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PECULIARITIES OF KINEMATICS OF ROCK MASS SHEAR DURING DEVELOPMENT OF SUBSEISMIC-SCALE FAULTS

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The article describes the mechanism of formation and development of subseismic-scale faults in sedimentary rock mass based on results of physical and mathematical simulation. Physical modelling of layered rock massif was carried out by using sand-gypsum mixture. The results of physical modeling made it possible to visually evaluate the process of formation and development of subseismic-scale faults, to establish the orientation and amplitude of the modeled faults. It was established that faults with higher amplitude had filler material formed because of friction of fault edges/walls. The volume of modelled formation after formation of faults depending on fault amplitudes changed from 2-3 to 10 %. To gain information on stress deformed condition of rock massif and identification of key peculiarities of fault propagation dynamics we used the mathematical modeling based on particle-flow algorithm. The results of mathematical modeling determined that during formation of low amplitude faults the shear field has several rock clusters. Due to interaction of clusters, which have coordinated movement and promote massif loosening, the rock mass accumulates voids, which are the prerequisite for formation of subseismic-scale faults. The gained results enable to specify the complex mechanism of irreversible shears and deformations of rock mass during formation and development of subseismic-scale faults. It contributes to the improvement of the methodology for predicting the SSF parameters, which is of practical importance in terms of reducing mining risks.

Key words: formation mechanism, modeling, faults, clusters

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Introduction. Geological deformations are one of the biggest problems in the development of mineral deposits, as they pose anthropogenic risks leading to economic losses and impair safety of mining operations [5].

Subseismic-scale faults (SSF) have particular uncertainty because they are hard to detect by geophysical exploration methods [1, 11]. Usually such faults are manifested during mining operations, which causes higher risks since there could be no time for taking preventive measures [2]. The danger of mining reserves damaged by subseismic-scale faulting is associated with the uncertainty of the degree of ore body damage, as well as the presence of localized high stress zones [12].

Several methods are used to study the mechanism of formation and propagation of SSF [3, 9]. Among them, the methods of physical and mathematical modeling became popular. In this paper, we describe the results of studying the kinematics and dynamics of the stressed state of rock mass during propagation of SSF based on models of equivalent materials and methods of computer simulation.

Characteristics of physical model and technique for modeling the subseismic-scale faulting. The model of rock mass had distinguishable layers of sedimentary rocks. Their thickness varied from 0.5 to 2.0 m. The strength of sand-clay rocks amounted, in terms of the massif, to 40-60 MPa. The selection of the mechanical characteristics of the equivalent material, which ensure the similarity of the mechanical characteristics of the processes in the model, was carried out by the formula

$$N_m = \frac{1}{L}\frac{\gamma_m}{\gamma_n}N_n .$$

The numerical values of corresponding characteristics of the mechanical properties of simulated material are calculated in accordance with the characteristics of the mechanical properties of the simulated rocks (numerical values of N_n) for the given scale of the model ($1/L$) and the ratio of the volume masses (γ_m/γ_n). To produce the equivalent material of the model, a mixture of sand, mica, gypsum and talc was used.

Simulation was carried out by applying shear stress models to its boundaries. In this case, the axes of the main normal stresses are oriented diagonally to the direction of displacement, and the axis of the algebraically minimal (maximum compressing force) normal stresses is located at an angle of

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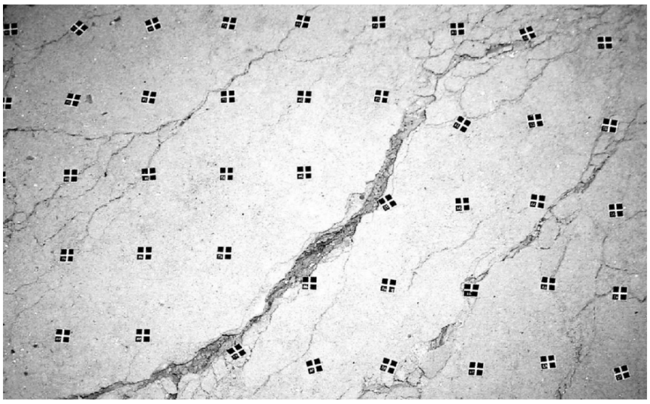

Fig. 1. Model after formation of subseismic-scale faults

45°, which facilitates the formation of faults. This approach is further supported by the work of V.A.Korchemagin [4] and others, who also showed that in those areas where there was a significant difference between the main and normal stresses in the bedding plane, the SSF displacement and faults prevailed. This served as the basis for modeling the boundary conditions by applying shearing forces at the boundaries of the physical model. For convenience in implementing the boundary conditions, the stand for the physical model was made in the form of a ball-and-socket rectangle.

The scale of the model was assumed to be 1:500. This scale provides sufficient modeling accuracy with acceptable model sizes. The mixing ratio is as follows, %: sand 92.2; gypsum 2,8; chalk 1,4; water 3.6. On a given scale, this mixture corresponds to the most typical rocks of the sand shale type with a strength of 55 MPa at a given geometric scale. The model is represented as a layered stratum, the layers are divided by mica.

