Mining of Mineral Deposits
Volume 19 (2025), Issue 2, 38-46

MMD JOURNAL / MINING.IN.UA

https://doi.org/10.33271/mining19.02.038

Assessment of the stress-strain state of the rock mass surrounding cutting workings during coal seam mining

Vladimir Demin [1], Elvira Khalikova [1*], Tatyana Demina [1],
Dinara Syzdykbaeva [1], Aibolat Karatayev [1], Murat Mustafin [1]

[1] *Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan*

**Corresponding author: e-mail e.khalikova@ktu.edu.kz*

Abstract

Purpose. The research is aimed at developing scientifically sound principles of the technology for maintaining mine workings to ensure their stability during mining of coal seams in the Karaganda coal basin (Republic of Kazakhstan). The influence of fastening parameters on strengthening effect under conditions of controlled stress-strain state of the "host rocks – fastening elements" system is studied.

Methods. The study includes an analysis of scientific-practical experience in operating mine workings and conditions for conducting underground operations. The stress-strain state of the mass is assessed by the finite element method in two-dimensional formulation using the RS2 software package. The inelastic deformation zones are calculated taking into account the geological-technological factors influencing the behavior of the mass in the area of the cutting zonal extraction workings.

Findings. For the first time, the patterns of change in the sizes of plastic deformation zones and stressed areas around mine workings with different technological fastening solutions have been quantified. The dependence of the stress-strain state on the characteristics and geometry of the fastening system has been revealed.

Originality. The patterns of changes in the size of deformation and stress zones in the vicinity of mine workings at different techno-logical fastening schemes have been determined. The dependence of the stress-strain state of the mass on the parameters of the fastening systems has been revealed.

Practical implications. Scientifically sound recommendations have been developed for the technology of fastening cutting ventilation mine workings using two-level roof-bolting systems in the case of stable roof layers. The optimum parameters for fastening operational mine workings that provide stability at different depths of seam occurrence have been substantiated.

Keywords: *mining operations, fastening, mine working, rock pressure, numerical modeling, rock mass, coal, stress-strain state*

1. Introduction

Improving the fastening efficiency of mine workings remains one of the key tasks of underground coal mining, especially in conditions of complex mining-geological structure and significant rock pressure. One of the most promising directions is the combined use of roof-bolting and metal-framed yielding support, which provides a transition from a limited yielding mode to a joint rigid interaction using the self-supporting effect of the surrounding rock mass [1], [2]. This approach significantly increases the load-bearing capacity of the fastening system, reduces the level of deformations and minimizes the probability of accidents. Similar integrative strategies aimed at enhancing the stability and efficiency of mining systems have been proposed in related areas, including the optimization of underground equipment operation [3], [4], the implementation of sustainable energy approaches [5]-[8], and risk-oriented methods for improving structural reliability [9], [10], and the development of selective mining technologies aimed at minimizing waste accumulation and improving coal quality [11].

The widespread implementation of support structures based on roof-bolting systems in cutting workings is constrained by a number of factors. The key one is the insufficient study of mechanical interactions in rock – roof-bolting structures formed in the process of mass strengthening. This makes it very difficult to quantify the contribution of various roof-bolting elements to the overall stability of mine working, limits the possibility of clearly distinguishing the areas of application of roof-bolting systems and hampers the development of scientifically sound methods for calculating their parameters [12], [13].

The peculiarities of the host mass deformation in case of roof-bolt support are formed in stages. At the stage of conducting the mine working before the roof-bolts are set, a zone of instantaneous failure is formed near its contour, accompanied by stress redistribution. This initiates the development of a failure front directed deep into the mass. After the roof-bolt support is set, the state stabilizes: the failure slows down, and from the moment of formation of a stable rock – roof-bolting structure, rock stratification near the contour stops. The structure begins to take up loads from loosened areas, prevents

Received: 15 January 2025. Accepted: 16 April 2025. Available online: 30 June 2025

further failure development and limits displacements in the direction of the mine working [14], [15].

Practice shows that resin-grouted roof-bolting systems are widely spread at a number of mines: at some sites, their share in the total volume of the conducted mine workings is 60-98% [16], [17]. This is due to their high technological efficiency, effectiveness in complex geomechanical situations and the ability to reduce the scope of auxiliary activities. However, to ensure the reliability of such systems, an in-depth study of their interaction with the mass and adaptation of parameters to specific operating conditions is required.

