Mining of Mineral Deposits
Volume 19 (2025), Issue 2, 107-120

https://doi.org/10.33271/mining19.02.107

Optimization of rational parameters for fastening and protection systems of mine workings in conditions of occurrence of unpredictable rock pressure manifestations

Hennadii Symanovych [1], Vyacheslav Krasnyk [2], Mykola Odnovol [1], Maksym Snihur [1], Ivan Sheka [1*]

[1] *Dnipro University of Technology, Dnipro, Ukraine*
[2] *SE "STC "Vuhleinnovatsiia", Kyiv, Ukraine*
**Corresponding author: e-mail vsheka1996@gmail.com*

Abstract

Purpose. To develop and substantiate rational parameters of a support and protective system for maintaining mine workings under conditions of potential unpredictable manifestations of rock pressure, ensuring the stability of the workings for their subsequent reuse after longwall face retreat.

Methods. The study is based on geomechanical modeling within an elastic-plastic framework using a bilinear "stress-strain" diagram for each lithological unit and support element. Calculations were performed considering the actual physical and mechanical properties of the surrounding rock. The modeling included standard and combined support schemes involving cable bolts (6.0 m length) and steel-polymer bolts (2.8 m length), with the inclusion of additional support elements in the zone of potential secondary caving.

Findings. The proposed combined support system comprising cable and steel-polymer bolts enabled the formation of a high-load-bearing reinforced rock plate. Comparative analysis of the stress-strain state (SSS) demonstrated a reduction in hazardous stress concentrations by 10-40%, and the affected areas decreased by a factor of 4.2-4.6. The recommended system effectively counteracts rock pressure even under unpredictable geotechnical conditions.

Originality. For the first time, the correlation between the structural configuration of the combined bolting system and the spatial stress distribution in the rock mass has been substantiated, ensuring the transition from a frame-bearing to a rock-reinforced bearing structure. A methodology for selecting support parameters is proposed, considering the integrated influence of jointing, water saturation, and rock rheology.

Practical implications. The obtained results allow for a significant improvement in the reliability and safety of mine workings in complex geotechnical conditions and facilitate their reuse with minimal repair costs.

Keywords: *coal, mine, rock pressure, mine workings, fastening system*

1. Introduction

In today's conditions of global challenges, ensuring energy independence is a priority issue for each country, and in the conditions of warfare, for Ukraine it is a national security strategy [1], [2]. Along with the development of alternative energy sources [3], [4], mining, especially coal, occupies an important place in providing the country with energy sources [5]-[7].

Over the past decade, Ukraine has made substantial efforts to diversify its energy mix and reduce dependence on imported fossil fuels, including the active development of renewable energy technologies, legislative reforms, and integration into European energy markets [8]. However, the volatility of global energy prices, logistical constraints, and infrastructural damages caused by hostilities have exposed the vulnerability of these initiatives and underscored the need for balanced, multifaceted energy strategies [9]-[11].

In this context, the mining industry, and coal mining in particular, continues to serve as a vital pillar in ensuring the country's energy security. Despite the environmental concerns and decarbonization goals, coal remains a readily available and controllable energy source, especially in critical situations where alternatives are either insufficient or inaccessible [12]-[14]. Its strategic significance has once again become evident amid the current conditions of warfare and infrastructure disruption [15]. Therefore, the role of coal in current conditions remains critically important in the transition to green energy, especially in the face of energy market instability [16], [17].

About 30-35% of the country's electricity is generated by thermal power plants, which are mainly fuelled by coal. Figure 1 compares the dynamics of coal mining in Ukraine for 8 months of 2023 and 8 months of 2024.

Received: 4 October 2024. Accepted: 9 June 2025. Available online: 30 June 2025

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

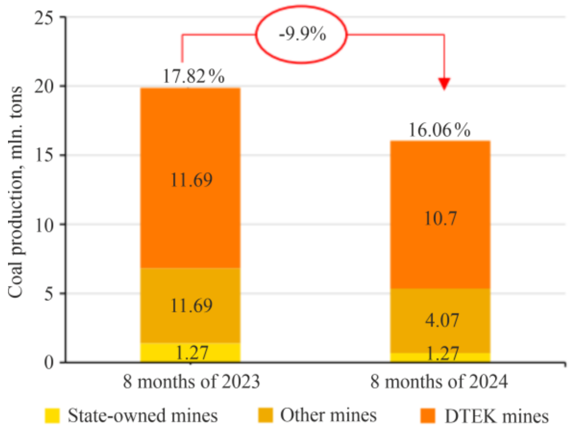


Figure 1. Coal mining dynamics in Ukraine for 8 months of 2023 / 8 months of 2024

A separate issue of ensuring the stability of the state of operation of coal mining enterprises is the maintenance of mine workings to ensure their stability and production safety during their operation [18]-[20]. This issue is of particular relevance in the mines of Western Donbas (Ukraine) [21]-, where about 77% of the mine workings, driven in weakly metamorphosed rocks, are reused [23]-[25]. In this context, the negative impact of underground coal mining on surface infrastructure, including critical facilities such as gas pipelines, has been confirmed by recent studies, highlighting the need for comprehensive monitoring and prediction of subsidence effects [26], [27]. Furthermore, maintaining the stability of mine workings under such conditions requires careful geomechanical justification, particularly in the case of auger mining in protective pillars during the extraction of thin seams [28], as well as proper design and control of mine ventilation systems to reduce air leakage and resistance directly affect operational safety [29]-[32].

In the practice of mining coal deposits, especially in Western Donbas, unpredictable rock pressure manifestations usually occur when several unfavourable factors are superimposed on each other to disturb the stability of the coal-bearing stratum around the extraction drifts [33]. This mining situation will be examined using the example of seam mining in the conditions of the mines of Vidokremlenyy Pidrozdil “Shakhtoupravlinnia Pershotravenske”, PJSC “DTEK Pavlohradvuhillya”.

Among the peculiarities of the coal-bearing stratum texture, as one of the factors that significantly influence the intensity of rock pressure manifestations, the following should be noted.

Firstly, using the example of three extraction sites (188 and 96 longwall faces of Stepova mine and 148 longwall face of Yuvileina mine), the coal-bearing mass texture is shown in Figures 2-4. The texture peculiarities are similar to each other and are characterized in terms of lithotype thickness as predominantly thin- to medium-bedded. In this sense, the classical provisions of rock mechanics, existing research and accumulated mining experience indicate reduced stability of rocks adjacent to extraction drifts, especially under the active influence of stope operations.

Secondly, it is well known that the adhesion between rock layers is very low [34], or even non-existent. In such circumstances, the rock layers, when deformed, behave as separate and sufficiently independent elements of the rock mass. This factor sharply reduces the stability of rock layers, which has been proved analytically [35] and by using modern technologies for performing computational experiments [36]. Practical absence of joint resistance of rock layers to geostatic pressure causes the process of their successive caving, which is clearly observed in the mined-out space near the extraction drifts; this process can develop into the roof over a considerable distance and will result in an intensification of the load not only on the fastening and protection systems of the extraction drifts, but also on the powered support of the stope face. These first and second factors are quite capable of provoking the so-called “uncontrolled collapse” of rock layers, which precisely corresponds to the concept of “unpredictable rock pressure manifestations”. It is also important to note that the process of rock instability and collapse is often accompanied by sudden methane emissions, which further complicate the prediction and management of hazardous manifestations in mining operations [37].

Third, most coal-bearing mass lithotypes are fractured, especially in the case of coal seams and sandstones; fracturing significantly reduces the lithotype resistance to compression [38].

