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Research into mine working fastening technology in the zones of increased rock pressure behind the longwall face to ensure safe mining operations

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Abstract

Purpose. The research aims to substantiate the technological solutions to ensure the rock mass stability through a rational approach to strengthening the zones of increased rock pressure behind the longwall face.

Methods. To achieve the purpose set, a complex research method is used, which includes an analysis of practical experience in mining medium-thickness flat-lying coal seams, a study of the stress-strain state of rocks above the coal mass marginal area, and mine research into the influence of mining-technical factors on the state of zonal preparatory workings.

Findings. The patterns of stress influence on the mine working stability have been determined depending on the mining-technological parameters of mining operations. Empirical dependences of the stress influence on the mine working stability have been revealed. The parameters of stress influence on the mine working stability have been found depending on the mining-technological parameters of mining operations.

Originality. The conducted research made it possible to determine the degree of influence of mining-technical conditions of mining operations on deformations in border rocks with various types of support in extraction workings, which helps to understand the dynamics of deformation processes occurring in the coal-rock mass surrounding mine workings maintained behind the longwall face.

Practical implications. The revealed deformation patterns can be used in calculating the rock pressure manifestations when conducting mine workings on deep levels under various mining-technical conditions of mining operations, which has practical significance for ensuring the stability and safety of maintaining mine workings at the stage of mining operations. The use of roof-bolt support is proposed as an effective means not only to ensure stability, but also to maintain safe operating conditions in mine workings.

Keywords: *mine workings, fastening, geomechanical processes, roof-bolt support, rock pressure*

1. Introduction

The problem of developing advanced technological solutions for strengthening rock masses in increased rock pressure zones behind the longwall face is known in the mines of China, Australia and other coal-producing countries when mining flat-lying and sloping coal seams [1]-[4]. The main factors determining the demand for this technology in modern market conditions of mines functioning are the possibility of achieving high labor productivity and low cost of preparatory and stope operations [5]-[7].

Significant disadvantages of strengthening rock masses in zones of increased rock pressure behind the longwall face are as follows: significant operating costs for maintaining mine workings, up to 20% of the cost for conducting mine workings, as well as the significant influence of zones of increased rock pressure on the state of the mine working contours [8]-[11]. This negative impact on the longwall face operation parameters, the economic performance of mines and the safety of mining operations increases as mining operations move to deeper levels [12], [13]. Transportation within mines presents challenges such as high infrastructure costs, energy consumption, environmental impact, material handling issues, safety concerns, logistical complexities, and the influence of distance and terrain on the efficiency of transportation [14]-[18].

The experience of using profiles of larger standard size and increased support setting density shows that even with a significant increase in the metal consumption for fastening

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mine working and the consequent labor-intensive construction of frame support, the overall effect is insignificant [19]. The practice of its operation has revealed a number of serious disadvantages that lead to significant deformations of mine workings: flattening of the cap boards, pressing-out of the side stumps into the section cavity, destruction of the coupling joists, and insignificant implementation of the support's yielding property [20]. With a significant increase in the load-bearing capacity of the support in the rigid mode of operation, there is no significant increase in the load-bearing capacity in a yielding mode, and the structural upgrading of the support itself and the technology for its setting cannot significantly improve the mine working stability [21], [22].

Roof-bolt and metal-frame supports have different approaches to fastening the roof of mine workings, based on geomechanical principles of changing the stress state of the mass during mining operations and maintaining mine workings during their planning and operation [23]-[26]. Steel arches are designed to passively support the weight of rocks that have collapsed in the mine working roof. When setting it, cavities usually remain in the roof, which further contribute to de-stressing and to the development of rock displacements with an increase in load on the arch frames [27]. The roof-bolts are intended to strengthen the roof rock-coal layers and prevent them from caving.

One of the promising directions of technical progress in the field of fastening and maintaining mine workings is the implementation of resource-saving technology for conducting preparatory workings using roof-bolt fastening, including in combination with metal arch support with the predominant use of rectangular shape of cross-section [28], [29]. The complexity of application of roof-bolt technology for a wide range of mining operations is determined by the mining-geological conditions of coal seam mining [30].

Geomechanical problems are of particular importance when using roof-bolt supports as the main supports for reused mine workings. Compared to frame supports, roof-bolt supports have a number of advantages that significantly reduce production costs and increase labor productivity [31], [32]. The use of roof-bolt support allows reducing the consumption of rolled metal, timber, and concrete by 5-9 times; increase productivity by 3-5 times when fastening mine workings; increase the rate of mine working driving by 2-3 times; reduce costs by 1.5-2.2 times or more to ensure a technologically satisfactory mine working state during its operational life [33]-[35]

In modern conditions, the coal mines use three schemes of pillarless mining technology: with preservation of mine workings for reuse; with conducting new mine workings by cutting to the mined-out space; with conducting conjugated mine workings with mining of the pillar between them through adjacent longwall face [36]-[38].

