The time-space relationship between strain, microstrain temperature fields and microseismic emission parameters in geomodels with hole under external loading

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Abstract. A complex analysis of evolution of microseismic emission signals, temperature field and microdeformation field under uniaxial loading before the destruction of prismatic samples from artificial geomaterial and rocks allowed to establish the relationship between the patterns of signal changes and the level of loading. The evolution of deformation process, development of microdamages and the formation of main rupture fracture lead to significant transformation of spectral composition of microseismic emission signals, microdeformation field, and the temperature field. In the region of future main discontinuity the temperature increases, localization of maximum microdeformations occurs and velocities of microdeformations components increase. Generation of powerful low-frequency harmonics at loads approaching the peak, can serve as a harbinger of a rupture on the surface and, consequently, destruction of the geomaterial.

1. Introduction

A literature review over the past three years has shown that there are a number of papers devoted to the study of the specific change in the parameters of the microdeformation field by the speckle method [1, 2, 5, 6] and acoustic emission signals (AE) [3, 4]. In the experiments on uniaxial compression of argillite [1] using a speckle method, heterogeneous local strain fields that correlate well with the microstructure of argillites are illustrated. Based on the monitoring of seismic signals and the use of the speckle method [2] for slip processes on gypsum samples with inhomogeneous contact surfaces (smooth and rough), it was noted that a distinct peak in the amplitude of the AE signal wave can be considered as a failure "precursor". According to the speckle – method, slips are identified as jumps in the displacement field along the crack. Two measurement methods with simultaneous measurement of stresses, deformations and AE signals [3] were compared under uniaxial compression of granite. It was concluded that the AE method is more preferable for assessing the level of damage. An extensive series of experimental studies of rock specimens of different genotypes during their mechanical loading and theoretical justification of the evolution laws concerning acoustic emission signals are considered in paper [4]. The use of speckle – photographic methods to study deformation and fracture of rocks was justified [5], an analysis of the deformation field in the process of loading prior to failure, and zones of maximum deformations localization was given. The deformation evolution of granitic samples with measurement of acoustic emission signals and method of digital image correlation were presented in paper [6]. A good agreement between the location of AE signals and the trajectory of a crack is shown.
In this paper, a laboratory study of the deformation process in artificial layered geomaterials prior to destruction with simultaneous measurement of stresses, deformations and MSE signals is given. The analysis of synchronized experimental data made it possible to determine the specific change in the parameters of microseismic signals depending on the stage of the deformation process in rock samples, and also to reveal the evolution dynamics of microdefections and the main discontinuity domain.

2. Experimental procedure and measurement equipment

In the experimental research it was used Instron-8802 servohydraulic testing machine for loading specimens by axial force. The test samples were made of argillite. The samples were rectangular prisms 50x50x20 mm with a hole diameter 15 mm in the center (Fig. 1). Tests of rock specimens were carried out under uniaxial strain-controlled compression prior to failure at a rate of 0.1÷6 mm/min. Microstrains were recorded using automated digital speckle photography analyzer ALMEC-tv at frequency of 27 frames per second and spatial resolution not less than 1 µm. The processing output is the coordinates and displacements of the specimen surface points and timing, which allows calculating strain tensor components [7]. Four microseismic KD 91 sensors were installed on four lateral faces of the cube to record the MSE signals. The measurement of the temperature field was carried out using by computer thermal imager TKVr-SVIT 101, the accuracy of the measurement is 0.03°K. Figure 2 illustrates general view of the experiment. Figure 3 presents the curve of the specimen stress and macrostrain and the specimen stress and time.

![Figure 1. Rock specimens before and after fracture.](image1)

![Figure 2. General view of the experiment: 1—optical/tv measurement complex ALMEC-tv; 2—rock specimen; 3—compression grips of the Instron-8802.](image2)

3. Experimental data analysis

The uniaxial strain-controlled compression used prismatic specimens of argillite at the mobile grip displacement rate of 0.1÷6 mm/min. Figure 3 shows the curves of the specimen stress and macrostrain and the specimen stress and time. Ultimate strength of the specimen was 39.1 MPa, ultimate strain along x, measured by the machine cross beam unit displacement, was 0.076.
Fig. 3. The curve of stresses and strain in the rock specimen in the direction of \( x \) (a) and the stress and time curve (b).

