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PREDICTION OF MINING INDUCED SEISMICITY AROUND MOVING LONGWALL

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При помощи компьютерного моделирования продемонстрирована возможность прогнозирования сейсмичности, индуцированной горными работами, учитывая динамику во времени.

За допомогою комп'ютерного моделювання продемонстровано можливість прогнозування сейсмічності, індукованої гірничими роботами, з огляду на динаміку в часі.

Recent publications indicate growing concern for mining induced seismicity (MIS) because increase of deposits extraction rate [2, 3, 5]. For instance longwall faces move with speed of 300-500 m per month that provides accumulation of potential energy of rock mass deformation. The more the rate of advance the higher the chance of dynamic event that might occur in vicinity of moving face. Dynamic failure of rock mass exposes miners to risk, causes severe damages for mining equipment and financial lost.

Our computer model explicitly uses inertial terms as a numerical mean to reach equilibrium state. However the more the rate of longwall face advance the farther state of surrounding rocks from equilibrium. Therefore the rate of a face advance can be calibrated by a proper number selection for cycling during solving current state of a model. It does mean that finish of cycling should be controlled not by convergence criterion but just reduction of force debalance to a level that corresponds to an actual debalance that occurs under concrete rate of a face advance.

This approach has been tested on a problem of MIS simulation due to coal face retreating.

Finite difference model has been used to simulate MIS that was induced by moving longwall face. Length of the face was 240 m and it moved by step increments. Size of the step was 40m that is six times less then the length of the panel. Every step cycled a number of iterations that provided rate of model continuum deformation that corresponds to the actual rate of rock mass strain. The actual rate has been adopted from data collected during strata movement monitoring in Zasiadko coal mine.

Immediate roof of the coal seam that has thickness 1,45 m has been presented with argillite having thickness from 8 m to 12 m and uniaxial compression strength 40 MPa. A hard thick sandstone presents main roof. This rock layer is usually the main source of dynamic failures that induce MIS. Fragment of mine map depicted in Figure 1. A single isolated coal longwall face retreated East panel in the direction that indicated by arrow. The face kept the rate of advance in diapason 5-7 m per day. MIS has been monitored during retreating of East coal face.

Eighteenth panel was employed to collect difference of rock mass deformation due to variation of rate advance of the 18th coal face that deviated from 2 m per day up to 7 m per day. This face was idle during several days that provided wide diapason of the rate advance. Strata deformation was monitored in a vertical hole that had been drilled in the head entry. Position of the hole indicated by cross and numbered by 1 in Figure 1. The hole has been instrumented by five extensometers that were installed to the depth of 7m. Distance between these extensometers was 2 m. The experimental entry has been maintained behind the longwall face to provide direct ventilation of the face for safety reasons. This helped to collect sufficient data for assessment of impact of face rate retreat.