Therefore, one of the stages for implementing the roof-bolt fastening technology is the formation of schemes for fastening mine workings using it. Analysis of technological schemes for conducting mine workings in the Karaganda Coal Basin using roof-bolt support made it possible to form the prerequisites for the formation of principles for fastening mine workings with roof bolts for various schemes of development of mining operations and their purpose. Below are considered the most frequently used in practice technological schemes for fastening the junctions of mine workings, longwall faces with adjacent mine workings, mine workings of the main and auxiliary purposes, based on which the schemes for fastening mine workings for the Karaganda Coal Basin mines can be developed [39], [40].

In connection with the above-mentioned, the research purpose is to develop a resource-saving technology for strengthening rock masses around mine workings in zones of increased rock pressure behind the longwall face, thereby ensuring a reduction in the volume of repair work in the zonal preparatory workings maintained behind the longwall face.

To achieve the purpose set, it is necessary to carry out a range of research aimed at identifying the patterns of stress influence on the mine working stability, taking into account the mining-technological parameters of mining operations, methods of implementation and protection, as well as types of support and technological scheme for fastening mine workings.

2. Study area

The development of the practice of using roof-bolt support at the Karaganda Coal Basin mines is constrained by the lack of advanced technological schemes for fastening mine workings, allowing them to be used effectively in various mining-geological and mining-technical operating conditions [41], [42]. To form such schemes, it is necessary to analyze the current state of the conditions for using various methods for maintaining mine workings according to their functional purpose.

The Karaganda coal basin is dominated by moderately stable roofs (51% of all mine seams), the share of low stable roofs is 26%, the share of unstable roofs is 21% and the share of stable roofs is only 4%. At the sites of the occurrence of thin platy argillites and carbonaceous argillites with a total thickness of no more than 0.3-0.5 m, the coal seams form a false roof. Bottom rocks are most often found to be moderately stable (46% of mine seams), less often low stable (19%) and unstable (21%), and increasingly less frequently represented by stable (14%) [43]-[45].

In the basin, up to 25% of all mined seams are classified as highly disturbed and very highly disturbed, including 16.6% in the Promyishlennyiy area, 16.7% in the Sherubaynurinsky area, 50% in the Saransky and Shakhansky areas. The increase in rock pressure in the zone of maintaining extraction workings is taken into account by the rock pressure concentration coefficient, the value of which reaches 2 at depths of up to 800 m. At present, at great depths of mining the seams in the Karaganda Basin, the multiplicity of repeated roof-bolting of preparatory workings adjacent to extraction panels reaches the value of 2.3 and even 4 [46]. In general, maintenance costs increase with increasing depth, ranging from total costs at medium depths (up to 600 m) 4-5%, and at high depths (up to 750-800 m) up to 15%. In the Karaganda Coal Basin as a whole, 25% of the balance coal reserves are confined to areas with simple, 40% – medium and 35% – difficult mining conditions [47]-[49].

An analysis of the state of mine workings inspected in the Karaganda Basin mines shows that at the tunneling stage, in approximately 25-30% of them, there are dangerous deformations and loss of stability of rock outcrops. During operation, increased deformations are typical for 40% of mine workings located outside the zone of stope operations influence and for 60%, when they are located in the zone of stope operations influence. The main reason for the deterioration of the state of preparatory workings is the decrease in the ratio of rock strength to geostatic pressure with increasing mining depth [50]-[52].

Loss of stability of rock outcrops leads to a 40-45% decrease in the advance rate of mine workings and an increase in the consumption of fastening materials. Also, 35-40% of accidents during mining-preparatory operations are caused by loss of stability of rock outcrops and rock failures in the roof and sides of mine workings [53],[54].

The main reason for deterioration of the state of preparatory workings is the decrease in the ratio of rock strength to geostatic pressure with increasing mining depth [55]. An additional factor of harmful influence is the presence of pillars and marginal parts of coal seams located above the mine workings. About 20-30% of all maintained mine workings fall annually into the zones influenced by increased rock pressure (ERP), and their state is assessed from satisfactory to very poor [56].

When arranging the junctions, it is seen by visual observations that the zone of disturbed rocks is broken by fractures parallel to the outcrop surfaces into blocks, which most often have rather large dimensions, and loosening is the result of turning of these blocks and increasing distances between them [57]. In some cases, the rock displacement process may be suspended, however, this equilibrium state is unstable [58]. Any impact, even minor in amplitude, causes further de-strengthening of the border rocks and leads to a renewed displacement process [59].

A roof-bolt is a means of compressing or compaction of the supported rocks to prevent them from tensile stresses [60]. For highly fractured roof, with one or more fracture systems, roof-bolts increase the friction force along the fractures and weakening planes, thereby eliminating or reducing sliding and/or separation along the weakening planes. The effect of compaction mainly depends on the tensioning force of the roof-bolts with the roof-bolt nuts. Tensioning of the roof-bolt rods causes stresses in the stratified rocks, which are compressive both along the bolt axis and perpendicular to the bolt [61]. Compression zones due to overlapping around the bolts form a continuous compression zone in the mine working roof, in which the tensile stresses decrease or completely disappear, while shear strength increases. Figure 1 shows a schematic representation of the roof mass contour strengthening above the mine working in order to create a stable arch.