Fourthly, a number of lithotypes of the coal-bearing stratum are in a water-cut state; this primarily refers to coal seams and sandstones. They themselves lose some of their own strength properties and moisten the adjacent lithotypes (usually argillites and siltstones), which are very sensitive to the reduction of compressive strength when exposed to watering; according to [39], water-cut siltstone loses 40% of the value of the sample resistance to compression, and an argillite loses 50%. This weakening of the lithological framework of coal-bearing strata due to water saturation significantly complicates mining operations, especially in areas affected by underground water inflow or artificial groundwater recharge. Numerous studies have addressed the mechanisms of infiltration, water leakage, and the interaction between hydrodynamic processes and geological media in coal-bearing formations. These include forecasting underground water dynamics in mining areas, modeling the effects of water leakage, and studying infiltration and colmatation in both natural and artificial conditions [40]-[45].

The mechanical characteristics of the coal-bearing stratum lithotypes are analyzed using the example of the 96 longwall face extraction site of the C_6 seam (Fig. 3). In the immediate roof, there is a 1.9 m thick siltstone with a resistance to compression σ_c = 31.431.4 MPa in the sample; it is water-cut, so it loses 40% of its strength [46]. In addition, the intensity of fracturing is 3-4 fr/m, which gives grounds to apply a reducing factor of rock disturbance by weakening surfaces K_p = 0.4. Adding the rheological factor [47], [48] in the form of a reducing factor of K_t = 0.7-0.9, we have the calculated strength of the immediate roof siltstone at the level of R = 5.28-6.78 MPa. That is, the immediate roof has a strength coefficient of f < 1 and it cannot provide any significant resistance to geostatic pressure. Also, according to this methodology, three layers of the main roof are analyzed.

Next, consider the state of the prefabricated drift bottom rocks of the C_6 seam. In the immediate bottom, there is a 1.3 m thick argillite with an ultimate resistance to compression of σ_c = 20.3-29.5 MPa in the sample and a fracture intensity of 2-4 fr/m. The argillite is water-cut due to the water-saturated coal seam C_6, therefore K_w = 0.5, and fractures add another K_p = 0.5 to the reduction in resistance to compression.

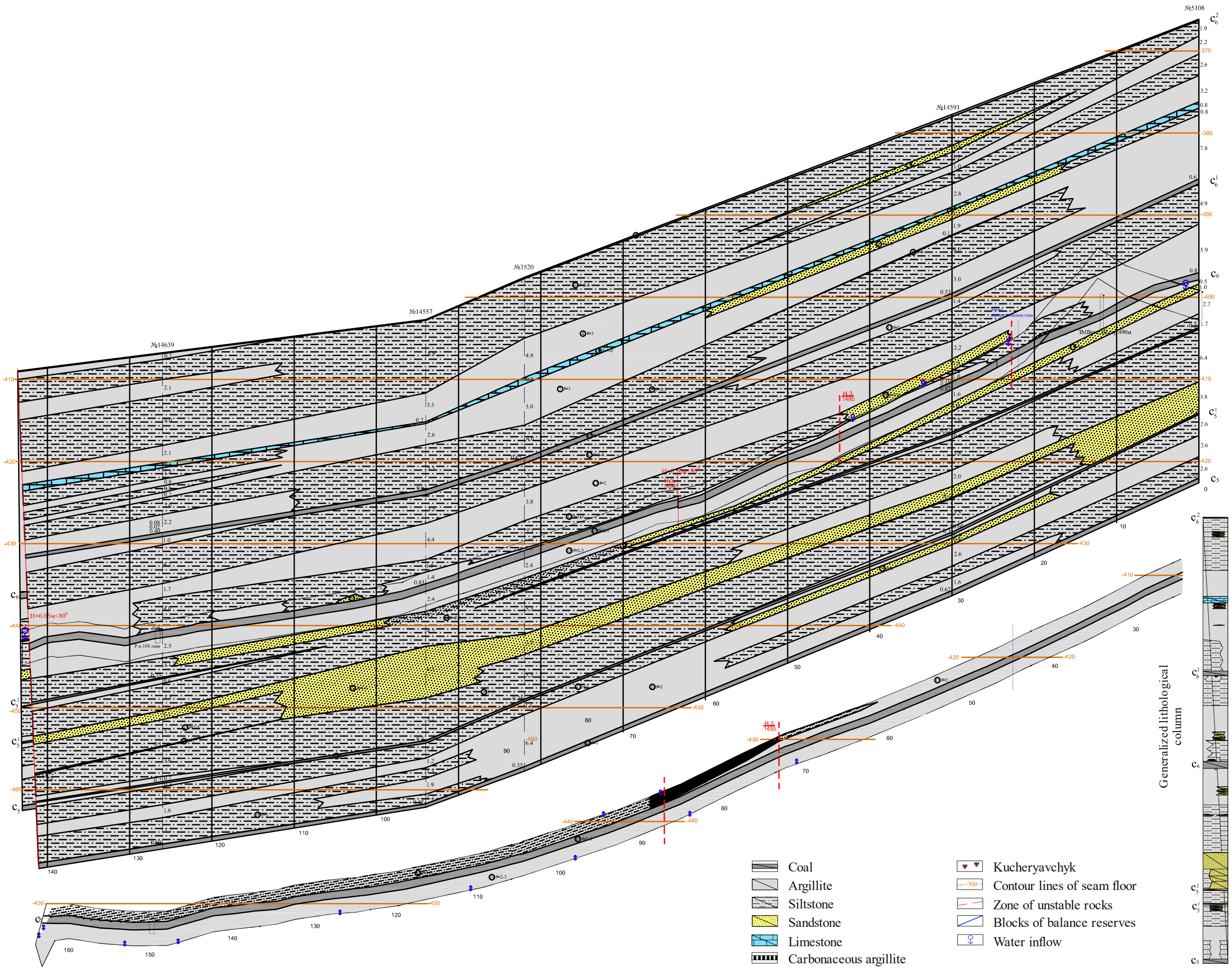


Figure 2. Fragment of the actual geological section along the 188 prefabricated drift

