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Ensuring a safe geomechanical state of the rock mass surrounding the mine workings in the Karaganda coal basin, Kazakhstan

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Abstract

Purpose. The research purpose is to determine the instability zones in the host rocks and the dynamics of propagation of active fracturing zones to ensure the stability of the rock mass surrounding the mine workings.

Methods. The research uses a set of analytical and experimental studies to determine the dynamics of the deformation process development in the coal-rock mass surrounding the mine workings. Mathematical modeling of the stress-strain state of the rock mass surrounding the active extraction workings is performed using the numerical method of finite elements in modern AN-SYS, Mergel and KMS-III software products.

Findings. The influence has been studied of the mine working section shape and the coal seam dip angle on the value of the maximum stresses that arise in the rock mass when the mine working is fastened with the roof-bolt support. The instability zones in the host rocks and the dynamics of propagation of active fracturing zones have been determined both ahead of the front of the conducted mine working and on its sides for rocks of different strength.

Originality. For the conditions of the Karaganda coal basin, the dependence of a change in the development of conventional inelastic deformation zones (CIDZ) on the host rock strength has been revealed. The influence of the coal seam dip angle on the dynamics of stratifications around preparatory working has also been substantiated. In addition, new data have been obtained on the influence of the roof rock strength on the stratification of the rock mass surrounding the mine working.

Practical implications. By determining instability zones in the host rocks and the dynamics of propagation of active fracturing zones, it is possible to control geomechanical processes in the border rock mass of a mine working and influence it in order to prevent the occurrence of negative rock pressure manifestations. The data obtained are the basis for the development of recommendations on the use of roof-bolting technology for fastening extraction workings to ensure their stability and reduce the cost of their operation.

Keywords: *geological faults, mine working, coal, mine, deformations, rock, roof bolt*

1. Introduction

The coal-mining industry in many countries of the world ensures the energy and raw material independence of mining countries [1]-[3]. This determines the particular relevance of the problem of ensuring the stability of mine workings, with the help of which coal reserves are mined [4], [5]. To date, the most promising are the combined frame-roof-bolt fastening systems, which create an additional synergistic effect of interaction between the roof bolts and yielding frames. This helps to maintain the stability of underground mine workings in difficult mining-geological conditions of significant mining depths or weak host rocks [6], [7]. The increasing depth of mining in-seam minerals and the associated increase in rock pressure requires the development of fundamentally new approaches to ensuring a stable state of underground mine workings [8].

At the present stage of scientific-technical development, there is a transition from a strategy for protecting a human from random manifestations of hazardous production factors to a strategy for predicting a hazard, eliminating or localizing it in the process of improving the existing and designing a new production technology [9], [10]. Conducting of mine workings is one of the main mining production technological processes. Accordingly, it is also characterized by the largest number of possible emergencies and accidents, among which rock caving ranks second (after gas-dynamic events) [11], [12].

The main directions of technical solutions to prevent emergency situations are the use of technology and equipment with a reliable and maximal covering of roof rocks; complex mechanization of stope operations: roof-bolt support with deformation (stress) sensors in preparatory workings and in the places of their junction with stoping faces [13].

Monitoring of the state of mine workings shows that at the stage of driving mine workings, dangerous deformations and stability loss of rock outcrops occur in about 25-30% of them. During operation, increased deformations are typical

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for 40% of the mine workings located outside the zone of stope operations influence, and 60% when they are in the zone of stope operations influence. The main reason for the deterioration in the state of preparatory workings is the decrease in the ratio of rock strength to geostatic pressure with increasing depth of mining operations [14]. The mine working state can have a significant impact on the mine's transport system. For example, when deformation processes occur in rocks, there may be a displacement and change in the shape of mine workings, which may lead to difficulties in maintaining the transport system performance [15]-[20].

The loss of stability of rock outcrops leads to a decrease in the rate of driving mine workings by 40-45% and an increase in the consumption of fastening materials. Also, 35-40% of accidents during mining and preparatory works are caused by the loss of stability of rock outcrops and the rock caving in the roof and sides of mine workings [21]. The restoration works and sealing of rock inrushes in mine workings are rather labor-consuming, unsafe and associated with additional consumption of fastening and other materials [22].

More than half of underground mine workings in the Karaganda coal basin mines are in an unstable state (displacements of rocks in the roof, bottom and sides) and are maintained with significant labor-consuming works and material costs. This is conditioned by the lack of substantiation of the compliance of their fastening parameters with the operating conditions in the specified mining conditions [23]. The application of reasonable parameters for conducting and the introduction of advanced technological systems, methods and means of fastening mine workings are constrained by the limited use of technology for controlling geomechanical processes occurring around them in the border rock mass [24], [25].

In the Karaganda coal basin mines, in this regard, the frequency of additional fastening of the maintained mine workings reaches a two-three-fold value during the operational life, and more than a quarter of them are annually repaired and subjected to a complex of work to improve their stability [26], [27]. The host rocks of the immediate roof in the coal seams are often unstable, and the immediate bottom rocks are prone to heaving.

The main mining-geological factors influencing the conditions of mining operations and determining the mining-technical operating parameters, the effectiveness of technology, systems and means of supporting mine workings, taking into account the border rock mass stress-strain state [28]-[30], are presented in Table 1.

