Numerical Modelling of Stress-Strain State Evolution of Rock Mass with Underground Openings: Triggering influence of Mining at Different Horizons

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Abstract: On the base of a quite simple structural model of a rock mass, containing coal seams on two horizons, the numerical modelling of coal mining is carried out. A finite difference numerical technique is applied. At first mining starts at upper horizon and then moves to lower horizon. It is shown that mining process at lower horizon has a significant triggering influence on a growth of damage zones in roof and floor at upper horizon. The features of spatio-temporal migration of deformation activity are studied numerically. The foci of a largescale fracture is located on the border of seismic silence zone and the zone, where the deformation activity migrates. This border also has another characteristic – the maximum gradient of the rock pressure is observed in this zone.

Keywords: rock mass; underground openings; triggering; numerical modelling

1. Introduction

According to the data of United Nations Organization, a coal reserve is enough for approximately next 400 years of mining and makes an essential share in energetic complex of many countries. However, the negative manifestations of rock pressure at mining decrease an economic effectiveness of mines because of different accidents, such as rock bursts, roof collapses and so on. These accidents cause fracture of development excavations, coal headings. Practice of rock pressure management demands an understanding of general features of damage accumulation in elements of rock mass at mining of mineral resources, for example, coal. The knowledge of general and set steps of roof caving is necessary for correct choice of lining parameters. The modern methods of geomechanical modelling provide an opportunity for investigating the stress-strain state evolution of rock mass at different horizons of underlying coal seams if the structural, elastic, non-elastic and strength characteristics are taken into account.

The amount of geotechnical problems is rather wide. The majority of investigations are dedicated to the estimations of stress-strain state around the underground tunnels or excavations with analytical [1-3] and numerical [4-5] solutions of boundary problem. The results of these estimations provide a good information about disintegration of rocks around the excavations and/or tunnels due to plastic deformations. To our mind, the most interesting papers concern the temporal mechanical behavior of rock mass with excavations as soon as it supposes the investigation of stability of development workings, rock mass elements (roof and floor) and the influence of rock pressure manifestation during mining [6-7]. The stability and/or development of inelastic strains/fracture around the underground openings is usually considered as the boundary problem of the media with tunnel of circle or other cross-section form subjected to multi-axial loading [5,8]. The lack of papers is observed concerning the problem of modelling the excavation at coal face moving [9-11].

Almost 40 years have passed since the time when Russian academician M.A. Sadovskii emphasized the importance of a natural lumpiness of rocks. Now the idea of hierarchical organization of geomedia is one of the basic ideas of modern geodynamics, tectonophysics and other Earth's sciences. The existence of structural nonlinearity defines the mechanisms of generation of stresses, localization of stress-strain state and the mechanisms of redistribution and migration of deformation activity. In other words, the nonlinearity is responsible for features of geomedia's "life" [12].

The instrumental observations of the last three decades showed that the migration of deformation activity and triggering effects are connected with each other. The seismic waves are the main mechanism of triggering which transport the energy, released at distant events, causing the overload of different parts of geomedia where the next events might occur if the critical condition is reached.

On the other hand, the growth of technology of highly productive underground openings led to appearance of technogenic earthquakes. In most of the cases, such earthquakes are of the same order with microseismic noise. However, the observations of the last decade showed that mining might cause catastrophic earthquakes

[13]. The monitoring of induced microseimicity, for example, is used to determine the change of stress paths on the boundaries of active fault systems and far and close geological structures that affect the stope performance [14]. Thus, an investigation of triggering effects is an important and modern goal of modern geodynamics.

In this paper, our goal is an underground opening scale (~ 1000 m) where the mining is carried out at different horizons. The features of spatio-temporal migration of microseismic events are of a particular interest.

2. Mathematical model and boundary conditions

Mathematical model includes the fundamental conservation laws of continuum mechanics.