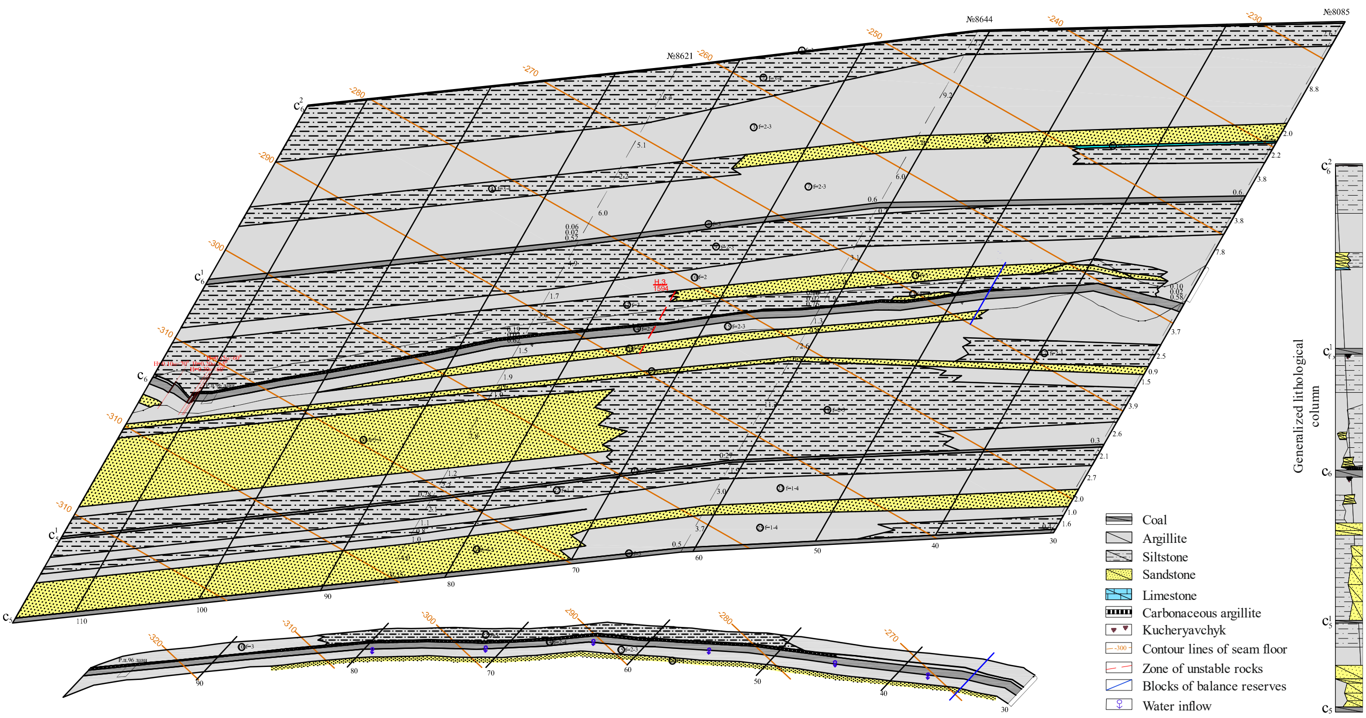


Figure 3. Fragment of the actual geological section along the 96 longwall face of the C_6 seam

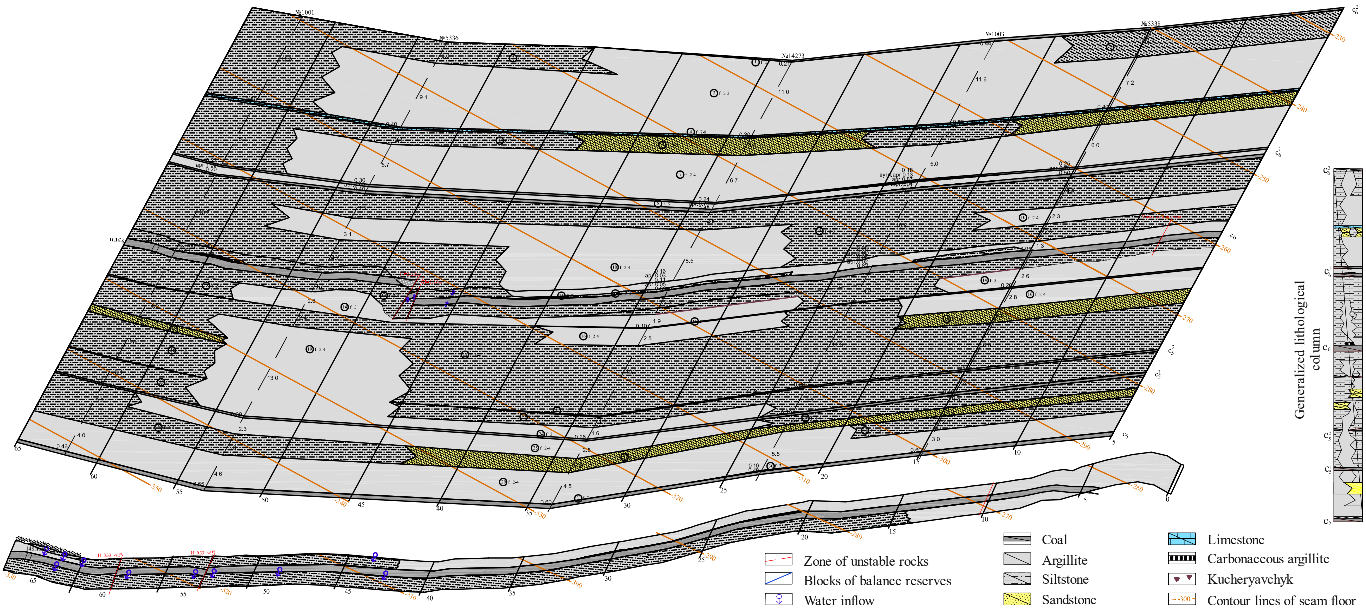


Figure 4. Fragment of the actual geological section along the 148 longwall face of the C_6 seam

Reduction of argillite strength due to the action of rheological factor is $K_t = 0.7$-0.9. As a result, the calculated resistance to compression is equal to $R = 3.55$-6.64 MPa. Such weak strength of the argillite provokes its heaving into the mine working cavity.

The analysis of the texture peculiarities and mechanical properties of the coal-bearing stratum lithotypes proved the possibility of occurrence of unpredictable rock pressure manifestations under conditions of a coincidence of negative circumstances of the action of factors weakening rock layers (watering, fracturing and rheology), mainly of thin- and medium-bedded texture. Frame support is not able to withstand unpredictable rock pressure, therefore, combined roof-bolting systems are required. Therefore, ensuring the stability of mine workings in such complex geological and hydrogeological environments necessitates the development and implementation of advanced geomechanical models and support systems specifically tailored to mitigate the risks associated with unpredictable rock pressure manifestations.

2. Methodology

An analysis of texture and mechanical properties of rocks in some areas of extraction panels in the PJSC "DTEK Pavlohradvuhillya" mines shows that there is a possibility of an unstable state of the coal-bearing stratum, which can extend over a long distance into the roof (up to 20 m or more). This poses a danger not only to the extraction faces, but also to the operation of modern powered supports of the stope faces.

When examining and substantiating the mechanism of the coal-overlaying formation displacement into the mined-out space, we used the currently existing understanding of this process in Western Donbas [49], [50]. Using the example of the coal-overlaying formation texture in the 96 longwall face of the C_6 seam, a scheme has been created (Fig. 5) for the possible loss of its stability at a considerable height into the roof, which will lead to unpredictable rock pressure manifestations. The scheme shows the classical uncontrolled collapse and hinged-block shear zones that occur in the roof when mining the coal seam C_6, but the essence of a possible negative situation is in details.

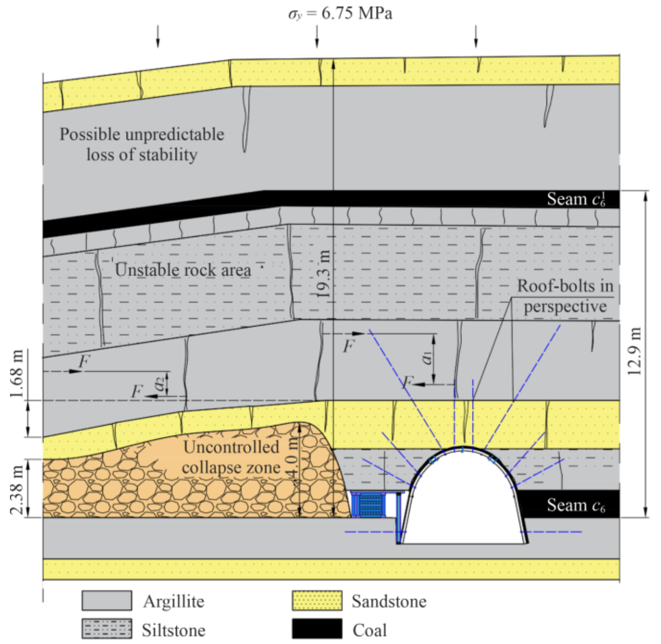


Figure 5. Scheme of an unstable rock zone formation

First, in accordance with the existing concepts, the initial height of the uncontrolled collapse zone is calculated by the Formula:

$$h_{u.c} = \frac{m_b}{K_p - 1}, \tag{1}$$

where:

m_b – thickness of the coal seam to be mined, $m_b = 1.20$ m;

K_p – the coefficient of loosening of the caving lithotype (we take the average value of K_p for siltstone and partially for sandstone $K_p = 0.3$).