Figure 2 demonstrates extensometers displacement as the longwall face retreated. The most intensive ground movement occurred in vicinity of the entry. Figure 2, A indicates movement of extensometers relatively of mouth of the hole as time elapsed. Figure 2, B provides dependence of hole intervals dilation on distance between the experimental hole and the 18th longwall face.
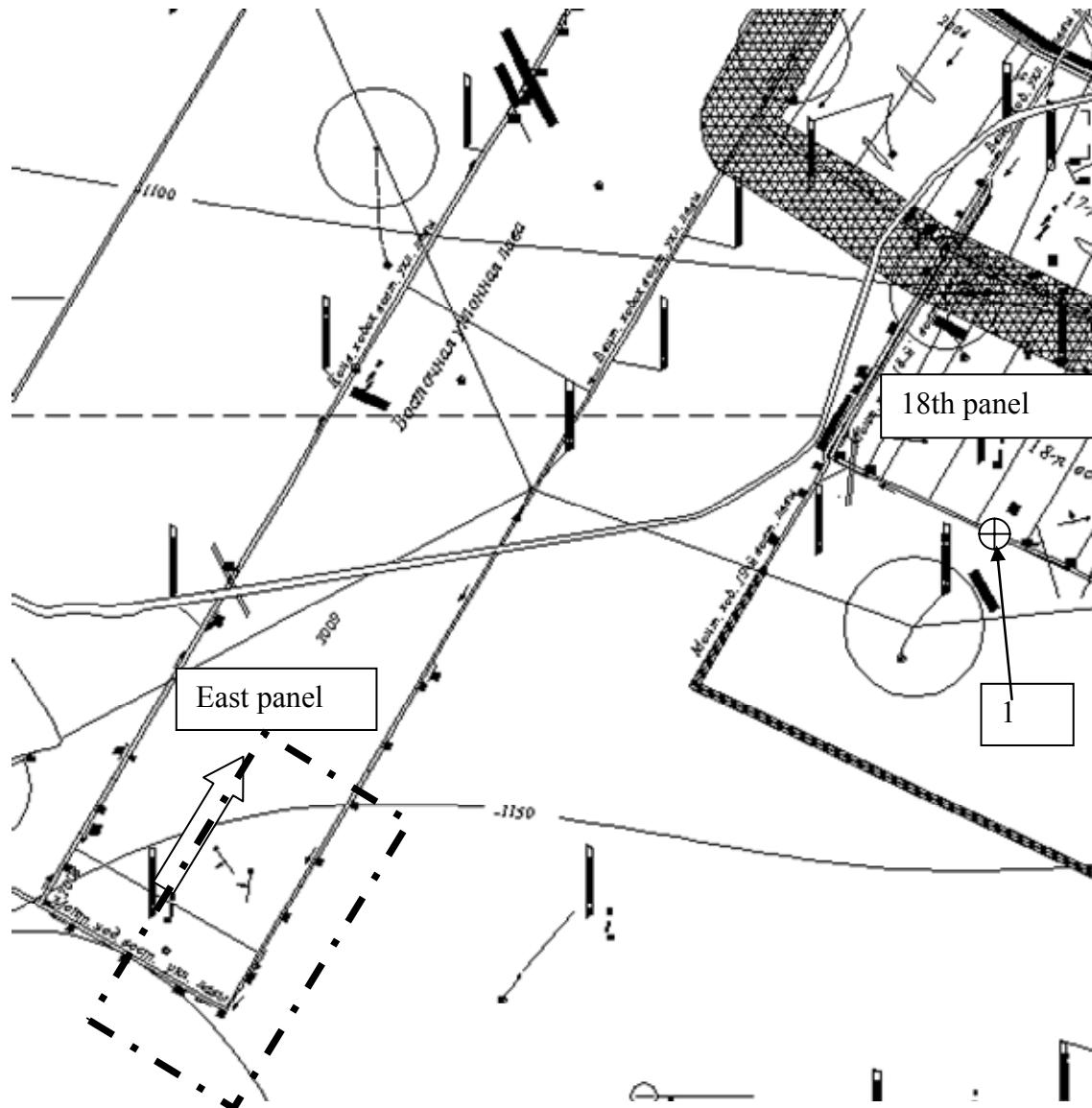
Fig. 1. Fragment of mine map

Minus corresponds to the interval where the face approached to the hole and plus indicates situation when the face moved away from the experimental hole. Period of 18th face idling indicated by arrow in the Figure 2, B. Both charts demonstrate that extensometers #1 and #2 have been installed out of a zone where entry impacts ground movement essentially. Hence dilation of the hole interval between these extensometers has been used for calibration because it is the most stable and reflects net deformation of rock mass.

Chart in Figure 2, A provides direct way to calculate rate of rock mass deformation or strain. This rate has dimension mm per day or day[-1]. However analysis has demonstrated that sensitivity of such a

