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Mesocracking structures of the 'source type' in highly stressed rocks

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Abstract

Definition of the mechanism and mathematical model of the phenomenon of deformation anomalies of the reversible type in samples of rocks at uniaxial compression on the basis of specially developed methods of the complex research which include deformation, acoustical and mathematical methods are described. The reversible character of the deformations of rocks was connected with a straining of highly stressed rock samples at uniaxial compression (Makarov et al. 2014b; Tomashevskaya & Khamidullin 1972). In this paper, based on a specially developed complex research method, including the deformation, acoustic and mathematical methods, the authors analyse deformation anomalies of the reversible type in samples of rocks at uniaxial compression and define the mechanism of their origin. Mesocracking structure of the 'contrast' type has been fixed at the source and around the source area's formation (Makarov et al. 2014a). The system of reliable precursors of rock sample failure has been determined, including the long-term and middle-term one. The precursors spreading to the mining situation with the rockburst is discussed.

Keywords: *rock sample, acoustic emission, reversible deformations, source, mesocracking structures*

1 Introduction

The search for reliable methods of forecasting macrofailure is one of the basic problems of modern geomechanics. This problem depends to a large extent on the possibility of reliably determining defined precursors to failure (Makarov et al. 2012; Sagiya 2011). Until now, these have been considered to be a rise in the acoustical activity of rock and massive and large anomalous deformations of the source area and connected with formation of the area. However, restricting searches for precursors to field sites only for an area sharply narrows their nomenclature, as well as the quantity of independent information sources. There is a need to search for additional precursors that are closely connected with the formation of the source of the macrofailure. Such precursors can be found in the area near the source which are directly bordering on the area. Attention to the reversible character of linear deformations of rock samples was presented, apparently, for the first time in Seldenrath and Gramberg (1958). The authors did not research the mechanisms of the origination of the deformation anomalies, but already in subsequent works such attempts have begun to be undertaken. So the reversible character of the deformations of rocks was contacted with a barrel-shaped straining of samples at uniaxial compression (Tomashevskaya & Khamidullin 1972). In the publications of other researchers, residual stresses were proposed in the capacity of reasons for deformation anomalies of various types (Tazhibaev 1986). However, these hypotheses are not supported by critics on closer examination (Guzev & Makarov 2007).

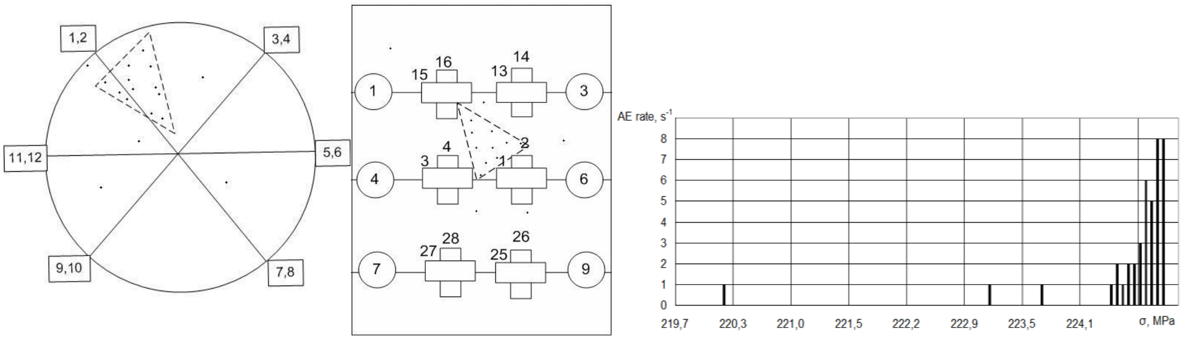
2 Experimental research of the regularity of a straining of rock samples in the source of macrofailure and its neighbourhoods

Based on previous researches, a two-phase model of the macrocracks 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 (Lockner et al. 1991). The source is often modelled by inhomogeneity in the form of the soft inclusion, causing around it the formation of an area of consolidation as the result of the redistribution of stress (Brace et al. 1966; Makarov 2013). Modern methods of research applying servocontrolled rigid loading devices allow measurements to be taken directly before, 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 multipoint deformation research of strongly compressed samples of 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 measurement of deformations, both in the central part of the sample, and on its height. Thus the cross form 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, end 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 (Guzev & Makarov 2007).