Table 1. Mining and geological operating conditions when mining the Karaganda coal basin seams

Mining-geological operating conditions	Quantitative values
Seam thickness, m	Minimal $m_{\min}$ < 1.2 m, maximum thickness $m_{\max}$ > 3.5 m, ranging not > 15%
Seam dip angle, deg	Maximum $\alpha_{\max}$ >18º, ranging not > 5º
Complex seam structure, the coal hardness	High resistance to cutting $A_{\max}$ > 300 kN/m; Interlayer with hardness f > 4 (according to M.M. Protodyakonov scale)
Roof rock cavability	Compressive strength of rocks σ_{comp} ≥7 0 MPa; Ratio of the immediate roof and the seam rock thicknesses $h/m \leq 3$
Stability of immediate roof rocks	Weak, unstable rocks with compressive strength σ_{comp} – 20-30 MPa
Bottom rock strength, MPa	Specific pressure (weak bottoms) $Q \leq 0.8$ MPa
Seam water content, m^3/h (W)	Weak bottom – $W \geq 3$ m^3/h; Hard bottom – $W \geq 7$ m^3/h
Seam gas content, m^3/h (G)	High – $G \geq 10$ m^3/h
Disjunctive faults	Amplitude of faults – $H/m_a \geq 0.5$
Presence of washouts in the seam	High frequency (over 3 washouts/km)
Seam outburst hazard	Rock strength – less than 2.0 MPa (prone)
Seam ignitability	Presence of disturbed zones (prone)
Coal resistance to cutting	Less than 1.0 kN/m (low)
Bottom rock stability	Rock strength is less than 2.0 MPa for weak rocks; Rock strength is more than 2.0 MPa for strong rocks

When conducting mine working, the rock equilibrium state is disturbed and this leads to a redistribution of stresses in the mass surrounding it. Moreover, the stress intensity on the mine working contour is much higher than in the disturbed mass [31]. Increased stresses on the mine working contour lead to the formation of an inelastic deformation zone around it [32]-[34]. The zone structure and the rock deformation nature in it depend on the depth of mine working location, the type of rocks, as well as their physical-mechanical and technological properties, the mine working size, the type and characteristics of the support, the structural dip of the host rocks [35].

In order to make sound technological decisions on determining the support parameters for its effective operation, it is necessary to assess the deformed state of the host rock mass surrounding the mine workings [36]-[38]. The development and implementation of technology and costs, taking into account the stress-strain state of the host rocks, will reduce material and labor costs, as well as optimize the fastening parameters for the mine workings [39], [40].

The variety of mining-geological and mining-technical conditions for the mine working operation, as well as the mechanism of interaction between rocks and support associated with them, determine the emergence of a number of different geomechanical models for the state of the rock mass surrounding the mine workings. In this case, mathematical modeling is the most promising [41].

Almost all mine workings are deformed, but a particularly difficult situation is observed in the zone of stope operations influence. The solution to this problem is possible when using the rock mass load-bearing capacity, which can be implemented by creating a safe system already at the initial stage of the mine working construction. The latter can be achieved by using protection methods that are aimed at including the border rock mass in the joint work with fastening element. One of the types of fastening elements that implement this is the roof-bolt support [42]. The main task in this case is the correct choice of its parameters [43]-[45].

Thus, the development of a technology for conducting, fastening and maintaining mine workings, taking into account the results of modeling the geomechanical state of the coal-rock mass and the schemes for fastening of the mine working contours for various mining-geological and mining-technical conditions for the development of coal mines is an important scientific task. Due to its solution, it is possible to reduce the cost and expenses of conducting and fastening of mine workings, ensuring an increase in the rate of their conduct for the timely preparation of the front of stope operations with the determination of the patterns of the rock pressure manifestations in the mine workings, depending on mining-geological factors and mining-technical conditions. In addition, it is relevant to study the peculiarities of the rock mass deformation around the preparatory workings, taking into account the seam dip angles and the depths of occurrence, the substantiation of the parameters for the roof-bolt support and the determination of the rational scope of its use to increase the stability and reduce the defectiveness of maintained mine workings.

The paper is aimed at studying the deformed state of the border coal-rock mass around a mine working with roof-bolt fastening in the conditions of the Karaganda coal basin. To achieve the purpose set, this paper gives an assessment of the influence of the mine working section shape and the coal seam dip angle on its state; the stress-strain state of host rocks has been studied depending on the free-caving rock layer thickness; the changes in the gas content of coal in depth of the drilled well and sorption isotherms for coal seams depending on the gas pressure in the rock mass have been studied; the patterns for the rock pressure manifestations in the mine workings of the Karaganda coal basin mines, depending on mining-geological factors, have been determined.

2. Materials and methods

This work includes conducting field observations in the conditions of the Karaganda coal basin mines. Analysis and assessment of stability, defectiveness, deformation processes and patterns of the support interaction with the rock mass in the mine workings is performed using modern research methods.

In order to determine the mining-geological factors influencing on the formation of stratification zones in border rocks around preparatory workings with roof-bolt fastening based on the development of dithalansia, mathematical modeling of the stress-strain state of the rock mass surrounding the mine workings is used. In the presented research, analytical modeling is performed using the numerical method of finite elements based on the obtained experimental data of deformation measurements in mine conditions.

