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THE SYSTEM OF RELIABLE DEFORMATIONAL PRECURSORS OF HIGHLY STRESSED ROCK SAMPLES FAILURE

Phenomena of anomalous deformation of rocks compressed up to failure have been studied in the laboratory on rock samples. A system of reliable deformational precursors of the failure stage has been developed. The system includes long-term, middle-term and short-term precursors. The threshold of dilatancy and the turning point of deformational curve are recognized as long-term precursor. The middle-term precursor is determined as a point of the increment sign change of the specific volume deformation. The short-term precursor is characterized by the specific volume deformation increments jump. The acoustic emission research method had been used to control the deformational and failure process. There was a tight correlation between the deformational precursors system of failure and the mesocracking process under the loading. Mathematical model of self equilibrium stresses had been successfully used to describe the anomalous deformations distribution.

Key words: acoustic emission, uniaxial loading, deformation precursors.

Система надежных деформационных предвестников разрушения сильно сжатых образцов горных пород. Голосов Андрей Михайлович – инженер, Макаров Владимир Владимирович – доктор технических наук, профессор, кафедра горного дела и комплексного освоения георесурсов Инженерной школы (Дальневосточный федеральный университет, Владивосток).

В лаборатории на образцах горных пород изучено явление аномального деформирования образцов горных пород в стадии предразрушения. Разработана система надежных деформационных предвестников разрушения, которая включает в себя долгосрочный, среднесрочный и краткосрочный предвестники. Порог дилатансии и поворотный момент кривой деформации принимается за долгосрочный предвестник. Среднесрочный предвестник определяется как точка изменения знака приращения объемных деформаций. Краткосрочный предвестник характеризуется резким скачком объемных деформаций. Для контроля процессов деформации и разрушения выбран метод акустической эмиссии. Установлена тесная взаимосвязь между системой деформационных предвестников разрушения и процессом образования мезотрещин в результате нагружения. Для описания аномального распределения деформаций успешно использовалась модель самоуравновешенных напряжений.

Ключевые слова: акустическая эмиссия, одноосное нагружение , деформационные предвестники.

Introduction

The phenomena of rock massif failure became in the recent years a global ecological threat. Earthquakes of 2010 in Haiti (the magnitude of 7) and in 2011 in Japan (the magnitude of 9) have resulted not only in significant human losses and unprecedented human tragedy, but also threats of epidemics and radioactive pollution across the globe. Despite the existence of extensive networks of seismoacoustic stations and a huge number of scientific works, prediction of such events has turned out to be impossible [7]. This fact is evidence of insufficient understanding of the destructive mechanisms in geomaterials at various structural levels. Thus, there is an evident need for an urgent departure from traditional conservative schemes of prediction of such catastrophic events. Insubstantial scientific effort has been invested to develop new conceptual approaches towards the definition of critical conditions of geodynamic systems.

According to new theoretical concepts the rock mass can be analyzed as a block hierarchical medium, in which the elements demonstrate self similar fractal characteristics on different hierarchical levels [4]. So the laboratory methods on rock samples may be successfully used for the forecasting failure in rock mass. Development of a reliable system of precursors including the long-term, middle-term and short-term one is an extremely important geodynamical task.

Deformational precursors have a prominent position over all another methods because their specific properties as methods of direct control. At the same time indirect methods such as, for example acoustic emission, have been widely used in laboratory research and could exactly characterised the cracking process in rocks [3]. So the complex method and system of criterions are more successful for use in geodynamical forecasting.

Laboratory research of rock samples destruction has the doubtless advantage that detailed measurements can be made with the elimination the numerous factors of heterogeneity which exist in a rock mass. Thus those criteria which have unequivocal interpretation will be reliable. In the presented work the system of reliable deformation precursors of the rock samples destruction, corresponding to formation stages of the dissipative mesocracking structures, is confirmed by a fixed acoustic method.

The mathematical model of the defective medium applied to the description of deformation anomalies determined in the experiments, considers the occurrence in the sample of rock a field of self-counterbalanced pressure caused by formation and development of the dissipative mesocracking structure before destruction.

Experimental research of the deformational relationships of rock samples in the prefailure area of loading

The process of rock samples macrodestruction proceeds in stages, which are characterized, at first, by a preparatory one of uniform material damage under the influence of the compressive stress. This is followed by localisation of mesocracks as the focus of the macrorupture formation; and at the last stage there is a macrodefect development [3].

On the basis of the general laws, the technique of deformation research should consider stages of the macrofailure development process and not be limited to control in the central part of the sample and local (in 1–2 points) arrangement of the gauges. Therefore experiments by definition of the rock sample deformation laws at compression in loading in the prefailure area have been done under multidot schemes, both in a horizontal, and in a vertical direction. To determine the character of rock sample deformation the research was undertaken using cylindrical samples. The relation of height to diameter is accepted h/d=2 according to recommendations of Guzev and Makarov [1].