$\rho V = \rho_0 V_0$ - The law of mass conservation (1)

$\rho \dot{v}_i = \sigma_{ij,j} + \rho F_i$ - The law of momentum conservation (2)

$2\dot{\varepsilon}_{ij}^T = v_{i,j} + v_{j,i}, 2\dot{\omega}_{ij} = v_{i,j} - v_{j,i}$ - the geometrical relations for strains rate and vorticity rate (3)

The equations above are basic equations necessary for estimating the stress-strain state of any loaded solid or media. The equation of state (EOS) is needed to close the system of equations and specify a particular response on loading. In this work, the EOS is taken in the form of Hooke's law for isotropic media: the components of stress tensor are divided into spherical and deviatoric parts (4).

$$\dot{P} = -K(\dot{\theta}^T - \dot{\theta}^P), \dot{S}_{ij} + S_{ik}\dot{\omega}_{kj} - S_{kj}\dot{\omega}_{ik} = 2\mu\left(\dot{\varepsilon}_{ij}^T - \frac{1}{3}\dot{\theta}^T\delta_{ij} - \dot{\varepsilon}_{ij}^{\mathrm{P}}\right), \dot{\theta}^T = \dot{\varepsilon}_{ii}^T \quad (4)$$

However, the rock mass, containing a coal seam, also has many overlying and underlying bedding planes of sedimentary rocks, which make it sufficiently anisotropic. In calculations that are shown lower, we suppose that the number of bedding planes might be eliminated to the minimum number of the most important elements of the rock mass: coal seam, immediate roof, main roof, overlying and underlying strata. Inside of one bedding plane, the material is supposed to be isotropic. Thus, quite a simple EOS (4) might be applied, and for the whole model of the rock mass, we have a quasi-isotropic structure. On the border of two different bedding planes, the condition of displacements compatibility is implied.

It should be mentioned that an inelastic deformation of rock mass elements is of a great importance. When the coal seam is mined out, an initial gravitational stress field is disturbed. It leads to a sufficient inhomogeneity and non-stationarity of stress field of main rock mass elements especially near the free surfaces such as air and conveyer belts, mining stope, etc. High level of abutment pressure causes fracturing of rock mass elements. Moreover, when the mining stope passes large enough distances, comparable with a step of general caving, the fracture process expands to the main roof, overlying and underlying strata. Large dome-shaped damage zone forms over the mined-out space. All these features of stress-strain state evolution should be taken into account.

In other words, the mathematical model should include the constitutive equations of inelastic deformation of media. In this work, the non-elastic deformation of rock mass elements undergoes the modified Drucker-Prager-Nikolaevskii model with non-associated flow rule. The components of inelastic strain rate tensor are defined according to the Nikolaevskii plastic potential (6) from the theory of plasticity equation (5):

$$\dot{\varepsilon}_{ij}^{\mathrm{P}} = \dot{\lambda}\frac{\partial g(\sigma_{ij})}{\partial \sigma_{ij}} \quad (5)$$

$$g(\sigma_{ij}) = \frac{3}{2}J_2 - \Lambda P(2Y + \alpha P) + const \quad (6)$$

The multiplier $\dot{\lambda}$ is defined in calculations when the equation (7) is satisfied (conical yield surface):

$$f(\sigma_{ij}) = -\alpha P + \sqrt{J_2} - Y, \ Y = Y_0(1-D) \quad (7)$$

Then we have the following equation for the components of inelastic strain rate tensor [15]:

$$\dot{\varepsilon}_{ij}^{\mathrm{P}} = (S_{ij} + \frac{2}{3}\Lambda(Y - \frac{\alpha}{3}J_1)\delta_{ij})\dot{\lambda}, \ \dot{\theta}^P = \dot{\varepsilon}_{ii}^P \quad (8)$$