A large number of microseismic signals were recorded under uniaxial compression prior to destruction of prismatic samples. Figure 4 shows the diagram \( \frac{\sigma}{\sigma_B} - \frac{t}{t_m} \) obtained from uniaxial compression data, where \( \frac{\sigma}{\sigma_B} \) is the ratio of the current stress value to the ultimate strength value \( \sigma_B \), and \( \frac{t}{t_m} \) is the ratio of the current experimental time to the value of \( t \) at \( \sigma = \sigma_B \). The typical signals recorded at points 1, 2, 3 are shown in Fig. 5.

Fig. 4. The diagram \( \frac{\sigma}{\sigma_B} - \frac{t}{t_m} \) obtained from uniaxial compression of a prismatic sample.

Based on the analysis of a large data bank on the MSE signals, the following regularities are revealed:
- At stress levels \( \frac{\sigma}{\sigma_B} = 0.3 \pm 0.4 \) (point 1), the first MSE signals are recorded, the acceleration magnitude is \( 2 \pm 4 \) m/sec\(^2\), the broadband frequency is \( 8 \pm 24 \text{ kHz} \) (Fig. 5a, b).
- At stress levels \( \frac{\sigma}{\sigma_B} = 0.5 \pm 0.8 \) (point 2), the amplitude of the MSE signal increases, its magnitude reaches a value of \( 0.35 \) m/sec\(^2\). At the same time, the frequency spectrum is somewhat narrowed and shifted towards low frequencies, up to \( f = 10 \pm 14 \text{ kHz} \) (Fig. 5c, d).
- At the last deformation stage at a stress close to \( \frac{\sigma}{\sigma_B} = 0.8 \pm 1 \) (point 3), the number of microdamages and MSE signals increases significantly, their energy increases, the frequency spectrum is further narrowed and shifted to low frequencies, up to \( f = 8 \pm 10 \text{ kHz} \).

A powerful low–frequency signal of \( 8 \pm 9 \text{ kHz} \) is generated at the time of the main discontinuity initiation (Fig. 5d, e).

In previous studies [7] the detailed analysis into the micro-level stress–strain state distribution and propagation over acting faces of rock specimens subject to uniaxial loading until failure, using automated digital speckle photography analyzer ALMEC-tv, have shown that:
- under uniaxial stiff loading of prismatic sandstone, marble and sylvinite specimens on the Instron-8802 servohydraulic testing machine at the mobile grip displacement rate \( 0.02 \pm 0.2 \) mm/min, at a certain level of stressing, low-frequency micro-deformation processes originate in the specimens due to slow (quasi-static) force;
- the amplitude of that deformation-wave processes greatly depends on the micro-loading stage:
  - at the elastic deformation stage, under the specimen stress lower than half ultimate strength of the specimen, there are no oscillations of microstrains;
— at the nonlinearly elastic deformation stage, under stress varied from 0.5 to 1 ultimate strength of the specimens, the amplitudes of microstrains grow, including the descending stage 3; the oscillation frequency \( f = 0.5 \pm 4 \) Hz;
— at the residual strength stage, the amplitudes of the microstrains drop abruptly (3–5 times) as against stages 2 and 3;
• in the elements of the scanned specimen surface in the region with the incipient crack, the microstrain rate amplitudes \( \varepsilon'_y \) are a few times higher than in the undamaged surface region of the same specimen. Deformation rate greatly grows with increase in the load.

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Fig. 5. The MSE signals registered at points 1 (a, b), 2 (c, d), 3 (e, f) of the diagram \( \sigma/\sigma^0 - t/t_m \).

