Mining Engineering, School of Engineering, Far-Eastern Federal University, Vladivostok, Russia. 8 Sukhanova St., Vladivostok, Russia, 690950, e-mail: neksan1@mail.ru

The mechanism of reversible deformation phenomena in highly stressed rock samples conditions

For the first time, attention to the reversible character of linear deformations of rocks was drawn, in all probability, by T.R. Seldenrath and J. Gramberg in 1958. While searching for precursors of deformations, the reversible deformations were determined also by I.S. Tomashevskaya and Ya.N. Khamidullin (1972), who advanced the dilatancy hypothesis. In 1986, K. Tazhibaev pointed to residual stresses as the causes of the reversible deformations. However, as M.A. Guzev and V.M. Makarov stated in 2005, none of the hypotheses can explain the occurring abnormalities in a conclusive way. The present article deals with the reversible deformations investigated by a complex acoustic and deformation method, whereas the results are presented from the position of the self-balanced stresses.

Key words: sample, reversible deformation, mathematical model.

Experimental research into the regularity of the high stressed rock samples field near to the source of macrofailure

Based on previous researches, a two-phase model of the macrocrack formation, consisting of a period of scattered microcracking followed by a stage of formation of the source of macrofailure and then macrodefect development, has been assumed [4]. The source field is often modeled by inhomogeneity in the form of a soft inclusion, calling the formation round it an area of consolidation at the expense of disproportionation of stress [1]. Modern methods of researches applying servocontrolled rigid loading devices allow measurements to be taken directly before failure, and multichannel measurement systems – to research the behaviour of the sample as a whole, including around the site of the failure source.

The technique of multidot deformation research of samples of strongly compressed rocks provides uniaxial loading of samples by the servocontrolled rigid loading machine MTS-816. This uses resistance strain gauges as a way of taking local measurements of deformations, both in the central part of the sample, and on its height. Thus the «cross» design of the resistance strain gauge allows measurements to be taken of both the longitudinal and lateral strains in a single position, which eliminates the possibility of the joining of individual measurements of the different processes. The conditions of loading, face conditions and sizes of the samples at compression are accepted, taking into account the effect of contacts of end faces with a load machine [3].

Research was conducted on samples of various rocks, including dacites, rhyolite, diorite, and granite-porphyry. Resistance strain gauges were attached at equal intervals on the whole of the sample, with from four to eight pairs in each row and from one (in the middle) to three rows in height. The special circuit design of their fastening has been developed to preserve the wire leading-outs on the sample. The readings from the resistance strain gauges were fixed by means of a computer program on the multichannel device UIU-2000. This research was carried out at the Geodynamics Laboratories at FEFU.

In Fig. 1b, the schema of the sensors displacement is shown during tests. In total, 4 series on 10 samples were tested. The tests were carried out at uniaxial compression of samples under the multidot schema of measurements with from 8 to 48 sensors (Fig. 1).

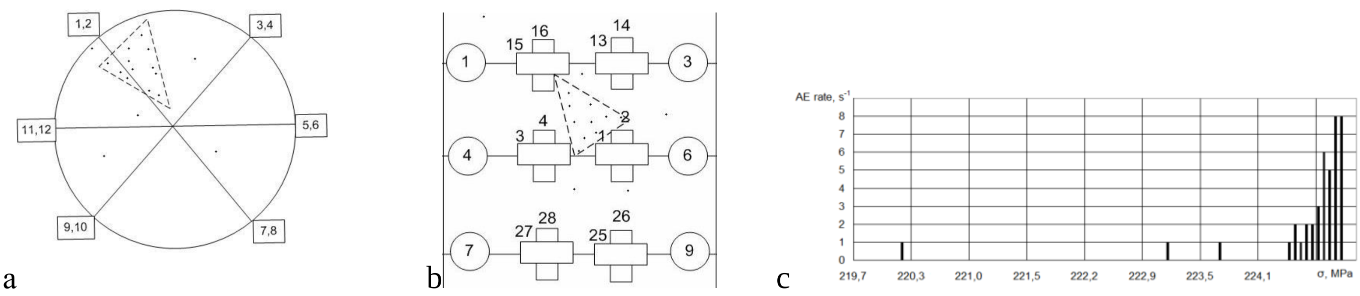


Fig. 1. Schema of measurements (a, b) of a sample of dacite, source position (triangle on a, b) and change of AE intensity (c)

The source position was fixed according to acoustic tests using a complex "Interjunis". The change of AE intensity during the time of loading is shown in Fig. 1c. It can be seen from Fig. 1c that the cracking begins at a level of loading of 224 MPa, which corresponds to the moment of the deflection of the stress strain curves from a linear relation. The position of the source of failure concerning pairs of deformation gauges is shown in Fig. 1a-b).