The fracture of the rock mass elements is described by the theory of damages accumulation. The process of damage accumulation and corresponding degradation of mechanical parameters are described through the measure of damage D = D(t, μ_σ, σ), $0 \le D \le 1$, which depend on invariant of stress state σ_{cur} and a type of stress state – the Lode-Nadai coefficient:

$$D = \int_{t_0}^{t} \frac{[H(\mu_\sigma)(\sigma_{\mathrm{cur}} - \sigma_0^{\mathrm{C}})^2 + (1 - H(\mu_\sigma))(\sigma_{\mathrm{cur}} - \sigma_0^{\mathrm{T}})^2]dt}{\sigma_*^2[H(\mu_\sigma)t_* + (1 - H(\mu_\sigma))t_*]} \quad (9)$$

$$\sigma_* = \sigma_{0*}(1+\mu_\sigma)^2, \ \mu_\sigma = 2\frac{S_2 - S_3}{S_1 - S_3} - 1, \sigma_{\text{cur}} = \sigma_{\text{int}} - \alpha P \tag{10}$$

The expression under the integral is constructed in a way to account for sufficiently different response of brittle and quasi-brittle media on stresses of different signs. If there are tensile stresses in media then the physical-mechanical properties undergo a drastic degradation. In particular, a cohesion of the media drastically decrease when tensile stresses appear. That gives an opportunity to model a catastrophic stage of media evolution when the fracture process evolves to blow-up regime.

A physical sense of other parameters of the damage measure is explained in detail in [15].

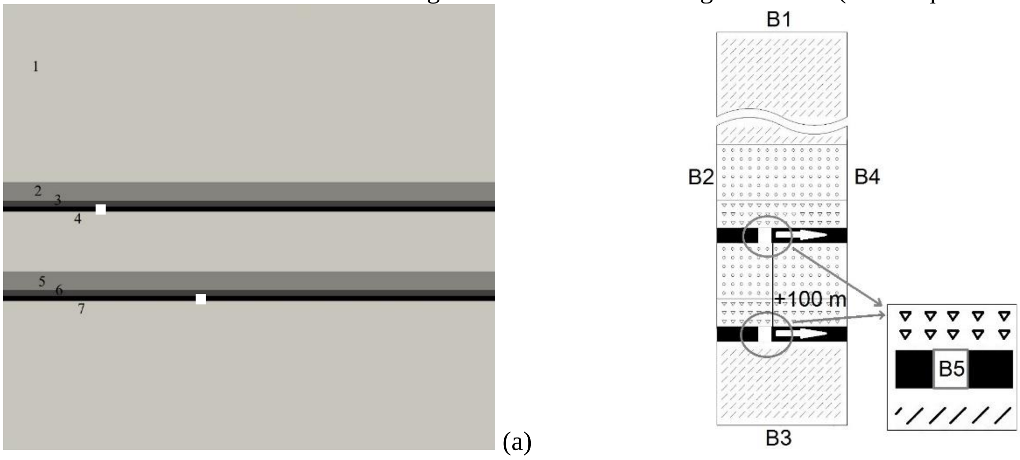
The following boundary conditions were applied:

1. $\sigma_{ij} n_j = 0, x_i \in B_1$
2. $U_x = 0, x_i \in B_2, B_4$
3. $U_y = 0, x_i \in B_3$
4. $\sigma_{ij}\delta_{ij} = -3P_0, S_{ij} = 0, x_i \in B_5, P_0 = 0.1MPa$

The list of symbols:

ρ_0, ρ – initial and current densities; V_0, V – initial and current volumes; v_i – velocity vector components; δ_{ij} – Kronecker delta; P – pressure; σ_{ij} - components of stress tensor; S_{ij} – components of deviatoric stress tensor; F_i - components of mass forces; $\dot{\omega}_{ij}$ - rotor rate; $\dot{\varepsilon}_{ij}^T$ – total strains rate; $\dot{\lambda}$ – multiplier for plasticity; J_1 - the first invariant of stress tensor; $J_2 = \frac{1}{2} S_{ij} S_{ij}$ – the second invariant of deviatoric stress tensor; $\dot{\varepsilon}_{ij}^{\text{P}}$ - components of inelastic strain rate tensor; $\dot{\theta}^T$ – the rate of total volumetric deformation; $\dot{\theta}^P$ – the rate of inelastic volumetric deformation; K – bulk modulus; μ – shear modulus; α – internal friction coefficient; Λ – dilation coefficient; $g(\sigma_{\text{ij}})$ - plastic potential; D – measure of damage; $H(\mu_\sigma)$ – Heaviside function; σ_{int} – intensity of stress tensor; σ_0^{C}, σ_0^{T} – initial values of stresses at elastic stage for tension and compression respectively, when they are reached the damage accumulation starts; μ_σ – Lode-Nadai coefficient; σ_{0*} – parameter of the model for damage accumulation; S_1, S_2, S_3 – main stresses of deviatoric stress tensor; Y – current value of cohesion; n_j – components of normal vector; U_x, U_y – displacements along the X and Y – axis, respectively; P_0 – air pressure.

