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SAFETY IN MINING AND PROCESSING INDUSTRY AND ENVIRONMENTAL PROTECTION

Research article

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Rock burst forecasting technique and selecting a safe coal face advance direction

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Abstract
Mine planning involves selecting an optimal mine layout. At the same time key factors, including those influencing mining safety, should be comprehensively taken into account. A developed rock burst forecasting technique taking into account mine workings of an extraction area and a mine goaf enables determining the safe direction of a coal face. The proposed technique also takes into account all faulting/joint systems, occurring beyond a mine field. The distribution of specific potential energy in an intact rock mass is proposed to be used as the basis of the input data required for rock burst forecasting. The forecast is carried out via estimating the Lode-Nadai coefficient at different directions of coal face advancing. The stress (intensity) coefficient is proposed to be used as a criterion in order to determine a safe direction. We determined the safety criterion is equal to 10 in the Komsomolskaya Mine conditions. Besides, the safest direction of a coal face advance to mitigate the risks of rock burst was determined for this mine. The direction between 138° and 128° counter-clockwise from the north direction was identified to be the safest for the Komsomolskaya Mine conditions for any values of deformation modulus and Poisson's ratio.

Keywords
coal mine, safety, rock burst, forecast, extraction area, algorithm

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Методика прогноза горных ударов и выбора безопасного направления фронта очистных работ

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Аннотация
Планирование горных работ связано с выбором оптимальных решений по раскройке шахтного поля. При этом необходимо комплексно учитывать основные факторы, влияющие в том числе на безопасность ведения горных работ. Разработанная методика прогноза горных ударов в процессе ведения горных работ, учитывающая горные выработки выемочного участка и выработанное пространство, позволяет определить безопасное направление фронта очистных работ. Предлагаемая методика учитывает также все геологические нарушения, которые находятся и за пределами шахтного поля. В основе исходных данных, необходимых для осуществления прогноза горных ударов, предлагается использовать распределение удельной потенциальной энергии в нетронутом массиве. Прогноз осуществляется путем оценки параметра Надаи–Лоде (Lode–Nadai coefficient) при различных направлениях движения фронта очистных работ. Для определения безопасного направления предлагается в качестве критерия использовать коэффициент напряженности. В статье определен критерий безопасности для условий ш. Комсомольская, равный 10. Также для данной шахты было определено направление фронта очистных работ, при котором существенно снижаются риски проявления горных ударов. Наиболее безопасным для условий ш. Комсомольская является вариант направления между 138° и 128° против часовой стрелки от Северного направления для любых реализаций модуля деформации и коэффициента Пуассона.

Ключевые слова
угольная шахта, безопасность, горный удар, прогноз, выемочный участок, алгоритм

Для цитирования
Kobylkin S.S., Pugach A.S. Rock burst forecasting technique and selecting a safe coal face advance direction. *Mining Science and Technology* (*Russia*). 2022;7(2):126–136. https://doi.org/10.17073/2500-0632-2022-2-126-136

Introduction

Mining safety assurance is a complex, system task to be solved long before drivage. At the same time different factors should be taken into account at different stages of a mining enterprise existence. Geotechnical safety is governed by a large number of influencing variables: physical properties of a rock mass, mining depth, occurrence of geological faults and their influence on stressed state of a coal seam [1, 2], structural features of a rock mass [3, 4, 5], influence of tectonic forces [6], etc. There are complex approaches to forecasting hazardous zones on the basis of assessing the stability (faulting) of a rock mass[1]. A mining area (mining allotment or mine field) is selected in locations with the least amount of major geological faults. In coal mining the influence of such faults located outside a mine field is not controlled. We propose a rock burst forecasting technique taking into account all adjacent geological faults with the aim of increasing mining safety. It is applicable in mining conditions when at least one geodynamic event has been recorded. The given technique allows determining a safe direction of coal face advance.

Input data for rock burst forecasting

One of the most attractive techniques for forecasting rock bursts is the evaluation of events based on the concept of seismicity of events [7]. According to the documents [8, 9] regulating the operation of seismic stations, 4 energy levels are distinguished. Energy level II corresponds to fracturing (disturbance) in the near-contour rock mass enclosing mine workings and is defined at 3500 J and more. Energy level III corresponds to the impact of coal-face work and is defined at 6000 J and more. Introducing such energy levels is based on selection of a safety criterion and recommendations of seismic services. This study considers energy levels II and III, while the others are excluded because rock burst manifestation hazard is assessed starting from energy level 3500 J and more. Energy levels II and III serve as threshold values for manifestation of minimum disturbance (fracturing), because an impact of coal-face work when extracting coal will take place in any case. Thus, we determine the boundary zone between the zone of fracturing in the near-contour rock mass enclosing mine workings and the coal-face impact zone. Application of energy level IV will overestimate the safety criterion value. In this case, one can note a general trend in the distribution of energies (determined based on seismic station data), calculated for an intact coal seam in accordance with a mathematical model developed by the authors. The mathematical model is based on the concepts of the nature of tectonic forces [6], the models of rock mass behavior [10, 11, 12], the results of laboratory sample testing [13] and the samples physical properties [14]. The authors [15] note that the accuracy of describing the behavior of a rock mass depends on the correct selection of a model. We summarized these approaches and integrated them into a single forecasting technique. The seismic energy values obtained for the Komsomolskaya Mine (Fig. 1, *a*) were compared with the calculated values of specific potential energy in an intact coal seam (Fig. 1, *b*).