Discussion of actual physical modeling results. Figure 1 shows the model after the SSF development. Because of shear deformations influence, a system of six faults appeared in the model, the amplitude of which varied from 0.05 to 9.84 m. This value is given here and further in terms of actual measurements. All faults were oriented approximately at an angle of 45 ° to the main normal stresses, which corresponds to the theory of occurrence of discontinuous displacements and faults [1, 3, 4].

The fault plane is oriented along the normal to bedding. All faults without exception have a kind of branching cracks, which decrease from the root of the SS fault to depth of the rock mass.

After completing the simulation, the body of the model was dismantled to study the morphology of the surface of the fault plane. The surface has a rough texture. In faults, the amplitude of which did not exceed 0.1 m, the gap between the edges of plane was free, and its thickness did not exceed 1 cm. In faults, the amplitude of which was greater, there was a filler material formed because of friction of one wall of the fault with another - the opposite one. The volume of the modeled formation after development of faults, depending on the amplitude of the fault, increased from 2-3 to 10 %.

Figure 2 shows the distribution of faults in the bedding plane after the formation of SSF. The area, where the gradient of the rock massif faulting isolines (in meters) is maximal, outlines the fault with maximal amplitude. Peculiarly contrast gradient is observed in the upper right corner of the model, it «weakens» in the direction of the lower left corner, which indicates the disappearance of SSF because of its limited influence on the rock mass [10].

The advantage of physical modeling is the visibility of results and the simplicity of their interpretation. However, information on the stressed-deformed state of the rock massif is limited, which does not

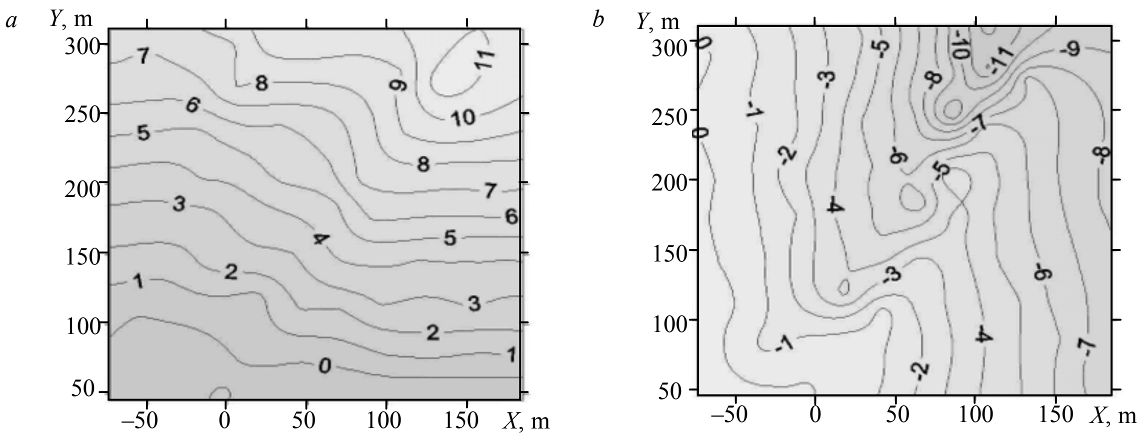

Fig.2. Distribution of faults of modelled massif in the bedding plane:
a – SSF formation; *b* – SSF development

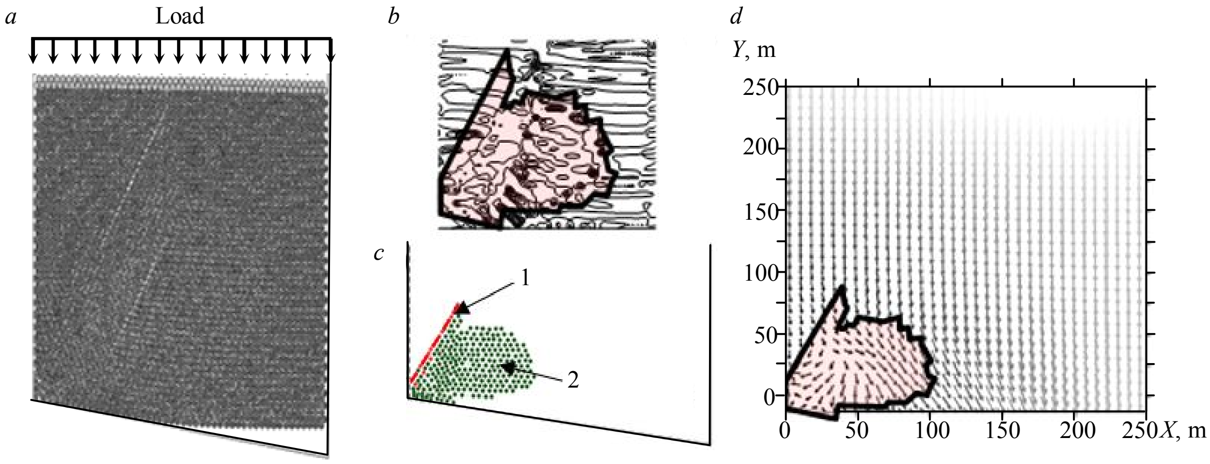

Fig.3. Results of computer modeling:

a – model after SSF development; *b* – area of disintegrated rock; *c* – shear field in bedding plane at the initial stage of disintegration (1 – fault area; 2 – deformation area); *d* – joint diagram of boundaries of disintegrated area and concentration of yield stress

allow to determine important features of the SSF propagation dynamics. That is why the computer simulation of the formation and propagation processes was applied based on the particle-flow algorithm.

