Integrated studies into characteristics of physical fields using discontinuous geomedium models under external loading

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Abstract. The article presents the laboratory study of deformation in artificial layered geomaterial samples down to failure with the simultaneous measurement of stresses, strains, micro-strains and signals of microseismic emission. The analysis of the synchronized experimental data made it possible to determine features of change in the microseismicity parameters and micro-strain fields in the samples depending on the deformation stage, and also to reveal the dynamics of evolution of microfailures and the main fracture zone.

The comprehensive analysis of different nature physical fields in geo-media under loading offers reliable information on initiation, accumulation and growth of different defects, and helps revealing regularities of the process of deformation up to complete failure. The review of the recent literature shows that there are studies into evolution of microseismic emission, fields of micro-strains using speckle-method and signals of electromagnetic emission [1–8]. The analysis of tests of artificial geomaterials and rocks shows good correlation between heterogeneous local deformation fields and microstructure of specimens [1, 2]. Based on the monitoring of acoustic emission of rock specimens under deformation, the character of change in AE signals and failure pre-cursors are examined in [3, 5]. The application of the speckle-photography methods to studying deformation and failure of rocks is validated in [6], and the fields of strains under loading to failure as well as zones of location of maximum strains are analyzed. In [8, 9], the description of the measurement system for the concurrent recording of pressure, displacement and electromagnetic emission during on-axial compression tests is given; it is also pointed at a stable growing trend of the signal amplitude as well as at the increase in the local electromagnetic activity at the stages of initiation and expansion of destructure zones. The research into the evolution of deformation of sandstone specimens with the measurement of acoustic emission signals and digital correlation of images [10] illustrates good agreement between locations of AE signals and crack trajectory. Using the digital image correlation, critical deformation values when strain localization zones become unstable and spalling takes place are determined.

The investigation of interaction between parameters of physical fields of different nature (deformation, micro-deformation, microseismic emission) in models of geomain subjected to deformation and failure used the testing equipment set designed and manufactured at the Institute of Mining, SB RAS [11]. During the tests, the fields of microstrains, microseismic emission (MSE), deformations and loads were recorded concurrently with video imaging. The uniaxial compression was
carried out of Instron 8802 servo testing machine. The speckle-recording of microstrains used the automated speckle photography analysis system ALMEC-tv, which allows microdisplacement measurement at an accuracy of 1 μm and frequency of 27 shoots per second. The signals of microseismic emission were measured using accelerometers KD 91 of the multichannel system Pulse. Video shooting was carried synchronously. The uniaxial compression was applied to artificial geomaterial cubes with an edge of 200 mm at the loading rate of 0.1 mm/min. On the four faces of a cube, 4 microseismic sensors KD 91 were mounted to register MSE signals. Displacements and axial (vertical) force were measured by Instron 8802 test machine. Displacements in two orthogonal horizontal directions were recorded by probes Solartron DP10S arranged in the plane perpendicular to the normal force. Figure 1 shows the general view of a cubic specimen between Instron 8802 presses with microseismicity sensors KD 91 and probes Solartron DP10S. The artificial geomaterial was made of a mixture of sand and cement, the cubic specimens were manufactured of two layers having strengths of 21.4 and 7.1 MPa, the angle of bedding in different specimens was Ψ = 0, 30, 45, 60, 90°.

The integrated analysis of the microseismic emission, microstrains, stresses and displacements shows that each of the methods satisfactorily describes the evolution of fracturing. Moreover, there is a clear interconnection between the regularities of variation in MSE signals, microstrain field components and their velocities and the stress–deformation diagram.

Figure 2 shows the curve \( P/P_{\text{max}} - t/t_{\text{m}} \) obtained under the uniaxial compression of the cubic specimen with the bedding angle \( \Psi = 45^\circ \), where \( P/P_{\text{max}} \) is the ratio of the current and maximum axial loads, \( t/t_{\text{m}} \) is the ratio of the current time to the time \( t \) when \( P = P_{\text{max}} \). The curve shows that deformation has a few stages: when stress changes from 0 to \( \sigma/\sigma_v = 0.2–0.3 \) closure of micropores and microcracks takes place; the next deformation stage up to \( \sigma/\sigma_v = 0.5–0.7 \) is linear elasticity, and the third stage of the stresses up to \( \sigma/\sigma_v = 1 \) is nonlinear elasticity, plasticity and pre-failure.