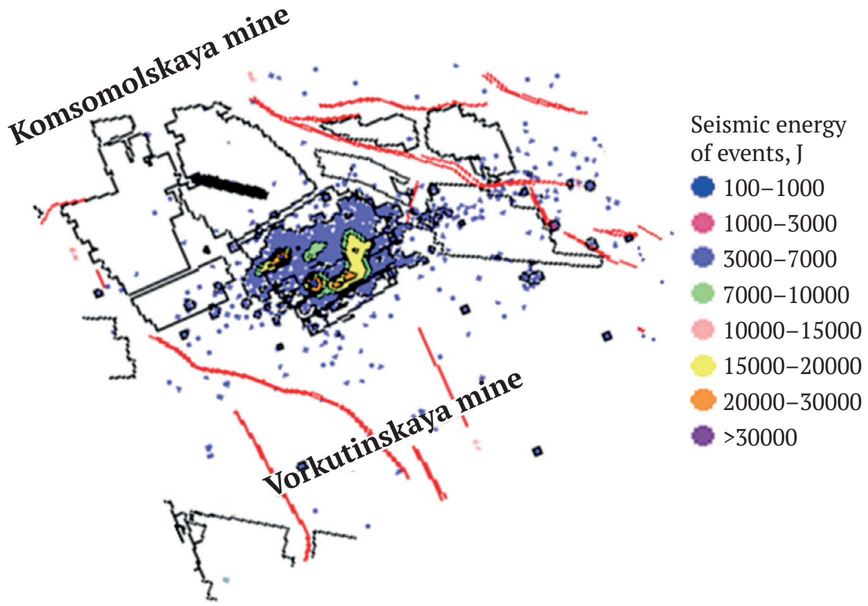
The resulting distribution of specific potential energy in an intact rock mass is the basis of the inputs required for rock burst forecasting. In addition, the inputs should contain a mine plan.

Technique for determining a safe direction of a coal face advance

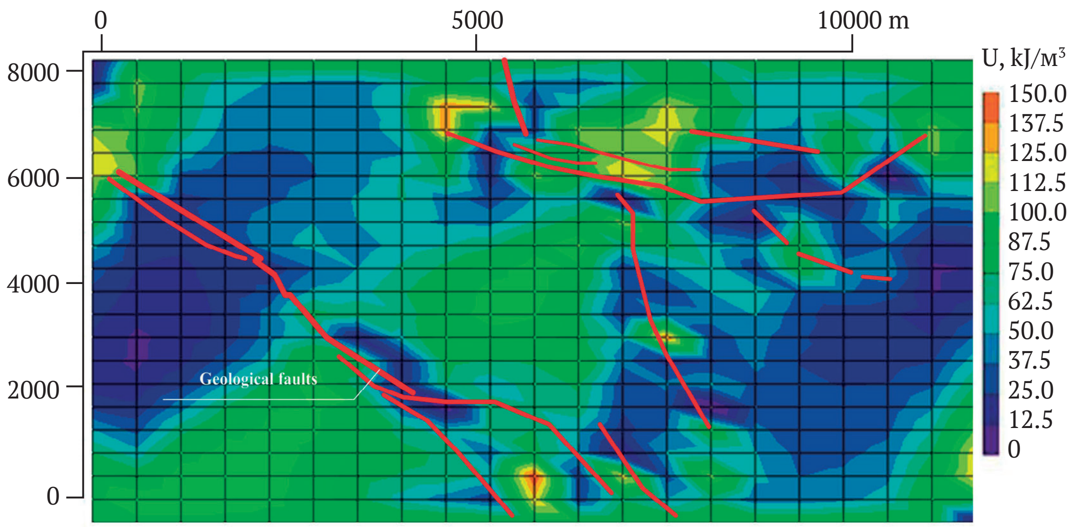
When solving the problem of rock burst forecasting at different values of deformation modulus E_{ur} and Poisson's ratio ν for an intact rock mass in a faulting (disturbance) zone, assessment of stress-strain state of a coal seam should be performed. Rock physical properties for the model are determined in accordance with the technical documentation of a mine and [16]. The most characteristic options of tasks are selected in accordance with a stress map. At the first stage, different tasks with different set of the values of deformation modulus and Poisson's ratio are solved, and the specific potential energy is determined. Then the solutions with the greatest qualitative differences are selected. For the example under consideration (Komsomolskaya Mine) the following options correspond to the characteristic solutions: 1) $E_{ur} = 1{,}489$ MPa, $\nu = 0.211$; 2) $E_{ur} = 1{,}335$ MPa, $\nu = 0.181$; 3) $E_{ur} = 1{,}037$ MPa, $\nu = 0.203$; 4) $E_{ur} = 1{,}305$ MPa, $\nu = 0.232$; 5) $E_{ur} = 1{,}296$ MPa, $\nu = 0.162$; 6) $E_{ur} = 1{,}395$ MPa, $\nu = 0.224$; 7) $E_{ur} = 1{,}524$ MPa, $\nu = 0.179$; 8) $E_{ur} = 1{,}036$ MPa, $\nu = 0.160$; 9) $E_{ur} = 1{,}331$ MPa, $\nu = 0.171$; 10) $E_{ur} = 1{,}433$ MPa, $\nu = 0.174$.

Then the considered extraction area comprising a set of mine workings (a coal face and adjoining drifts, as well as mined-out space) was added into the simulation model. For each set of the parameters, we estimated the Lode–Nadai coefficient to compare with that of an intact coal seam (see Fig. 1, *b*). Fig. 2 shows a map of the Lode–Nadai coefficient values depending on the location of an extraction area for the 1st direction of coal face advancing (218° from the north direction). In the model plane, the direction change in increments of 10° was selected (from the initial position of 218° clockwise from the north direction). At the Komsomolskaya Mine, the direction of coal face advance is selected depending on the mine field boundaries (in a direction orthogonal to the boundaries). The boundaries, as a rule, correspond to the geometry of faults/joint systems. A coal face in this case falls on the 5–6th directions in accordance with the chosen designations (168–158° clockwise from the north direction).