Studies was performed on samples of various rocks, including dacites, rhyolite, diorite, granite-porphyry and others. 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 scheme of their fastening has been developed to preserve the wire ends on the sample. The reading from the resistance strain gauges were fixed by means of a computer program on the multichannel device UIU-2002. This study was carried out at the Geomechanics Laboratories at Far-Eastern Federal University (FEFU).

In Figure 1(b), the schema of the sensors displacement is shown during tests. In total, four series on 10 samples were tested. The tests were carried out at uniaxial compression of samples under the multipoint schema of measurements from eight to 48 sensors (Figure 1).

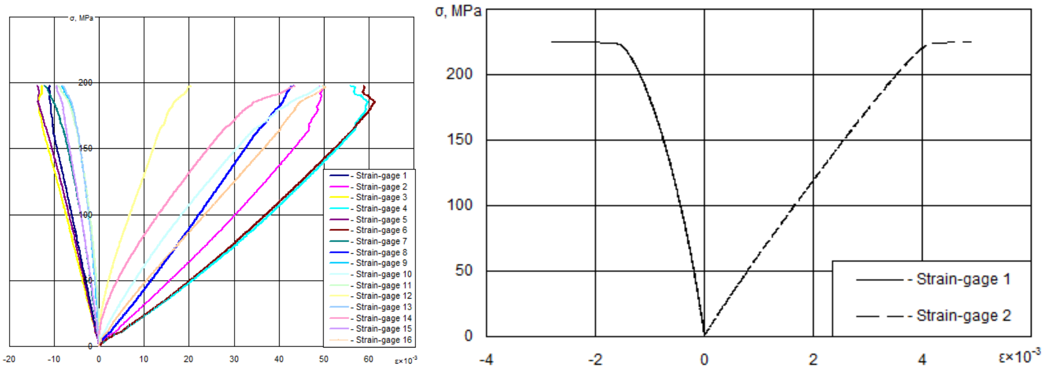


(a) (b) (c)

Figure 1 Schematic of measurements (a, b) of a sample of dacite; source position (triangle on a, b); and change of acoustic emission (AE) intensity (c)

The source position was fixed according to acoustic tests using a ‘InterUnis’ device. The change of AE intensity during the time of loading is shown in Figure 1(c). It can be seen from Figure 1(c), that the cracking process 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 gages is shown in Figures 1(a) and (b). The basic results of the tests of the deformation laws of rock samples in a pre-failure state can be reduced to the following. In a pre-failure stage of loading a series of anomalous deformation effects which could be used as precursors are observed.

First, this flattening out of the deformation curves with reduction by its fields of modulus of deformations in 1.5 to 3 and more times can be seen in Figure 2(a). It is displayed especially clearly in the source area, as shown in Figure 2(b). In this part, there are two anomalous deformation effects where, apart from the already noted effect of significant (in several times) decreases of the modulus of deformation, there are naturally fixed sharp augmentations of the increments of lateral deformations, which are comparable in size or even exceeding the increments of longitudinal strain. The first anomalous effect can be considered to be within the frame of the model of 'soft inclusion', as already mentioned.



(a) (b)

Figure 2 Laws of deforming of rock samples: (a) dacite in a pre-failure stage of loading: linear strains, the central part; (b) character of linear strains in source parts of the rhyolite sample

3 Source model of 'defective heterogeneity' with reference to samples of rocks at axial compression

Modelling source areas by soft inclusion is well known in geomechanics (Rice 1980). The inclusion can be 'perfectly' soft with an inclusion rock modulus of deformation E = 0. This is the case for a circular hole in a semi-plane with a uniformly distributed symmetrical load on a part of its border. Such a problem is considered by the author in (Makarov 2013), where the character of the displacements of a contour of the hole is shown in Table 1.