Then the initial height of uncontrolled collapse zone is obtained $h_{u.c} = 4.0$ m. We called this indicator the initial height, because, as studies have shown precisely for the Western Donbas conditions, under the influence of geostatic pressure, the caved rocks are compacted and at a certain small distance from the longwall face (about 25-30 m), the final height $h_{u.c}$

decreases very significantly. Figure 6 shows two experimentally determined graphs of pressure P increase on the caved rocks and their relative compaction δ as the longwall face L_l retreats.

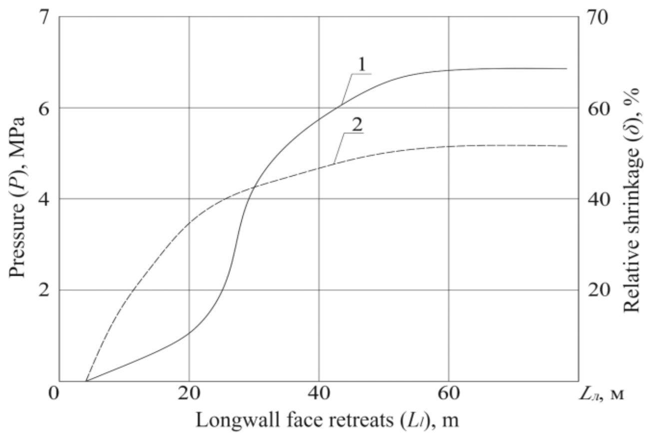


Figure 6. Dependences of pressure increase P (1) in the zone of uncontrolled collapse and relative shrinkage δ (2) of disturbed rocks as the longwall face L_l retreats

It can be assumed that similar patterns occur in the direction of the extraction site width. The area of the extraction panel studied is located at a depth of about $H = 270$ m, then the geostatic pressure of the overlying rocks up to the earth's surface are:

$$\sigma_y = \gamma H = 6.75 \text{ MPa}, \tag{2}$$

where:

$\gamma = 25$ KN/m^3 – weighted average volume weight of rocks.

Suppose that not the entire weight of the coal-overlaying formation rocks will put pressure on the destroyed rocks of the uncontrolled collapse zone, and take only half of them, that is, the load is $P = 3.48$ MPa; for this indicator P, according to the graph in Figure 6, we obtain the relative compaction value $\delta = 42\%$; accordingly, the height of the uncontrolled collapse zone is reduced by 1.68 m, its final height is $h_{u.c} = 2.32$ m. These dimensions are shown in Figure 5.

Now it is necessary to find out how the compaction of caved rocks influences the stability of lithotypes in the hinged-block shear zone. These rocks have a certain resistance to rock pressure due to the formation of spacer systems, when individual rock blocks contact each other during their deflection and in areas of action of compressive stresses σ_x generate spacer forces F. As shown in the scheme, the pair of spacer forces F creates a restoring moment that resists further deflection and gives the fracture-broken layer a certain stability. It is well known that as the lithotype moves towards the roof of the seam, the lithotype deflections decrease and at a certain height they no longer lose stability, but resist to rock pressure without caving.

This stable state of the spacer systems depends on several factors, and the first of them is the value of the lithotype deflection U_y. It operates in such a way that with an increase in U_y, the arm of the force pair F decreases (Fig.5, which shows that $\alpha_2 < \alpha_1$, the restoring moment decreases accordingly and the stability of the individual backing system decreases.

Secondly, it is necessary to consider the effect of the layer thickness m_i in combination with the effect of lowering it U_y into the mined-out space. For a more visual representation, Figure 7 shows schematically two cases of the same rock block lowering U_y at different its thickness m_i.

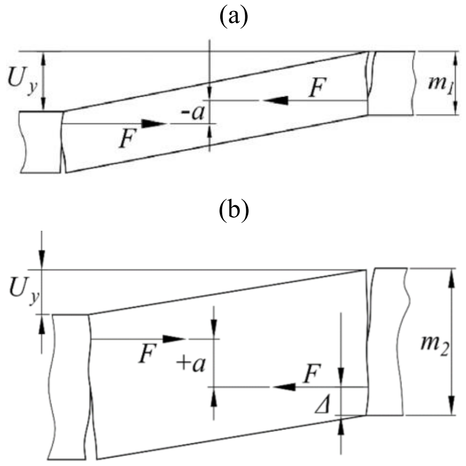


Figure 7. Scheme for substantiating the effect of layer thickness m_i on the rock block stability in a spacer system: (a) thin layer; (b) high thickness layer

It has already been noted that a certain stability of the spacer-block system is provided by a pair of forces F that creates a restoring moment aimed at resisting to geostatic pressure. Spacer forces F occur on opposite contacts of the block in the area (according to the height of its thickness) where compressive forces σ_x act. If the classical provisions of the material resistance discipline are used, compressive stresses σ_x occur at half the block thickness and have a triangular distribution curve along the height of the compression area. Then, the resultant force F will be located at one-third of the height of the compression area, which is close to the block surface. That is, in the end, the distance $\varDelta$ of the force F action from the block surface is equal to:

$$\varDelta = \frac{1}{6} m_i , \tag{3}$$

and the arm a of the force pair F action is calculated as follows:

$$a = \frac{2}{3} m_i . \tag{4}$$

Formula (4) is valid when the block is in an approximately horizontal position. If to take into account the lowering U_y of one end of the block relative to the other, then the arm a is reduced:

$$a = \frac{2}{3} m_i - U_y , \tag{5}$$

and with a low thickness of the rock block, a situation may arise when the arm a completely disappears and there is no restoring moment, that is, at least one rock block loses stability, and the entire spacer system with it. Moreover, with a small rock block thickness m_i and a rather significant lowering U_y, the arm of the force pair F action may acquire a negative sign (Fig. 7a); then the restoring moment becomes a caving-facilitating moment.

The third and last factor that significantly affects the stability of spacer-block systems is the lithotype resistance to compression; moreover, we operate with such an indicator as the calculated resistance R, which already takes into account the weakening factors of fracturing, water-cut and rheology. When analyzing the mechanical properties of the coal-overlaying formation lithotypes, very low resistance to compression was noted: the vast majority of rock layers have a strength coefficient of less than one ($f < 1$), and slightly stronger sandstone (f = 1.3-1.6) refers to thin and medium thickness lithotypes. In these conditions, the destruction of the so-called rock hinges located in the areas of action of compressive horizontal stresses σ_x (Fig. 8) and determine the stability of any lithotype in the general area of the spacer systems, is very likely. In such a situation, some contact between adjacent rock blocks may remain, but the spacer forces F many times decrease – accordingly the resistance to rock pressure of this spacer system will decrease; it can cave onto underlying rocks. Such a process can behave like a chain reaction and the caving of the rock layers can spread into the roof over a considerable distance.