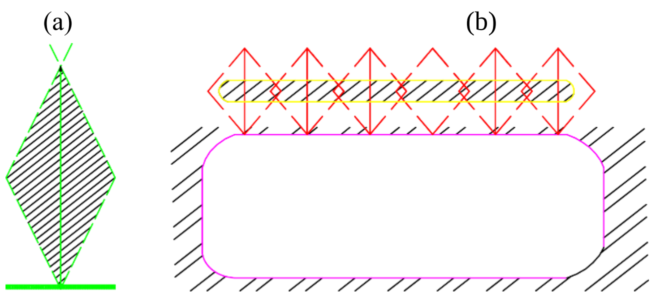

***Figure 1.** Schematic representation of the roof mass contour strengthening above the mine working: (a) contour of fastening with the roof-bolt; (b) contour scheme for the roof-bolt fastening*

The rock mass deformation mechanism in the combined method of fastening the junctions of longwall faces with mine workings using rope bolts and metal-arch is presented in Figure 2.

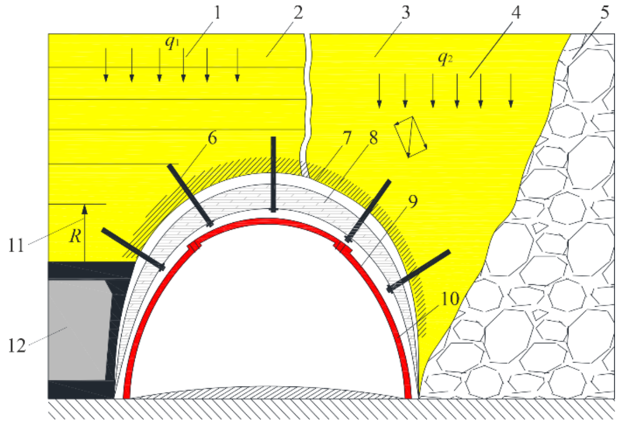

***Figure 2.** Rock mass deformation mechanism in combined support: 1 – acting rock pressure forces; 2 – stable roof rocks; 3 – roof rocks spalling along a fracture; 4 – rock pressure forces contained in the spalling fracture; 5 – caved rocks; 6 – roof-bolts; 7 – section in tunneling; 8 – arch rock spalling; 9 – mine working arch support; 10 – coal seam; 11 – coal seam reaction*

In stable state of the longwall face/drift junction, it is assumed that processes within the rock mass maintain equilibrium and promote uniform contact between the longwall face and the drift. Such conditions are usually characterized by the absence of significant fluctuations or changes, thus ensuring stable interaction. On the other hand, unstable junction state may include rock falls, indicating the presence of unpredictable and unstable processes in the rock mass. These rock falls can be caused by various factors, such as gas outbursts, changes in pressure or temperature, resulting in discontinuities between the longwall face and the drift [62], [63].

Figure 3 shows a representation of both types of states. The stable state shows a uniform junction, while the unstable state displays rock falls, indicating possible difficulties in maintaining stable contact between the longwall face and the drift. Understanding these differences is important for predicting and controlling rock mass processes, as well as for improving safety when mining the longwall face and the drift.

As a result of analyzing the use of roof-bolt support at the Karaganda coal mines, it has been determined that the main reasons for not so large frequency of using roof-bolt fastening in mine workings are as follows: complication of mining-geological and mining-technical conditions with the transition to a mining depth of more than 500 m. There has been a significant increase in the size of bearing pressure zones in the vicinity of mine workings and intense rock pressure manifestations in the mine workings inside the extraction fields. There was a 35-40% increase in the cross-sectional area of mine workings, especially of the extraction workings of stoping faces, and in the volume of pillarless protection of mine workings on the border with the mined-out space, namely in the zone of shearing and rock failures in adjacent mined-out longwall faces.

It should be noted that there is a lack of knowledge of geomechanical processes in the rocks surrounding mine workings on the lower levels and the performance of the roof-bolt support in these conditions. This applies most of all to the size of zones of dangerous deformations (displacement, stratification and destruction) of rocks in the roof and sides of mine workings, protected by coal-pillar and pillarless methods.