The influence of the mine working section shape and the coal seam dip angle is assessed on the basis of determining the value of the maximum stresses that arise in the rock mass when the mine working is fastened with the roof-bolt support [46].

Mathematical modeling of the stress-strain state of the rock mass surrounding the active extraction working is performed using the numerical method of finite elements in the ANSYS software package. This software package is used to assess the influence of mining-geological factors on the operating conditions of mine working supports for the conditions of in-seam conveyor mining of the k_{10} seam of the Kostenko mine in the Karaganda coal basin at a mining depth of 500 m and a seam thickness of 3.8 m. The solution is made in an elastic approach due to the relatively short time of rock deformation in the vicinity of the preparatory face when it is advanced. The research is performed using mathematical models in the ANSYS software package, which makes it possible to determine the influence of mining-geological factors on the operating conditions of mine working supports.

The conditions for maintaining mine workings with various types of fastening in the zone of stope operations influence are studied for the conditions of intermediate conveyor drift 50 k_{10} of the Kostenko mine in the Karaganda coal basin. The extraction thickness of the k_{10} seam on the mine western wing is 3.7-4.0 m. The immediate roof varies along the strike from 3 to 7 m and is represented by argillites. The main roof is composed of weakly fractured sandstones 24-32 m thick. The maximum bottom heaving value after two years of the mine working maintenance is 0.55 m. In order to provide the required section ahead of the longwall face at a distance of 50-80 m, the drift ripping is conducted to a height of 0.5-0.6 m.

The stress-strain state of host rocks depending on the free-caving rock layer thickness at different lengths of their roof-bolting is studied on the example of a mine working of a rectangular cross-section with the following parameters: the seam dip angle is 15º, its thickness is 3.8 m; mining depth is 450 m; the mine working section is 14.4 m^2.

The variation of the gas content of coal in depth is studied according to the drilled well data and sorption isotherms for coal seams depending on the gas pressure in the mass (rock pressure). The studies are conducted for the conditions of the k_{10} seam intermediate drift of the Abayskaya coal mine and the d_6 seam ventilation inclined winze of the Kazakhstanskaya coal mine in the Karaganda coal basin.

Calculations to determine the influence of various factors on the displacement process development of rock layers in the border mass around the preparatory working are performed for a single mine working, driven in a homogeneous mass with an average rock strength for uniaxial compression of 24 MPa, which is typical for the Karaganda coal basin. The mine working section shape is arched: width – 5.7 m and height – 3.55 m. The mine working location depth varies from 400 to 800 m (depth range for the Karaganda coal basin mines).

To determine the influence of mining-geological and mining-technical factors on the formation of inelastic deformation zones in the host rocks surrounding the mine workings, based on the development of conventional inelastic deformation zones (CIDZ), the "Mergel" computer program is used when modeling the stress-strain state of the mass adjacent to mine workings [47]. This computer program is intended for determination of the mine working fastening parameters, predicting and calculation of convergence, horizontal displacements of rocks in various schemes of work development with consideration of the rock mass geomechanical state. The program, developed on the basis of theories of elasticity and kinetic strength of solid bodies, as well as the "KMS-III" program for predicting the expected displacements (displacement modeling complex for mines) [48], make it possible to determine the stress-strain state and displacements at the considered point in the technogenic space, to identify the object durability (time before destruction) and to assess the rock outcrop stability for subsequent technological measures.

For geomechanical interpretation of the results of modeling the patterns for rock pressure manifestations in the mine workings of the Karaganda coal basin mines depending on mining-geological factors, a conveyor drift for the k_7 seam of the Kostenko mine in the Karaganda coal basin with a section of 16.2 m² is considered. Seam k_7 is driven at a depth of 630-640 m.

The destruction zones are determined by the "Calculation of stress and durability" computer program (durability is the time before rock destruction). The file contains information about the number of sections in the mine working contour, *n*; rock layers, k_s; horizontal stresses in the undisturbed mass, in MPa, c_x; vertical stresses in the undisturbed mass, in MPa, c_y; shearing stresses in the undisturbed mass, in MPa, t_{xy}; Poison's ratio, n_u; gradient angle to the rock layer horizon, in degrees, a_s.

3. Results and discussion

The actual rock mass, as a rule, is represented by layers of different strength with weakened interlayer bonds. In addition, the fractures that occur in the mass, especially after mining operations, create additional weakening planes. Therefore, the rocks occurring in the mine working bottom should be considered taking into account the complexity of their structural and, in particular, stratified texture.

The roof-bolt fastening structure is most often determined by the layout plan and parameters of roof bolts. The main parameters of the roof-bolt fastening structures are the mine working cross-sectional shape, the distance between the roof bolts in a row and between the rows, the distance from the outermost roof bolt in the row to the mine working wall and the protrusion of its bottom end over the mine working wall, the gradient angles of the roof bolts when setting, the length of the roof-bolt rods and their diameter. The mine working cross-sectional shape is one of the determining factors. The mine working cross-sectional shape should be chosen in accordance with the mining-geological conditions of its conduct and the mining-technical conditions of operation.

Figure 1 presents the hodographs of the maximum stress vector – the curves connecting the ends of the variable value vector plotted at different time moments from the same point – the trajectory described by the vector end σ_{xy} when changing the dip angle of the seam. In this case, the angle between the vector σ_{xy} and the *X*-axis – σ_x is the side thrust coefficient, which with a rectangular and arched cross-sectional shape changes more widely than with a polygonal one.