Today, the scope of application of resin-grouted roof-bolt support covers a wide range of underground mine workings [18], [19]. It is actively used in capital mine workings of the near-wellbore yard, crosscuts, field and in-seam main crosscuts, slopes and drifts, as well as in in-seam extraction workings with the tunneling width of up to 6 m. The roof-bolt support efficiency has also been confirmed in adjacent areas, including assembly chambers and junction units for different mine workings. Depending on geological conditions and the nature of operation, the service life of such mine workings varies from one year to thirty or more years [20]-[23].

The roof-bolting systems perform a complex function of stabilizing the surrounding mass. Their main tasks include: fixation of weak roof rocks to more stable rock layers; integration of stratified rocks into a single load-bearing structure with high rigidity and resistance to bending; increased friction forces between the contacting rock layers and perception of tensile stresses arising in the roof during rock pressure redistribution [24]-[26]. In most cases, these mechanisms act synchronously, forming a stable engineering-geomechanical state of the mass surrounding the mine working.

The practice of operation at mining enterprises shows that roof-bolt support is gradually replacing traditional types of fastening (metal-arch, frame, wooden, etc.). Roof-bolting systems are particularly effective in large-section mine workings, where both high load-bearing capacity and minimizing the clutter of the working space are important [27]-[29].

The key design advantage of roof-bolt support is the possibility to increase its load-bearing capacity by increasing the density of setting roof-bolts without significant interference with the dimensions of the mine working. In this case, the bearings (roof-bolt rods) remain motionless with a sufficient length, and their deformation is only possible under elastic displacements. The rock blocks surrounding the rod are compressed and have no possibility of de-strengthening and loosening, which, taken together, provides a significant increase in the strength characteristics of the mass compared to the unstrengthened state [30]-[34]. Thus, the roof-bolt support acts not only as a means of preserving the mine working contours, but also as an element of active control of the stress-strain state of the mass in zones with potentially unstable conditions.

To ensure the stability of mine workings in the conditions of complex geomechanical environment, structural solutions aimed at increasing the load-bearing capacity of the rock mass are required [35], [36]. One of the most effective ways to achieve this is the use of roof-bolt supports capable of forming an active supporting and stress redistribution system.

Reliable and durable fastening of preparatory workings, conducted in the roof of weakly-cemented fractured rocks at considerable depths and in the zones influenced by stope operations, is achieved by using resin-grouted roof-bolts. These roof-bolts, fixed along the entire length of the borehole using fast-curing composite resins, provide load-bearing capacities of up to 250-300 kN at a length of 2-3 m. In conditions of increased geodynamic activity or in the presence of significant mass disturbances, the structure can be strengthened by using special deep-lying roof-bolts up to 6-7 m long, which significantly expands the area of stability [37], [38].

If the roof is characterized by severe stratification or is crossed by a system of fractures, it is advisable to use metal roof-bolts cemented or wedged into the boreholes. Such rods with a clamping plate and a fixing nut create the effect of “squeezing” the loosened near-contour layers to the more stable layers of the main roof, thus preventing them from cleavage and participating in the failure.

In the process of tensioning the roof-bolt, tensile stresses are generated in the rock at the ends of the rod, perpendicular to its axis. As the stresses are removed from these zones, they decrease in value, moving towards the middle part of the roof-bolt where compressive stresses predominate. This creates a local volumetric compression zone, providing stabilization of the mass near the mine working. When several roof-bolts are densely placed within one mine working, their zones of influence overlap, forming a joint reinforced space in which rocks are in a stable stress state and have increased resistance to deformation and failure [39], [40]. Such a system makes it possible not only to reduce the level of rock pressure on the support, but also to significantly increase the stability of mine workings when mining the seams in conditions of weak rocks and increased depth.

2. Study area

The research object is the Shakhtinskaya Mine field, located in the western part of the Sherubai-Nura District of the Karaganda coal basin (Republic of Kazakhstan). From an administrative point of view, this territory falls under the jurisdiction of the Shakhtinsky maslihat of Karaganda Oblast. According to the project documentation, the mine has a production capacity of 2.4 million tons of coal per year with a remaining service life of 29 years.

The mining-geological structure is characterized by complex tectonic conditions. The field is opened on a two-horizon scheme with the use of horizon-oriented crosscuts. The mining system is based on the use of long panels along the strike with the formation of cutting workings. The tectonic disturbances are dominated by meridional and submeridional upcast faults, the dip of which is oriented to the west and south-west. The amplitude of faults varies from a few to hundreds of meters.