The compression force was applied by a servocontrole loading device MTS-816 with constant speed of deformation before strength achievement [6]. Tensoresistors were used for deformation measurement and these allowed definition of local deformations, both in the central part of the sample, and over its height. Research was undertaken on various rock types, including dacites, granodiorite, granity-porphyry and others. Measurement of deformations was undertaken not only in a separate part of the sample, but also around its entire perimeter. Tensoresisters were pasted under various schemes. Schemes of a label of gauges and the samples prepared for experiment are presented on Fig. 1. Indications of the tensoresisters were fixed by means of device UIU-2002 software in an automatic mode.

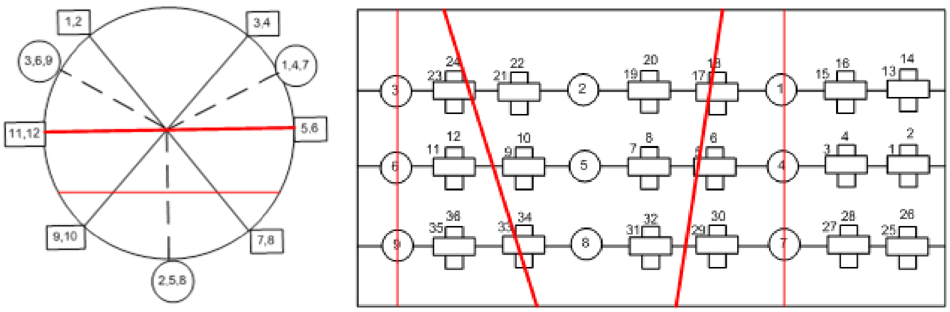
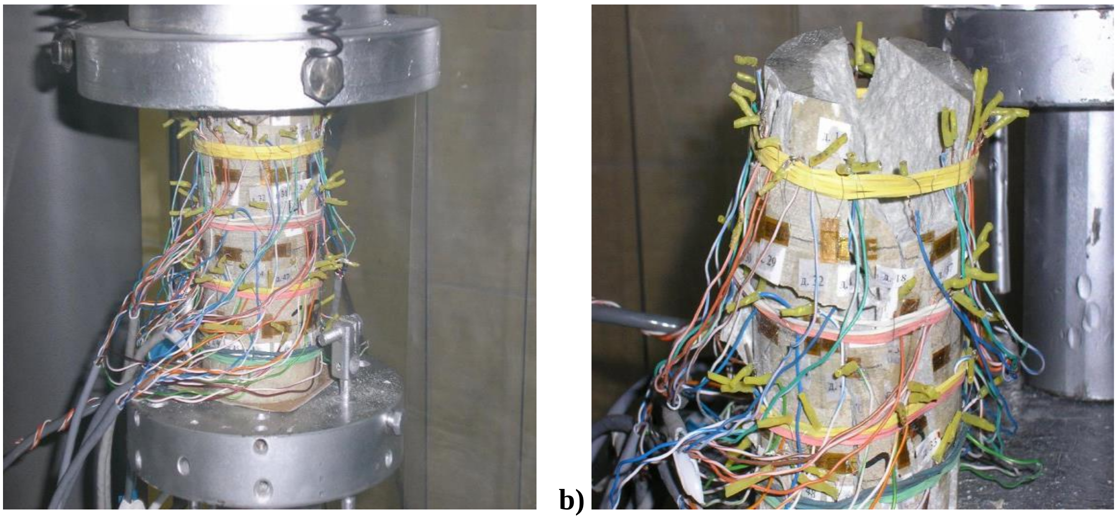


Fig. 1. Measurement scheme and macrocracks directions

Research has been done in the Laboratory of Geodynamics, FEFU (Vladivostok) and Laboratory of Failure, West Australia Uni (Perth). On Fig. 2 the laboratory used for the testing is shown. In Fig. 3 samples prepared for testing are also shown. In total 4 series of 10 samples in everyone of the rock types have been tested. Results were provided for uniaxial compression of rocks samples conditions under the multidot scheme of measurements, with the quantity of measuring points varying from 4 to 24 (Fig. 3). Fig. 4 shows a failed sample of dacite.

Fig. 2. MTS-816 load system in Laboratory on Geodynamics FEFU



a) b)

Fig. 3. Rock sample before (a) and after (b) failure

Let's consider some results of rocks samples deformation research in a prefailure condition with use of the high stiffness and servocontroled loading system.