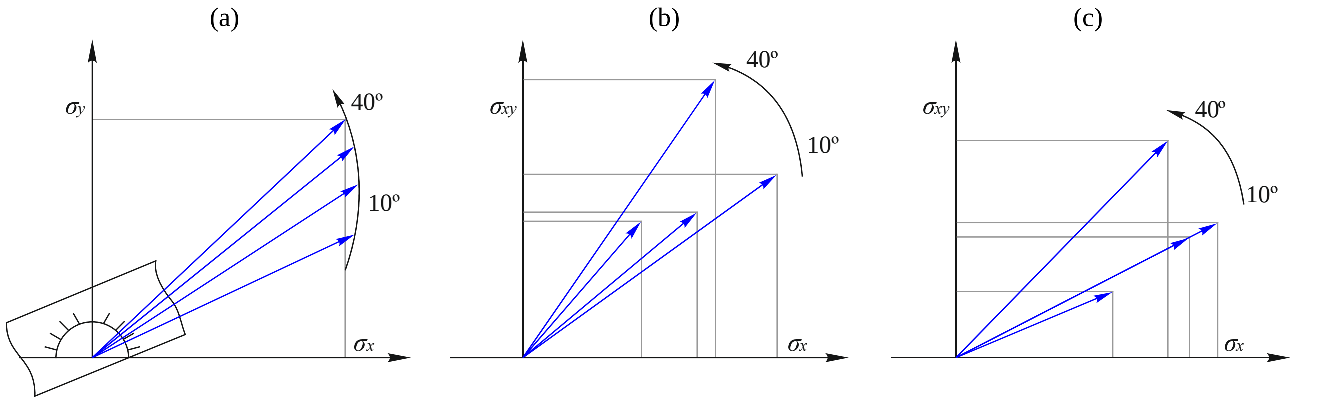

Figure 1. Variation of the maximum stress vector (σ_{xy}) hodographs depending on the dip angle of the seam and the cross-sectional shapes of the mine workings: (a) arched; (b) rectangular; (c) polygonal

The maximum stresses are significantly higher for arched and rectangular supports compared to supports with a polygonal cross-sectional shape in maintained mine workings in terms of value and variation in the side thrust coefficient. It should be noted that the rock stratification planes coincide with the tangent to the hodograph, which gives reason to recommend the setting of roof bolts taking this factor into account, that is, the roof bolts should be located orthogonally to the stratification plane. Thus, it can be concluded that it is preferable to use extraction workings of rectangular cross-sectional shape with roof-bolt fastening of the host rocks when mining the k_{10} seam of the Kostenko mine in the Karaganda coal basin.

Solving the problem of determining the stress-strain state (SSS) of a mine working when it is conducted in a weakened or disturbed rock mass includes determining stresses (normal, longitudinal and shearing), reactions and internal forces, as well as displacements and deformations. At the same time, the geomechanical model includes the geometric dimensions and shape of the mine working, the physical characteristics of the host rock mass (uniaxial compressive strength) and the parameters of the advanced roof-bolt fastening.

The normal stress components σ_y^{comp} (compression) and σ_y^p (tension) are characterized by a linear dependence on the layer thickness and the roof-bolting length (*L*), with both components growing in absolute value. The reverse patterns are characteristic of transverse σ_x^{comp} and σ_x^p components, and in the range of roof-bolting depths from 1.5 to 4.5 m, a decrease in the absolute values of σ_x^p is noted. The reason for this may be the redistribution of stresses characteristic of mine workings with polygonal and rectangular sections (Fig. 2).

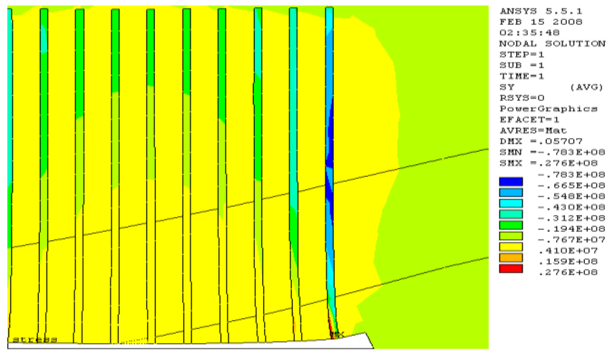

Figure 2. The nature of the development of horizontal stress patterns in the roof bolts located in the mine working roof

Stress distribution analysis shows that the maximum stresses occur in the roof bolts near preparatory working face and begin to decrease at 2.5 m from the working face bottom. It is typical that at the initial stage of the roof-bolt resistance to the rock pressure forces, there is a gradual tension of their rods from the tail joints to the front sections. This order of tension is well consistent with the nature of the roof rock stratification, which begins in the mine working contour and extends into the mass depth. As the load increases, the tension is redistributed along the roof-bolt support body.