Fig. 6 shows mapping of the scanned surface by the microstrain \( \varepsilon_y \) in longitudinal direction \( y \) of a specimen at points 1, 2, 3 in the stress–time curve in Fig. 4. In the surface of specimen deformation scan in longitudinal direction in Fig. 5, the negative values of deformation (shortening) correspond to blue color. The zero strains are shown by black color. The positive values of deformation (elongation) comply with red color. White color shows strains over 0.02 mm. In the cross direction deformation scans in Fig. 6, white color also marks the strain above 0.02.
At the first stage (point 1) of loading at voltages not exceeding 0.25 ÷ 0.5 of the peak load, the field of microdeformations is chaotically inhomogeneous, the vibrations of the components of microdeformations are practically absent (Fig. 6 a). At the second stage of deformation (point 2), when the voltage takes values from 0.4 ÷ 0.5 to 0.7 ÷ 0.8, the field of microdeformations becomes more non-uniform, zones of maximum microdeformation occur, the values of which exceed the average values over the surface of the sample (Fig. 6 b). At the third stage of deformation (point 3) at the stresses from 0.8 of the ultimate strength to the peak load, the zones of maximum microdeformations are localized in a certain volume of the rock sample, which indicates the beginning of the formation of the main discontinuity, whose exit location on the sample surface can be determined at loads less than the peak (Fig. 6 c).

Figure 6. Mapping of the scanned surface by the microstrain \( \varepsilon_y \) in longitudinal direction \( x \) of a part of specimen at the compression moment at points 1 (a), 2 (b), 3 (c) of the diagram \( \mathcal{G}_f / \mathcal{G}_B - t / t_m \) (Fig. 4).

The microdeformation rates at the second and third deformation stages were estimated for two different region types of the scanned sample surface: 1 – region with a subsequently formed crack, 2 – region of the nondestructed material. A typical diagram of the change in the rates of microdeformations is shown in Fig. 7. It can be seen that in the elements of the scanned sample surface in the regions with a future crack (region 1), the amplitude of the microdeformation rate \( \varepsilon_y \) exceeds several times the rate observed in surface region of the indestructible geomaterial (region 2). In a number of cases, there is a tendency for a significant increase in the deformation rate with increasing loading.

Figure 7. Typical dependences of the lateral microdeformation rates on the time for element 0.5 x 0.5 mm in size for the region with a future crack (1, 2) and region of the nondestructed material (3, 4).

Temperature measurement on the sample surface was carried out using the computer thermal imager TKVr-SVIT 101, the accuracy of the measurement is 0.03°K. Analysis of temperature data shows that at the beginning stage of loading, temperature field exhibits no obvious change. With the loading
development, strains focus around the hole gradually, over and under of the hole appear tensile strain along the direction of loading and grow gradually.

\( t=0.8 \text{ t}_m \) the temperature increases in the region with an X-shaped shape near the hole. When the loading time is \( t=0.9 \text{ t}_m \), the red area to the left of the hole increases in size. On the diagram of y-component of the microdeformation it is a correspondence - this is the region of higher values of tensile microdeformations. With further increase in the load, a main crack appears at the top left of the hole, then from the top right, at the last moment - a vertical crack under the slope and the sample is completely destroyed. The temperature rise in the zones of localization of the maximum microdeformation is 1.5°K. With an increase of loading rate from 0.1 mm per second to 6 mm per second, these patterns of temperature field variation manifest more contrastively.

Figure 8. Temperature field on the sample surface at loading moments \( t=0.8 \text{ t}_m \) (a, d, e) and \( t=0.9 \text{ t}_m \) (b, f, g), photograph of the corresponding destroyed rock sample (c).
4. Conclusion
Complex analysis of the evolution of microseismic emission signals, microdeformations, temperature field, strain and deformation showed that the evolution of crack formation in the rock samples is completely satisfactorily characterized by each of the methods.

There is precise relationship between the patterns of change of the parameters of microseismic emission signals, the components of microdeformations field, their velocities, the temperature field in correlation with the stress-strain diagram.

The character of the change of parameters of these physical fields makes it possible to determine the location of the exit of main discontinuity to the sample surface at loads less than the peak when the sample still preserves its integrity.

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