[1] Forecasting possible faulting zones. 2017. URL: https://www.micromine.ru/possible-zones-of-tectonic-fault-prediction/ (accessed date: 31.12.2021)



a



b

Fig. 1. Data of seismic observations (*a*); map of specific potential energy in intact rock mass (*b*)

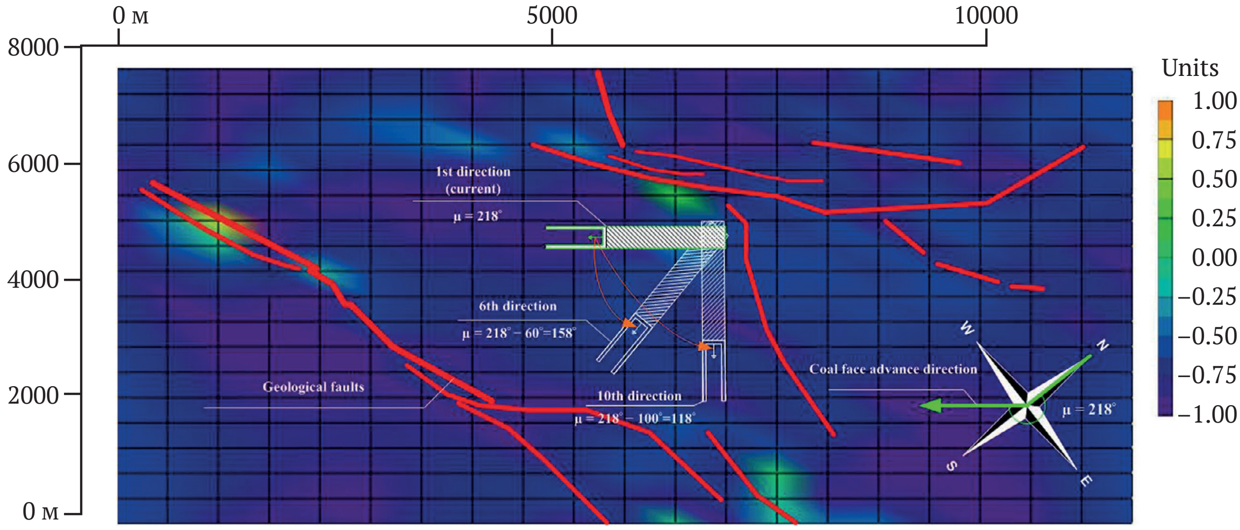


Fig. 2. Map of Nadai-Lode coefficient values at the 1st direction of coal face advancing

Fig. 4 shows the distribution of maximum and minimum principal stresses along a coal face advance direction (Fig. 5) inward the rock mass at different combinations of the physical properties.

Interpreting graphs in Fig. 4 via the representation of specific potential energy allows determining the gradient between the maximum principal stress and the stress on the boundary of the simulated coal face. The sandstone rock pressure is represented in the form of gravity per unit area (a stress equivalent). On this basis specific energy is calculated as follows:

$$E_{grav\_sandst} = \frac{(\rho_{sandst} gH)^2}{2E_{sandst}}, \qquad (1)$$

where ρ_{sandst} is the sandstone density, kg/m^3; g is the gravitational acceleration, m/s^2; H is a depth of coal extraction, m; E_{sandst} is the sandstone modulus of deformation, MPa.

The ratio of the specific activation energy W_a, representing the gradient from the maximum or minimum stresses (two curve behavior types in Fig. 4) towards the free surface, to the specific potential energy of the overlying rocks weight E, is a value characterizing the degree of rock burst hazard used when selecting an option of coal face advance direction in the framework of designing optimal mine layout. The obtained value should be compared with the critical value corresponding to the safe specific potential energy. This ratio can be called as a stress coefficient K.

Depending on the maximum principal stresses observed at a coal face (local maximums or local minimums) we present two options of calculations.

The formulas describing a local stress maximum on the boundary of a simulated coal face are presented below. The model solutions with E_{ur} = 1,036 MPa, ν = 0.160 (Fig. 6) correspond to this case.