rate to the face advance is not sufficient because variation of the strain rate is in diapason of error of measurement. On the other hand, gradient of the rock mass deformation or its strain deviates 4-5 times as rate of face advance varies 2-3 times. This gradient has dimension mm per m of distance the face from experimental hole when deformation is measured in mm or m^{-1} when rock mass dimensionless strain is used.
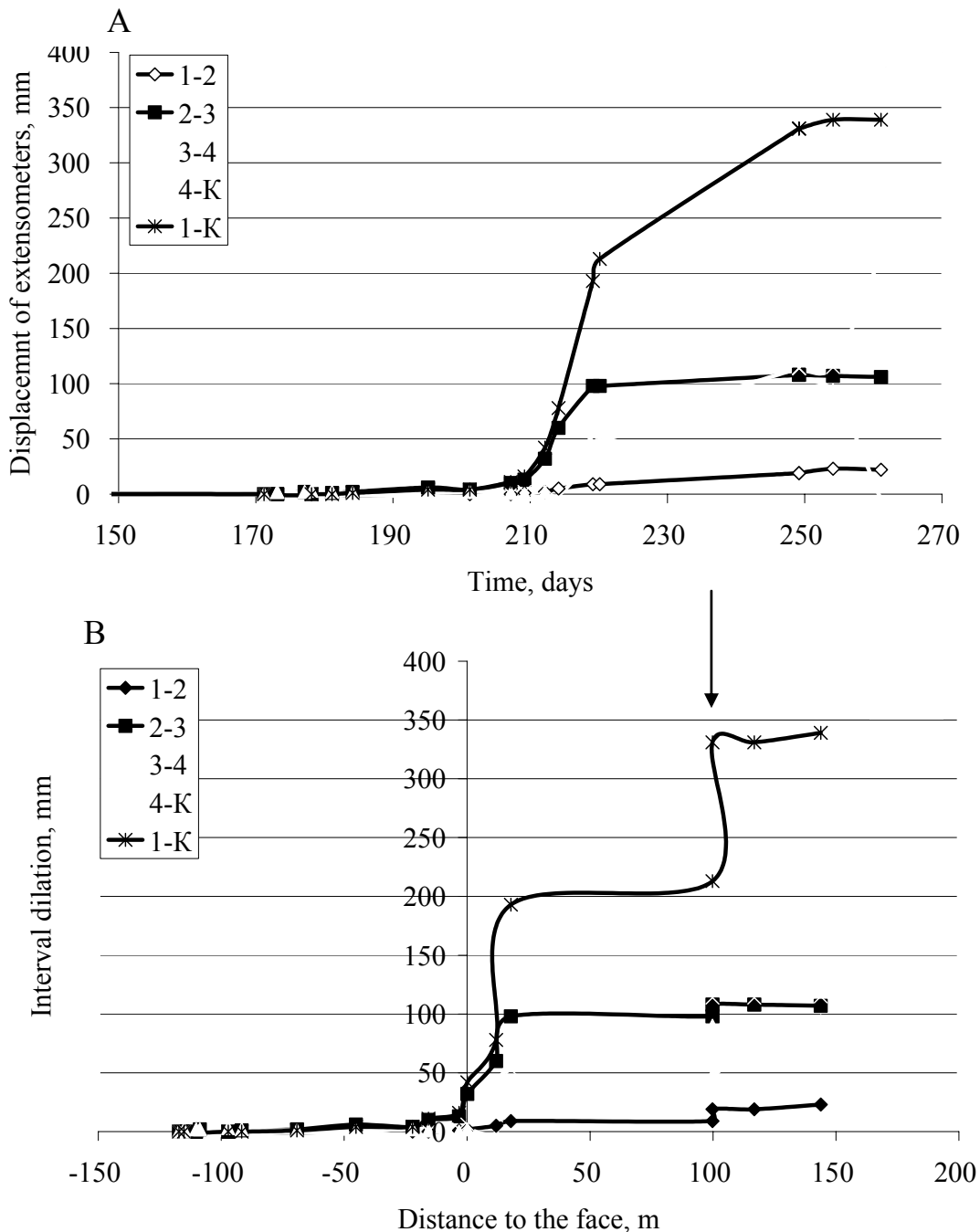

Fig. 2. Ground movement registered in situ with extensometers

Another advantage of strain or deformation gradient is absence of the problem of time scale coordination in the model and in situ. This problem involves a great number of physical and geologic parameters and can not be solved without a set of assumptions that increase uncertainty of final results. That is why strain gradient has been chosen as a parameter that was used to calibrate the rate of face advance in the model.

Monitoring of MIS in situ proved that if rate of longwall advance in Zasiadko coal mine is not succeed 2 m per day, energy of registered MIS may be neglected. This critical rate of advance v_0 has been adopted as initial rate that used for calibration process. Rock mass stain gradient was proportional to ratio v/v_0. To calibrate the model, number of cycles should be found that satisfies correspondent proportion for ratio of strain gradients. At first stage, the problem has been solved using a number of cycles that provide convergence 1e-5. Then relevant number of cycles has been found by error and trial approach for the rate of advance that used during East panel extraction.

Dynamic destruction of rock mass has not theoretical solution so far. Constitutive model of dynamic failure should account either traditional parameters that are used for description of nonlinear behavior of rock mass and additional factors such as rate of loading and rate of relaxation first of all. We used empirical constitutive model that has been proposed by [1] as a basis. They found good agreement between surface deformation index I and seismic energy that has been induced by longwall movement. Index I was calculated as product of subsidence to their derivative. From physical point of view, such empirical dependence describes rock mass dynamic failure properly because the more ground deformation and its rate or time derivative the more probable dynamic failure.