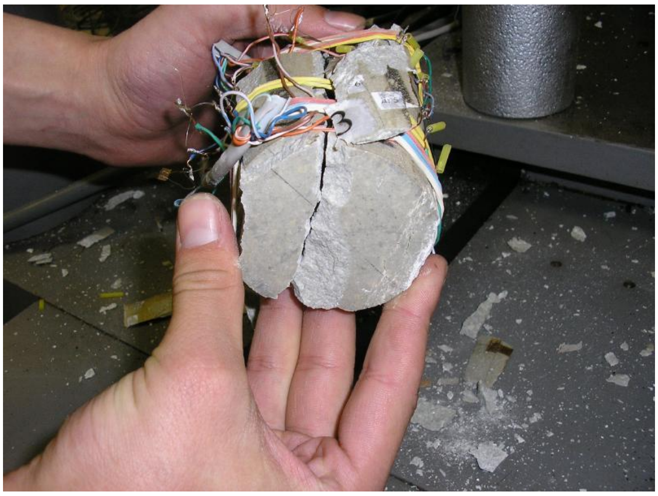


Fig. 4. Macrofailure character of dacite sample (N 3)

Deformation curves of linear deformations for the central part of the sample are shown on Fig. 5. It is seen that in the prefailure stage of loading flattening of the curves can be observerd with a corresponding reduction in the modulus of deformations from 1.5 to 3 times. The cases of a reversal of the linear deformations are marked also.

In Fig. 6 and Fig. 7 the typical picture of distribution of the specific volume deformations on perimeter of the sample in its central part in the prefailure area of loading is shown. Specific volume deformations are considered in connection with the necessity for the reduction of the volume deformation increment values to unit pressure and rcorresponding to a comparable loading curve at all stages of deformation:

$$\varepsilon_v^{sp} = \Delta\varepsilon_v / \Delta\sigma, \text{ MPa.}$$

It can be seen that the process of decompaction is changed by the sudden change in increments of deformation of a different sign, followed by a short period of stabilization after which the stage of preparation of the macrorupture commences, coming to the end with abrupt change of sign of the increment of volume deformation in all parts of structure. After that there is a macrodestruction.

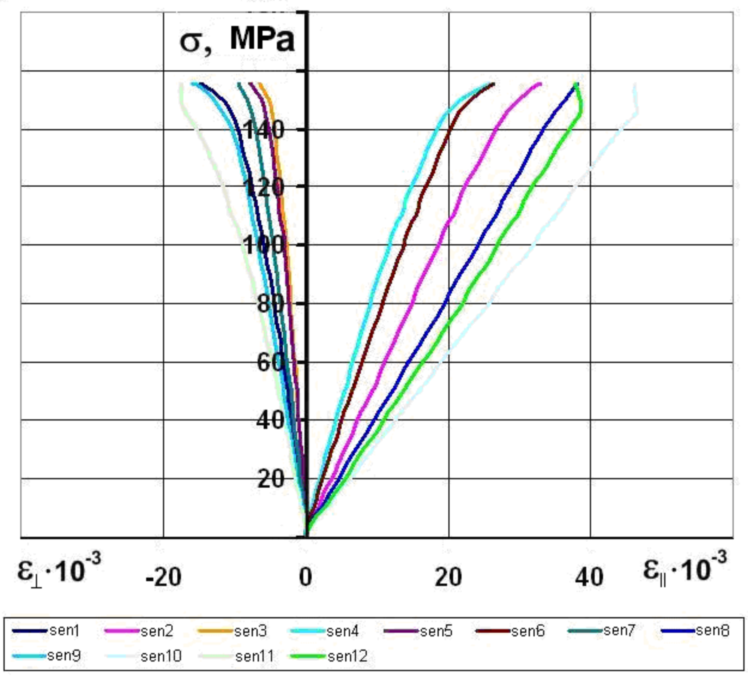


Fig. 5. Relationships of rock samples deformation in prefailure stage of loading: linear deformations in central part

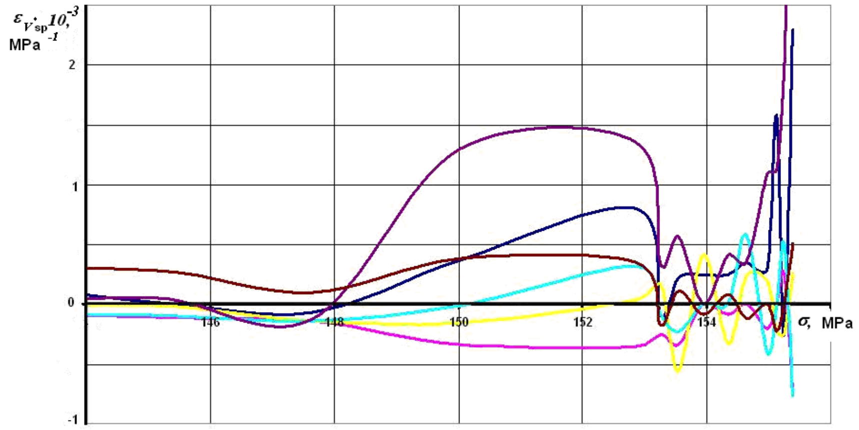


Fig.6. Relationship of rock sample deformation in prefailure stage of loading (granodiorite, sample N 8)