The proposed model of the rock mass and boundary conditions are given on the figure 1. The structural model has a length of 500 m along the X-axis and 450 m along the Y-axis. The roofs of both horizons consist of two bedding planes – 7 m of immediate roof and 19 m of main roof. The physical-mechanical parameters are in table 1. An initial distance between mining chambers is 100 m along the X-axis (white squares in the model).



(a) (b)

Figure 1. Structural model of rock mass, containing two coal seams at different horizons (170 m and 260 m) (a). 1 - upperlying strata, 2 - main roof, 3 - immediate roof of the first horizon, 4 - the strata between horizons, 5 - main roof, 6 - immediate roof of the second horizon, 7 - floor of the second horizon, the coal seams are marked with black color, the mining chambers are schematically shown with white color; boundary conditions (b).

Table 1. Physical-mechanical parameters of bedding planes.

Rock	ρ, g/cm^3	K, GPa	μ, GPa	Y_0, MPa	α	Λ
1/Siltstone	2,5	9	8,7	7	0,62	0,22
2,5/Sandstone	2,2	12,28	5,34	8	0,6	0,12
3,6/Mudstone	2,5	9	8,7	6	0,62	0,22
4,7/Coal	1,4	1,95	0,42	4	0,4	0,08

3. Results of modelling and discussion

If we look at character of stress-strain state evolution then we can find that when the stope starts to move, from the very beginning the rock mass elements transit to inelastic state and the stress state satisfies the condition of the yield surface. It is convenient to analyze the stress-strain state in the form of relative Coulomb stresses:

$$\sigma_C = \frac{\sigma_{\text{int}}}{Y + \alpha P} \tag{11}$$

If the value of σ_C is equal to 1 or -1 then the stress-strain state satisfy the condition of yield surface. It means that the local volumes of the rock mass elements lose a stability (figure 2a). Figure 2b shows that the stope advancing causes an appearance of tensile stresses (the distribution of Lode-Nadai coefficient, $\mu_\sigma = -1$ correspond to a stress state of uniaxial tension). The measure of damage shows that the loss of stability occurs in blow-up regime. The cohesion of rock mass elements is lost catastrophically and the regions of localized inelastic strain and/or damage form.