Figure 1. General view of the cubic specimen arranged between presses of Instron 8802 test machine, with microseismicity sensors KD 91 (1) and displacement probes Solartron DP10S (2).

Figure 2. Curve \( P/P_{\text{max}} - t/t_{\text{m}} \) under uniaxial compression of the cubic specimen with the bedding angle \( \Psi = 45^\circ \).
Figure 3. (a), (b), (c) MSE signals; (d), (e), (f) speckle-method mapping of the specimen surface in transverse direction; spatial distribution of accumulated MSE events (g), (h), (i) at deformation stage (a), (d), (a) 1; (b), (e) (h) 2; (c), (e) (i) 3, respectively.

After processing of many microseismic signals at different deformation stages, the curves of the acceleration $\ddot{a}$ and time $t$, and the acceleration spectral density $S$ and frequency $f$ were plotted. Figures 3a–3c show the typical plots of $S$ in the specimen with the bedding angle $\Psi = 45^\circ$.

In [6, 10, 11] it is shown that the plastic deformation is nonuniform from the very beginning of loading due to mineralogical and structural heterogeneities of a geomaterial specimen. Despite the same pre-set type of loading by uniaxial compression at constant rate, the space-and-time field of microstrains on scanned surfaces contains both contraction and elongation domains. In a series of tests on the cubic specimens, the analysis of change in the microstrain field component in the perpendicular direction to the axial loading using the speckle method has been preformed. Figures 3d–3f present the images of the deformation mapping of the scanned surface of the cubic specimen with $\Psi = 45^\circ$ by the deformation component in the Y-direction of the specimen, in perpendicular to the axial load, at the moments when $\alpha \sigma_c = 0.25$, $\alpha \sigma_c = 0.75$, $\alpha \sigma_c = 0.95$. The negative value of the deformation component (reduction is size)
corresponds with the color close to red. Nearly black color depicts zero deformations. The positive values (increase in size) are presented by green. White color means deformation higher than 0.007.

In order to locate MSE sources (defects) in a geomaterial specimen by the data from 4 microseismic sensors, a location program was developed. The program was checked using a cinogram of test fracturing of a cubic organic glass specimen by fluid, and the agreement between the fracturing zone and the data on location of MSE signals was satisfactory. Figure 3g–3i show the special distribution of accumulated MSE events in a cubic specimen under different loading levels.

The comprehensive analysis of the experimental results has revealed some regularities.

At loading stage 1, under stresses lower than 0.25–0.5 peak load, the quantity of MSE signals is insignificant and the signals are wideband. The field of microstrains is chaotically nonuniform, the fluctuation in the microstrain components is almost absent (Figs. 3a, 3d and 3g).

At loading stage 2, when the stress is from 0.4–0.5 to 0.7–0.8 of the strength limit, the number of MSE signals grows, their amplitude increases while the frequency spectrum somewhat narrows and drifts toward lower frequencies. The microstrain field is even more nonuniform, the zones of maximum microstrains, higher than the average values over the specimen surface, appear (Figure 3b, 3e and 3h).

At stage 3, when the stresses vary from 0.8 of limits strength to the peak load, the number MSE signals increases by a few times as compared with the previous deformation stage, the amplitude of the signals grows, while the frequency spectrum shifts event more to the range of low frequencies and the spectrum band narrows considerably. The maps of the time-and-space distribution of MSE signals show their nonuniform distribution in the volume of the specimen. The maximum microstrains localize in a certain volume of the geomaterial, which is reflective of the initiation of a main fracture, the outlet point of which on the specimen surface can be determined under loads less than the peak loading (Figs. 3c, 3f and 3i). As the fracture comes out at the surface, a strong low-frequency signal is generated.

These regularities are the most clearly observed in the tests of the specimens with the bedding angle $\psi=45^\circ$, which is probably connected with the stronger deformation than in the specimens with $\psi=90^\circ$ and with the more intensive destructuring of the geomaterial with the formation of microdefects.

**Conclusion**

The integrated analysis of the microseismic emission, microstrains, stresses and displacements shows that evolution of fracturing in geomaterial specimens is satisfactorily described using any of these methods.

There is a clear interconnection between the regularities of change in the parameters of signals of microseismic emission and components of the microstrain field per stages of deformation of geomaterial.

The authors have revealed basic regularities in the change of MSE signal parameters and microstrain field components depending on the specimen deformation stage.

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