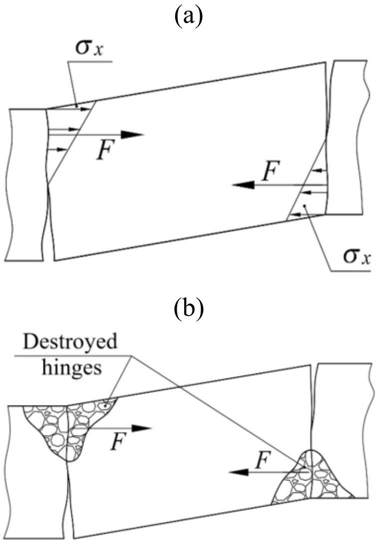


Figure 8. Schemes of rock hinge failure and significant loss of stability of the spacer system: (a) stable state; (b) stage of destruction

Thus, three main reasons for the loss of stability of the spacer-rock systems in the main roof of a mine working and near it from the side of the mined-out space have been formulated. In case of probable coincidence of all three factors, the "chain reaction" of successive caving of rock layers over a long distance into the C_6 seam roof is possible, which is equivalent to the concept of "unpredictable rock pressure manifestations".

3. Results and discussion

3.1. Analysis of rock mass SSS in hazardous extraction site areas

In accordance with the methodology commonly used in the Western Donbas mines for performing a computational experiment to study the processes of coal-bearing mass shear around the extraction drifts in the zone of influence of stope operations [51], [52], a geomechanical model has been constructed that contains all the necessary and sufficient positions to reflect the state of the object.

Firstly, the coal-bearing mass is modeled to the height of the roof, to the depth of the bottom, and to the width along the strike of the C_6 seam, which are sufficient to fully and adequately reflect the parameters of rock pressure anomalies in the zone of influence of stope operations, and most importantly, behind the longwall face.

Secondly, the uncontrolled collapse zone from the side of the mined-out space is reflected with parameters substantiated in [53], [54]. The height of the zone is calculated according to the recommendations in [34]. The resistance to compression of the destroyed weakly metamorphosed Western Donbas rocks is determined according to [55], the deformation modulus is determined according to the graphs in Figure 6, and the Poisson's coefficient. Thus, we have a complete set of necessary initial data for modeling the deformation process of the uncontrolled collapse zone.

The third is the hinged-block shear zone above the mined-out space. The rock layers are divided into blocks based on the analysis of fields of horizontal stress σ_x and stress intensity σ distribution. The loss of adhesion between lithotypes is also necessarily taken into account.

Fourth, the zone of smooth deflection of rock layers without breaking the continuity is reflecte, and contact disturbance along the surfaces of bedding of adjacent lithological varieties is modelled, which is substantiated in [56]-[58].

Fifthly, the 148 prefabricated drift location relative to the C_6 seam in accordance with the technical documentation for mining the extraction site of the 148 longwall face.

Sixth – an adequate reflection of the structural and technological peculiarities of the fastening and protection systems of the 148 prefabricated drift according to the methodological developments [59], [60].

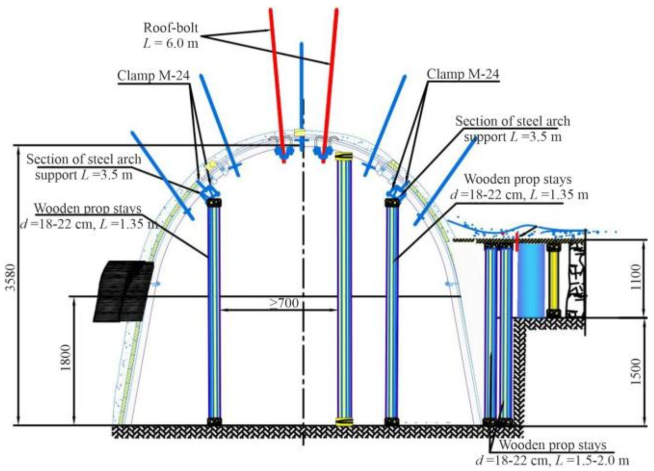
The following should be noted from the general information. Calculation of the stress-strain state (SSS) was performed in the elastic-plastic formulation with a bilinear function reflecting the real diagram "stress – relative deformation" of each lithological variety and fastening materials. This made it possible, when taking into account the plastic deformations of the geomechanical system elements, to avoid significant "failures" in the calculation technology and increase the reliability of its implementation.

Now, study the fastening and protection schemes in more detail: the first, according to the technical documentation for mining the 148 extraction site of the C_6 seam at Yuvileina mine, will be considered the "basic" one; the second scheme is proposed on the basis of the performed modeling of geomechanical processes around the 148 prefabricated drift, and has some variations in order to achieve more efficient maintenance of the extraction working.

The positions of the basic scheme for maintaining the prefabricated drift and boundary entry are taken from the technical documentation of the Yuvileina mine and fragments are shown in Figure 9 in the area behind the longwall face. A positive aspect is the use of resin-grouted rockbolts and rope bolts in the systems for fastening mine workings – this technical solution is usually called a combined roof-bolting system and is becoming increasingly common in the Western Donbas mines. We have tried to eliminate the disadvantages of the basic fastening and protection systems in the proposed variants of fastening and protection structures. The main positions of their improvement are as follows.

Firstly, despite the significant strengthening of the frame support, there is no certainty that the required section of the drift can be preserved for its reuse. The reason for this is the probability of exceeding the vertical load (from the weight of unstable rocks) of the total load-bearing capacity of the basic fastening system. An alternative to directly counteracting vertical load is to strengthen the roof rocks with combined roof-bolting systems, which is partially incorporated into the basic support structure.

(a)



(b)

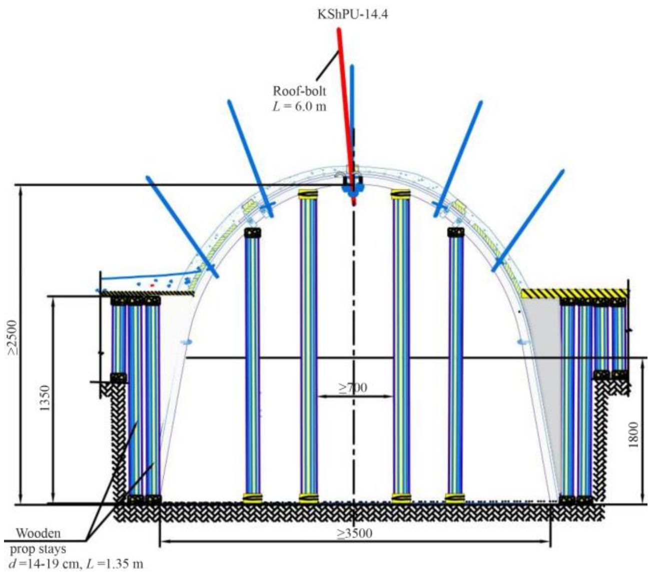


Figure 9. Basic schemes for maintaining drifts at the 148 extraction site of the C_6 seam at Yuvileina mine: (a) prefabricated drift; (b) boundary entry

In this regard, the recommended combination of roof-bolts creates an armoured and rock plate in the roof.

Secondly, the recommended parameters for the location of the roof-bolting system are designed to perform the following tasks:

– to create a load-bearing spacer-block system that rests on the rock mass beyond the mine working width and protects it from excessive rock pressure;

– certain inclination angles of resin-grouted rockbolts and rope bolts are provided for "extending" the load-bearing structure bearings beyond the mine working width in such a way as to strengthen the rock volumes above the side prop stays of the strengthening support and adjacent breaker-prop rows; then the most probable caving of rock cantilevers occurs outside (vertically) the breaker-prop rows, and a relatively monolithic rock plate will remain in the mine working roof.