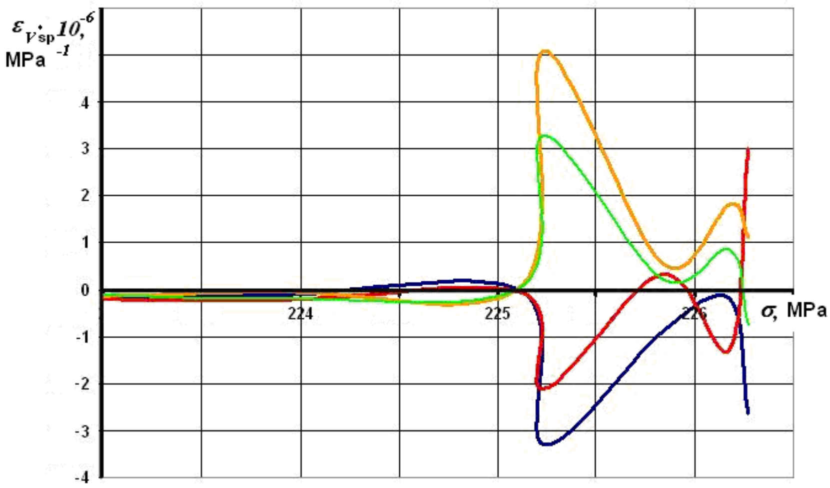


Fig. 7. Relationship of rock sample deformation in prefailure stage of loading (granity-porphyry, sample N 1, source part)

Thus, three stages of deformation of the rock samples, having their own precursors are identified:

- material transform in a dilatancy condition (Stage I),
- formation of zones of relative consolidation and dilatancy (Stage II), and
- change of the distribution character of the volume deformations increment (Stage III).

To these stages there are corresponding deformation precursors of rock failure (Fig. 8):

- a long-term precursor – a point of intersection of the graph line of the volume specific deformation increment with an axis of pressure;
- an intermediate term precursor – the moment of simultaneous differing increments of volume specific deformation; and
- a short-term precursor – the moment of sudden change of sign of the volume specific deformation increment.

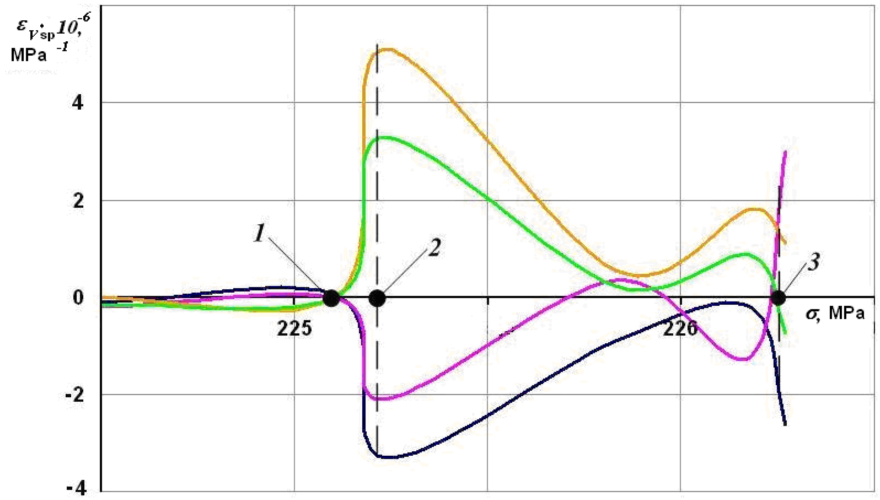


Fig. 8. Deformation precursors of failure: 1 – long-term, 2 – immediate-term, 3 – short-term

For confident fixing of the above-named precursors of destruction, the following demands are made to a technique of rock samples test:

- measurements of linear deformations are necessary for making not less than in four local points located in the central part of the sample, the deviation of measuring position of devices from the central part of the sample shouldn't exceed 0.1 part of its height; and
- fixing of loading and removal of the data with tensoresisters should be made with the minimum frequency of 2 measurements in a second, and the speed of deformation changing in limits from 0.01 to 0.2 mm/sec.

The loading device, with which help the research was made, should be servocontroled, allowing readings with the accuracy demanded for fixing all three stages of deformation.

For more detailed study of the processes which areoccurring in samples of rock in the prefailure loading area independent research of the development of the source of destruction in the sample has been undertaken using the method of the acoustic emission thusallowing identification of the acoustic-issue events connected with cracking in the sample.