Table 1 Size of displacement of a contour of a section of a round hole in a semi-plane at the attitude of symmetrically applied load to depth *B/H = 5.0* (where H = distance from the plane boundary to hole centre; B = width of the load application; R = hole radius)

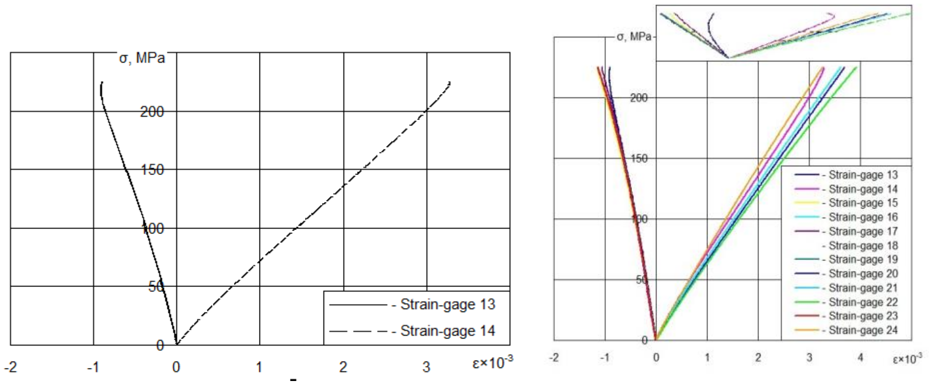
ϴ (degrees)	Displacements	
	u/R	v/R
90	0	-1.321
60	-0.011	-0.827
30	0.610	-0.142
0	1.029	-0.071
-30	0.567	0.018
-60	-0.012	0.664
-90	0	1.104

The second deformation anomaly of the source area, consisting of large lateral strains, as a rule, exceeding the longitudinal increments of deformations, can be explained by a shear-tension character of a meso-defect part of the source development, leading to the wedge action of such defects (Odintsev 1996).

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 area of the sample are formed by the cause of defects of the shear-tension type, where the wedge action of a shift element prevails (Odintsev 1996). 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.

Direct overseeing by deformations of areas of rocks testify the same character is lower and nearer to the source (Figures 3(a) and (b) respectively) also. On the border of the source area 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.



(a) (b)

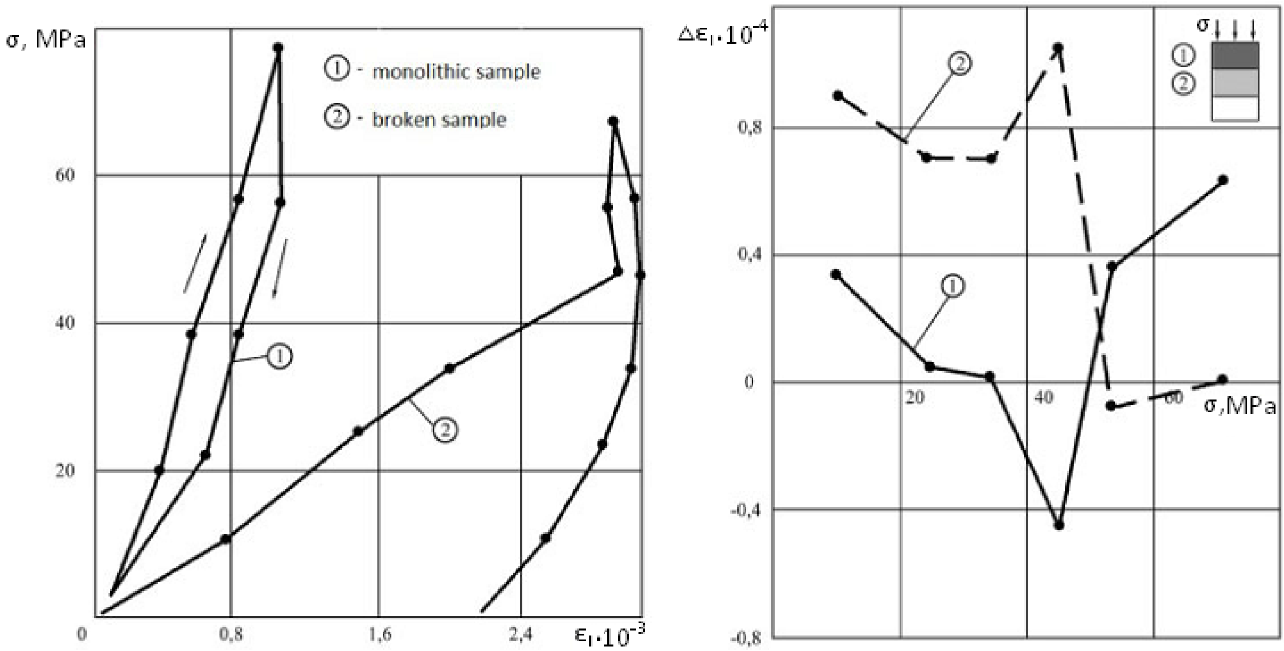
Figure 3 Reversible character of linear strains in the direction of an axis of the sample (a); and perpendicular to it (b)