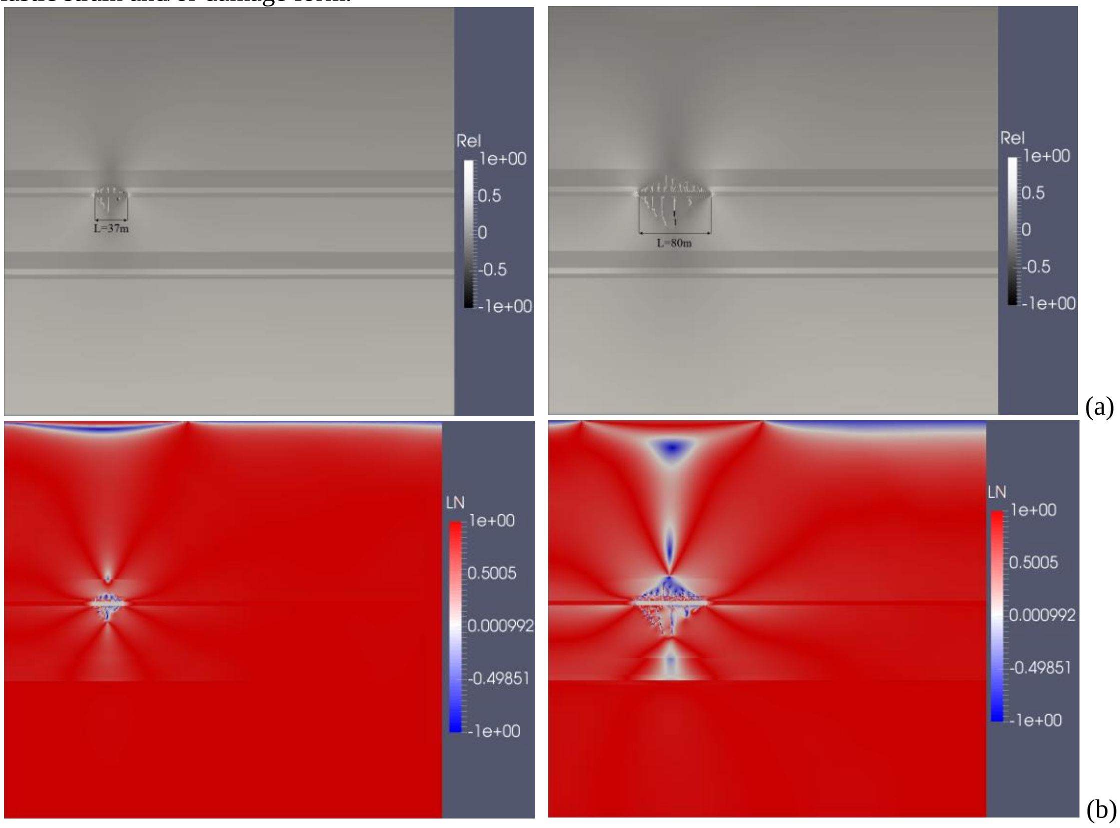


Figure 2. The pattern of relative Coulomb stresses (a), the pattern of Lode-Nadai coefficient (b) for different mined-out space (the left correspond to 37 m, the right correspond to 80 m).

An existence of blow-up regimes in stress-strain state evolution (catastrophic stages) gives an opportunity to model seismic events when the coal face (stope) is advanced.

While modelling the fracturing of rock mass elements, the spatio-temporal structure of calculated seismic events was studied. Calculated seismic events are the set of events – fracturing of rock mass elements when the coal face is advanced. For this purpose, the class of a separate event was estimated by the means of well-known formula in seismology:

$$k=\log_n(E) \tag{12}$$

where E is an energy of event, calculated from the relation:

$$E = 3G(d\varepsilon^T)^2 \tag{13}$$

$d\varepsilon^T$ is an increment of total strain tensor intensity during the time of event, n is the logarithmic base.

The results of modelling showed lower are obtained for the case of mining at two horizons – at first the mining is made on the depth of 170 m, after the coal is advanced for 100 m the mining at the first horizon is stopped and it is started at the second horizon on the depth of 260 m.

For the convenience of analysis, a whole spectrum was divided into 29 conditional classes. One can see the distribution of accumulated inelastic strain and calculated seismic events of 25-29 classes on the figure 3.