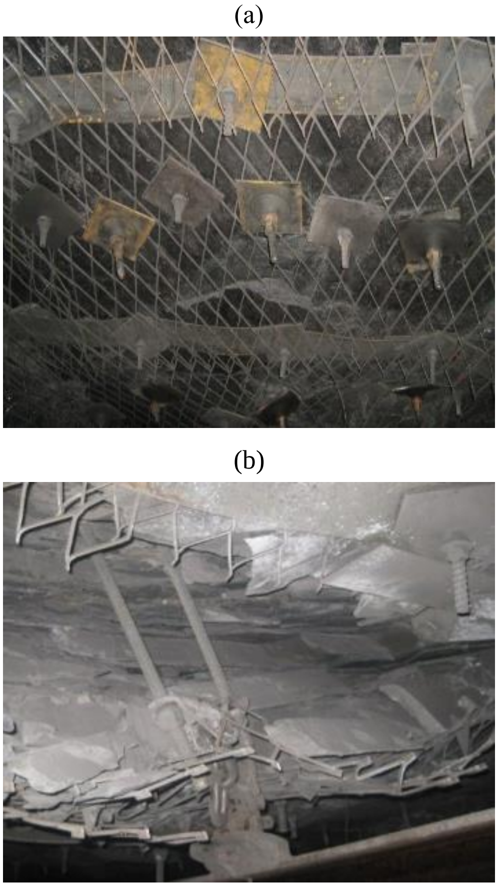

Figure 3. Rock mass state in the longwall face/drift junction point: (a) stable state; (b) unstable state

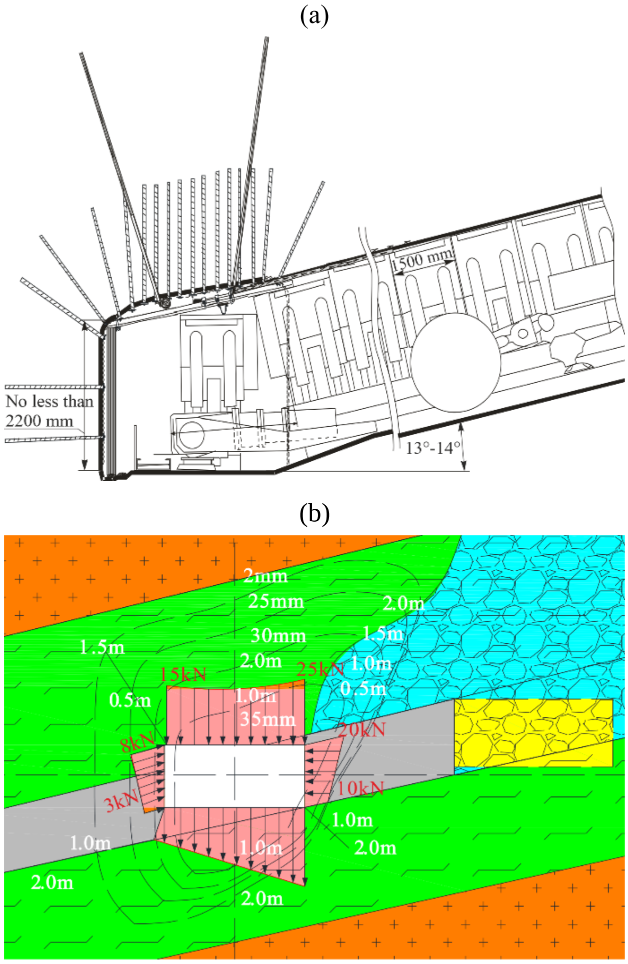

Figure 4. Technological scheme for strengthening the fastening of the longwall face junction with the conveyor intermediate drift using rope bolts: (a) junction fastening scheme; (b) scheme for the support interaction with the host rocks

3. Methodology

Fastening of the fault zone between the linear sections of the powered support and the drift support using resin-grouted rockbolts provides rock stability in the roof and reduces material and labor costs for repeated roof-bolting of the fault zone. In 10-15 m ahead of the longwall face, two “lines” of the purlin made of SCP-22(27) 2.0-2.5 m long are set, with a GVKU (ST-20) prop stay set under the purlin with a spacing of 1 m. Ahead of the longwall face at a distance of at least 5 m under the “lines” of the purlin, additional GVKU (ST-20) prop stays are set with a spacing of 0.5 m. From the longwall face side, before the combine approaches, the MM side grid is dismantled at a distance of 1.0 m ahead of the longwall face [64]-[67].

When connecting the longwall face to the conveyor intermediate drift, rope bolts are used to strengthen the fastening. In addition, the strengthened fastening interaction with the surrounding rocks is shown, and elements demonstrating the stability and safety of the process are presented. Figure 4 shows a technological scheme for fastening the longwall face junction with the conveyor intermediate drift using rope bolts.

Technological solutions developed for fastening mine workings behind the longwall face are associated with the preliminary setting of fastening means ahead of the longwall face bearing pressure zone with subsequent strengthening of the support after the longwall face advance with the creation of the strengthening support edged structures on the boundary with the mined-out space (Fig. 4).

As part of the development of technological solutions to maintain mine workings behind the longwall face, it is provided to set preliminary fastening means ahead of the longwall face bearing pressure zone. This stage is critical to ensure the stability and safety of mine workings that may be exposed to the longwall face impact. Figure 4 illustrates this approach by focusing on the construction of strengthening support structures on the boundary with the mined-out space.

The first stage involves setting the fastening means ahead of the longwall face bearing pressure zone to provide a secure base for subsequent longwall face impact. After the longwall face passes through the area, the previously prepared support is strengthened. This may include the structures created to strengthen the support on the boundary with the mined-out space, providing additional stability.