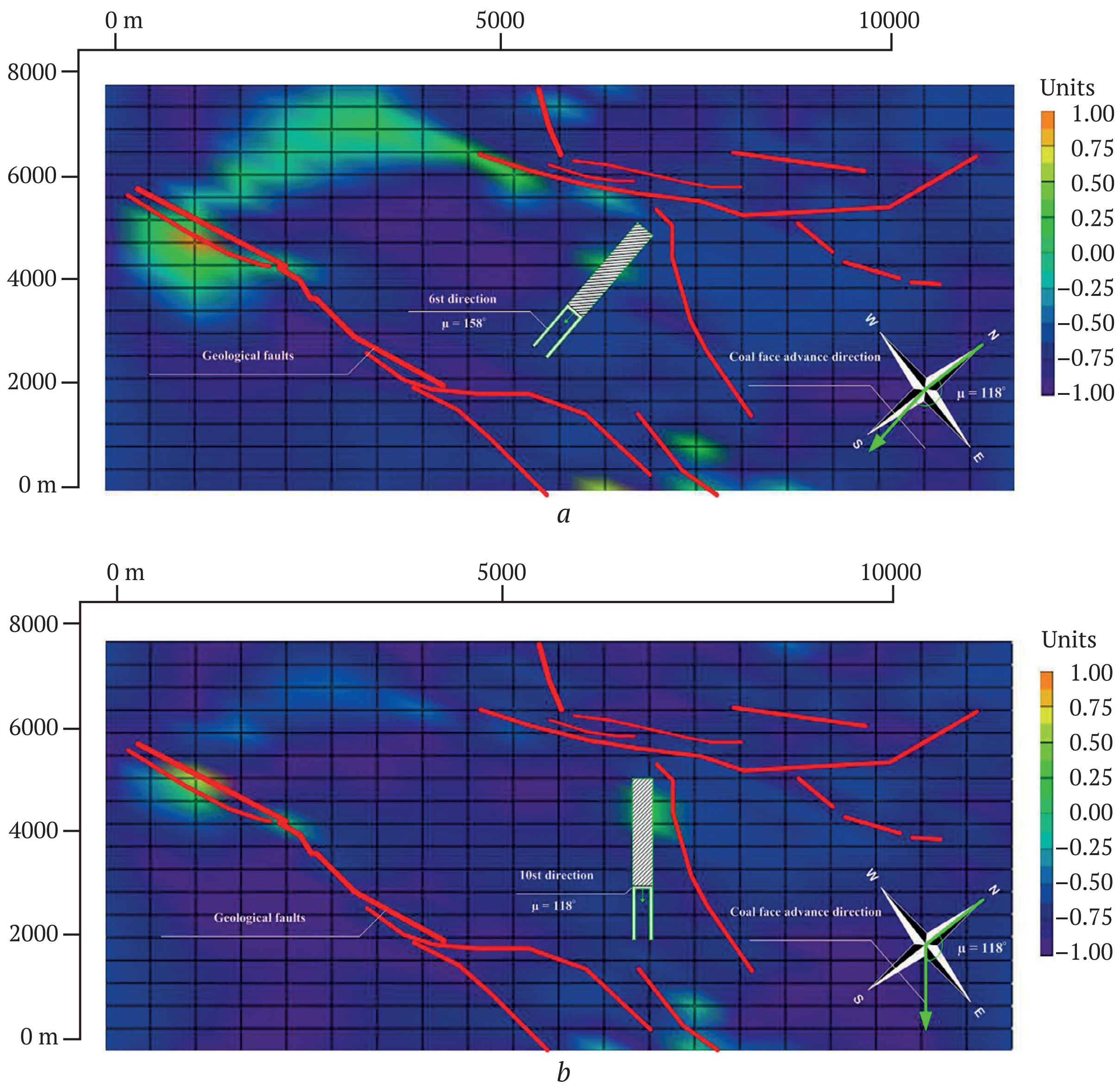


Fig. 3. Map of Nadai-Lode coefficient values at different positions of a mine working: (*a*) the 6th direction (158°) [current], (*b*) the 10th direction (118°)

Stress coefficient at the local maximums of stresses observed on the boundary of the simulated coal face

$$K_1 = \frac{W_{a_1}}{E_{grav\_sandst}}. \quad (2)$$

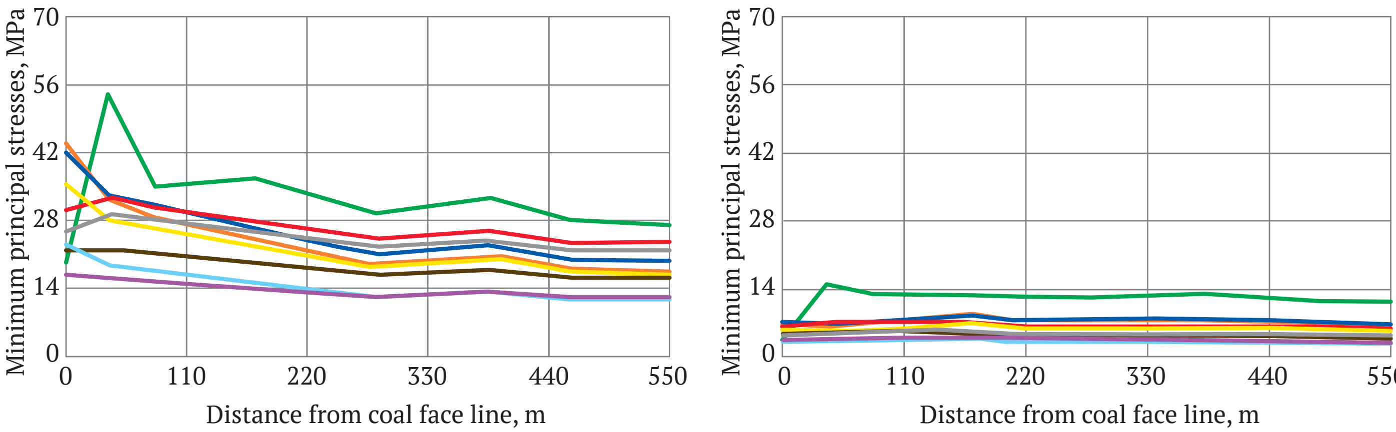
Specific potential activation energy at local maximums of stresses observed on the boundary of the simulated coal face

$$W_{a_1} = 0.5\left(\frac{[\sigma_1^{\text{max face}} - \sigma_3^{\text{max face}}]^2}{E_i} - \frac{[\sigma_1^{\text{min}} - \sigma_3^{\text{min}}]^2}{E_i}\right); \quad (3)$$

stress gradient at local maximums of stresses observed on the boundary of the simulated coal face

$$grad_1 = \frac{\sigma_1^{\text{min}} - \sigma_1^{\text{max face}}}{r^{\text{min}}}, \quad (4)$$

where $\sigma^{\text{max face}}$ are the local maximums of stresses on the boundary of the simulated coal face, MPa; σ^{min} are the local minimums of stress inward the rock mass, MPa; E_i is the calculated modulus of deformation at the i-th point of the rock mass corresponding to maximums/maximums of stresses, MPa; r^{min} is the distance from the



a *b*

Fig. 4. Distribution of principal stresses along a coal face advance direction inward the rock mass for the 1st direction: *a* – for the maximum principal stresses σ_1; *b* – for the minimum principal stresses σ_3