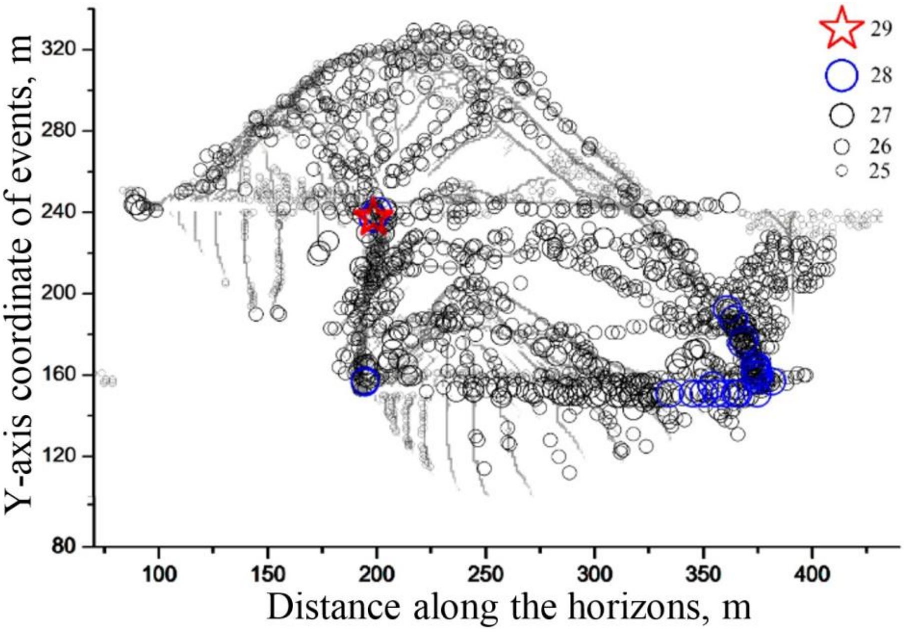


Figure 3. The spatial distribution of seismic events in the rock mass for the whole time of excavation at different horizons, the numbers identify the conditional class of seismic events. The units of the axes indicate the location of events related to the model coordinates system.

In this calculation, an effective coal seam of a total length of 100 m was mined at upper horizon before the stope was moved to lower horizon. By that moment, several not interacting cracks (zones of localization of stress-strain state and damage) have formed in the roof of the first horizon (figure 4 a, b). The calculated seismic process follows the stope. The results of calculations showed that the amount of events of higher classes (25-29) is relatively small. That is why to study the features of spatio-temporal migration of deformation activity, triggering and formation of seismic silence zones it is necessary to analyze the calculated seismic events of lower classes, which amount is relatively big. Calculated seismic events from 19 to 24th class, which are joint into clusters, are shown on the figure 4. Each figure correspond to different time intervals. Total amount of 12 time intervals were analyzed, covering the whole process of formation of catastrophic fracturing of rock mass elements, six time intervals are shown on the figure 4.

Numerical modelling shows that mining at lower horizon produces the triggering effect on the growth of damage zones of roof and floor of upper horizon. However, before the time of general caving at lower horizon, trigerring manifests in small incremental growing of damage zones and thus occurrence of seismic events in the vicinity of growing zones at upper horizon. At the same time, the seismic silence zone is observed in immediate and main roofs in the central part of roof flap at upper horizon. The silence is maintained until the formation of large-scale damage zone, connecting upper and lower horizons.

When the stope is advanced for ~150 m, a general roof caving occurs. A large scale zone of catastrophic fractures is formed – a dome over two horizons. A distribution of calculated seismic events in time intervals points out that when the general caving occurs a deformation activity moves towards the right border of lower horizon (where the events of the 28 class are clustered) and peripheral localized damage zones of a common dome (a significant swarm of events is observed). An activation of deformation activity is also observed in the zone of already formed peripheral damage zones of upper horizon. The largest event of the 29th class occurs at upper horizon – at the right border of a mine-out space, where the maximum rock pressure is observed.

Thus, the foci of a largescale fracture is located on the border of seismic silence zone and the zone, where the deformation activity migrates. A radial localized damage zones of a common dome point towards the zone of a largest event.