Monitoring of the state of mine workings and displacements of their contours was made selectively using the example of the 50 k_{10}-1 conveyor drift junction with the longwall face in the Saransk Mine, Karaganda Coal Basin. The 50 k_{10}-1 ventilation slope was driven at a depth of 428-554 m, at an angle of 10°. The mine working length is 630 m. The total seam thickness at the site is 4.65 m. Seam k_{10} has a complex structure and consists of 9 coal bands 0.05-1.17 m thick, separated by interlayers of carbonaceous argillite and argillite of 0.01-0.04 m thick.

Seam k_{10} is categorized as a hazardous seam due to sudden coal-gas outbursts from a depth of 300 m [68]-[71]. The seam is hazardous in terms of gas and dust, and is prone to spontaneous combustion [72], [73]. Sandstones occur in the main roof of the seam (m = 23.7-29.56 m, f = 60 MPa). The immediate roof is represented by argillites with a thickness of 1.24-2.09 m (f = 25 MPa). The false roof is composed of carbonaceous argillite and argillite of 0.45 m thick (f = 15 MPa). The seam bottom contains argillites of 5.25-6.35 m thick (f = 20-25 MPa), unstable, prone to heaving. The water inflow is expected to be up to 5m^3/hour.

To fasten the mine working, the roof-bolt support is used with a spacing of 0.8 m. The number of roof-bolts per 1 m of mine working is 12 in the roof and 6 in the sides. Physical-mechanical properties of rocks during mining of the k_{10} seam in the conditions of Saransk Mine are presented in Table 1.

Table 1. Physical-mechanical properties of rock mass surrounding the k_{10} seam in the conditions of Saransk Mine of the Karaganda Coal Basin

Parameters	Lithological varieties				
	Sandstone	Siltstone	Argillite	Coal	Mergel
Elasticity modulus, MPa	8.5-29.0	4.3-21.0	3.7-10.5	3.0-3.5	35.1
Poison's ratio	0.22-0.25	0.28-0.33	0.25-0.33	0.33	0.21
Compressive resistance, MPa	45-95	33-45	15-35	5-11	52-53
Tensile strength, MPa	10-16	7-13	1-6	1-1.8	5.1-9.7
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	9-14
Internal friction angle, deg	25-40	18-39	25-39	18-25	23-27

For the conditions of the 50 k_{10}-1 conveyor drift of the Saransk Mine, Karaganda Coal Basin (Table 2), the border rock mass deformations have been measured to determine the geomechanical characteristics of maintaining mine working under different mining-geological operating conditions.

Table 2. Mining-technological characteristics of the 50 k_{10}-1 conveyor drift of the Saransk Mine, Karaganda Coal Basin

Mine working name	Conveyor drift
Length, m	810
Width, m	4.5-5.12 (5.5)
Height, m	3.5-4.0
Section area, m^2	12
Type of fastening	Roof-bolting, 9 roof-bolts/running meter

An integral part of the research is the measurement of the deformation process parameters in operational mine workings using different types of fastening. This helps to determine the nature of the stability of mine workings, including the zones affected by mining operations.

4. Results and discussion

Systematization of the measurement results for extraction workings depending on the main influencing mining-technological factors made it possible to identify the corresponding patterns given in this section.

As a result of the research, systematic patterns have been identified regarding the stress impact on the stability of mine workings. These patterns are conditioned by different mining-technological parameters, methods of carrying out and ensuring safety, as well as types of support and complexity of the technological scheme for fastening mine workings. This research allows not only to identify the main patterns of stress influence on the stability of mine workings, but also to reveal the factors that play a key role in the formation of stability of mine workings under various operating conditions and scenarios. In addition, the performed complex of studies, including an analysis on stability of mine workings, instrumental observations on stability of rock outcrops in in-seam workings, with processing of results of in-situ studies, made it possible to predict the nature of the defectiveness of mine workings depending on the influencing factors. The approach to analyzing the stability of mine workings included in the scope of this research involves not only a general analysis of the physical-geomechanical parameters of mine workings, but also a detailed examination of instrumental data obtained under actual operating conditions. This data includes observations of rock deformations, stress measurements, and the recording of all changes occurring around the mine workings.

Measurements of the deformation process parameters in operational mine workings with various types of fastening made it possible to determine the nature of their stability, including in zones influenced by mining operations. At the same time, deformations of mine working contours with combined roof-bolt-frame support are 4-5 times less than in case of yielding metal-arch frame support (Fig. 5).

In extraction workings, there is an intensive increase in rock displacements, which correlates with the mining depth and a change in the degree of controllability from difficult-to-control to easy-to-control. As a result of field observations, it has been confirmed that the use of roof-bolt support provides satisfactory stability of mine workings. The selected roof-bolt support parameters prove to be sufficient to ensure safe operation of the mine workings. The total roof displacements, when using roof-bolt support, do not exceed 30 mm. The accepted roof-bolt length in the roof (2.4 m) and in the sides (1.8 m) of mine workings provides the required stability. The total horizontal rock displacements in the sides of mine workings do not exceed 100 mm, which is acceptable when using roof-bolt support. The displacement values in the zone of stope operations influence have been determined (up to 2.5 m), which requires advance setting of rope or cable bolts to ensure stability.