Polish investigators used surface subsidence because they are easy to measure in situ. However process of rock mass failure usually has been described using equivalent stress. In addition, dynamic failure has a less chance when rate of stress relaxation is big. That is why we proposed to use equivalent stress in place of subsidence and accounted the rate of relaxation. Finally we used next formula to calculate MIS:

$$I = \frac{\sigma_e \, d\sigma_e / dt}{d\varepsilon / dt} \tag{1}$$

where σ_e - equivalent stress;

ε - relaxation strain;

t - time.

Dimension of I can be presented as $(J/m^3)^2$ that means square of specific energy. Parameter $\acute{\varepsilon}=d\varepsilon/dt$ stands for a rate of potential energy dissipation. Volumetric strain rate that model calculates substitutes $\acute{\varepsilon}$.

Equivalent stress was calculated according formula [4]:

$$\sigma_e = \frac{(1-\psi)(\sigma_1 + \sigma_2) + \sqrt{(1-\psi)^2\left((\sigma_1 + \sigma_2)^2 + 4\psi(\sigma_1 - \sigma_2)^2\right)}}{2\psi} \tag{2}$$

where σ_i - principal components of the stress;

ψ - σ_t / σ_c where σ_t and σ_c denote tension and compression limits of rock mass strength respectively.

Constitutive low that has been described by equations (1) and (2) is empirical and has no strict theoretical basis. However it properly reflects main geomechanic behavior of rock mass under dynamic loading. This low simplifies algorithm of MIS calculation and saves efforts owing utilization existent tools and advantages that has been developed in the model so far.

A symmetric half of rock mass volume that surrounds the correspondent half of the East longwall face has been chosen as indicated by dotted rectangular in Figure 1. Bottom of the model was 200 m and lateral boundaries of the model were at 200 m from the goaf of East panel that provided sufficient distance to minimize boundary conditions in vicinity of the longwall where MIS causes real danger for miners. Normal displacements were restricted on all lateral and bottom boundaries of the model. Gravity and specific weight of the rock mass 2500 kg/m^3 generated ground pressure around the face that has been moved at the depth of 500 m. Rock mass properties are collected in Table 1.

Figure 3 demonstrates grid of the model and MIS events distribution. First, elastic model had been assigned and stress equilibrium was reached in the intact model. Then model has been changed to Mohre-Colomb and five successive steps were employed to move the

face during MIS problem solving. Therefore every next step used stress state that has been developed at the previous step of modeling.

Table 1

Rock mass properties

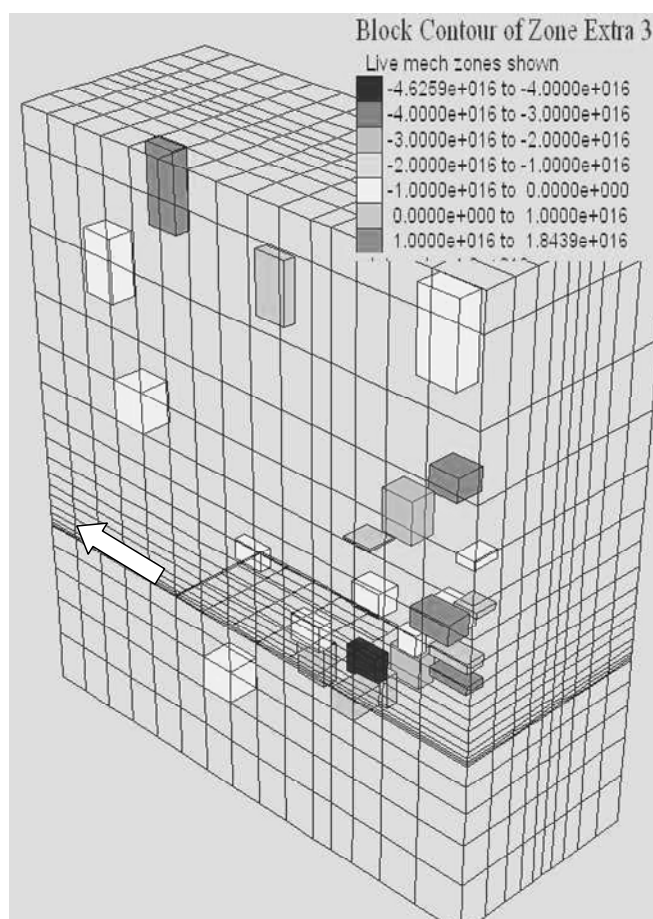| Rock type	Modules, GPa		Friction angle, degree	Cohe-sion, MPa	Tension limit, MPa	Dilation, degree
	Bulk	Shear				
Coal	5.0	3.4	18	0.1	0.1	4
Argillite	8.6	6.0	28	20	8.0	5
Sandstone	15.3	10.2	34	25	12.0	8