Monoclinal occurrence of seams is represented by residual areas of synclinal folds. A particularly well-defined synclinal structure is observed in the northern part of the mine field, where an almost complete folded wave, including both syncline and anticline, has been preserved. As a result of the impact of discontinuous faults, the area is divided into four separate tectonic blocks: western, central, south-eastern and north-eastern, each characterized by a unique combination of folded and discontinuous deformations.

The working seams on the territory of a mine field comprise d_{11}, d_{10}, d_9, d_7, d_6, d_5, d_4 and d_1. All coal seams are grouped into three stratigraphic groups. The lower group includes thin seams d_1-d_5, of which seams d_1, d_4 and partially d_5 are of industrial importance. The distance between these seams is about 67 m.

The middle group is represented by seams d_6, d_7 and d_8, while d_6 and d_7 are the main ones in the mining; the distance between d_6 and d_8 reaches 60 m. The upper group covers the seams from d_9 to d_{11}, where d_9, d_{10} and partially d_{11} are industrially important, with inter-seam spacing of up to 39 m.

Thus, the geological-tectonic peculiarities of the mine field create complex conditions for the design and implementation of schemes for fastening mine workings, which requires a comprehensive geomechanical analysis taking into account the tectonic block structure, variability of seam thickness and coal layer occurrence parameters.

All mined seams are characterized by the presence of widespread friable roof with a thickness of 0.15 to 0.3 m. The friable roof is represented by weakly-cemented, in some cases clay-like argillites, as well as by interlayering of low-carbonaceous and carbonaceous varieties with extremely low strength characteristics. The temporal compression resistance of the friable roof rocks does not exceed 10 MPa, which allows them to be classified as very weak rocks prone to loosening under mechanical influence.

The immediate and main roof rocks are mainly represented by dense siltstones and, less frequently, by sandstones with interlayers of medium-strength argillite. Directly beneath the coal seams, friable bottom rocks occur, composed of easily soakable clay-like argillites 0.1-0.4 m thick, often containing carbonaceous intercalations. In conditions of mechanized stoping, such rocks quickly lose strength, are cut together with coal, which leads to an increase in ash content of extracted raw materials. The gas content of coal seams in the 300-500 m depth range reaches 15-20 m^3/ton, with the gas weathering depth ranging from 116 to 256 m. Shakhtinskaya Mine is classified as hazardous due to sudden coal and gas outbursts.

The rocks of the roof, sides and bottom within the conducted mine workings are characterized by low values of uniaxial compression strength from 20 to 37 MPa and belong to the category of unstable rocks. When over a one meter of rocks outcrop, they are prone to caving and the bottom rocks are prone to intense soaking and heaving.

A number of rock pressure manifestations occur in the supported cutting working, leading to its unsatisfactory state (Figs. 1 and 2). Mostly metal-arch and combined types of supports are used for supporting cutting workings. Metal-arch support is used when there are significant loads from the roof and sides, including unstable structure of the mass and the presence of de-stressing zones. Combined schemes include the use of roof-bolting systems in conjunction with metal arches or temporary wooden supports and are used in zones with well-defined roof fracturing and in difficult mining-geological conditions. Two-level roof-bolting systems with uniform load distribution and creation of a load-bearing reinforcing belt, preventing the development of local failures and reducing the degree of rock deformation on the sides and in the roof, are recognized as the most effective ones.

From a practical point of view, an important aspect is to ensure safe drifting and stable maintenance of ventilation workings located in the undercut with previously mined-out extraction space, using roof-bolt fastening. Based on the analysis of conditions of rock pressure manifestation in such zones, the purpose of this research is to identify the stress-strain state peculiarities of the coal-rock mass surrounding the mine workings, and to substantiate the fastening parameters that ensure their stability.

(a) (b)

Figure1. Deformations of contours of cutting workings at mixed fastening: (a) pressing out of the lower roof layers into the mine working, strengthening with wooden mine prop stays; (b) lateral mesh rupture, rock breakage and spillage from movable sides

(a) (b)

Figure 2. Deformations of contours of cutting workings at roof-bolt fastening: (a) roof deflection and strengthening with wooden mine center posts in case of deformation of contours; (b) strengthening of the roof with intermediate roof-bolts when the upper layers of the roof shift according to the readings of the reference station sensors

3. Methodology

This section presents an algorithm for assessing the stress-strain state of the rock mass adjacent to the mine working, driven on the ventilation horizon of the extraction panel. The peculiarities of stress redistribution and formation of deformation zones in the mass depending on the depth of occurrence, properties of host rocks and mine working parameters are analyzed. The analysis is based on numerical modeling, taking into account geomechanical characteristics of the mass and fastening schemes, in order to identify patterns of development of the stress-strain state and possible instability zones.