The basic results of the tests on the laws of the deformation of rock samples in a prefailure state using the newest equipment can be reduced to the following. In a prefailure stage of loading, a series of anomalous deformation effects which can be used as precursors is observed. First, this flattening out of the deformation curves with reduction by it fields of modules of deformations by 1.5-3 and more times can be seen in Fig. 2a. It is displayed especially clearly in the field of the source, as shown in Fig. 2b. In this part, there are two anomalous deformation effects where, apart from the already noted effect of significant (repeated) decreases of the module of deformation, there are naturally fixed sharp augmentations of the increments of lateral deformation, which are comparable in size or even exceeding the increments of longitudinal strain. The first anomalous effect can be considered to be within the limits of the model of “soft inclusion”, as already mentioned above.

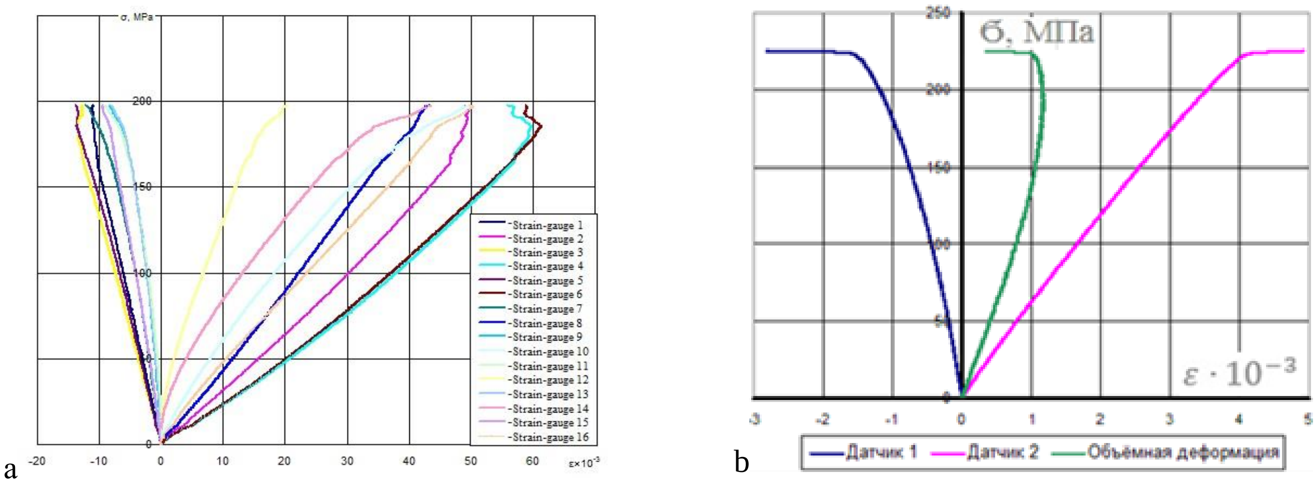


Fig 2. Laws of deforming of rock samples: a – dacite in a prefailure stage of loading: linear strains, the central part, b – character of linear strains in source parts of the rhyolite sample

Source model of «Defective heterogeneity» with reference to rocks samples at axial compression

Modelling source areas by «soft inclusion» is good knowing in geomechanics [7]. The inclusion can be ideal soft at the rock module of deformation E = 0. It is a case of a circular hole in a semiplane with evenly distributed symmetrical load on a part of its border. This problem is considered by the author in [5], where the character of the displacements of a contour of the hole is shown as in Table 1.

The second deformation anomaly of the source part, consisting of large lateral strains, as a rule, exceeding the longitudinal increments of deformation, indicates a shear-rupture of a developmental character in the mesodefect part of the source, leading to the wedge action of such defects [6]. Within the frame of the «soft inclusion» model, this effect cannot be considered directly, as the Poisson's ratio of a continuous material cannot exceed 0.5. Properties of the source parts of the sample are formed at the expense of defects of the shear-rupture type, where the wedge action of a shift element [6] prevails. Therefore research on mechanisms of deformation anomalies should be divided into two stages, caused by the presence of two source deformation anomalies: longitudinal and across the direction of loading.