The aforementioned procedure allows the undertaking of such researches, the results of which are shown in Figure 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 (Guzev et al. 2005). At the rising of strains, there is an original reversal of linear strains. This can be called a phenomenon of reversible linear deformation in the immediate vicinity of source areas of the rock sample at uniaxial compression. The size of negative increments of longitudinal strain in this case exceeds the size of the negative increments of lateral deformations (Figure 3(a)). The reversible deforming of that part of the sample which also adjoins the source area has a different character from the part of the sample in a direction perpendicular to the direction of loading (Figure 3(b)). In this case, by contrast, the size of the negative increments of lateral deformations exceeds the size of the negative increments of longitudinal strain. Sometimes only negative increments of lateral deformations are identified.

Thus, the results of complex acoustic, deformation and theoretical tests allow us to formulate a hypothesis of the conditions for reversible linear strains of rock samples in the immediate proximity of the source area by specificity of defective heterogeneous deformation which can be present at the source area.

4 Experimental reproduction of reversible deformations near to source areas

Features of deformation and failure of heterogeneous materials (e.g. rocks) were studied using a special method. Prepared specimens involved soft inclusions. Multiple gauges fixed to the specimen allowed measuring the variation of local stresses and deformations at loading in different zones of the artificial heterogeneous material – within and outside inclusions (Guzev & Makarov 2007). For the experiments, samples of strong low-porosity granite was collected. The samples were loaded in two stages: first, deformations of the monolithic sample were measured at loading to $0.8\sigma_{l-ts}$, (where σ_{l-ts} is the long-term strength) and the sample was then unloaded. Then it was loaded up to a long-term strength, and after unloading, the deformations were measured at cyclic loading to σ_{l-ts} level. The loading of samples of strong granite to a stress close to a long-term strength shows that anomalous deformation effects in this case are absent (Figure 4(a)). After reaching σ_{l-ts} and then unloading, the samples were loaded again to a stress of $0.8\sigma_{l-ts}$. The appearance in this case of reversible anomalies at the top area of the sample (Figure 4(a)) occurs. At a cyclic load, the anomalous character of the deformations is conserved (Makarov et al. 2012) F_{elast}.