The deformation process parameters have been determined near the mine workings when they are in the zone of stope operations influence. Observations have been conducted on the stability of mine workings under various schemes for the development of mining operations, the service life and operational purpose at the Karaganda Coal Basin mines. Mine workings fastened with different types of supports have been examined. Based on the processing of statistical experimental data, statistical patterns and empirical dependences on influencing mining-technical factors have been determined.

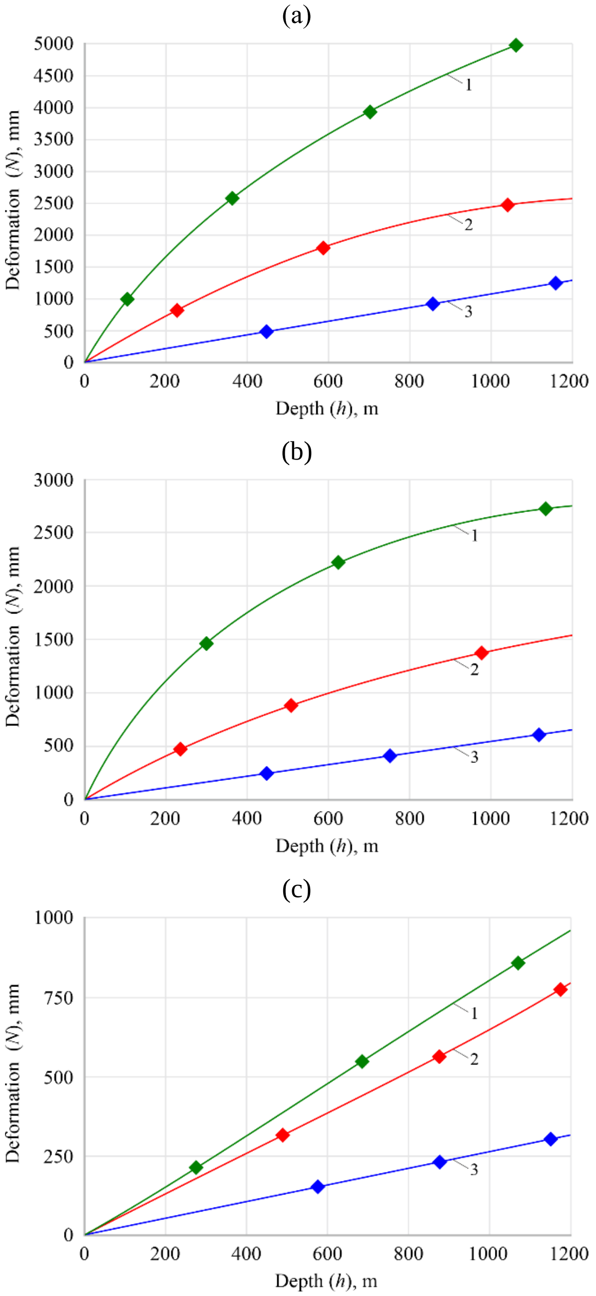

Figure 5. Dependence of rock deformations (N, mm) in extraction workings on mining depth (h, m): (a) when using arch support; (b) when using roof-bolt support; (c) when using combined support; 1 – easy-to-control roof; 2 – medium-to-control roof; 3 – difficult-to-control roof

The conducted research, covering the mining-geological and mining-technical conditions of the Karaganda Basin, has revealed a number of significant factors influencing the rock outcrop stability. The main mining-geological factors identified during the research are stratification, fracturing and moisture content of the rocks.

It is important to note that the uniaxial compressive strength of layers plays a key role in determining the rock outcrop stability. When the strength of the layers is 50-60 MPa, the roof rock outcrops maintain a stable state. However, when the rocks are compressed up to 40 MPa, the stable state time is significantly reduced and limited to within an hour. Additionally, the influence of rock fracturing on stability is taken into account. In highly fractured and disturbed rocks, mostly overlying coal-bearing rocks, stability usually does not exceed 0.3 hours, with fracture spacing within 0.01 and 0.2 m. In terms of the rock moisture content, it is shown that it has a significant influence on the strength characteristics of different rock types. For example, with increasing moisture content, sandstones lose strength by about 5%, siltstones – by 14%, argillites – by 40-60%, and carbonaceous argillites – even up to 80%. These findings underline the importance of considering mining-geological factors when planning and conducting operations in mining regions to ensure safe and efficient mining-technical processes.

The research has also revealed a number of significant mining-technological factors that have a significant impact on geomechanical processes. In particular, the following factors have been identified as key factors in determining the stability of mine workings and displacements in rocks. When the mine working width increases from 5 to 6 m, the displacements in the mine working increase by 25-30%, which emphasizes the importance of careful control and mine working width optimization to prevent excessive displacements and ensure stability.