Table 1

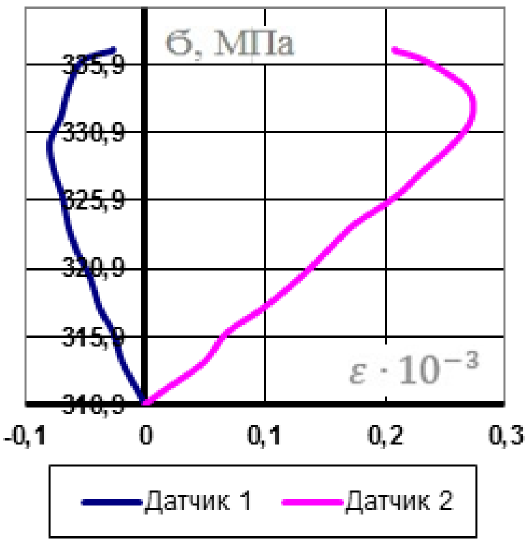
Size of displacements of a contour of a section of a round hole in a semiplane at the attitude of symmetrically applied load to depth B/H = 5.0 (R – hole radius)

Θ, degree	Displacements	
	u/R	v/R
90	0	-1,321
60	-0,011	-0,827
30	0,610	-0,142
0	1,029	-0,071
-30	0,567	0,018
-60	-0,012	0,664
-90	0	1,104

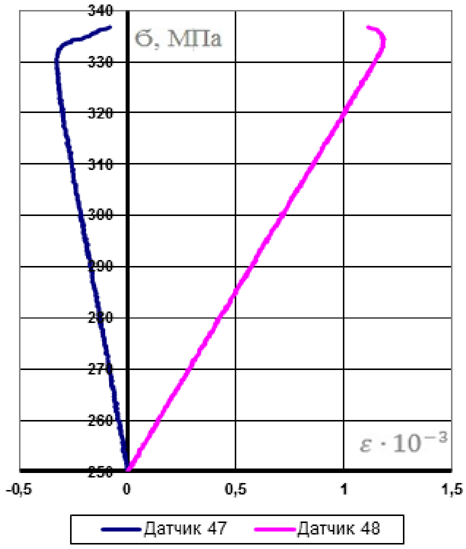
Direct overseeing by deformations of fields of rocks testify that it is lower and nearer to the source (Fig. 3a and 3b respectively) also. On the border of the source and the surrounding material, the condition of a continuity of displacements is met, so it is logical to expect deformation anomalies not only in the source area, but also in the adjoining parts of the rock.

The procedure considered above allows making such supervision, the results of which are shown in Fig. 3. The gauges located immediately under the source part of the sample have fixed the negative increments of the deformations, similar to the results described in [2]. At augmentation of strains, there is an original reversal of linear strains in this connection, and this can be called a phenomenon of reversive linear deforming in the immediate vicinity of source areas of the rock sample at uniaxial compression. The size of the negative increments of longitudinal strain in this case exceeds the size of the negative increments of lateral deformation (Fig.3a).The reversive deforming of that part of the sample which also adjoins the source areas has a different character from the source parts of the sample in a direction perpendicular to the direction of action of the load (Fig. 3,b). In this case, by contrast, the size of the negative increments of lateral deformation exceeds the size of the negative increments of longitudinal strain. Sometimes only negative increments of lateral deformation are identified.

Thus, the results of complex acoustic, deformation and theoretical tests allow us to formulate a hypothesis of the conditionality of reversive linear strains of rocks samples in immediate proximity to source parts specificity of deforming of defective heterogeneity to what can present the source.



a



b

Fig. 3. Reversive character of linear strains in the direction of an axis of the sample (a) and perpendicular to it (b)

Experimental reproduction of reversive deformations near to Source Areas

The laws of deformation of heterogeneous rock samples in a kind of «soft inclusion» were researched using an expressly developed procedure that enables the building of a preliminarily relaxed field in the centre of the sample, its division in height in some parts and installation on their borders metal thresholds, serving by the supports for indicators of hour type. Gauges of hour type settle down on special posts [3].