The fact of keeping the connection between the rock mass and the roof-bolt rods is confirmed by computer mode-ling, where the destruction of the contacts is observed only in the roof-bolt front sections located in the depth of the mass. This means that in the process of intense rock landslides around the preparatory working, the contact of the front deep sections of the roof bolts is disrupted and their front sections are removed from the mass, losing some of the tension. However, about three-quarters of the roof-bolt rod length maintain contact and actively resist the rock pressure forces. The positive effect that the roof bolt has on the frame is noticeable by the high compressive longitudinal forces generated in the upper part of the fastening, which is clearly seen in Figure 2. It is these forces that create a positive effect of the self-wedging of the support and destroyed rocks, which can increase the load-bearing capacity of the rock fastening by several times.

The use of joint resistance roof-bolt support has the maximum positive effect on the stability of the mine working roof rocks. This effect occurs due to the mutual positive influence of roof bolts and frame fasteners. In this case, the frames are strengthened with roof bolts at the attachment points, and the roof bolts can maintain the integrity of contact with the host rocks. The results obtained are well consistent with the previously existing ideas about the role of roof-bolt support.

The results of the research on the variation in the gas content of coal in depth of the drilled well and sorption isotherms for k_{10} coal seams of the Abayskaya coal mine and d_6 seam of the Kazakhstanskaya coal mine in the Karaganda coal basin are shown in Figures 3a, b.

Figure 3, a show that the zone of the rock pressure wave propagation ahead of the preparatory working front in the active zone is 6 m. The research is conducted for the conditions of the k_{10} seam intermediate drift of the Abayskaya coal mine in the Karaganda coal basin, 65 m from the mounting chamber in the downward direction along the conveyor drift with a section of 15 m^2: total gas content is 19.3 m^3/t (gas content at a pressure of 1 bar is 2.8 m^3/t, the desorbed gas volume is 16.5 m^3/t). The experiments are carried out along an extended mine working to determine the zone of acting bearing pressure around the contour from the preparatory working deep into the mass, which in the intensive zone is 4 m (Fig. 3a). Variation in sorption isotherms, where for the conditions of the ventilation inclined winze of the $д_6$ seam of the Kazakhstanskaya coal mine with a section of 15 m^2 with a dead end length of 179 m deep into the face has shown that the total gas content is 19.4 m^3/t (gas content at a pressure of 1 bar is 2.3 m^3/t, the desorbed gas volume is 17.1 m^3/t (Fig. 3b).

To determine the influence of various factors on the displacement process development of the border mass rock layers around the preparatory working, it is possible to use a numerical experiment in a computer program for modeling displacements [49]-[51].

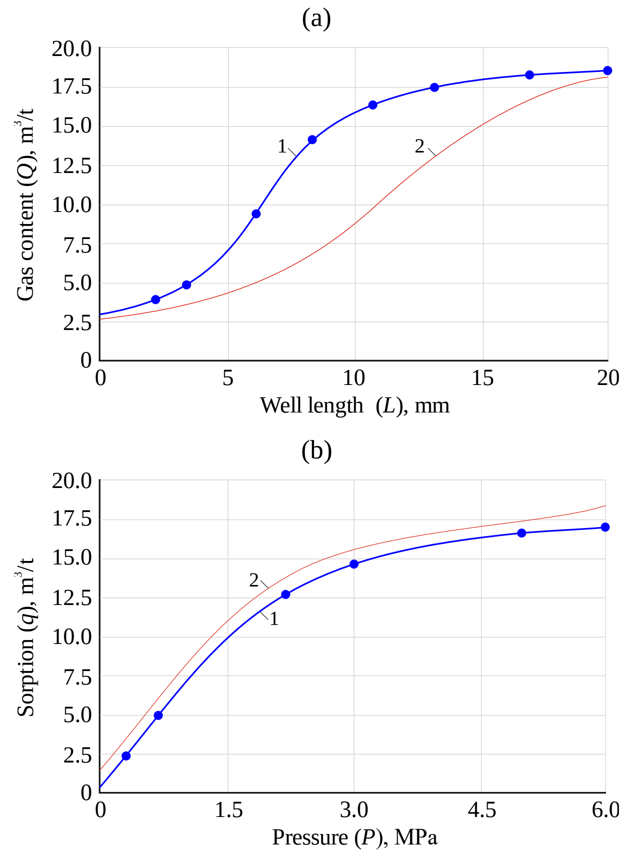

Figure 3. Variation in the gas content of coal seam: (a) mine working border rock mass; (b) sorption isotherms; 1 – k_{10} seam of the Abayskaya coal mine; 2 – d_6 seam of the Kazakhstanskaya coal mine in the Karaganda coal basin

The main factor influencing the displacement development is the rock pressure, which depends on the mining depth. The analytical dependence of the border rock mass displacements on the depth of mining operations is shown in Figure 4. The side thrust coefficient value is assumed to be 1.0.

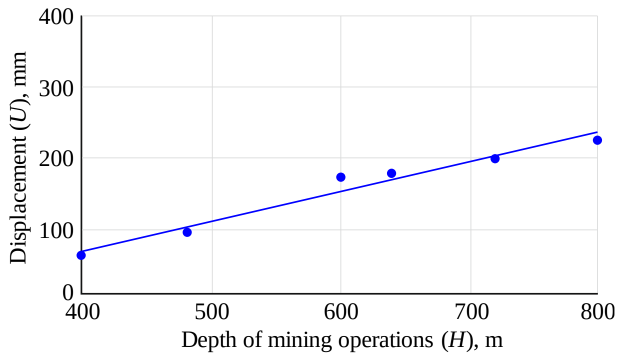

Figure 4. Dependence of the border rock mass displacements on the depth of mining operations

For the considered depth interval, a linear dependence between the expected displacements of the mass from the side of the unfastened mine working roof and the depth of mining operations (Fig. 4), expressed by the formula (correlation coefficient $r = 0.97$), has been determined:

$$U_{ex} = 0.3093H - 21.322\,. \tag{1}$$

An important factor influencing the displacements of the contour mass surrounding the mine working is the rock strength, which in the experiment varies within the limits characteristic of the Karaganda coal basin (10-40 MPa).