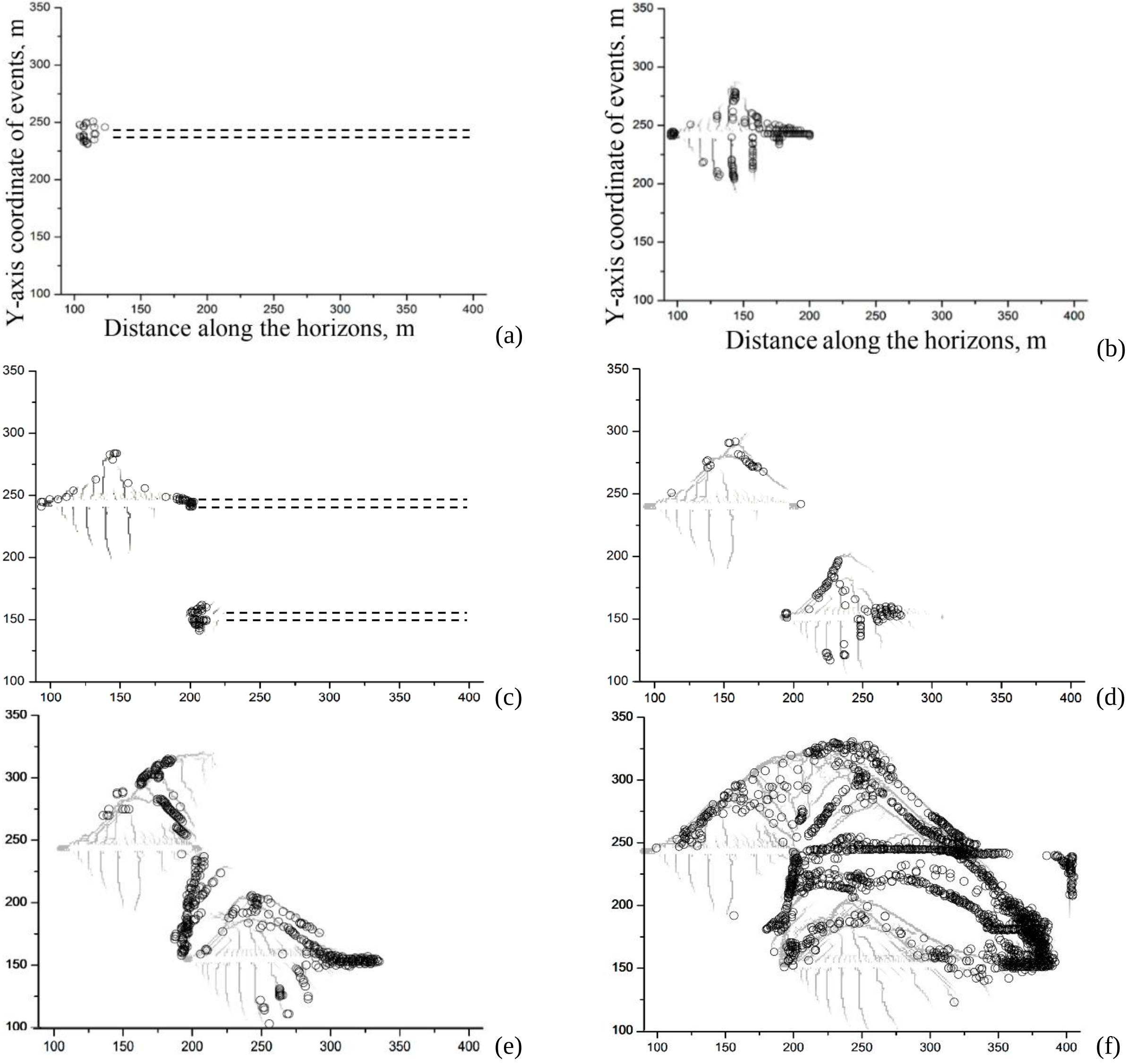


Figure 4. The spatial distribution of seismic events in the rock mass for several time periods (a - f) of excavation at different horizons.

4. Conclusion

The new data on the features of deformation activity and triggering effects are obtained by the means of numerical modelling of deformation and fracture of rock mass elements. It is found that when the mining is produced on two horizons there is a significant triggering influence when the initial distance between mining chambers is comparable with the step of general caving. That might be considered as a recommendation for mining companies. If the geologic structure of the rock mass shows the existence of more than one horizon (e.g. coal seams) then it means that mining chamber at lower horizons should be located in the bedding plane on a distance of approximately 3-4 steps of general caving from the mining chamber of upper horizon when a simultaneous mining is carried out. Otherwise, the catastrophic large-scale domes will be formed causing the significant surface subsidence and other effects.

The foci of a largescale fracture is located on the border of seismic silence zone and the zone, where the deformation activity migrates. This border also has another characteristic – the maximum gradient of the rock pressure is observed in this zone.

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