For the experiments, samples of strong low-porosity granite were collected. The samples were loaded in two stages: first, deformations of the monolithic sample were measured at loading to $0.8\sigma_{l\text{-}ts}$, (where $\sigma_{l\text{-}ts}$ is the long-term strength) and the sample was then unloaded. Then it was lead up to a long-term strength and, after unloading, the deformations were measured at cyclic loading to $\sigma_{l\text{-}ts}$. The loading of samples of strong granite to strains close to a long-term strength shows that anomalous deformation effects in this case are absent (Fig. 4a). After reaching$\sigma_{l\text{-}ts}$ and then unloading, the samples were loaded again to strains of $0.8\sigma_{l\text{-}ts}$. The appearance in this case of reversible anomalies at the top of the sample (Fig. 4a) is positioned. At a cyclic load, the anomalous character of the deformations is conserved.

Note also that in all situations that demonstrate a reversive ("negative") deformation anomaly, on the next fields of the sample on its height a "positive" deformation anomaly is also formed. This fully explains the cause of the reversal of deformations in the area near the source in a longitudinal direction (reversive anomaly of the first type) and confirms the hypothesis of defective heterogeneity.

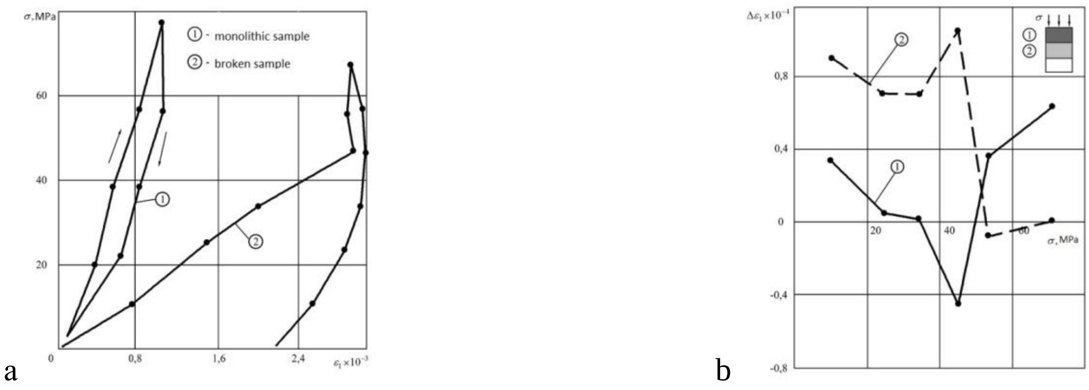


Fig. 4. Reversive character of deforming of samples of rocks in conditions of axial compression: a – relative tests of the monolithic and preliminarily broken granite samples, b – character of deforming of separate parts of the sample

The modelling of cross-wise reversal of deformations in near-source areas (reversive anomaly of the second type) can be done by building on local fields of the sample of holding apart efforts of sufficient size to reflect the holding apart action shear-rupture of defects in the area of the source. This effect is modelled to the full by thin cuts (thickness 0.2 – 0.3 mm) made by a cutting tool in the material of rocks well enough giving in to cutting, by introducing the cutting tool in the rock (wedge effect). The size of the deformations depends on the distance to a cut, its depth and length. The optimum depth of a cut is 3 mm, and it is rational to make the cuts at a distance of 3 mm from the gauge.

Experimental reproduction of the reversive deformation effects shown in Fig. 3b is done by making imitation shear-rupture fractures in a preliminarily loaded sample. From the experiments, it is determined that anomalous longitudinal and lateral deformations of the reversive type arise close to these imitation fractures (Fig. 5b). Thus, this direct experiment on the drawing of imitation fractures in a preliminarily loaded sample shows that the anomalous character of its deforming at axial compression is replicated qualitatively.