Modeling is performed in RS2 software (Rockscience package, Canada), which implements finite element method for analyzing the stress-strain state of rock mass adjacent to underground mine workings [41], [42]. The process of modeling consists of five steps: constructing a computational model with a mine working in the specified mining-technical operating conditions; inclusion of physical-mechanical properties of rocks in the mining-geological model of the studied mine working site; creating a triangulated finite element network around the mine working contour; calculating the rock strength parameters based on determined boundary conditions with accepted criteria for assessing the stress-strain state of the mass; interpretation and assessment of the data obtained [43]-[45]. Approaches to computational mode-ling and resource allocation have also been explored in broader contexts, including cloud computing [46], data mining applications [47], and logistics systems using robotic process automation [48].

Physical-mechanical and rheological properties of rocks during mining the seams in the Sherubai-Nura District of the Karaganda coal basin are presented in Table 1; mining-technological characteristics – in Table 2.

Table 1. Physical-mechanical and rheological properties of rocks during mining the seams of the Sherubai-Nura District of the Karaganda coal basin

Parameters	Rock-coal mass according to lithological varieties				
	Sandstone	Siltstone	Argillite	Coal	Mergel
Modulus of elasticity, MPa	25.0-27.0	1.3-20.0	4.7-8.5	2.0-2.5	30.1
Poisson ratio	0.21-0.23	0.23-0.30	0.23-0.30	0.28	0.20
Compression resistance, MPa	55-65	35-40	25-30	5-7	50-51
Tension resistance, MPa	11-15	6-10	2-5	1.0-1.3	5.0-9.0
Unit specific gravity, MN/m^3	2.61	2.37	2.31	1.32	2.70
Adhesion, MPa	7.6-18.5	4.7-17.5	2.5-7.5	1.5-3.2	9.0-14.0
Internal friction angle, deg.	25-40	19-37	20-36	15-20	23-27
GSI	60	50	30	20	60
m_i	17	7	4	5	7
m_b	2.851	1.170	0.671	0.838	1.174
s	0.0039	0.0039	0.0039	0.0039	0.0039
a	0.506	0.506	0.506	0.506	0.506

Table 2. Mining-technological characteristics of cutting working on the ventilation horizon in the Sherubai-Nura District seams of the Karaganda coal basin

Parameter name	Value
Mine working name	Cutting working of the ventilation horizon in the seams of the Sherubai-Nura coal-bearing area
Width, m	4.9-6.0
Height, m	3.5-3.7
Sectional area, m^2	12.0-14.4
Fastening type	9 roof-bolts/linear meter
Lagging type	MM

Figure 3 shows the geomechanical model of a ventilated cutting working located within the extraction panel. The model is divided into a fine-cell finite grid near the mine working contour and a coarser-cell finite grid at a distance, which provides a detailed analysis of the stress-strain state of rocks directly near the contour and at a distance from the mine working.

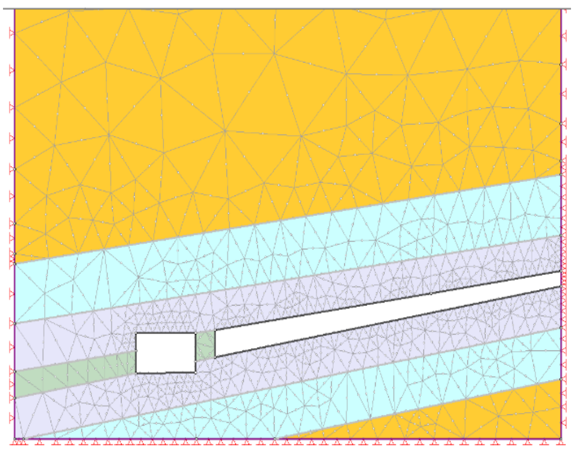

Figure 3. Geomechanical model of a ventilation cutting working of a mined-out extraction panel, broken down into finite elements

The constructed finite element grid covers the lithological varieties of the mass, including the zone of the extraction panel zone and adjacent areas. Each finite domain is characterized by certain physical-mechanical properties, serving as a basis for calculating stresses and strains within the selected rock behavior model. The computer modeling approach provides a comprehensive assessment of the rock pressure distribution and prediction of deformations around the mine working. The model takes into account both the geological structure peculiarities and technological factors (for example, mine working configuration and fastening scheme). The results of the computational experiments are applicable to substantiate support and mine working parameters, as well as to reduce the risks associated with gas and water inflows.