Thirdly, rope bolts, connected to the peripheral part of the frame cap boards by flexible crown runners, dramatically increase their load-bearing capacity and allow for stability in the area of longwall face "window" when dismantling the frame prop stays; this makes it possible to abandon the central prop stays of the strengthening support.

Fourthly, lateral horizontal roof-bolts in the immediate bottom of the seam strengthen the rock volumes of the weak bottom to create stronger bearings for the load-bearing plate in the roof; in addition, lateral roof-bolts in the immediate bottom of the coal seam help to reduce its heaving intensity, as one of the factors of the sectional plane loss of the drift.

From the perspective of the above concepts, a scheme has been developed for fastening and protecting the 148 prefabricated drift and boundary entry of the Yuvileina mine seam C_6, which is an integral part of the model of the general geomechanical system. Computational experiments have been conducted for the comparative assessment of the basic and proposed maintenance schemes to analyze their advantages and disadvantages.

3.2 Comparative analysis of the rock mass SSS

In our opinion, the most informative and useful are the comparative analysis results of the SSS of the geomechanical model main elements and they will be the basis for the feasibility of some improvements in the fastening and protection systems on the example of 148 prefabricated drift. This comparative analysis of SSS is performed for three stress components: vertical σ_y, horizontal σ_x and stress intensity σ.

The vertical stress curve σ_y, shown in Figure 10, is characterized by the following peculiarities of the distribution of vertical rock pressure anomalies around the 148 prefabricated drift. A sufficiently homogeneous distribution field σ_y is observed from the side of the mined-out space, varying in the main range of 2.3-6.7 MPa and indicating a de-stressed state of the rocks with a value of 0.21-0.61 from the initial state γH of the undisturbed mass. The most homogeneous distribution σ_y occurs in the rocks of the C_6 seam bottom for the entire depth of the model, and laterally extends to its vertical boundary and covers a width of 17.1-20.9 m. Localised pressure concentrations of σ_y = 11.0-15.3 MPa are observed in the mine working side up to 7.7 m in height, which are associated with the influence of the fastening and protection systems of the drift. The compressive σ_y concentrations are only K_y = 1.0-1.39: these values are lower than the resistance of argillite σ_c to compression in sample, but many times higher than the calculated resistances R to compression of the immediate roof and bottom rocks.

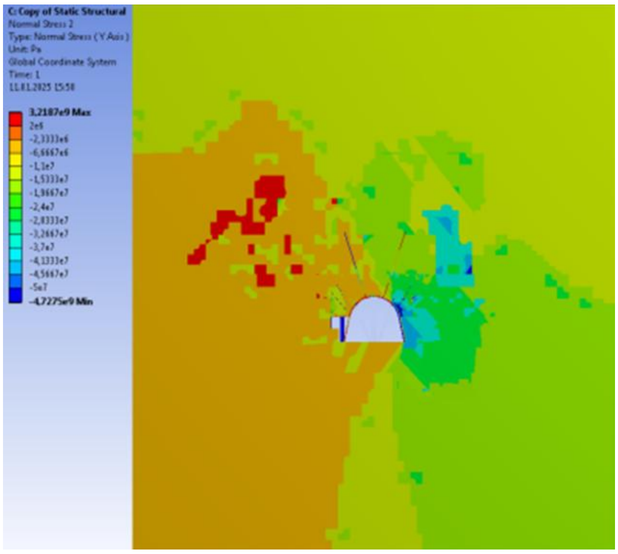


Figure 10. Curve of vertical stresses σ_y in the coal-bearing stratum around the 148 prefabricated drift of the C_6 seam according to the recommended scheme of its maintenance

There is another restricted area above the rows of wooden prop stays of the breaker-prop where σ_y = 15.3-19.7 MPa; in this area, the weakening of weak argillite is even more intense, but its small size (up to 1.4 m in height and 0.4 m in width) does not have a significant influence on the general de-stressed state of the immediate roof rocks from the side of the mined-out space.

In the main roof rocks, against the background of de-stressing mainly at the level of K_y = 0.21-0.61, sufficiently limited areas of tensile stress up to 2 MPa of rocks with even more local areas of compressive stress concentration σ_y up to the value of K_y = 1.39 are formed. These areas of σ_y with different signs appeared due to fracturing of the main roof rock layers into blocks and their interaction with each other during lowering into the mined-out space. Here, the main factors of sign-variable disturbances σ_y are contact stresses on the surfaces of interacting blocks and their bending deformations under the influence of the weight of overlying rock layers. In general, these local areas of component σ_y disturbances do not have a significant impact on the overall pattern of de-stressed state of the main roof rocks up to a height of 16.6 m.

A lateral bearing pressure zone is formed from the side of the undisturbed mass, which has the following peculiarities of the distribution of compressive σ_y concentrations. Manifestations of lateral bearing pressure extend up to 13.1 m in height into the roof above the mine working. Here, the concentration of σ_y is K_y = 1.39-1.79; the area is elongated into the roof and has an irregular shape with asymmetry towards the undisturbed mass; only in some local areas, the vertical stress concentration reaches K_y = 2.18, and in absolute dimension does not exceed 24 MPa. The area of σ_y concentration is limited by the thickness of the hinged-block shear zone. Comparison of the strength characteristics within this area with the acting σ_y concentrations hows that all lithotypes are exposed to weakening, taking into account the calculated strength value.

Similar conclusions can be drawn for the remaining areas of lateral bearing pressure, which are located beyond a certain zone adjacent to the mine working, formed at its side and occupying a position of up to 9.7 m in height and up to 7.2 m in width. In this area, σ_y concentrations in the range of K_y = 1.79-2.18 are destructive for almost all lithotypes, taking into account the action of weakening factors of fracturing, water-cut and rheology. Within this area, a second-order area with concentration of σ_y in the range of K_y = 3.75-4.15 is formed along the width up to 1.2 m and the entire height of the drift, where intensive destruction of the near-contour rocks of the immediate roof and bottom, as well as the coal seam C_6, definitely occurs. This area requires resin-grouted rockbolts to strengthen both the roof and the bottom of the seam, which is implemented in the proposed drift support scheme.

Attention should be paid to another area of σ_y concentration, which is located in the main roof and extends up to 7.0 m in height and 3.1 m in width; it is spaced 2.5-3.0 m from the mine working contour towards the undisturbed mass. Its significance is as follows. Firstly, the area is located in the reach of strengthening with rope bolts or strengthening of the rock layers that are part of this area. Secondly, it is from these rock layers of the main roof that the load-bearing armoured and rock structure is formed using the rope bolts, which is designed to protect the frame support from excessive rock pressure. Thirdly, if there is a significant break in the continuity of these lithotypes, then the width of this area of 3.1 m is quite enough to cause such displacements in the spacer system from the main roof rock blocks, at which it would lose stability; in this case, the task of forming an armoured and rock plate in the roof would not be fulfilled and the entire load from the weight of unstable rocks would act on the frame support.

The above considerations for the analysis of the vertical stress distribution field sufficiently substantiate the expediency of strengthening the main roof with rope bolts. As for the resin-grouted rockbolts, their positive strengthening effect contributes to the stability of the immediate roof rocks in two areas of relatively low σ_y concentrations: in the lower part of the end sections of the armoured and rock plate and in the sides of the mine working above the protection system from the side of the mined-out space and from side of the undisturbed mass. These areas serve as a kind of bearings for the armoured and rock plate, and the degree of their stability determines the efficiency of the load-bearing armoured and rock structure in limiting the rock pressure manifestations in the 148 prefabricated drift.