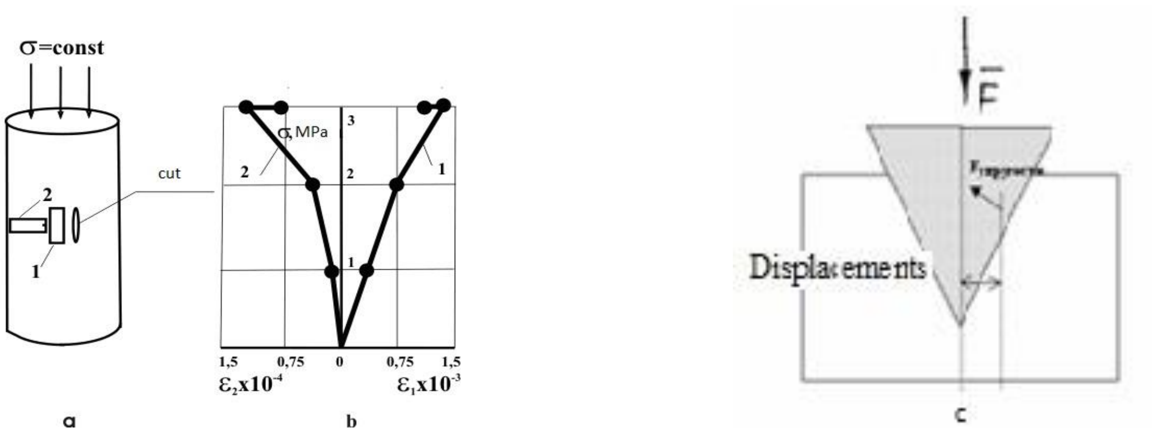


Fig. 5. Reversive deformations of the second type: a – the experiment schema, b – deformations of rock samples at compression and the subsequent drawing of a cut, c – wedge effect of cutting

Mathematical model of the phenomenon of reversible deformation of rock samples at uniaxial compression

The modelling of highly compressed rocks where the deformations ‘conditions of compatibility are not satisfied and the state of the thermodynamic conditions is far from equilibrium by dissipation system generally has well proved at the description of the phenomenon of zonal failure of a massive around the underground openings. Therefore a mathematical model has been developed and the solution of a problem on the highly compressed sample of rock is developed on the same principles [2].

Deformation anomalies of a reversive type occur in the sample of rock at achievement by a load σ some of critical values σ*. If σ is less than σ*the stress-strain state of the sample is described within the limits of the elastic theory

$$\sigma_{ij} = \frac{E}{1+\nu}\left(\varepsilon_{ij} + \frac{\nu}{1-2\nu}\varepsilon_{kk}\delta_{ij}\right), \tag{1}$$

where E – elastic modulus, ν – Poisson's ratio.

At σ is less than σ * the equation of balance for the sample of rock in cylindrical co-ordinates looks as follows:

$$\frac{\partial\sigma_{rr}}{\partial r} + \frac{1}{r}\frac{\partial\sigma_{r\varphi}}{\partial\varphi} + \frac{\partial\sigma_{rz}}{\partial z} + \frac{\sigma_{rr}-\sigma_{\varphi\varphi}}{r} = 0,$$

$$\frac{\partial\sigma_{r\varphi}}{\partial r} + \frac{1}{r}\frac{\partial\sigma_{\varphi\varphi}}{\partial\varphi} + \frac{\partial\sigma_{\varphi z}}{\partial z} + \frac{2\sigma_{r\varphi}}{r} = 0,$$

$$\frac{\partial\sigma_{rz}}{\partial r} + \frac{1}{r}\frac{\partial\sigma_{\varphi z}}{\partial\varphi} + \frac{\partial\sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r} = 0, \tag{2}$$

And the problem boundary conditions for the stress-strain state in a cylindrical sample at uniaxial compression are registered as

$$\sigma_{zz}\big|_{z=\pm h} = -\sigma, \quad \sigma_{zr}\big|_{z=\pm h} = 0, \quad \sigma_{z\varphi}\big|_{z=\pm h} = 0,$$

$$\sigma_{rr}\big|_{r=R} = 0, \quad \sigma_{r\varphi}\big|_{r=R} = 0, \quad \sigma_{rz}\big|_{r=R} = 0. \tag{3}$$

From experimental researches, it follows (see Fig. 2) that anomalous reversive deformations in the area of loading where σ is more than σ * (we will designate these deformations E_{ij}), coincide in the order of sizes with subcritical deformations in ε_{ij} area when σ is less than σ *. This makes it possible to bind the strains corresponding Π_{ij} to deformations E_{ij} , to the linear E_{ij} interrelations similar in algebraic structure to Hooke's law for conditions of area where σ is less than σ *:

$$\Pi_{ij} = \frac{E}{1+\nu}\left(E_{ij} + \frac{\nu}{1-2\nu}E_{kk}\delta_{ij}\right), \ (\iota,\varphi{=}1,2,3), \tag{4}$$

where E – elastic modulus, ν – Poisson's ratio.