The input data for constructing this model are shown in Table 1. The presented parameters (modulus of elasticity, Poisson ratio, compression and tension resistance, adhesion, internal friction angle, etc.) serve as input data for correct description of rock behavior in numerical modeling using the finite element method. These values allow us to set the necessary input conditions for calculating the stress-strain state of the mass, taking into account its heterogeneous structure and varying lithological properties. In addition, the parameters GSI, mi, mb, s and a characterize the mass within the framework of the Hooke-Brown strength criterion, which provides a more accurate assessment of the stress distribution and plastic deformation zones under different mining schemes and fastening methods.

4. Results and discussion

This section presents the results of the stress-strain state of the rock mass surrounding the ventilation cutting working, using numerical modeling in the RS2 software package. The main focus is on distribution of main stresses, deformations and displacements near mine working under different conditions of occurrence and fastening parameters. Figure 4 shows the σ_3 (lateral – horizontal) stresses around the mine working contour.

Figure 4 shows the distribution of the minimum main stresses σ_3 (horizontal lateral) in the mass around the ventilation cutting working. Zones of high negative values of σ_3 (up to -15 MPa) are localized in the area of interfacing of the mine working with the chambers and along the contact lines with heterogeneous geological layers, indicating a significant redistribution of stresses and the formation of local tension zones. This stress distribution indicates the presence of potentially unstable areas prone to stratification and cleavage of rock in the roof and sides of the mine working.

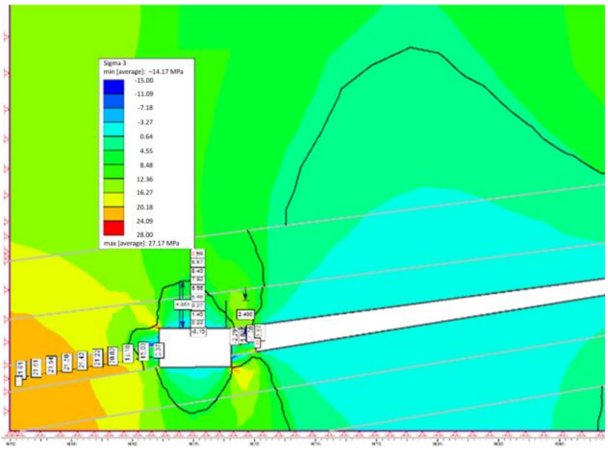

Figure 4. Stress distribution dynamics σ₃ (lateral – horizontal) stresses around the mine working contour

The highest compressive stresses (up to +24 MPa) are recorded in the mass distant from the mine working, which corresponds to the area of undisturbed stress state. The zone surrounding the mine working is characterized by a sharp stress gradient from compressive to tensile, indicating the presence of a stress screen formed as a result of local mass de-stressing.

It is natural that the increase in roof thickness leads to redistribution of stresses towards the σ_3 growth in the middle parts of the roof, which should be taken into account when planning support parameters. It has been determined that in areas with thinned roof (less than 1 m), peak stress zones are formed, requiring the use of two-level roof-bolt fastening or its strengthening.

Figure 5 shows the Strength Factor distribution in the area of the cutting working, located with a pillar of 2 m width from the previously mined-out extraction panel. Contour areas with strength factor less than 1.0 (orange-red gamma) indicate zones where the stress state exceeds the rock strength limits, indicating the development of plastic deformation and potential instability.

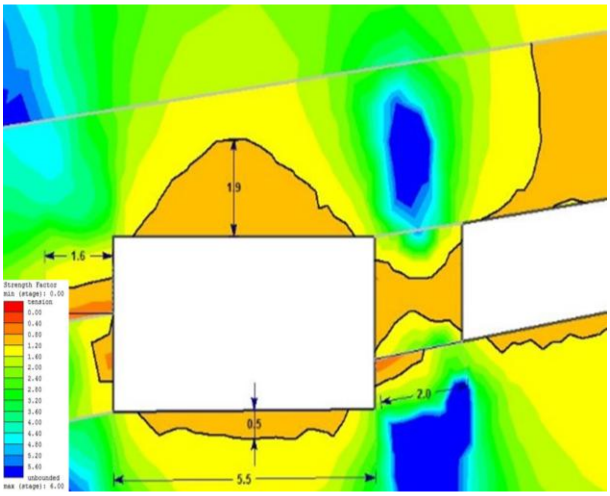

Figure 5. Contour stress deformations around a cutting working with a previously mined-out extraction panel equal to 2 m

The maximum failure zone is localized in the roof, at a height of up to 1.9 m from the mine working contour, which indicates a high probability of cleavage and caving in the upper part, especially in the conditions of weakly-cemented argillites. A zone of stress deformation is observed in the bottom to a depth of 0.5 m, potentially indicating local pressing out and possible heaving of the rock from below. The lateral displacement of the rock by 1.6 m towards the coal mass and by 2.0 m towards the mined-out space is also recorded.