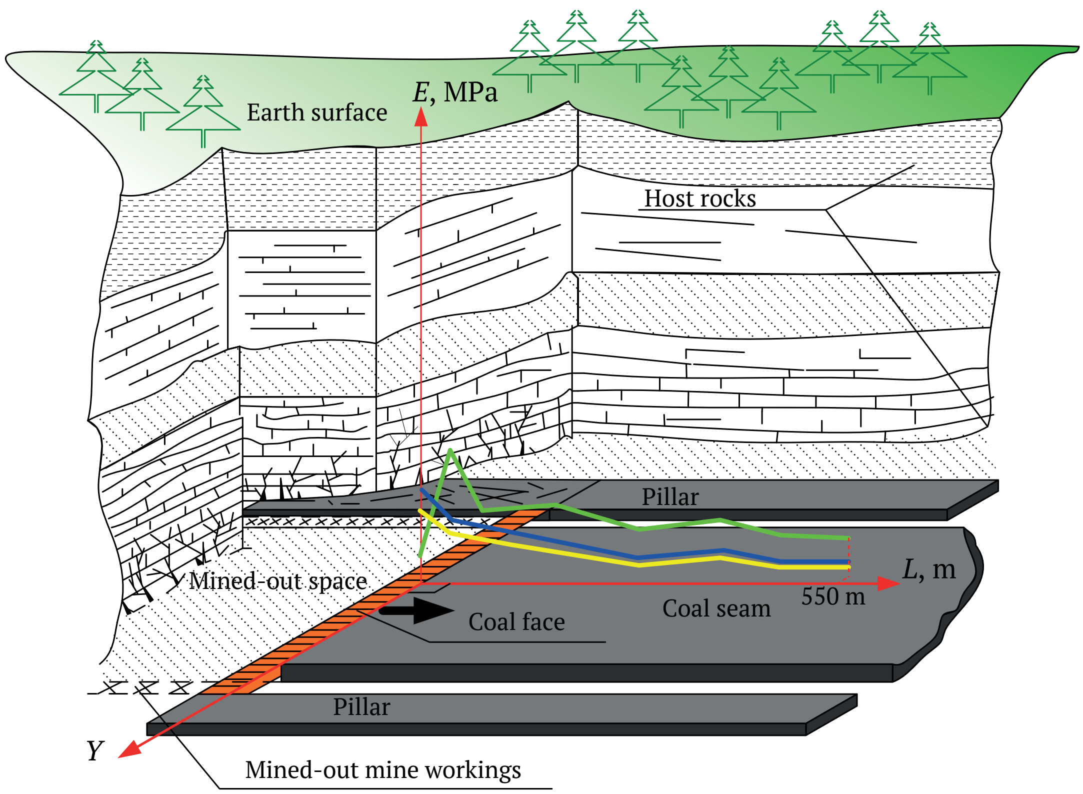


Fig. 5. Schematic diagram for determining the distribution of maximum and minimum principal stresses along a coal face advance direction

boundary of the simulated coal face to a local minimum of stresses, m.

Table 1 presents the values used for the distribution determination.

The value $r = 0$ is the boundary of the simulated coal face (the face plane). For the graph of the presented form, we determined $\sigma_1^{max\ face}$ = 43.86 MPa, σ_1^{min} = 18.41 MPa, r^{min} = 280 m and made calculations according to formulas (2)–(4).

Then, we considered the second case, when local minimums occur on the boundary of the simulated face. The model solutions with E_{ur} = 1,037 MPa, ν = 0.203 correspond to this case (Fig. 7).

Stress coefficient at the local minimums of stress observed on the boundary of the simulated coal face is equal to:

$$K_2 = \frac{W_{a_2}}{E_{grav\_sandst}}. \qquad (5)$$

Specific potential activation energy at the local maximums of stresses observed on the boundary of the simulated coal face is equal to:

$$W_{a_2} = 0.5\left(\frac{[\sigma_1^{max} - \sigma_3^{max}]^2}{E_i} - \frac{[\sigma_1^{min\ face} - \sigma_3^{min\ face}]^2}{E_i}\right); \qquad (6)$$

stress gradient at the local maximums of stresses observed on the boundary of the simulated coal face is equal to:

$$grad_2 = \frac{\sigma_1^{max} - \sigma_1^{min\ face}}{r^{max}}, \qquad (7)$$

where $\sigma^{min\ face}$ are the local minimums of stresses on the boundary of the simulated coal face, MPa; σ^{max} are the local maximums of stress inward the rock mass, MPa; E_i is the calculated modulus of deformation at the i-th point of the rock mass corresponding to maximums/maximums of stresses, MPa; r^{max} is the distance from the boundary of the simulated coal face to a local maximum of stresses, m.

Table 1

Data for plotting maximum principal stresses as a function of the distance from the boundary of the simulated coal face (inward the rock mass) (for E_{ur} = 1,036 MPa, ν = 0.160)

Parameters	Values									
Maximum principal stresses σ_1, MPa	43.86	32.38	28.51	23.53	21.78	18.41	20.26	17.62	16.96	16.67
The distance from the boundary of the simulated coal face (inward the rock mass) r, m	0	38	79	172	212	280	387	459	564	649

Table 2

Data for plotting maximum principal stresses as a function of the distance from the boundary of the simulated coal face (inward the rock mass) (for E_{ur} = 1,037 MPa, ν = 0.203)

Parameters	Values									
Maximum principal stresses σ_1, MPa	20.97	54.54	35.14	36.92	34.1	29.67	32.85	28.39	26.94	25.98
The distance from the boundary of the simulated coal face (inward the rock mass) r, m	0	38	79	172	212	280	387	459	564	649