Dependence of the rock mass displacements from the side of the roof on their uniaxial compressive strength is shown in Figure 5.

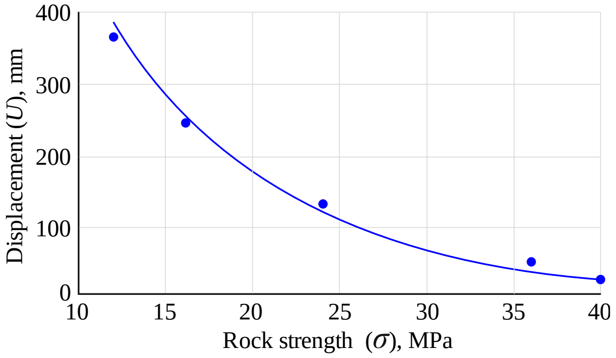

Figure 5. Dependence of border rock mass displacements from the side of the roof on their uniaxial compressive strength

It follows from Figure 5 that the maximum displacements correspond to the minimum rock strength, and, accordingly, the minimum displacements correspond to the maximum rock strength. Thus, the exponential dependence of the host rock mass displacements on the rock strength has been determined at $r = 0.96$:

$$U_{ex} = 1294.4e^{-0.1003\sigma_{comp}} . \qquad (2)$$

Based on the results of geomechanical interpretation of modeling the patterns of rock pressure manifestations in mine workings, depending on the mining-geological factors of the conveyor drift along the κ_7 seam of the Kostenko mine in the Karaganda coal basin, it has been revealed that fracturing is most common remotely. Moreover, this occurs from all sides of the mine working at a distance of 2.4-2.5 m from the contour and even less remotely (0.4-0.5 m) at the side prop stays in the bottom near the mine working – with an easy and medium-to-control roof (Fig. 6).

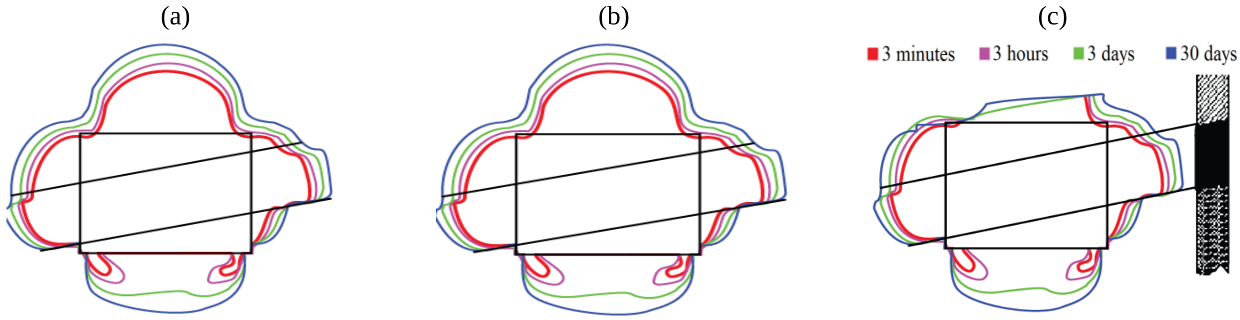

Figure 6. Influence of the roof rock strength on the stratification of the rock mass surrounding the mine working: (a) weak strength; (b) moderate strength; (c) strong rocks

In the case of a hard-to-control roof, fractures in the roof occur near the mine working and are located at a distance from the mine working section not exceeding 0.5 m. Thus, the characteristics of the host rock controllability (taking into account their strength characteristics) are manifested to a greater extent by the proximity of newly formed fractures to the mine working contour only with a hard-to-control roof. The dependence of the fracture propagation depth in the host rocks depending on the dip angle of the seam and the controllability of the roof rocks has been determined.

Empirical dependences (at $R^2 = 0.96$):

$$R = 1.03 + 0.063\frac{H_{n.k}}{m} \qquad R = 1.8 + 0.05\alpha . \qquad (3)$$

It has been revealed that the dip angle of the seam significantly influences on the fracture propagation depth: the steeper the dip angle, the deeper the fractures can propagate. However, roof rock controllability also plays an important role in this process. If the roof rocks have good controllability, this can help to reduce the depth of fracture propagation, even with a steep dip angle of the seam. Understanding these dependences can be used to develop more effective strategies for preventing and controlling rock stratification in mine workings. Figure 7 shows the dependence of the variation in the size of the conventional inelastic deformation zones on the rock strength.