Results of computer modeling. The dynamics and kinematics of the SSF formation and propagation were studied using the algorithm similar to the method of discrete elements [8], but discrete blocks were replaced by elementary particles. Thus, this approach was devoid of errors that arise when specifying the shape and size of discrete blocks of rock mass in advance [7].

These blocks and clusters of the rock massif appeared naturally due to the interaction of elementary particles, which corresponds to the real mechanism of irreversible destruction and deformation of the rock massif. It is also important to note that the fault propagation can be investigated from the very beginning of its development [13], since the result depends on the way the load is applied. The history of the fault propagation in rock massif is very important for understanding the result.

The size of the rock massif, boundary conditions and mechanical properties of the rocks were assumed to be the same as for physical modeling. Figure 3 shows the state of the model after the experiment is completed. As you can see, several parallel faults appeared during computer modeling, and they are oriented from the bottom left corner of the model to the right upper one. This confirms the qualitative coincidence of the results of physical and computer simulation.

The initial stage of the process of rock mass destruction occurs in the lower left corner of the model and moves along its diagonal (Fig. 3, *a*). The subpicture of Fig. 3, *c* illustrates the elementary volumes of the rock massif, which became loose and broke off from the surrounding rocks. Figure 3, *b* presents the shear field of the rock mass, which shows that the displacement vectors in the zone of rock mass destruction are disoriented with respect to the remaining displacement vectors of the massif. In addition, in the middle of ruptured zone, marked by bold line and superimposed on the shear field true to scale, there can be singled out several rock clusters. The left cluster resembles a vortex that spins down clockwise, the middle cluster moves down, and the right cluster moves to the right and down. Thus, the fault formation is accompanied by a complex kinetics of extreme or irreversible faults of the disintegrated rocks.

The right cluster extends beyond the boundaries of the disintegrated section of rocks. This means that to reliably determine the position of the boundaries of the destroyed zone, it is necessary to consider the additional stresses of rocks. The subpicture in Fig. 3, *d* demonstrates that the right boundary of the rock disintegration zone practically coincides with several massif elements in which high shear stresses act, which corresponds to the Mohr-Coulomb theory and leads to a transition to yield state.

Thus, the mechanism of formation and propagation of subseismic scale faults in a sedimentary rock massif is based not only on the transition to a yield state, but also on the intensive interaction of clusters of previously disintegrated rocks.

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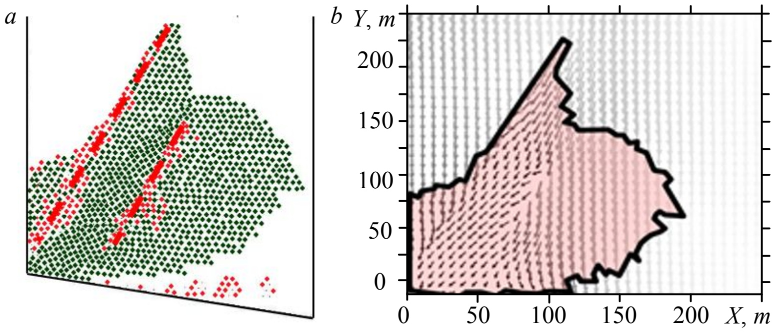

Fig.4. Final stage of SSF development: *a* – connections between elements of computer model (95000 cycles); *b* – joint map of stress field and displacement vectors

The distribution of the shear field confirms this conclusion (Fig.4). It can be seen that along the SSF, which are shown in dotted lines, there are several rock clusters. The left cluster is adjacent to the left SSF and moves along the vertical. The middle cluster moves down parallel to the displaced neighboring SSF, the right domain is shifted mainly down, but it consists of several clusters, the direction of their motion is different. It is this mechanism of coordinated irreversible rock mass displacement in the form of clusters of disintegrated rocks contributes to the accumulation of voids in the rock massif [6], development of faults and expansion of fault plane edges. Without such a reserve, the rock massif may disintegrate, but fault propagation will be restrained by a deficit of voids, since the extreme deformation rock requires softening and loosening.

Conclusions

1. Based on physical and mathematical modeling, the mechanism of formation and propagation of faults in the sedimentary massif have been specified.

2. The prerequisite for SSF propagation is accumulation of voids of the massif due to the interaction of clusters of the rock massif that coordinate their movement and promote the loosening of disintegrated mass.

3. This research made it possible to specify the complex mechanism of irreversible shears and deformations of the rock massif during the formation and propagation of SSF. It contributes to the improvement of the methodology for predicting the SSF parameters, which is of practical importance in terms of reducing mining risks.

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