The formation of periodic mesocracking structures involves the appearance of some new field of strains in which T_{ij} generally depends on the type of cracking defects considered. As the sample is in balance, the forces defined by a field T_{ij} , should be compensated, and therefore they are often referred to as self-counterbalanced. Π_{ij} acts as a compensatory field. Thus a full field of strains in Σ_{ij} the sample equals:

$$\Sigma_{ij} = \Pi_{ij} + T_{ij}. \tag{5}$$

This satisfies the equations of balance (2) and regional conditions (3). In turn for fields also Π_{ij} it is possible T_{ij} to write down the conforming equations of balance:

$$\frac{\partial\Pi_{ij}}{\partial x_j} = 0, \ \frac{\partial T_{ij}}{\partial x_j} = 0 \tag{6}$$

and boundary conditions:

$$\Pi_{ij} n_i \big|_{\partial V} = -T_{ij} n_i \big|_{\partial V} \tag{7}$$

and

$$T_{ij} = 2\sigma_0 l^2 \varepsilon_{ipq} \varepsilon_{jmk} \frac{\partial \Gamma_{qm,p}}{\partial x_k}, \tag{8}$$

where ε_{ipq} – a Levi–Chivity symbol, constants σ_0, l have dimensions of strain and length respectively. The concrete kind of functions $\Gamma_{qm,p}$ depends on the type of defective structure, so it is necessary to analyze the background of the formation of defects and dissipative processes in a material (Table 2).

Table 2

Results of comparison of the data from theoretical and experimental researches

Parameters	Longitudinal deformations meaning in the gauge positions							
	4-6		5-7		2-8		3-9	
	Experiment	Theory	Experiment	Theory	Experiment	Theory	Experiment	Theory
Longitudinal deformations, 10^{-6}	-1067	-899	704	704	-899	-899	679	679
Difference, %	18.7		0.0		0.0		0.0	

Statement of the problem for equation (5) consists in the construction of an elastic field such that Π_{ij} deformations corresponding to it coincided E_{ij} with the measured values on the border of the sample in a discrete panel of points.

The field of elastic stresses and Π_{ij} deformations can E_{ij} be bound linear interrelations

$$\Pi_{ij} = A(E_{ij} + BE_{kk}\delta_{ij}) \tag{9}$$

with some coefficients A, B.

Without restriction of generality parameters A, it is possible to choose B as in the elastic theory:

$$A = \frac{E}{1+\nu} = 2\mu, \quad B = \frac{\nu}{1-2\nu}, \tag{10}$$

where μ – a shear modulus.

As the equations (5) are linear, we will present a field in the form of the Π_{ij} sum of the classical solution and σ_{ij} some field π_{ij}:

$$\Pi_{ij} = \sigma_{ij} + \pi_{ij}. \tag{11}$$

As the solution is under construction in the prefailure area load level σ = σ * is initial, therefore in formula (3) it is necessary σ_{ij} to believe instead of $\delta\sigma = \sigma - \sigma^* \ \sigma^*$. We will follow-up demand, that the first invariant reverted π_{kk} in zero. Then the tensor is bound π_{ij} to the conforming deformation tensor an interrelation

$$\pi_{ij} = \mu\left(\frac{\partial a_i}{\partial x_j} + \frac{\partial a_j}{\partial x_i}\right), \tag{12}$$

where a_i – components of a vector of the displacements, loads counted from level $\sigma = \sigma^*$.

Components (a_i $i=1,2,3$) are defined from the equations of balance which in a cylindrical frame of axes look like:

$$\Delta a_r - \frac{a_r}{r^2} - \frac{2}{r^2}\frac{\partial a_\varphi}{\partial \varphi} = 0,$$

$$\Delta a_\varphi - \frac{a_\varphi}{r^2} + \frac{2}{r^2}\frac{\partial a_r}{\partial \varphi} = 0, \qquad (13)$$

$$\Delta a_z = 0.$$

A limited solution of the system equations (13) for the cylinder can be written in the form of Fourier series in the trigonometric functions [3]:

$$a_r = \sum_{n,m=1} \left(u_{nm}^{(1)}(\rho)\cos n\varphi + u_{nm}^{(2)}(\rho)\sin n\varphi\right)\cos m\gamma z,$$

$$a_\varphi = \sum_{n,m=1} \left(v_{nm}^{(1)}(\rho)\sin n\varphi - v_{nm}^{(2)}(\rho)\cos n\varphi\right)\cos m\gamma z,$$

$$a_z = \sum_{n,m=1} \left(w_{nm}^{(1)}(\rho)\cos n\varphi + w_{nm}^{(2)}(\rho)\sin n\varphi\right)\sin m\gamma z,$$

$$u_{nm}^{(i)}(\rho) = \frac{A_{nm}^{(i)} I_{n+1}(\rho) + B_{nm}^{(i)} I_{n-1}(\rho)}{2\gamma},\ v_{nm}^{(i)}(\rho) = \frac{A_{nm}^{(i)} I_{n+1}(\rho) - B_{nm}^{(i)} I_{n-1}(\rho)}{2\gamma},\ w_{nm}^{(i)}(\rho) = -\frac{(A_{nm}^{(i)} + B_{nm}^{(i)}) I_n(\rho)}{2\gamma},$$

$$\rho = m\gamma r,\ \gamma = \frac{\pi}{h},$$

where $I_n(\rho)-$ real Bessel function of order n imaginary argument, $A_{nm}^{(i)}$, $B_{nm}^{(i)}$ — arbitrary constants.