Next, consider the peculiarities of the horizontal stress σ_x distribution field (Fig. 11) according to the recommended scheme for maintaining the 148 prefabricated drift. It is worth mentioning here that the curve σ_x clearly shows the bending deformations of the rock layers and their direction.

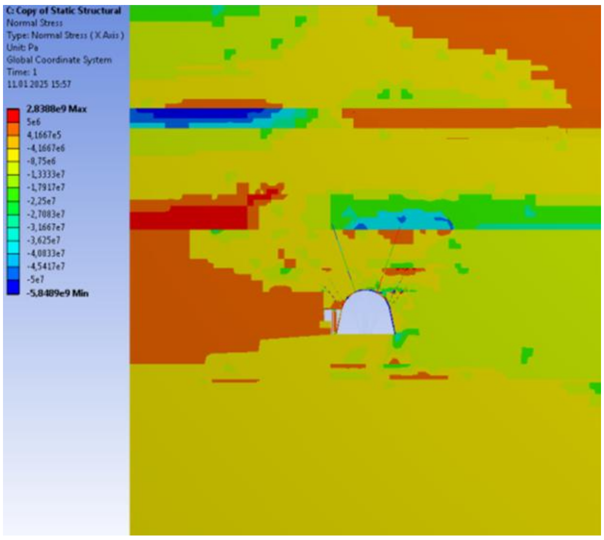


Figure 11. Curve of horizontal stresses σ_x in the coal-bearing stratum around the 148 prefabricated drift with the recommended scheme of its maintenance

In general, the action of horizontal stresses σ_x can indicate the compatibility of the influence of stable and unstable rock volumes around the drift, and this ambiguity can significantly change the extent and nature of rock pressure manifestations, depending on the intensity of the action of rock-weakening factors.

3.3. Comparative analysis of the SSS of fastening and protection systems for drift maintenance

In accordance with the previously substantiated geomechanical model, which reflects the loading conditions of the fastening and protection systems of the 148 prefabricated drift after the longwall face advance, a set of SSS calculations for each of the constituent elements has been performed. A detailed SSS analysis of each main element of the basic and recommended schemes for mine working maintenance has been made in terms of fulfilling the main task – ensuring the conditions for its reuse.

In the frame support, the component σ_y reflects the following distribution peculiarities, which are typical for the Western Donbas mining-geological conditions. Thus, the frame cap board is in de-stressed state under the action of sign-variable stresses σ_y from 30 MPa of compression to 30 MPa of tension, which is only 11% in relation to the calculated yield strength value of SCP steel. At the same time, the frame prop stays are under the action of a more or less uniform field of compressive stresses with a value approaching or exceeding the calculated yield strength of St.5 steel. The uniformity of the field σ_y indicates the absence of a significant bending moment in the prop stays, but their limiting state predicts a high probability of plastic bending into the mine working cavity. Therefore, it is advisable to attach the frame prop stays to the side resin-grouted rockbolts with pliable rope binders.

Rope bolts have different spacing σ_y depending on their place of setting. Along the length of the rope bolts set from the side of the undisturbed mass, there is a periodic alternation of areas with high tensile σ_y (30-80% of their load-bearing capacity) with compression areas of the same level. This phenomenon is caused by different deformations of individual rock layers and blocks relative to each other along the length of the rope bolt, which indirectly confirms the existence of significant displacement of certain roof rock volumes, on the one hand, and active resistance to lateral bearing pressure acting from the mass as a result of stope operations, on the other hand. The rope bolt from the side of mined-out space is exposed to mainly compressive σ_y, which is caused by the lowering of rock layers and blocks, and the rope bolt connects them. It can be argued that the rope bolts form a certain similarity in the roof to a relatively holistic rock plate of considerable thickness (up to 5.0-5.5 m), which is capable of withstanding a vertical load that is many times higher than the load-bearing capacity of the frame support.

Assessing the overall vertical stresses σ_y and σ_x distribution in the elements of the fastening and protection systems, it can be concluded that the recommended scheme for maintaining the 148 prefabricated drift of the C_6 seam can be used.

In the final part of the analysis, the stress intensity curve is studied as the most informative and summarising parameter.

In general, the frame cap board is in a stable state with varying levels of loading along its length. The central area near the arch keystone, 0.8-1.0 m long, is exposed to action of σ = 200-240 MPa, which is 74-89% of the ultimate yield strength of St.5 steel. In the peripheral areas of the cap board, the stress intensity gradually decreases from 120-190 MPa to 20-80 MPa near the yielding joists. Here, additional bearings in the form of pliable rope binders attached to rope bolts have a significant impact. Nevertheless, for most of the cap board, it is loaded by more than 50%. The active resistance to vertical rock pressure of the roof-bolting system should also be taken into account.

The analysis of the stress intensity distribution in rope bolts shows their high loading. More specifically, it should be noted that rope bolts operate at 85-100% of their own load-bearing capacity along the length, which is 75-80% of the active length of the bolts. The high load of the rope bolts indicates the effectiveness of their performance in forming the armoured and rock plate in the roof and the expediency of the selected setting parameters.

The immediate roof of the C_6 seam and a part of the main roof lower layer are strengthened in the sides of the mine working with resin-grouted rockbolts. They are designed to create relatively solid and stable bearings in the sides of the mine working for effective resistance of the armoured and rock plate in the roof. The loading on resin-grouted rockbolts is very high both from the side of the undisturbed mass and from the side of the mined-out space, which means that they actively resist not only vertical but also oblique rock pressure. The specific quantitative values of this resistance are as follows:

– the upper resin-grouted rockbolt in the immediate roof from the side of the mined-out space is loaded by 80-100% (of the load-bearing capacity) by 40% of its own length adjacent to the mine working; the rest of its buried part resists with a force of 30-75%;

– the lower bolt from the side of the mined-out space is exposed to a loading in the range of 80-100% of the load-bearing capacity by 90-95% of its length;

– from the side of the undisturbed mass, the upper side bolt is similarly loaded by 50% of its length, located in the buried part of the bolt, and the resistance is 40-75% along the remaining length adjacent to the mine working;

– the lower side bolt from the side of the undisturbed mass is loaded to a lesser extent (up to 70-80%).

The need to set the side roof-bolts at the depth of bottom dinting of the drift is substantiated by their sufficient stress σ loading. The level of stress intensity in the roof-bolt from the side of the mined-out space is 30-55% of its load-bearing capacity, which is explained by the relative unloading of the near-contour area of the drift berm. At the same time, the lateral bearing pressure from the side of the mass contributes to 100% loading of the roof-bolt by 40-45% of its length adjacent to the mine working. Such results confirm the expediency of roof-bolt strengthening of the immediate bottom of the drift at the depth of its bottom dinting.

Thus, the SSS calculation data confirm the efficiency of the combined roof-bolting system as a whole: rope bolts create an armoured and rock plate of high load-bearing capacity, and side resin-grouted rockbolts provide reliable bearings for it.

3.4. Recommendations for choosing the parameters of fastening and protection systems

Based on the analysis of the mining-geological conditions for maintaining the 148 prefabricated drift and the results of a computational experiment to calculate the geomechanical model SSS, recommendations have been developed for determining the parameters of the fastening and protection systems for the mine working with the purpose of its reuse. The proposed technical solution is shown in Figure 12, a and is characterized by the following parameters. The frame support of the SCP series is set in accordance with the passport for maintaining the 148 prefabricated drift.

The 6.0 m long rope bolts are arranged symmetrically relative to the vertical axis of the mine working with an inclination angle to the horizontal of 60°. Along the length of the extraction working, the rope bolts are set at $L_{r.b}$ = 3.8 m intervals, that is, every four frames in the middle of the inter-frame spacing. For the most dangerous area (PK5- PK2), the step of setting the rope bolts is halved ($L_{r.b}$ = 1.6 m).