Fig. 3. Distribution of MIS around the face after its advance to 200 m

Deterioration of rock mass cohesion and mobilization of internal friction were simulated to imitate process of undermined strata caving.

Contact of roof and floor has been accounted by shifting null zone to ubiquitous when sum of immediate roof subsidence and heave of immediate floor exceeded thickness of extracted coal seam. This procedure enhanced solution owing accounting of gob compaction effect.

Square of calculated MIS energy was by order 4.6e16 J^2 that corresponds to experimental results of [1] who registered amount of induced energy at order 1.6e8 J. As can bee seen in Figure 3, most MIS occur behind start room and in front of moving longwall face, where abutment zones developed.

Sum of the MIS behind the start room was greater because abutment zone developed on the same place here that did not move. Abutment zone in front of the face moved as the face retreated. Therefore current MIS intensity is less here.

Approximately same MIS activity has been registered over the gob in undermined strata. Figure 4 demonstrates actual MIS distribution for fixed positions of the East longwall face. Fragment A in Figure 4 depicted a case when all MIS expressed behind the start room, whereas fragment B illustrates situation when MIS occurred both in front of the moving face and behind it in the zone of active subsidence.

Histograms of actual and calculated energy of MIS depicted in Figure 5. Both histograms can be described by exponential distribution. The most frequent are low energetic seismic events whereas powerful dynamic failures of rock mass occur rarely. Histograms of actual data and calculated energy have no essential difference according Pierson test. Therefore developed algorithm may be used for prediction mining induced seismicity during longwall mining.