Experimental research of cracking regularities in rocks samples in the prefailure loading area

The method of acoustic tomographical research of cracking laws in loading is well developed in experimental geomechanics [3]. In a problem of determination of reliable deformation precursors this method raises the reliability of the received results, and allows to connection of the occurrence of the processes of meso- and macrocracks with deformation anomalies.

The primary goal of geoacoustic control is the fixing of the positions of the source of destruction in samples of rock in the prefailure loading area. For this purpose gauges were mounted on the lateral surface of rock samples. The system used not less than four piezoelectric gauges. By the fixing the acoustic-issue event by system of gauges allows the calculation of the coordinates of each event according to the scheme of a relative arrangement of gauges set in a measuring complex and the linear sizes of the sample.

By preparation for the experiment data-acquisition equipment parameters the following were preliminary set:

- method of a signal fixation (on time of receipt/on achievement of peak amplitude);
- the maximum time of a signal increase;
- the maximum duration of a signal;
- speed of a sound distribution in a material; and
- the linear sizes of the sample and a relative arrangement of gauges.

Realization of a three-dimensional location it is necessary to set the linear sizes on three axes. Thus, the model of the sample created in system, will have the parallelepiped form. It is necessary for considering the analysis of the received data. The obtained data allows not only to define coordinates of the source of destruction, but also its development in time that allows it to be compared with the results of the deformation data.

In the experiments, vibrating piezoelectric converters with fluctuations on a thickness were used, having disk-shaped the form, resonant frequency 1300 kHz and diameter of 10 mm – MSAE-P500. These are highly sensitive gauges on usingniobate of lithium with a broadband lownoise preamplifier, working in a frequency range 50–1500 kHz with cable connection (Fig. 9). Characteristics of the gauges are presented in Table 1. Gauges are completely tight and protected from external electric interferences.

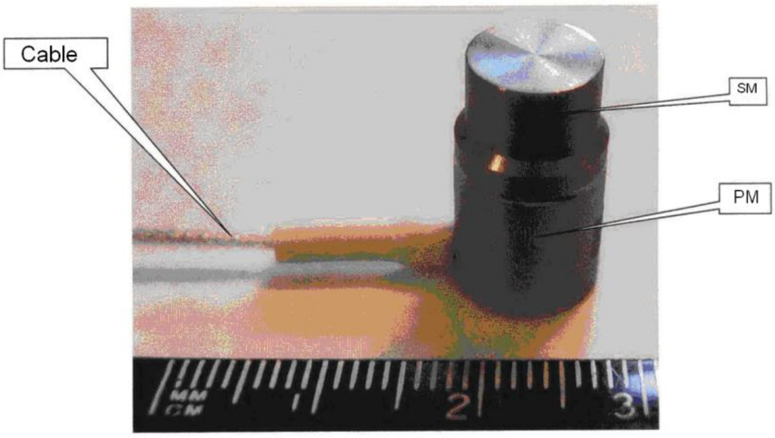


Fig. 9. Gauge AE MSAE-P500: SM – sensitivity modules, PM – preamplification modules

Table 1

Main characteristics of gauges MSAE-P500

Characteristics	Meaning
Peak sensitivity	74 dB
Fringe of signal transmission	50–1500 kHz
Extremal resonance frequency	1300 kHz
Coefficient of preamplifier amplification	27 dB
Mean square noise level	< 3 mV

For data-acquisition the measurement of the acoustic-issue used a complex A-Line 32D. The complex is intended for carrying out the nondestructive control of objects. The control purpose is the definition of the coordinates and tracking of the sources of acoustic issue of the cracks. The information received after processing is used for revealing and localization of possible defects in objects (Fig. 10).

Fig. 10. Acoustic-emissive measurement complex A-Line 32D

Complex A-Line 32D represents a multichannel system of gathering and processing of the acoustic-emissive information received in real time from investigated object from acoustic gauges for carrying out of experiment.

By preparation for acoustic-emissive measurements it is necessary to provide as much as possible dense contact of piezoelectric gauges to a lateral surface of the sample. For this purpose on a lateral surface of the sample of the cylindrical form it is necessary to create an equal smooth surface, perpendicular to end faces.

For removal of emptiness between the gauge and the sample it is necessary to use greasing in a place of contact and to provide uniform pressing of gauges to a lateral surface of the sample. Gauges are established in 6 points on a lateral surface of the sample symmetrically around the cylinder axis (Fig. 11).