After determining the conventional inelastic deformation zones (CIDZ), depending on the host rock strength, the pattern of the average distance between fractures has been revealed according to the uniaxial compressive strength of the rocks:

$$L_c = 0.025e^{0.003R_c} , \qquad (4)$$

where:

R_c – a uniaxial compressive strength of the rocks, kg/cm^2;

L_c – the average distance between fractures, m.

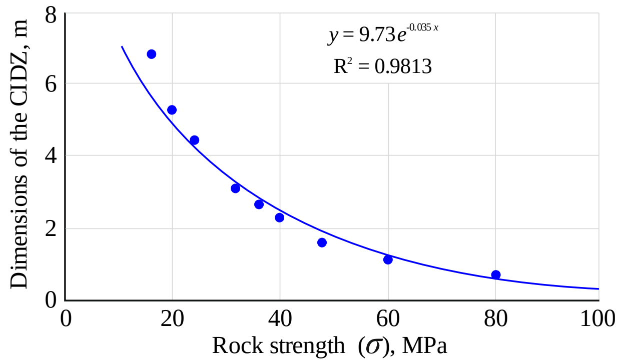

Figure 7. Change in the development of conventional inelastic deformation zones depending on the host rock strength

Numerical modeling is performed to determine the dependence of the stratification zone development on the depth of mining operations. For the studied mine working, the depth of conducted modeling varies from 300 to 800 m (the nature and parameters of the stressed zones and the dynamics of changing boundaries). The depth of mining operations influences on the development of conventional inelastic deformation zones and has a non-linear nature with increasing depth. The first curves of conventional inelastic deformation zones from the mine working contour are located at a distance of 1.6-20.0 m, reaching a value of 4.5-5.5 m.

An analysis of modeling results shows that the development of conventional inelastic deformation zones in time, depending on the depth of mining operations, follows a logarithmic law. The dependence of the sizes of conventional inelastic deformation zones (h_{CIDZ}, m) on the depth of mining operations (H, m) can be represented in the following form:

$$h_{CIDZ} = a\ln(H) - b, \quad (5)$$

where:

a, b – empirical coefficients that take into account the rock strength, the mine working size and other factors that influence on the mine working stability.

According to the factors influencing the development of conventional inelastic deformation zones adjacent to mine workings, the strength of rocks and the degree of their fracturing have been determined. The revealed patterns of changes in the stress-strain state of coal-rock masses (displacements, stresses, fracture zones), depending on the main mining-geological and mining-technical factors, will allow, under specific operating conditions, to determine optimal fastening parameters to increase the stability of preparatory workings. This will make it possible to develop new and improve existing technologies for effective and safe fastening of border rocks in the conduct of mine workings on flat and inclined coal seams, adaptable to changing mining-geological and mining-technical operating conditions.

It should be noted that the development of rock fracturing (dithalansia – D_m) in time (T) depending on the location depth (H_p) with combined (roof-bolt and metal-arched) fastening can be represented in the form of empirical dependences:

– for roof and sides of the mine working:

$$D_m^{\ 1} = 1.028 + 0.0004H_p + 0.056T; \quad (6)$$

– for the mine working bottom:

$$D_m^{\ 2} = 1.387 + 0.0004H_p + 0.109T. \quad (7)$$

As a research result, the dependence has been revealed of the roof rock displacement rate on the depth of mining operations (H) and the hardness factor (f).

Dynamics of change in the sizes of conventional inelastic deformation zones [52]-[54] depending on the rock strength:

$$h_{CIDZ} = 9.8e^{-0.04R_c}. \quad (8)$$

Stronger rocks can resist deformations and the propagation of inelastic deformation zones over long distances, while less resistant rocks are more prone to deformations and the formation of inelastic deformation zones over shorter distances. It is also worth noting that when the stress-strain state of rocks changes, for example, when new technological processes occur in mine workings, the sizes of inelastic deformation zones can also change. Understanding these dependences between the sizes of inelastic deformation zones and the rock strength can be used to develop more effective strategies for managing deformation processes in mine workings and ensuring the safety of workers in mining enterprises.

Figure 8 shows the influence of the coal seam dip angle on the dynamics of stratification and on the parameters of the formed arch of unstable rocks in the roof and sides of the mine working, which will determine the load on the support.

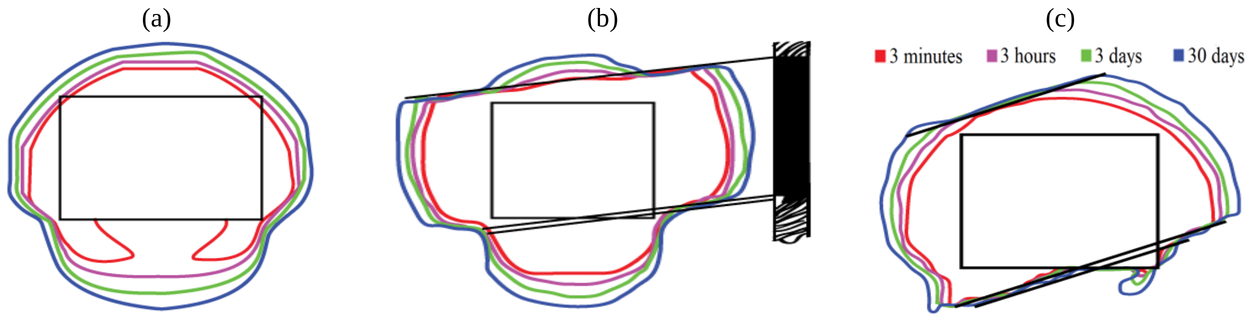

Figure 8. Influence of the coal seam dip angle (α) on the dynamics of stratifications around preparatory working: (a) α =0º; (b) α =10º; (c) α =20º

Based on Figure 8 and the research results, it can be stated that the coal seam dip angle has a significant impact on the dynamics of stratification around the preparatory working. In particular, at the dip angles of steeper seams, there is more and more intense stratification around the mine working. This can lead to increased stresses and deformations in the surrounding rocks, which in turn can affect the stability of mine workings and the safety of people working there. Thus, the coal seam dip angle is an important factor in the planning and conducting underground mining operations.