Below is brought a field of elastic stresses π_{ij} in cylindrical coordinates:

$$\pi_{rr} = \mu \sum_{n,m=1} \left(\pi_{rr}^{(1)}(n,\rho)\cos n\varphi + \pi_{rr}^{(2)}(n,\rho)\sin n\varphi\right)\cos m\gamma z,$$

$$\pi_{\varphi\varphi} = \mu \sum_{n,m=1} \left(\pi_{\varphi\varphi}^{(1)}(n,\rho)\cos n\varphi + \pi_{\varphi\varphi}^{(2)}(n,\rho)\sin n\varphi\right)\cos m\gamma z,$$

$$\pi_{zz} = \mu \sum_{n,m=1} \left(\pi_{zz}^{(1)}(n,\rho)\cos n\varphi + \pi_{zz}^{(2)}(n,\rho)\sin n\varphi\right)\cos m\gamma z,$$

$$\pi_{r\varphi} = \mu \sum_{n,m=1} \left(\pi_{r\varphi}^{(1)}(n,\rho)\sin n\varphi - \pi_{r\varphi}^{(2)}(n,\rho)\cos n\varphi\right)\cos m\gamma z,$$

$$\pi_{rz} = \mu \sum_{n,m=1} \left(\pi_{rz}^{(1)}(n,\rho)\cos n\varphi + \pi_{rz}^{(2)}(n,\rho)\sin n\varphi\right)\sin m\gamma z,$$

$$\pi_{\varphi z} = \mu \sum_{n,m=1} \left(\pi_{\varphi z}^{(1)}(n,\rho)\sin n\varphi - \pi_{\varphi z}^{(2)}(n,\rho)\cos n\varphi\right)\sin m\gamma z, \qquad (14)$$

$$\pi_{rr}^{(i)}(n,\rho) = m\left[B_{nm}^{(i)}\left(I_n + \frac{n-1}{\rho}I_{n-1}\right) + A_{nm}^{(i)}\left(-\frac{n+1}{\rho}I_{n-1} + I_n + \frac{2n^2+2n}{\rho^2}I_n\right)\right],$$

$$\pi_{\varphi\varphi}^{(i)}(n,\rho) = m\left[A_{nm}^{(i)}\left(\frac{n+1}{\rho}I_{n-1} - \frac{2n^2+2n}{\rho^2}I_n\right) - B_{nm}^{(i)}\frac{n-1}{\rho}I_{n-1}\right],$$

$$\pi_{zz}^{(i)}(n,\rho) = -m\left(A_{nm}^{(i)} + B_{nm}^{(i)}\right)I_n,$$

$$\pi_{r\varphi}^{(i)}(n,\rho) = m\left[A_{nm}^{(i)}\left(-\frac{n+1}{\rho}I_{n-1} + \frac{1}{2}I_n + \frac{2n^2+2n}{\rho^2}I_n\right) - B_{nm}^{(i)}\left(\frac{n-1}{\rho}I_{n-1} + \frac{1}{2}I_n\right)\right],$$

$$\pi_{rz}^{(i)}(n,\rho) = m\left[A_{nm}^{(i)}\left(-I_{n-1} + \frac{3n}{2\rho}I_n\right) + B_{nm}^{(i)}\left(-I_{n-1} + \frac{n}{2\rho}I_n\right)\right],$$

$$\pi_{\varphi z}^{(i)}(n,\rho) = m\left[A_{nm}^{(i)}\left(-\frac{1}{2}I_{n-1} + \frac{3n}{2\rho}I_n\right) + B_{nm}^{(i)}\left(\frac{1}{2}I_{n-1} + \frac{n}{2\rho}I_n\right)\right]. \quad (15)$$

The solution (14), (15) comprises a set of unknown parameters $A_{nm}^{(i)}$, $B_{nm}^{(i)}$. According to the above formulation of the task, they must be determined from the condition of coincidence the strain tensor components E_{ij} with values that are measured experimentally in a discrete set of points at $r = R$ and $z = 0$.