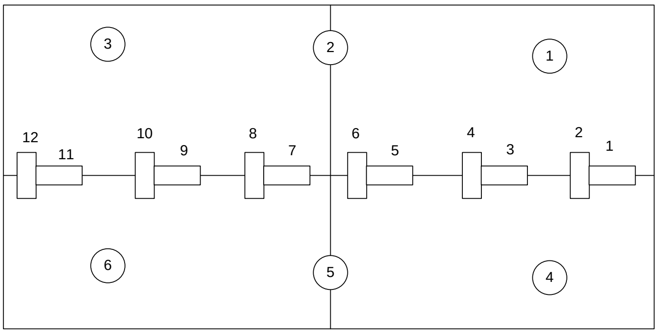


Fig. 11. Scheme of acoustic-emission gauges displacement. (1) – acoustic-emission gauges

The determination of the elastic wave speeds in the axial and orthogonal directions, was achieved using a generator of impulses on the piezoelectric converters. After the calculation of the speed of a wave the speed between two opposite gauges was made taking into account the wave form. For an increase in the accuracy of the measurement speeds adistribution of waves between various steams of gauges are calculated, then these values are compared.

All data from the acoustic gauges was fixed and processed using the acoustic-emission measuring complex INTERUNIS A-Line 32D. The sample was placed in th test machine MTS-816 and loaded uniaxially, with the constant velocity up to failure (Fig. 12).

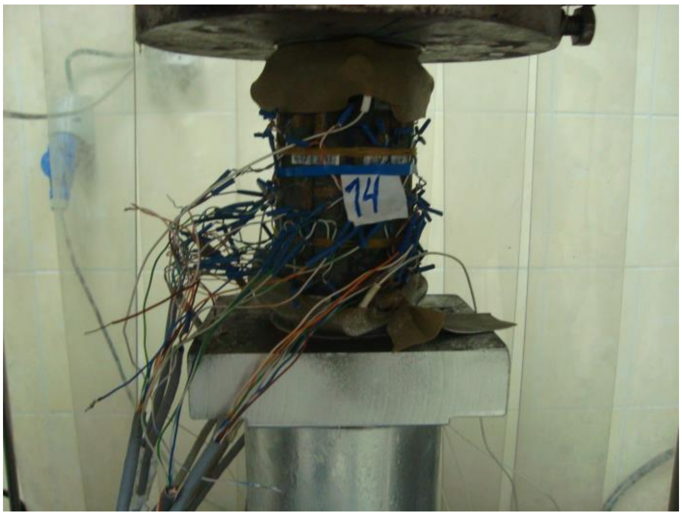
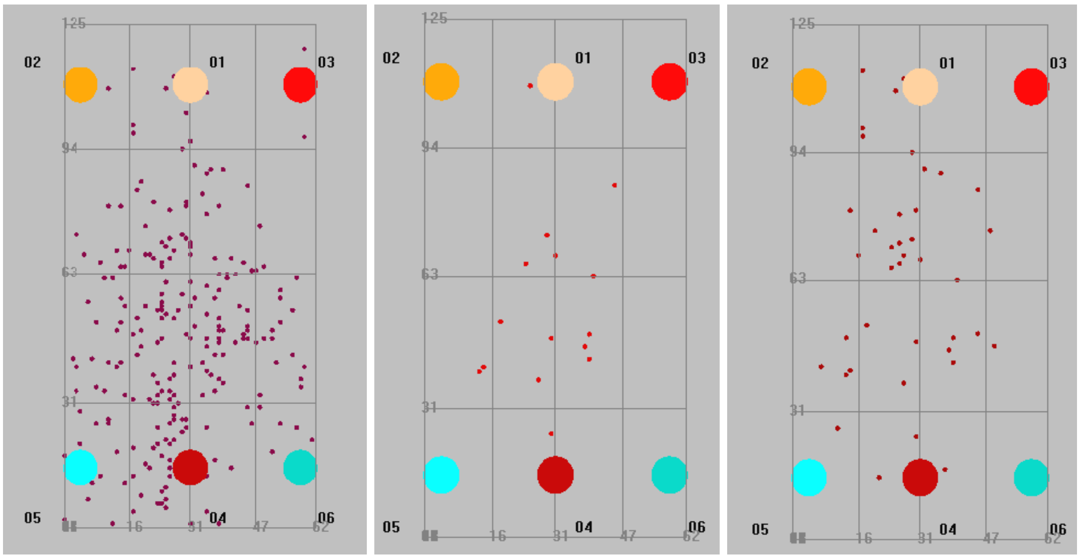


Fig. 12. Rock sample in the loading process

The analysis of the received acoustic-emission data allows tracking the stages of the source development in the rock sample (Fig. 13). At the first stage (Fig. 13, a) it is shown that until time moment t1 defects are randomly distributed around the sample in regular intervals.