An increase in the location depth from 450 to 800 m in 1.6-3.5 m thickness seams leads to an increase in the displacement of rocks of varying strength. In rocks with a compression level of less than 45 MPa, displacements increase by 3.1-3.6 times, while in rocks with a compression level from 45 to 80 MPa – by 2.1-2.5 times, indicating the importance of adapting mining-technical methods depending on the rock location depth.

Pillarless extraction workings may be adversely affected by the mutual influence of stope and preparatory operations in adjacent panels at certain location depths. For example, at a depth of up to 550 m, the minimum distance between mine workings should be at least 50-75 m, at a depth greater than 550 m – 80-100 m, and at a depth greater than 600 m – 100-120 m. These mine protection recommendations emphasize the need to take into account geological-technical conditions to ensure safe and efficient mining.

In schemes for fastening junctions between longwall faces and conveyor workings in difficult mining-geological conditions, it is advisable to use a chemical strengthening effect with sealing roof-bolts of the "Irma" type or using perforated pipes. The following are the developed means for fastening mine workings maintained behind stoping faces, zones of increased rock pressure, and for protecting mine workings in zones influenced by stope operations.

Figure 6 shows a reinforcing system in which a pressurized fastening mixture is injected into a well fitted with a rope bolt. Sealers with clamps are set along the well length. Outlets connected to the axial opening are provided for the release of the fastening mixture from the rope locking coupling. The use of such a rope bolt design allows for reliable delivery of the fastening mixture, bypassing the coal-rock mass fracture zones where it can propagate without fixing with the rope bolt of the rocks near the caved space. Failure to do so could result in increased pressure on the extraction working support or rock failure into the mine working space.

Figure 7 illustrates the technology for setting a reinforcing system in a well on the mine working contour to maintain stability behind the junction with the longwall face.

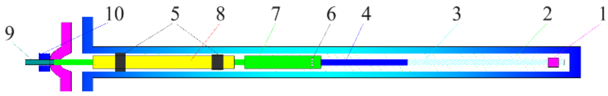

Figure 6. Reinforcing system for supporting the rock mass behind the stoping face: 1 – end fitting; 2 – well with fastening solution (pressurized injection); 3 – rope bolt; 4 – guiding fitting; 5 – sealer with clamps; 6 – outlet openings; 7 – rope locking coupling; 8 – axial opening; 9 – backing coupling; 10 – nut

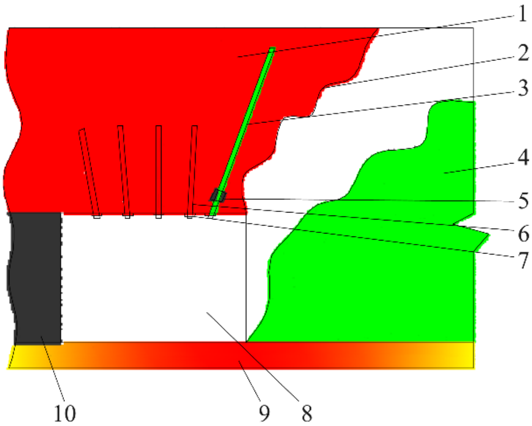

Figure 7. Technology for setting a reinforcing system in a well on the mine working contour to maintain stability behind the junction with the longwall face: 1 – roof rocks; 2 – break line; 3 – shock-absorbing system; 4 – caved rocks; 5 – sealer; 6 – steel roof-bolts; 7 – mine working roof; 8 – active mine working (junction); 9 – seam bottom; 10 – coal seam

Figure 7 shows a shock-absorbing system designed to absorb and dissipate the energy generated by rock failures, which is particularly important in mining environments where rock masses can be subjected to dynamic loads, creating shock waves and vibrations. By absorbing shocks, the shock-absorbing system reduces the risk of equipment damage to maintain the stope equipment integrity and plays a critical role in ensuring safe production processes.

A scheme for fastening junctions using cable bolts has been developed, which allows increasing the load-bearing capacity of the fastening system, shown in Figure 8.

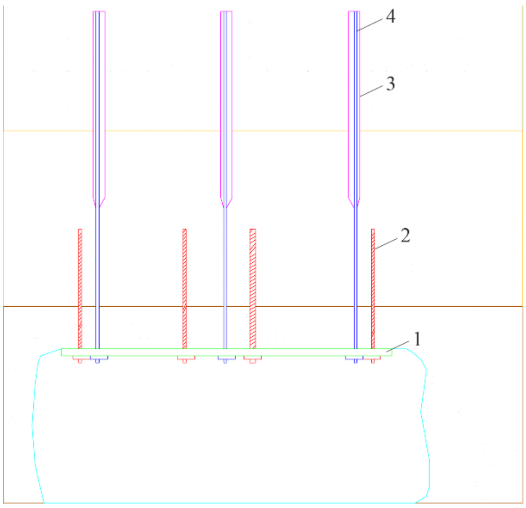

Figure 8. Scheme for fastening mine workings maintained behind stoping faces with the use of cable bolts: 1 – pickup; 2 – 2.4 m long rod bolts; 3 – polymer resin 2.5 m; 4 – 5 m cable

The junction fastening scheme using cable bolts (Fig. 8) is an innovative system designed to increase the load-bearing capacity of the fastening system. This fastening scheme is an example of advanced mining-technical solutions aimed at improving the efficiency and safety of mining processes.