Exceeding the strength factor in these zones indicates the need to use strengthened fastening schemes – in particular, intermediate and rope bolts in the roof and sides, as well as measures to strengthen the bottom. The spatial nature of the deformations emphasizes the importance of the pillar geometry: with a width of less than 2.0 m, there is a sharp increase in the failure zone.

Figure 6 shows the distribution of the host rock deformation zones when using rope bolts set outside the active failure zone. Geomechanical modeling has shown that the use of this fastening type effectively reduces stress concentrations in the area of the roof and sidewalls of the mine working. The maximum vertical displacement in the roof does not exceed 2.7 m from the contour, while the zone with a strength factor of less than 1.0 is practically absent.

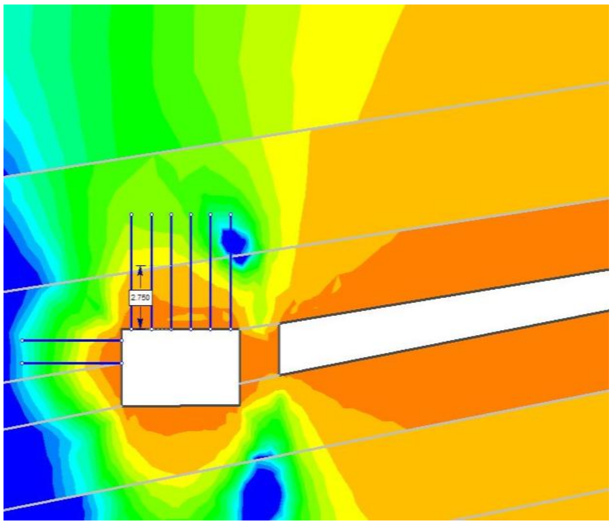

Figure 6. Contour deformations of the host rock around the mine working fastened with rope bolts outside the failure zone

The absence of localization of plastic deformations in the immediate vicinity of the mine working confirms that the rope bolts form a stable load-bearing structure that redistributes loads to more stable rock mass areas. It has been found that with the correct length of roof-bolts and depth of their setting, the formation of a volumetric compression zone is achieved, preventing the development of tension zones and subsequent caving.

Thus, this scheme of supporting can be recommended for application in conditions of high roof fracturing and deep horizons, where traditional types of temporary support are not effective enough.

Figure 7 shows the distribution of vertical maximum stresses σ_1 and layer displacement values in the zone of the ventilation cutting working location at a depth of 750 m.

The calculation is performed using a geomechanical model in the RS2 software package, taking into account the actual physical-mechanical characteristics of rocks, including argillite in the immediate roof.

Curve *1* (Fig. 7) shows the variation of layer displacement values with distance from the mine working contour, showing a linear increase in displacements when approaching the mine working.

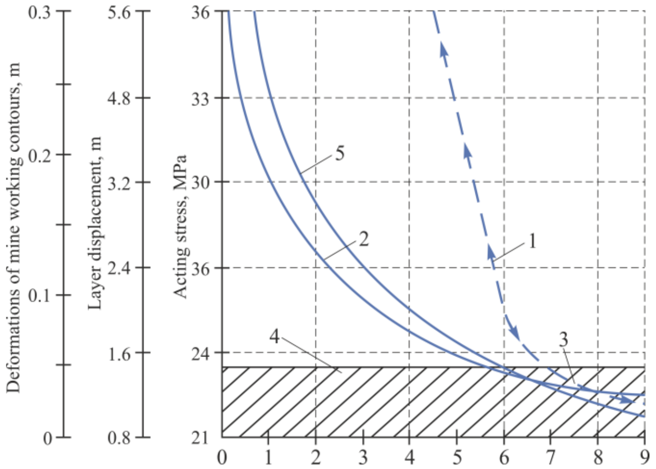

Figure 7. Distribution of stresses σ_1 (vertical maximum) and layer displacements in the rocks at the mine working depth of 750 m: 1 – displacements; 2 – stresses; 1 – displacements (linear); 2 – stresses; 3 – minimum compression strength of argillite; 4 – zone of unstable (caving) rocks without fastening the mine working contours and not creating a load-bearing fastening bridge; 5 – deformation of mine working contours

Curve *2* shows the nature of change in the acting stress σ_1 values, which increase rapidly according to a logarithmic dependence, reaching a maximum near the mine working walls. Curve *3* corresponds to the minimum compression strength of argillite, which makes it possible to identify zones where the permissible stress state is exceeded.