Developed computer model explicitly uses inertial terms as a numerical mean to reach equilibrium state. However force debalance occurs naturally during intensive deposit extraction. This debalance is proportional to the rate of longwall movement and can be simulated by selection of proper number of cycles during solving dynamic problem. Rate of longwall advance was calibrated using actual measurement of rock mass strain intensity with extensometers.
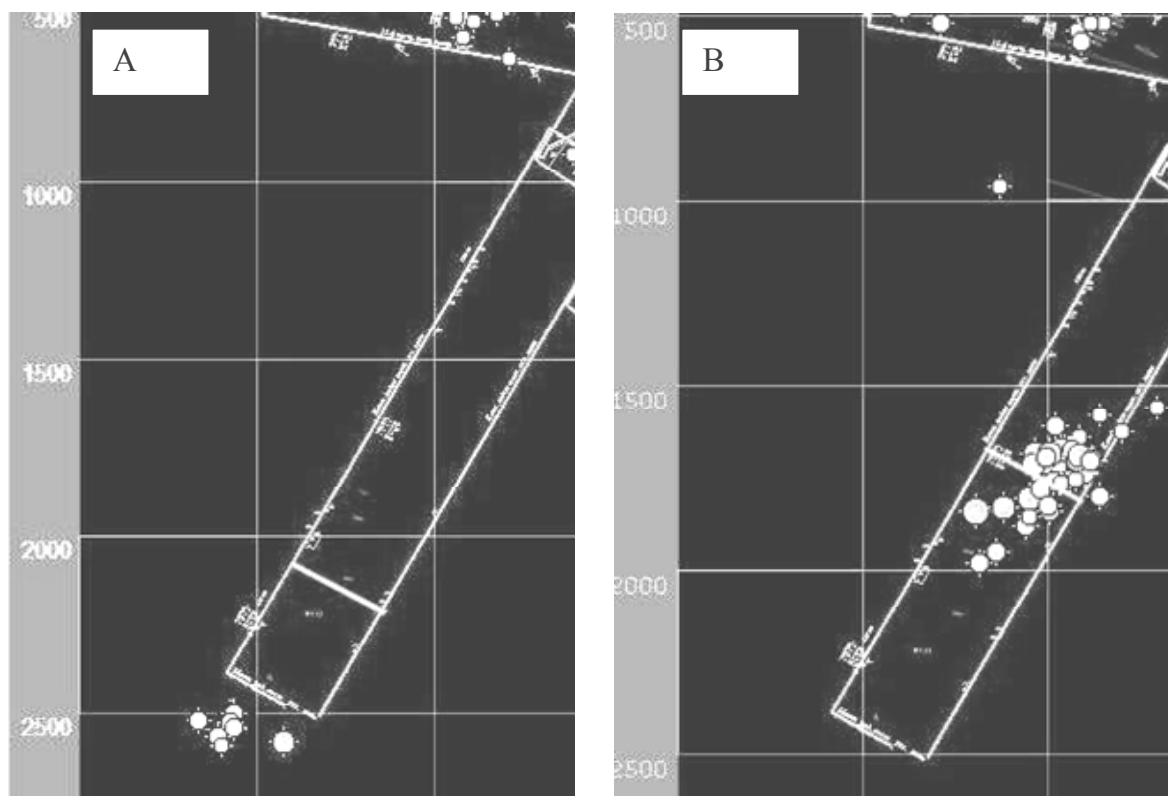
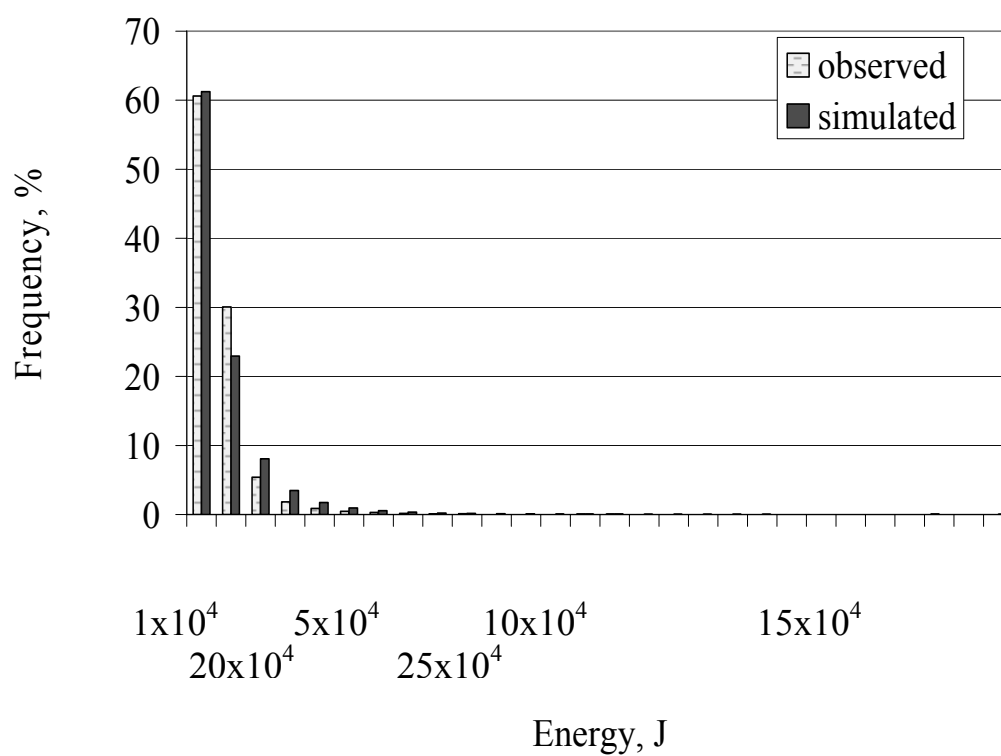Fig. 4. MIS distributions monitored in Zasiadko coal mine

Fig. 5. MIS energy histograms

Dynamic failure of rock mass due to intensive longwalling has been simulated on approach that exploits an idea that increase of the equivalent stress and of its rate builds up the potential energy of rock mass deformation and raises probability of dynamic failure as a result of potential energy transition to kinetic form if the rate of the energy dissipation is small.

Comparison of simulated and experimental seismic events distributions demonstrated good agreement. Space distribution of mining induced seismicity around moving longwall face in the model and in situ demonstrated qualitative agreement. Histograms of seismic energy that have been collected on the basis of numeric simulation and actual measurement have no difference according Pearson test. Therefore the model can be used to predict mining induced seismicity during longwall retreat on different rate.

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