After time moment t1 and until time moment t2 there is a localization of the destruction source. In the most part of the signals concentrate in the area, located at the subcentre of the sample (Fig. 13, b). Following time moment t2 there is a sharp increase in the quantity of registered events and macrorupture development (Fig. 13, c) begins.

Thus, we see that the stages of deformation of the samples and the stages of formation of the destruction source practically coincide in time (Fig. 14). It testifies the dependence of deformation anomalies on the development of the degree of mesocracking structures within the sample.



a) b) c)

Fig. 13. Stages of destruction source development in rock sample: a – signals, registered in time period 0-t1, chaotic stage of cracking; b – signals, registered in time period t1-t2, source localization stage; c – signals, registered in time period t2-tкр, stage of macrofailure source development

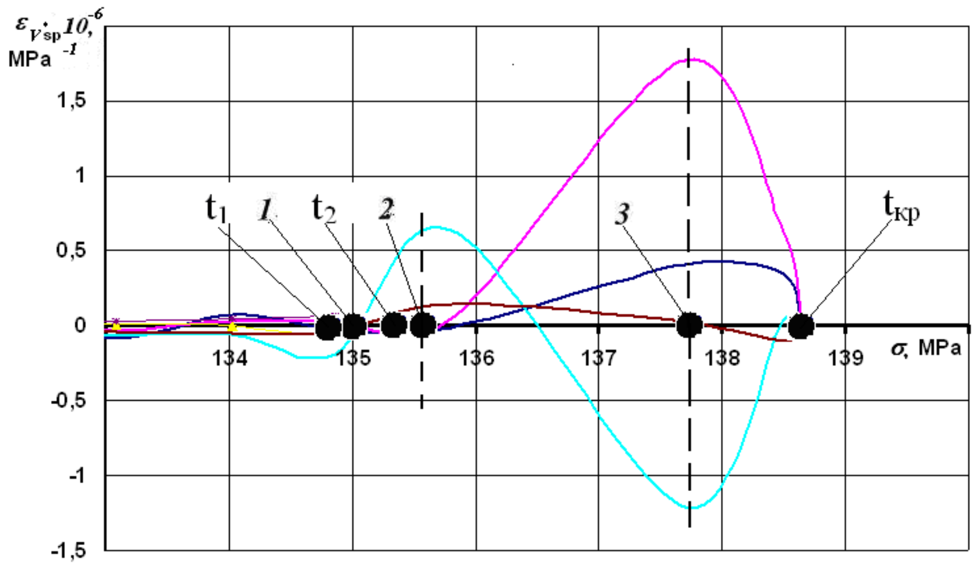


Fig. 14. Precursors of rock samples failure. Deformational precursors: 1 – long-term, 2 – middle-term, 3 – short-term. Acoustic precursors: t1 – moment of the coherent mesocracking process beginning, t2 – moment of the mesocracking localization process beginning, tкр – moment of the macrocracking process beginning

On the basis of the research undertaken, the complex deformational-acoustic method of the forecast of rocks sample destruction in a condition of the high stress is demonstrated. It is different to the long-term precursor at the threshold of dilatancy, defined as a point of an excess of a curve of volume deformations and corresponding to the beginning of coherent formation of mesocracks as accepted; as the middle-term precursors the moment of sign-different increments of the specific volume deformations, corresponding to the beginning formation of dissipative mesocracking structures of the sample is accepted; and as a short-term precursors the moment of rapid change of increments of the specific volume deformations, corresponding to the beginning of formation of macrorupture is accepted.

Theoretical research of cracking regularities in rocks samples prefailure loading area

Modelling of highly stressed rock, where conditions of compatibility of the deformations aren't satisfied, by the far from a condition of thermodynamic balance dissipative system generally has well proved at the description of the phenomenon of zone destruction of a rock mass around the underground openings. Therefore the mathematical model has been developed and the decision of a problem on highly stressed rock sample is given [2].

Deformation anomalies of reversive type appear in the rock sample at achievement by loading σ some critical values σ*. If σ it is less then σ* there is stress-strain condition of the sample is described within the frames of the elasticity theory:

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

where E = Young's modulus, ν = Poisson's ratio.

When σ it is less then σ* the equations of balance for the rock sample in cylindrical coordinates look like:

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

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

$$\frac{\partial \sigma_{rz}}{\partial r} + \frac{1}{r}\frac{\partial \sigma_{\varphi z}}{\partial \varphi} + \frac{\partial \sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r} = 0. \qquad (2)$$

and boundary conditions of the task about the stress-strain condition of the cylindrical sample at uniaxial compression are formulated as

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

$$\sigma_{rr}\big|_{r=R} = 0,\ \sigma_{r\varphi}\big|_{r=R} = 0,\ \sigma_{rz}\big|_{r=R} = 0. \qquad (3)$$

From the experimental results it follows (Fig. 5) that the abnormal character of deformations in the loading area where σ it is more than σ* (we will designate these deformations $x = 0{,}5\pi$), coincide with the order of sizes with subcritical deformations in area σ less than σ*. It allows us to connect the pressure Π_{ij}, corresponding to deformations, with the linear relationship similar on the algebraic structure to the Hooke's law for conditions of area where σ it is less than σ*:

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

where E = Young's modulus; ν = Poisson's ratio.