The shaded area (zone *4*) corresponds to the zone of unstable rocks, where failure centers are formed in the absence of fastening. The deformation values of the mine working contours (curve *5*) reach 0.3 m, which is a critical value to ensure the operating mine working state.

The results of the analysis show that at a depth of 750 m, a zone of maximum stresses and displacements occurs within 6-7 m from the contour, which confirms the need to form a load-bearing fastening bridge of roof-bolts in combination with arch support. Such measures make it possible to limit the development of plastic deformations and ensure the mine working stability during deep mining of coal seams.

For the processing of statistical data on the dynamics of the distribution of acting stresses and layer displacements (stratifications) in the rocks depending on the depth of mining operations and, accordingly, the location of the preparatory working, a summary Table 3 is presented (intermediate values are given as an example).

Table 3. Dynamics of the distribution of active stresses and layer displacements (stratifications) in the rocks depending on the depth of the preparatory working location

Value of layer displacements (with formation of stratification fractures) in the host rocks from the mine working contour, m	Acting stresses, MPa	Depth of the preparatory working location, m	Depth of the rock occurrence from the mine working contour, m	Contour deformations of the mine working at a distance, m		
				1	2	3
3.65/3.5	34.0/36.5	550/750	0.1	0.27/0.29	0.12/0.11	0.1/0.09
1.9/1.8	27.0/28.0	550/750	3.0	0.25/0.27	0.11/0.1	0.09/0.08
1.1/1.0	23.0/24.0	550/750	6.0	0.15/0.13	0.1/0.09	0.08/0.07
0.5/0.3	22.5/23.5	550/750	9.0	1.2/0.1	0.09/0.08	0.07/0.06
0.3/0.2	22.0/23.0	550/750	12.0	0.11/0.08	0.08/0.07	0.06/0.05

Note: mine working state: 1 – unfastened mine working; 2 – around the mine working fastened with single-level resin-grouted roof-bolts (load-bearing bridge); 3 – mine working fastened with rope bolts outside the failure zone

Analysis of the data presented in Table 3 makes it possible to identify the patterns of changes in the stress-strain state of the rock mass at different location depth of the preparatory workings. With the increase in the depth of the mine working location from 550 to 750 m, there is an increase in the acting stresses from 22.0-27.0 to 23.5-36.5 MPa, which corresponds to an increase in rock pressure. In this case, the layer displacements, accompanied by the formation of stratification fractures, decrease with distance from the mine working contour: from 3.65-3.50 m at a distance of 0.1 to 0.3-0.2 m at a distance of 12.0 m.

The contour deformations of the mine working also show a steady decrease when switching from an unfastened state (option 1) to the use of resin-grouted roof-bolts (option 2) and rope bolts outside the failure zone (option 3). Thus, at a depth of 750 m at a distance of 3.0 m from the contour, the deformation value decreases from 0.29 m (without fastening) to 0.08 m (rope bolts).

The analysis shows that both at mining depth from 550 to 750 m (given as an example), the displacements $u(h)$ near the mine working sharply increase according to a linear dependence when approaching the mine working contours. At the same time, the stresses $\sigma(h)$ decrease with distance from the mine working according to a power-law regression dependence, in the following interpretation $\sigma(h) = \beta \ln h$, with elasticity coefficient of $\beta \le 0$. Thus, the setting of roof-bolting systems enables a significant reduction of plastic deformation zones and stabilization of the mass with increasing depth of mining operations.

For mining depth of 750 m:

$$\sigma(h) = 21.14 + e^{-0.27h+2.59};$$

$$u(h) = -1.44 \cdot h + 9.88.$$

Stresses σ_1 (vertical maximum) with increasing depth of mining operations (from 550 to 750 m) increase by 1.7-1.9 times, and contour displacements – by 1.2-1.35 times, respectively. In general, estimating the size of displacements depending on the distance from the mine working face, it can be noted that deformations are within the permissible zone (0.05-0.15 m) when using two-level and combined fastening of ventilation workings.

The use of a metal-arch support only for strengthening the roof of mine workings does not ensure their operating condition in the zone of bearing pressure caused by stoping face during mining of the seams. The use of a complex of active methods and means for controlling roof with deep-lying rope bolts together with metal-frame support, as well as two-level roof-bolt support provides safety of mining operations and operating condition of extraction workings during mining the seams. Due to a complex of active methods, it is possible to prevent destructive consequences in mine workings, reduce the intensity or exclude a significant impact of dynamic subsidence of the main roof on the stable state of mine workings.