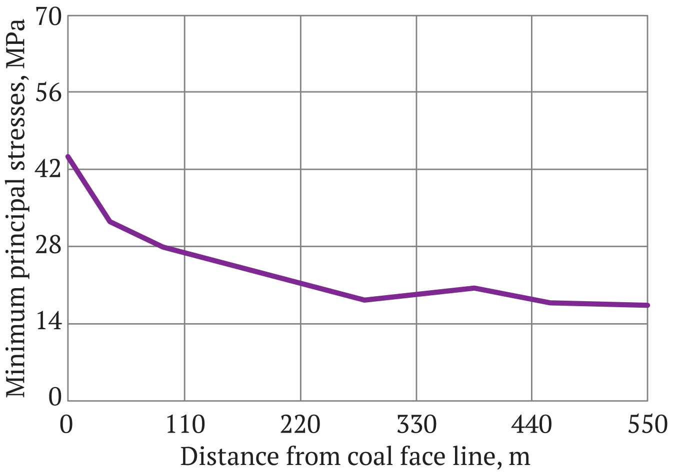


Fig. 6. Distribution of the principal stresses along a coal face advance direction inward the rock mass by the example of the 1st direction for E_{ur} = 1,036 MPa, ν = 0.160

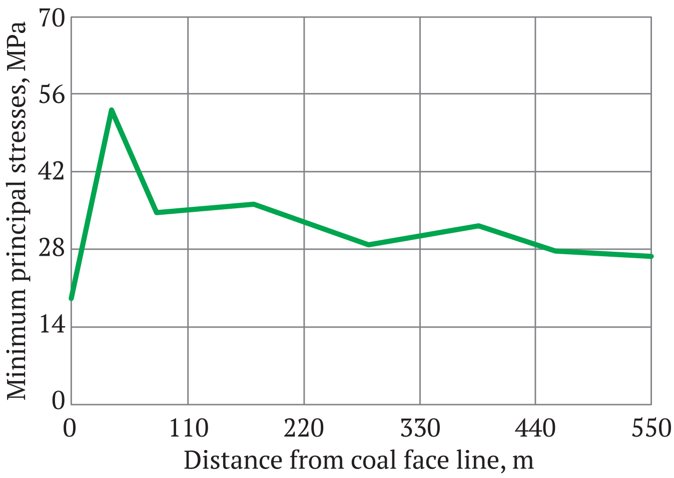


Fig. 7. Distribution of the principal stresses along the coal face advance direction inward the rock mass by the example of the 1st direction for E_{ur} = 1,037 MPa, ν = 0.203

Table 2 presents the values used for the distribution determination for this option.

Then $\sigma_1^{\text{min face}}$ = 20.97 MPa, $\sigma_1^{\max}$ = 54.54 MPa, $r^{\max}$ = 38 m were inserted into formulas (5)–(7), and calculations were made.

Referring graphs in Fig. 4 to the first or second options, we made the corresponding calculations and obtained 10 values of activation energy for the maximum principal stresses and 10 values of stress gradient.

Similarly, the minimum principal stresses were determined for the graphs of each considered coal face advance direction (angle μ in Fig. 2). Within a direction, we obtained 10 values of activation energy for the maximum principal stresses and 10 values of stress gradient. Stress coefficients K_1 and K_2 were calculated for each option. Further K_1 and K_2 were represented as one characteristic K. We performed the above-described calculations for each of the directions presented in Fig. 2. The results were summarized and integrated into a single matrix. This matrix of the values was used to draw an isogram (Fig. 8).

The isogram is a surface of the stress coefficients. In the matrix's rows, the gradient values determined by formulas (5) and (7) depending on the type of distribution are presented; the columns present the directions of the simulated coal face advance. The matrix included the vectors of stress coefficients for each direction, calculated by analogy with the example shown above.

To assess the safety of a selected coal face advance direction, we proposed using a safety criterion, a comparison of safe energy (dimensionless safety criterion [K]). The criterion is determined on the basis of the comparison of data from the seismic station and the ratio of the calculated specific potential activation energy to the specific potential energy of gravity of the overlying rocks E_{grav_sandst} (2) and (3), i.e. [K] is compared with K_{a1} and K_{a2}.

Taking into account the data from Fig. 1 and the inputs on energy levels, we calculated that the boundaries of the II energy level (see Fig. 1, a) were characterized by the specific potential energy in an intact coal seam of 60 kJ/m³ (see Fig. 1, *b*), while the boundaries of the III energy level (see Fig. 1, *a*), by that of 112.5 kJ/m³ (see Fig. 1, *b*).

Let's substitute these values into the numerator in formula (1) as the activation energy. The specific potential energy of gravity remains unchanged. The square brackets below denote that the value is a criterion.

E_{grav_sandst} = 18 kJ/m³.

At W_a = 60 kJ/m³ $[K]_{intact}^{\text{II}}$ = 3.333.

At W_a = 112.5 kJ/m³ $[K]_{intact}^{\text{III}}$ = 6.25.

$[K]_{intact}$ is a safe value corresponding to an intact coal seam. The upper index denotes a reference to the corresponding energy level.

Mining-induced stresses in a rock mass exceed an intact rock strength due to the action of complicating factors. For the transition to the criterion in the conditions of coal extraction we used the fact that in practice relatively safe coal faces at deep levels can be referred to the III stability category according to the studies