Formation of periodic mesocracking structures involves the occurrence of some new field of stress which generally depends on the type of cracking defects. As the sample is in balance the forces defined by a field T_{ij}, should be compensated, therefore often they are called "self-counterbalanced". As a compensating field acts Π_{ij},. Thus a full field of pressure in the sample E_{ij} equally:

$$\Sigma_{ij} = \Pi_{ij} + T_{ij}. \qquad (5)$$

It is satisfied to equilibrium eqation (2) and boundary conditions (3). In turn for fields Π_{ij} and T_{ij}, also it is possible to write down the corresponding equations of equilibrium:

$$\frac{\partial \Pi_{ij}}{\partial x_j} = 0\ \ \frac{\partial T_{ij}}{\partial x_j} = 0, \qquad (6)$$

and boundary conditions:

$$\Pi_{ij}n_i\big|_{\partial V} = -T_{ij}n_i\big|_{\partial V}. \qquad (7)$$

In that case

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

where ε_{ipq} = symbol of Levi–Chivity, constant; σ_0, l = have dimension of pressure and length accordingly.

Concrete kind of functions $\Gamma_{gm,p}$ depends on type of defective structure, thus it is necessary to analyze background of formation of defects and dissipative processes in a material.

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

The field of elastic pressure and deformations can be connected by linear relationships

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

with the some coefficients A, B.

Without restriction of a generality of the parameters *A*, *B*, it is possible to choose them as in the elasticity theory:

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

where μ = shear modulus.

As the equation (5) is linear we will present a field Π_{ij} in the form of the sum of the classical decision σ_{ij} and some field π_{ij}:

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

As the decision is under construction in the prefailure area is loading level σ = σ* as the start point, therefore in the formula (3) for σ_{ij} it is necessary to believe $\delta\sigma = \sigma - \sigma^*$ instead of σ^*. We will in addition demand, that the first invariant π_{kk} addressed is zero. Then the tensor π_{ij} is connected with a corresponding tensor of deformation by a parity

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

where a_i = components of a vector of the displacement, loadings counted from level $\sigma = \sigma^*$.

Components a_i (i = 1,2,3) are defined from the equations of balance which in cylindrical coordinates system look like:

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

After the decision of system (12) in the form of a Fourier series on trigonometrical functions and carrying out of numerical calculations for experimental conditions at values of parameters of model: $\nu = 0,26$, $E = 1,7 * 10^4$ MPa, $x = 0,5\pi$, $h = 5\,cm$, $R = 2,5\,cm$, we receive values of series coefficients:

$$A_{21}^{(1)} = -3519 \cdot 10^{-6} \, , \; A_{41}^{(1)} = -29410 \cdot 10^{-6} \, , \; A_{11}^{(2)} = -1167 \cdot 10^{-6} \, ,$$

$$B_{21}^{(1)} = -700 \cdot 10^{-6} \, , \; B_{41}^{(1)} = 885 \cdot 10^{-6} \, , \; B_{11}^{(2)} = 1143 \cdot 10^{-6} \, . \tag{14}$$

Calculating now deformations, corresponding to Fig. 5, and displaying them in comparison with the data of this experiment in Table 2, we can see that at full qualitative coincidence of the analytical and experimental results the maximum quantitative divergence of values of longitudinal deformations doesn't exceed 19 %.

Table 2

Results of comparison of the data theoretical and experimental research

Parameter	Volumetric deformations number in places of gauges [6]							
	4–6		5–7		2–8		3–9	
	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory
Volumetric deformations, 10-6	-1067	-899	704	704	-899	-899	679	679
Deviation, %	18,7		0,0		0,0		0,0	

Conclusions

Thus, satisfactory results of mathematical modelling allow us to determine the mechanism of phenomenon oscillation periodic deformation of high stressed rocks samples which consists in the conditions of strong unequal-component compression and caused by this mesoshear destruction on discontinuities in the media, pressure in the sample get oscillation periodic character that has a consequence development on local sites of action of the maximum normal tangential pressure of the sources of concentration of cooperating mesodefects, and in a vicinity of the sources – formation concerning the unloaded sites where deformations get reversive character.

Determination the phenomenon oscillation periodic deformation of high stressed rocks samples allows us to formulate system of deformation precursors of destruction that has great value for the forecast of the geodynamic phenomena in a rock massifs and earth crust.

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