In the bearing pressure zone ahead of the longwall face, the authors in the studies [55]-[58] note an increase in convergence in the preparatory workings of longwall face sections by 30% with each face advance. In our case, the convergence value increases by 5-10% every 10-20 m, and the depth of the bearing pressure zone propagation ahead of the longwall face is 30-40 m, while maximum displacements are observed at a distance of 20 m ahead of the longwall face. The results obtained are important for understanding the processes occurring in the bearing pressure zones during underground mining operations and can be used to optimize mining under such conditions.

4. Conclusions

The scientific novelty of the presented paper is in the substantiation of the qualitative and quantitative parameters of the mine working contour fastening systems, taking into account the geotechnical processes occurring in the coal-rock mass. The main purpose is to create safe working conditions and labor productivity in high-performance stoping and preparatory faces, taking into account the rock mass stress-strain state when fastening mine workings. The influence of technological factors on the conditions for maintaining the contours of mine workings is confirmed. In addition, the host rock strength has an influence on the values of stresses and contour rock stratification.

The completed set of analytical and experimental studies makes it possible to reveal the dynamics of the deformation process development in the coal-rock mass surrounding the mine workings. The instability zones in the host rocks and the dynamics of propagation of active fracturing zones have been determined both ahead of the front of the conducted mine working (5 m) and on its sides (7.5 m), which makes it possible to control geomechanical processes in the mine working border mass. It also provides the opportunity to influence geomechanical processes to overcome undesirable rock pressure manifestations and ensure the stability of maintained mine workings. Moreover, it is possible to develop recommendations for the use of roof-bolt technology for fastening extraction workings to ensure their stability and reduce operating costs.

The linear dependence of the expected host rock mass displacements from the side of the mine working roof on the depth of mining operations, as well as an exponential dependence of the border rock mass displacements on the rock strength, have been determined. Comparing the analytical values, obtained in the "KMS-III" software package for modeling displacements of mines with the data obtained by the experimental method, it is possible to draw a conclusion about their convergence. The calculation error of the roof displacements between field measurements and the analytical method is no more than 2%, and in the mine working sides no more than 6%. The displacements in the bottom, obtained analytically, are almost twice as large as those obtained in natural conditions.

An important conclusion of this paper is that the conducted research makes it possible to determine the degree of influence of mining-technical conditions of mining operations on displacements in border rocks with various types of support in extraction workings. The revealed patterns of deformations can be used to calculate the rock pressure manifestations in the course of conducting mine workings under various mining-technical operating conditions.

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Забезпечення безпечного геомеханічного стану масиву навколо гірських виробок Карагандинського вугільного басейну, Казахстан

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Мета. Визначення нестійких областей вміщуючих породах і динаміки поширення зон активного тріщиноутворення для забезпечення стійкості гірського масиву навколо гірничих виробок.

Методика. У роботі використано комплекс аналітичних та експериментальних досліджень для встановлення динаміки розвитку деформаційних процесів у вуглепородному масиві навколо гірничих виробок. Математичне моделювання напружено-деформованого стану масиву навколо діючої виїмкової виробки виконувалося із застосуванням чисельного методу скінченних елементів із використанням сучасних програмних продуктів ANSYS, Mergel і KMS-III.

Результати. Досліджено вплив форми перерізу гірничої виробки та кута падіння вугільного пласта на величину максимальних напружень, що виникають у масиві гірських порід при закріпленні виробки анкерним кріпленням. Визначено нестійкі області у вміщуючих породах і динаміку зон поширення активного тріщиноутворення як попереду фронту проведеної виробки, так з її боків для порід різної міцності.

Наукова новизна. Для умов Карагандинського вугільного басейну встановлено залежність зміни розвитку умовних зон непружних деформацій від міцності вміщуючих порід. Також обґрунтовано вплив кута падіння вугільного пласта на динаміку розшарування навколо підготовчої виробки. Крім цього, отримані нові дані про вплив міцності порід покрівлі на розшаровування гірського масиву навколо виробки.

Практична значимість. Визначення нестійких областей у вміщуючих породах та динаміки зон поширення активного тріщиноутворення дозволить управляти геомеханічними процесами у приконтурному масиві виробки та впливати на нього для запобігання появі негативних проявів гірського тиску. Отримані дані можуть лягти в основу розробки рекомендацій щодо застосування технології анкерного кріплення виїмкових виробок для забезпечення їхньої стійкості та зниження витрат на їх експлуатацію.

Ключові слова: *геологічні порушення, виробка, вугілля, шахта, деформації, порода, анкер*