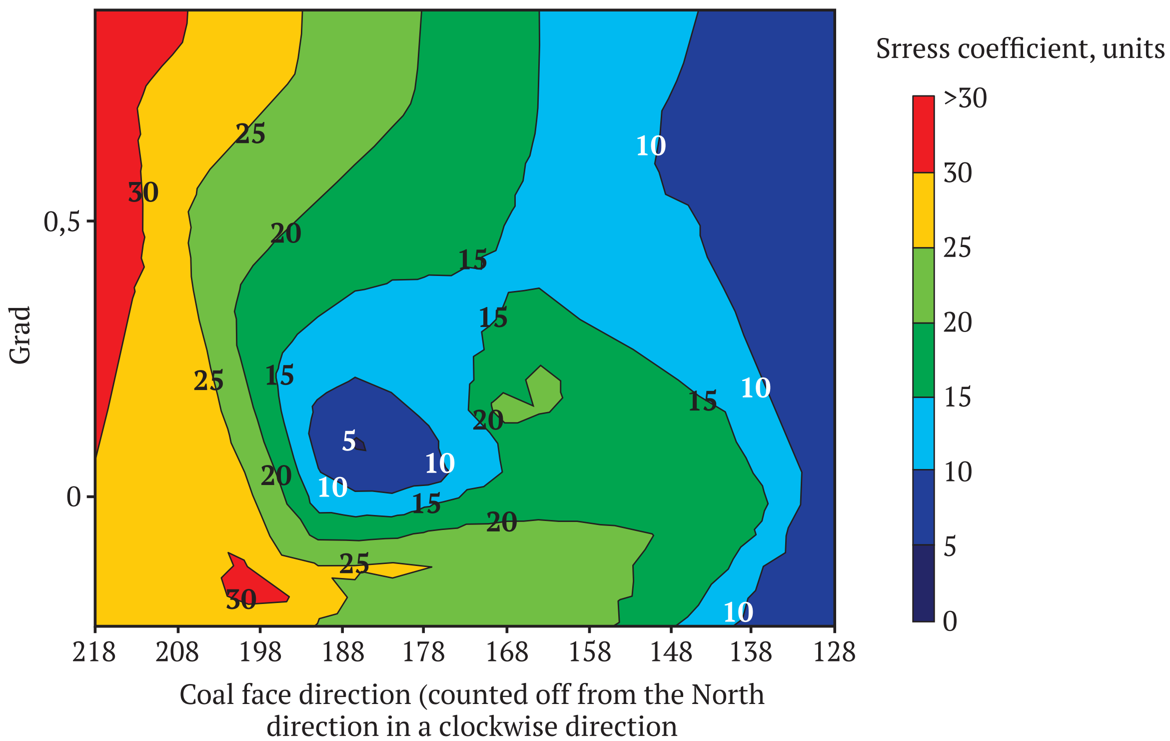


Fig. 8. Isogram of stress coefficient depending on the stress gradient and coal face advance direction

described in [17, 18]. Stability category III is characterized by stabilization of deformation growth after 1–2 weeks. The coefficient taking into account the excess of the actual stresses over the calculated rock strength amounts to 1.61–3.0. Taking into account this coefficient, $[K]_{intact}^{II}$ varies in the range of 5.37–10, while $[K]_{intact}^{III}$ ranges 10.06–18.75. This principle is based on analogy with the recommendations on introducing a coal strength variability factor, presented in normative documentation and Safety rules instructions[2]. The validity of such a transition from an intact rock mass to unstable (disturbed) rocks finds confirmation in laboratory tests conducted by researchers [19].

When changing from an intact rock mass to rocks of stability category III as relatively stable and determining the boundary zone between the disturbed zone in the near-contour rock mass enclosing mine workings and the coal face impact zone we adopted safety criterion $[K] = 10$ at the coal face working stage.

According to Fig. 6, in the conditions of the Komsomolskaya Mine, the safest option is the coal face advance direction between 138 and 128° counter-clockwise from the north direction for any values of deformation modulus and Poisson's ratio. The direction around 188° is also characterized by a lower stress coefficient, but not at all values of deformation modulus and Poisson's ratio. Substantiating the parameters of safe coal extraction at deep levels should be guided by this principle. Insignificant deviations of the angle lead to redistribution of stresses in the face plane and may cause accidents or incidents.

Algorithm for rock bursts forecasting in conditions of coal face work

Based on the above, we concluded that at the stage of a mine design an important prerequisite is selecting safe direction of a coal face advance. In coal seams disturbed by faults, even prior mining, unfavorable conditions arise due to accumulation of potential energy in a rock mass. The excesses of this energy manifest themselves as rock bursts [20, 14]. In coal mines energy manifestations in a rock mass are recorded by sensors sending the data to seismic stations. These manifestations are recorded as events. The above-described example of rock burst forecasting and selecting a safe direction of coal face advance can be written as an algorithm (Fig. 9).

[2] Industrial safety federal norms and rules "Instruction for dynamic effects forecasting and rock mass monitoring in the course of coal deposit development". Order #515 of the Federal Service for Ecological, Technological, and Nuclear Supervision of December 10, 2020. Accessed in the Electronic Fund of Legal and Regulatory Documents. URL: https://docs.cntd.ru/document/573264171

The procedure of the algorithm application is as follows:

1. At the first stage, required data are collected (locations of rock burst manifestation, geological documents, and physical properties of rocks).
2. Then a 2D model is built in a vertical cross-section, taking into account the intersection of the maximum number of faults. The possibility of applying the first assumption (not taking into account the vertical component of a rock pressure) should be confirmed.
3. In addition, the components of rock pressure (horizontal stresses taking into account a side pressure coefficient) are determined in the vertical cross-section. Thus we obtain the boundary conditions for further simulation.
4. Then, a 2D model is built in a horizontal cross-section. Then, the directions of tectonic forces are determined and hazardous zones are identified taking into account the ratio of horizontal stresses to vertical ones. The construction of the 2D model in the horizontal cross-section is performed with the assumption that the extracted coal seam dip angle, height differences, local disturbances (seam crumple, bifurcation, plicative dislocations) are not considered. These seam features are taken into account in a more detailed local forecasting.
5. Further, the probability density function of the number of stress materializations depending on the set of physical property variations in the system of set values “Deformation modulus – Poisson’s ratio” (200 sets) is determined.
6. The behavior pattern of an intact coal seam is calculated using the Lode–Nadai coefficient: generalized tension, compression, and shear. The subsequent selection of a coal face advance direction should be based on the fact that generalized compression should be observed in the potential locations of a coal face construction. A significant part of mining areas meets to generalized compression conditions [20].
7. After the analysis of stresses in an intact rock mass the analysis of stresses in the mining-disturbed rock mass is performed taking into account the mine workings at changing directions of their axes in increments of 10°. The Lode–Nadai coefficient is also calculated in this case in order to identify the pattern of stress redistribution.
8. Then the safety criterion is determined. The safety criterion value corresponding to the most favorable conditions is selected on the basis of comparison of the data of seismic station and the specific potential energy distribution. The value of factor of safety is taken with the correction for a coal seam disturbance due to formation of weakening zones (adjacent to mine workings) and compared with the resulting stress coefficient. Stress coefficient is a value depending on the stress gradient along the normal to a face line.