Further research into mine working stability can focus on a number of promising areas to better understand the processes and optimize the methods to ensure stability, namely, the study of new technologies and fastening methods, aimed at improving the mine working stability, can contribute to the development of more effective safety systems in the mining industry; exploring the possibility of using new fastening materials that can provide greater stability and durability of mine workings, as well as the use of modern technologies, such as automation and artificial intelligence, to better control and manage the mine working stability. Further research in the above areas could contribute to better understanding and optimization of mining processes, as well as improve the level of safety in this area.

5. Conclusions

The conducted research has determined the dynamics of deformation processes occurring in the coal-rock mass around the mine workings maintained behind the longwall face. The unstable areas in the host rocks and the dynamics of active fracturing propagation zones have been identified and technological solutions for rock mass strengthening in zones of increased rock pressure behind the longwall face are proposed. Based on the conducted research results, means have been developed and fastening parameters have been determined for mine workings maintained behind stoping faces, in the zones of increased rock pressure, and for protecting mine workings in zones influenced by stope operations.

The use of roof-bolt support not only ensures the mine working stability, but also maintains safe operating conditions. The research results indicate that the total roof displacements, not exceeding 30 mm, are acceptable and confirm the effectiveness of the selected roof-bolt support parameters.

The accepted roof-bolt length in the roof and sides of the mine workings, 2.4 and 1.8 m, respectively, not only provides the necessary stability, but also guarantees stability in operation. Horizontal rock displacements in the sides of mine workings, not exceeding 100 mm, confirm the effectiveness of the roof-bolt support.

The conducted research made it possible to determine the degree of influence of mining-technical conditions of mining operations on deformations in border rocks with various types of support in extraction workings. The displacement values of up to 2.5 m in the zone of stope operations influence have also been identified, indicating the need for advance setting of rope or cable bolts to effectively manage displacements and ensure stability of mine workings when conducting stope operations. The revealed deformation patterns can be used in calculating the rock pressure manifestations when conducting mine workings on deep levels under various mining-technical conditions of mining operations.

Thus, this research represents an important contribution to understanding and improving the mine working fastening technology in conditions of increased rock pressure behind the longwall face.

Author contributions

Conceptualization: VD; Formal analysis: DS; Investigation: MR, ZA; Methodology: AZ, GB; Project administration: EK; Software: YY; Supervision: VD; Validation: VD, EK; Writing – original draft: VD, EK, MR, ZA, AZ, DS, GB, YY; Writing – review & editing: VD, EK. All authors have read and agreed to the published version of the manuscript.

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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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Дослідження технології кріплення виробок у зонах підвищеного гірського тиску позаду лави для забезпечення безпеки ведення гірничих робіт

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Мета. Обґрунтування технологічних рішень для забезпечення стійкості масиву гірських порід за рахунок раціонального підходу до кріплення в зонах підвищеного гірського тиску за лавою.

Методика. Для вирішення поставленої мети застосовано комплексний метод досліджень, який включав аналіз практичного досвіду відпрацювання пологих вугільних пластів середньої потужності, вивчення напружено-деформованого стану порід над крайовою частиною вугільного масиву, а також шахтні дослідження впливу гірничотехнічних факторів на стан дільничних підготовчих виробок.

Результати. Визначено закономірності впливу напружень на стійкість виробок залежно від гірничо-технологічних параметрів розробки. Встановлено емпіричні залежності впливу напружень на стійкість виробок. Визначено параметри впливу напружень на стійкість виробок залежно від гірничо-технологічних параметрів розробки.

Наукова новизна. Проведені дослідження дозволили визначити ступінь впливу гірничо-технічних умов розробки на деформації в приконтурних породах при різних видах кріплення у виїмкових виробках, що робить внесок у розуміння динаміки розвитку деформаційних процесів у вуглепородному масиві навколо виробок, що підтримуються позаду лави.

Практична значимість. Виявлені закономірності деформацій можуть бути використані при розрахунках проявів гірського тиску при проведенні виробок на глибоких горизонтах за різних гірничотехнічних умов експлуатації, що має практичну значущість для забезпечення стійкості та безпеки підтримання виробок на етапі ведення гірничих робіт. Використання анкерного кріплення пропонується як ефективний засіб не лише для забезпечення стійкості, але й для підтримання безпечних умов експлуатації виробок.

Ключові слова: *гірничі виробки, кріплення, геомеханічні процеси, анкерне кріплення, гірський тиск*

Publisher’s note