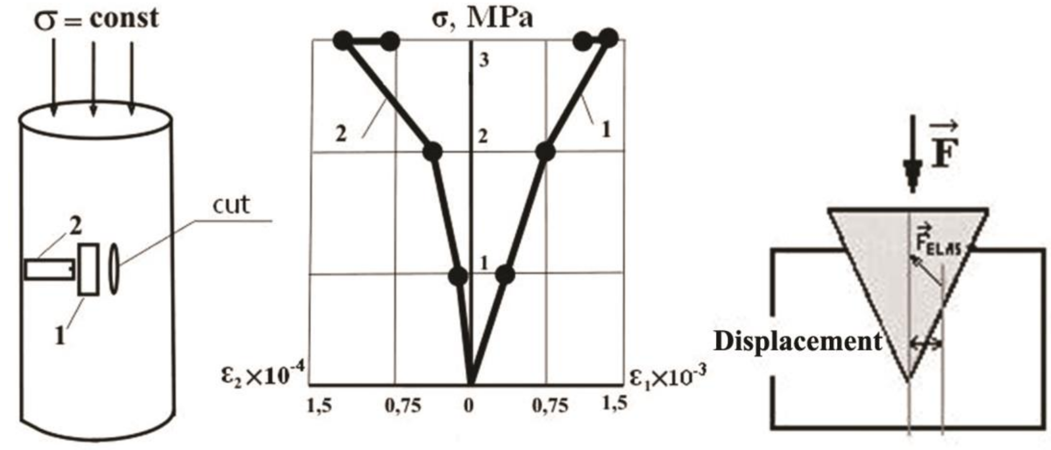
(a) (b)

Figure 4 Reversible 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

Note also that in all situations that demonstrate a reversible (negative) deformation anomaly, a positive deformation anomaly occurs on the next vertical section of the sample. This fully explains the cause of the reversal of deformations near the source area in a longitudinal direction (reversible anomaly of the first type) and confirms the hypothesis of defect heterogeneity.

The modelling of lateral reversal deformations in near-source area (reversible anomaly of the second type) can be done by on local areas, applying separation forces of magnitude similar to shear-tensile defects in the area of the source. This effect is modelled fully by introducing thin cuts (0.2-0.3 mm wide) made by a cutting, by introduction of the cutting tool in the rock (wedge effect). The value of 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 reversible deformation effects shown in Figure 3(b) is done by making imitation shear-tension fractures in a preliminarily loaded sample. From the experiments, it is determined that anomalous longitudinal and lateral deformations of the reversible type arise close to these imitation fractures (Figure 5(b)). Thus, 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 well enough replicated qualitatively.



(a) (b) (c)

Figure 5 **Reversible deformations of the second type: (a) the experiment schema; (b) deformations of rocks samples at compression and the subsequent drawing of a cut; (c) wedge effect of cutting**

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

The modelling of highly compressed rocks where the deformation conditions of compatibility are not satisfied and the state of the thermodynamic conditions is far from equilibrium by dissipation system generally has been well-proven at the description of the phenomenon of zonal failure of a massive around the underground openings (Makarov et al. 2016). Therefore, the mathematical model has been developed and the solution of a problem on the highly compressed sample of rock is developed on the same principles (Guzev et al. 2005).

Deformation anomalies of the reversible type occur in the rock sample at achievement by a load σ some critical values σ*. If σ is less than σ* the stress–strain state of the sample can be described by 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.

For σ less than σ* the equation of balance for the sample of rock in cylindrical coordinates is as follows:

$$\begin{aligned}
&\frac{\partial\sigma_{rr}}{\partial r} + \frac{1}{r}\frac{\partial\sigma_{r\varphi}}{\partial\varphi} + \frac{\partial\sigma_{rz}}{\partial z} + \frac{\sigma_{rr} - \sigma_{\varphi\varphi}}{r} = 0,\\
&\frac{\partial\sigma_{r\varphi}}{\partial r} + \frac{1}{r}\frac{\partial\sigma_{\varphi\varphi}}{\partial\varphi} + \frac{\partial\sigma_{\varphi z}}{\partial z} + \frac{2\sigma_{r\varphi}}{r} = 0,\\
&\frac{\partial\sigma_{rz}}{\partial r} + \frac{1}{r}\frac{\partial\sigma_{\varphi z}}{\partial\varphi} + \frac{\partial\sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r} = 0.
\end{aligned} \tag{2}$$