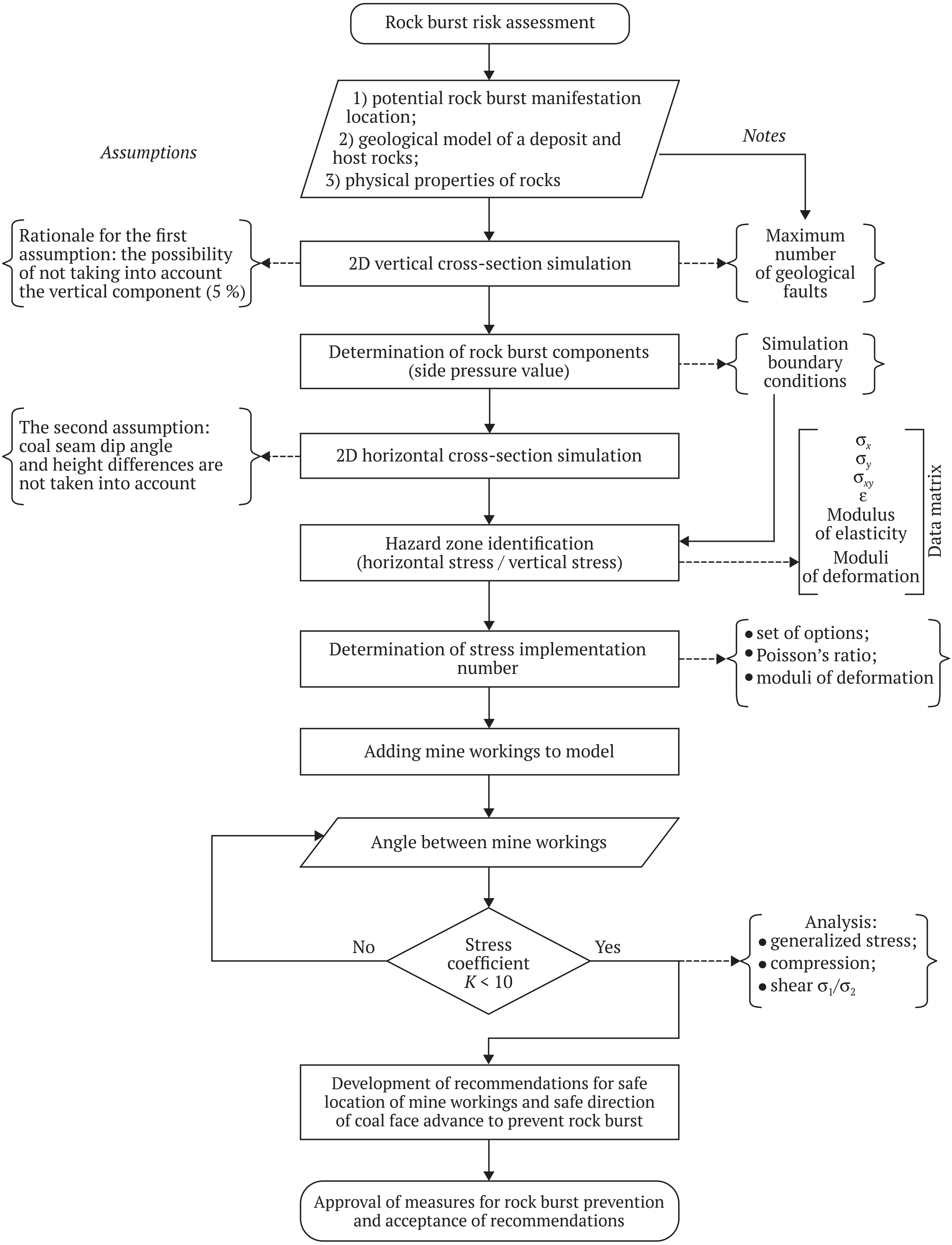


Рис. 9. Алгоритм регионального текущего прогноза горных ударов

9. If the stress coefficient is less than 10, mining is safer in terms of rock burst risk. If the criterion is more than 10, it is recommended to develop additional measures to ensure control and safety of mining.

The presented algorithm is universal for all mining enterprises. Its application is possible at any mine or in any design organization. Special software can be additionally used for its implementation. When using this algorithm for the Komsomolskaya Mine conditions, Plaxis and MathCad software was used.

Conclusion

The developed techniques for rock burst forecasting make it possible to take into account geological faults outside a mine field and the effect of mine workings with their mutual influence, as well as that of a mined-out space.

To estimate the hazard of rock bursts, a criterion, stress coefficient, was introduced. The criterion is determined on the basis of comparison of data from a seismic station and the ratio of the calculated specific potential activation energy to the specific potential energy of gravity of the overlying rocks. The forecast is carried out via estimating the Lode-Nadai coefficient at different directions of coal face advancing.

To implement the technique, an algorithm for current regional rock burst forecasting at coal mines has been developed and tested in the conditions of the Komsomolskaya Mine.

The developed solutions make it possible to improve mining safety.

According to this algorithm, which is based on the developed technique of rock burst forecasting in the conditions of the Komsomolskaya Mine, the safety criterion value was determined to be 10. Besides, the safest direction of a coal face advance to mitigate the risks of rock burst was determined for this mine. The direction between 138° and 128° counter-clockwise from the North direction was identified to be the safest for the Komsomolskaya mine conditions for any values of deformation modulus and Poisson's ratio.

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