5. Conclusions

This paper studies the stress-strain state of the rock mass in the conditions of formation of a ventilation cutting working driven in the undercut to the previously mined-out space. Modeling is performed in the RS2 software package using the finite element method, which provides a quantitative assessment of stresses and displacements in the zone of influence of the extraction panel when using the technology of roof-bolt fastening.

Geometric and geomechanical models have been formed, taking into account actual physical-mechanical properties of rocks. The distribution of horizontal stresses σ_3 and vertical stresses σ_1 have been calculated, and the parameters of deformation behaviour of the mass at different depths of occurrence have been determined. It has been revealed that with the width of the left pillar of 2.0 m, the maximum deformations are: in the roof – 1.9 m, in the bottom – 0.5 m, from the side of the coal mass – 1.5 m, from the side of the mined-out space – 2.0 m.

The patterns of influence of mining depth on the stress-strain state of the mass have been revealed: vertical maximum stresses σ_1 increase by 1.72-1.85times, and contour displacements – by 1.2-1.35 times. Lateral longitu-dinal stresses in the roof increase by 2.23-2.48 times, while those from the side of the extraction panel decrease by 1.81-1.92 times. There is a 1.73-1.82 fold increase on the sides adjacent to the previously mined-out panels. Vertical minimum stresses σ_3 in the roof decrease by 1.32-1.41 times, in the coal mass they increase by 1.34-1.51 times, and in the zones adjacent to previous extraction workings they decrease by 1.25-1.33 times.

The resulting dependences make it possible to form reasonable fastening parameters taking into account changes in physical-mechanical characteristics of the mass during deepening of mining operations. The identified patterns of behaviour of the host rocks are the basis for the design of technological schemes using level roof-bolt fastening, which ensures the formation of a load-bearing fastening bridge in the zone of ventilation cutting workings at different mining depths.

Author contributions

Formal analysis: MM; Investigation: TD, DS; Methodology: VD, KA; Project administration: EK; Supervision: VD; Validation: VD, EK; Writing – original draft: VD, EK, TD, DS, KA, MM; Writing – review & editing: VD, EK. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP22785093).

Acknowledgements

The authors express their sincere gratitude to the research and technical staff who contributed to the modeling and data analysis presented in this study. The authors also thank the anonymous reviewers for their valuable comments and suggestions, which helped improve the quality of the manuscript.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Оцінка напружено-деформованого стану масиву гірських порід навколо присічних виробок при відпрацюванні вугільних пластів

В. Дьомін, Е. Халікова, Т. Дьоміна, Д. Сиздикбаєва, А. Каратаєв, М. Мустафін

Мета. Розробка науково обґрунтованих принципів технології підтримання гірничих виробок для забезпечення їхньої стійкості при відпрацюванні вугільних пластів Карагандинського вугільного басейну (Республіка Казахстан). Досліджується вплив параметрів кріплення на зміцнювальний ефект в умовах керованого напружено-деформованого стану системи "вміщуючі породи – елементи кріплення".

Методика. Дослідження включало аналіз науково-практичного досвіду експлуатації гірничих виробок та умов ведення підземних робіт. Оцінку напружено-деформованого стану масиву виконано методом скінченних елементів у двовимірній постановці з використанням програмного комплексу RS2. Розрахунки зон непружних деформацій проведено з урахуванням геолого-технологічних факторів, що впливають на поведінку масиву в районі присічних дільничних виїмкових виробок.

Результати. Вперше кількісно визначено закономірності зміни розмірів зон пластичних деформацій і напружених областей навколо виробок при різних технологічних рішеннях щодо кріплення. Встановлено залежність напружено-деформованого стану від характеристик та геометрії кріпильної системи.

Наукова новизна. Визначено закономірності зміни розмірів зон деформацій та напружень в околиці виробок при різних технологічних схемах кріплення. Виявлено залежність напружено-деформованого стану масиву від параметрів кріпильних систем.

Практична значимість. Розроблено науково обґрунтовані рекомендації щодо технології кріплення присічних вентиляційних виробок із застосуванням дворівневих анкерних систем за наявності стійких шарів покрівлі. Обґрунтовано оптимальні параметри кріплення експлуатаційних виробок, що забезпечують стійкість на різних глибинах залягання пластів.

Ключові слова: *гірничі роботи, кріплення, виробка, гірський тиск, чисельне моделювання, гірський масив, вугілля, напружено-деформований стан*

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