The boundary conditions for the stress–strain state in a cylindrical sample at uniaxial compression are registered as:

$$\sigma_{zz}\big|_{z=\pm h} = \sigma,\ \ \sigma_{zr}\big|_{z=\pm h} = 0,\ \ \sigma_{z\varphi}\big|_{z=\pm h} = 0,\ \ \sigma_{rr}\big|_{r=R} = 0,\ \ \sigma_{r\varphi}\big|_{r=R} = 0,\ \ \sigma_{rz}\big|_{r=R} = 0. \tag{3}$$

From the experimental results it follows (Figure 2) that anomalous reversible 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 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 on the algebraic structure to Hooke's law when σ it is less than σ*:

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

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

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

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 dimension 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 analyse the background of the formation of defects and dissipative processes in a material.

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:

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

with some coefficients A, B.

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

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

where:

μ is a shear modulus.

As Equation (5) is 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}:

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

For pre-failure area the load is counted from σ = σ *, therefore in Equation (3) for σ_{ij} it is necessary to consider $\delta\sigma = \sigma - \sigma^*$ instead of σ^*. Since the first invariant of π_{ij} reverted to zero (π_{kk} = 0), the tensor π_{ij} is bound 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 is 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:

$$\Delta a_r - \frac{a_r}{r^2} - \frac{2}{r^2}\frac{\partial a_\varphi}{\partial\varphi} = 0,\quad \Delta a_\varphi - \frac{a_\varphi}{r^2} + \frac{2}{r^2}\frac{\partial a_r}{\partial\varphi} = 0,\quad \Delta a_z = 0 \tag{13}$$

After the solution system (Equation (13)) in the form of rows the Fourier on trigonometrical functions and carrying out numerical calculations for experimental conditions at values of parameters of model: $\nu = 0{,}26,\ E = 1{,}7\cdot10^4\,Pa,\ x = 0{,}5\cdot\pi,\ h = 5\,cm,\ R = 2{,}5\,cm$, we obtain values of quotients of rows (Guzev et al. 2005):

$$\begin{aligned} &A_{21}^{(1)} = -3519\cdot10^{-6}, A_{41}^{(1)} = -29410\cdot10^{-6}, A_{11}^{(2)} = -1167\cdot10^{-6} \\ &B_{21}^{(1)} = -700\cdot10^{-6}, B_{41}^{(1)} = 885\cdot10^{-6}, B_{11}^{(2)} = 1143\cdot10^{-6}. \end{aligned} \tag{14}$$

Now, calculating sizes of deformations of the experimental conditions and displaying them in comparison with the data of this experiment in Table 2, we can see a very good correlation between the results of the analytical and experimental studies, the maximum difference between the analytical and measured longitudinal strain is less than 19% (Guzev et al. 2005).

Table 2 Comparison of theoretical and experimental results

Parameters	**Longitudinal deformations meaning in the gages positions**							
	4–6		**5–7**		**2–8**		**3–9**	
	Experiment	**Theory**	**Experiment**	**Theory**	**Experiment**	**Theory**	**Experiment**	**Theory**
Longitudinal deformations (10^{-6})	-1,067	-899	704	704	-899	-899	679	679
Difference (%)	18.7		0		0		0	

6 Conclusion

Satisfactory results of mathematical modelling allow us to determine the mechanism of the phenomenon of reversible deforming of highly compressed rock samples. According to the model, inhomogeneous materials at high non-uniform compressive stresses ($\sigma 1 > \sigma 2 > \sigma 3$) are subjected to multitudinous local failure (mesocracking). The failure zones are randomly distributed within the material body. Due to interaction between these zones the deformation and stress conditions in the material has an oscillating (or periodical) character, accompanied by reversible deformation on the local decrease position in compressive stress.

The establishment of the phenomenon of reversible 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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