After carrying out numerical calculations for experimental conditions at values of parameters of model: $\nu = 0{,}26$, $E = 1{,}7 \bullet 10^4$ Pa, $x = 0{,}5 \cdot \pi$, $h = 5см$, $R = 2{,}5см$ we obtain values of quotients of rows (15):

$A_{21}^{(1)} = -3519 \cdot 10^{-6}$, $A_{41}^{(1)} = -29410 \cdot 10^{-6}$, $A_{11}^{(2)} = -1167 \cdot 10^{-6}$, $B_{21}^{(1)} = -700 \cdot 10^{-6}$, $B_{41}^{(1)} = 885 \cdot 10^{-6}$, $B_{11}^{(2)} = 1143 \cdot 10^{-6}$.

Now, calculating the sizes of deformations for the experimental conditions and displaying them in comparison with the data of this experiment in Table 2, we can see that at full qualitative coincidence of the results of the analytical and experimental researches, the maximum quantitative difference of values of longitudinal strain does not exceed 19 % [2].

Conclusion

Thus, satisfactory results of mathematical modelling allow us to determine the mechanism of the phenomenon of reversive deformation of highly compressed rock samples. which consists of conditions of strong non-equal components of compression which cause mesocracking destruction on inhomogeneities of the medium, while strains in the sample have an oscillation of a periodic character that has a consequential development in local fields of action of the maximum normal tangential stresses of the source of concentration of interacting mesodefects, and in the vicinity of the source – the formation of places where deformations assume a reversive character.

The establishment of the phenomenon of reversive deformation of highly compressed samples of rocks allows us to formulate a system of deformation precursors of failure that is of great value in the forecasting of geodynamic phenomena in a rock mass.

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Механизмы разрушения горных пород / Rock Failure Mechanism

В.В. Макаров, А.М. Голосов, Л.С. Ксендзенко, Н.А. Опанасюк

МАКАРОВ ВЛАДИМИР ВЛАДИМИРОВИЧ – доктор технических наук, профессор кафедры горного дела и комплексного освоения георесурсов Инженерной школы, руководитель образовательной программы «Шахтное и подземное строительство», (Дальневосточный федеральный университет, Владивосток). Суханова ул., 8, Владивосток, 690950. E-mail: vlmvv@ mail.ru

ГОЛОСОВ АНДРЕЙ МИХАЙЛОВИЧ – инженер кафедры горного дела и комплексного освоения георесурсов Инженерной школы (Дальневосточный федеральный университет, Владивосток). Суханова ул., 8, Владивосток, 690950. E-mail: a-dune@mail.ru

КСЕНДЗЕНКО ЛЮДМИЛА СТЕПАНОВНА – кандидат физико-математических наук, доцент кафедры алгебры, геометрии и анализа Школы естественных наук (Дальневосточный федеральный университет, Владивосток). Суханова ул., 8, Владивосток, 690950. E-mail: ksendzenko@mail.ru

ОПАНАСЮК НИКОЛАЙ АЛЕКСАНДРОВИЧ – старший преподаватель кафедры горного дела и комплексного освоения георесурсов Инженерной школы (Дальневосточный федеральный университет, Владивосток). Суханова ул., 8, Владивосток, 690950. E-mail: neksan1@mail.ru

О механизме явления реверсивного деформирования образцов сильно сжатых горных пород

На реверсивный характер линейных деформаций при сжатии образцов горных пород, по-видимому, впервые, было обращено внимание в 1958 г. исследователями T.R. Seldenrath и J. Gramberg. При поиске деформационных предвестников реверсивные деформации были установлены также И.С. Томашевской и Я.Н. Хамидуллиным (1972), которые выдвинули гипотезу дилатансионного расширения. Причиной реверсивного деформирования К.Т. Тажибаевым были названы также остаточные напряжения (1986). Однако ни одна из рассмотренных гипотез не объясняет все имеющие место аномальные эффекты с единых позиций, как было показано М.А. Гузевым и В.М. Макаровым (2005). В рассматриваемой статье явление реверсивного деформирования исследуется комплексным акустическим и деформационным методом, а результаты эксперимента описываются с позиций модели самоуравновешенных напряжений.

Ключевые слова: образец, реверсивные деформации, математическая модель.