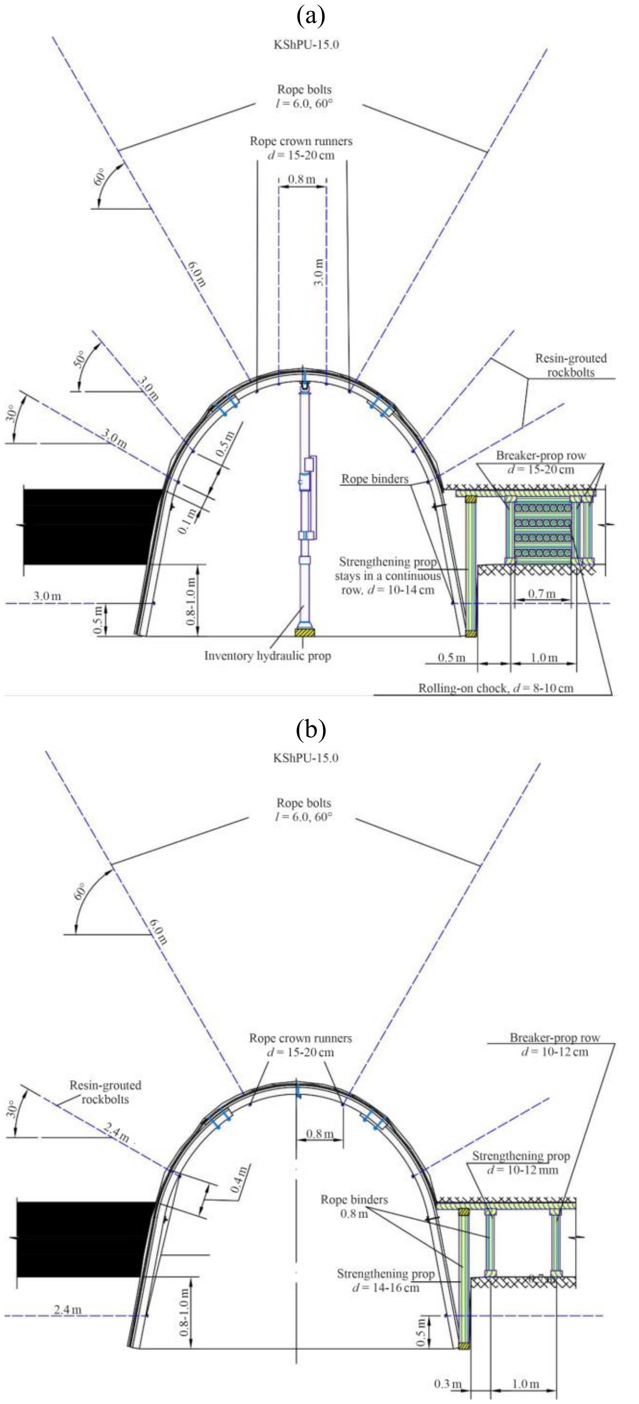


Figure 12. Recommended schemes for maintaining the 148 prefabricated drift of the C_6 seam at the Yuvileina mine in case of geotechnical situations: (a) "ordinary"; (b) unpredictable rock pressure manifestations

The distance between the tail joints of the rope bolts in the mine working cross-section is 1.6 m (0.8 m from the vertical axis of the mine working). This scheme of setting will allow for the "deep" strengthening of the main roof rocks and the formation of an armoured and rock plate, which rests on the strengthened (resin-grouted rockbolts) rocks of the immediate roof and bottom, a number of side wooden prop stays of the strengthening support and a breaker-prop row of prop stays from the side of the mined-out space.

The coupling (along the mine working) of the frame cap board with flexible spatially pliable binders will provide a number of technological advantages:

– strengthening of the frame cap board, especially when dismantling prop stays in the area of the longwall face "window", which increases the safety of work in the area of junction;

– the need for assembly/disassembly wooden prop stays for strengthening support during the subsequent bottom dinting after the longwall face advance is eliminated;

– the "live" drift section increases and the resistance to air jet movement decreases, which increases the ventilation efficiency of the extraction site;

– it is easier to provide distances and clearances in accordance with safety rules and regulations.

The 2.8 m long resin-grouted rockbolts are set in the immediate roof of the C_6 seam in the middle of the interframe space. Setting parameters: lower roof-bolts – at a distance of 0.1 m from the edge of the coal seam at an angle of 300° into the roof; upper roof-bolts – at a distance of 0.5 m from the lower roof-bolts at an angle of 500° into the roof. This arrangement of roof-bolts provides the formation of a holistic rock bearing, which transfers the load from the armoured and rock plate in the main roof to a number of side wooden prop stays of the strengthening support and to a number of prop stays of the breaker-prop row. Increased resistance of bearings limits the lowering of the armoured and rock plate in the roof and reduces the drift section loss.

At the immediate bottom of the C_6 seam, 2.8 m long resin-grouted rockbolts are set horizontally in the interframe space in the middle of the depth of the drift bottom dinting. Along the length of the drift, the tail joints of the resin-grouted rockbolts are attached to the frame prop stays with pliable rope binders. This provides:

– creating a sufficiently rigid lower part of the bearing for the armoured and rock plate by strengthening the weak rocks of the immediate bottom;

– limiting the bending of the frame prop stays into the mine working cavity and reducing the intensity of bottom heaving, which helps to reduce the drift section loss.

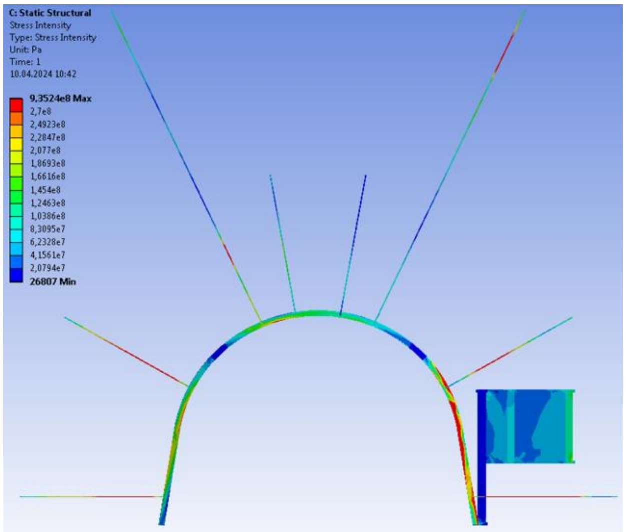
A number of side wooden prop stays of the strengthening support are loaded with a full load and provide forced caving of the main roof rock cantilevers beyond the mine working width, which reduces the load on the fastening system.

The single-row breaker-prop support serves as a temporary support in the area of junction and in a limited area behind the longwall face; its task is to provoke the caving of the immediate and lower layers of the main roof (almost to the seam C_6^1), to create a backing from caved rocks, sufficient to stabilize the rock pressure behind the stope face with a small distance of its retreat. The above recommendations will ensure the reuse of the prefabricated drift as a side adjacent one to the extraction site.

At the final stage, the situation concerning the probability of unpredictable rock pressure is modelled. To complete the research tasks, we simulate such a situation by simultaneously changing the parameters of the combined roof-bolting system (while searching for its rational values): two resin-grouted rockbolts are added near the roof arch keystone of the mine working and only one roof-bolt is left in its sides; other elements of the fastening system are unchanged.

For greater clarity of comparison, Figure 13 shows two curves of stress σ intensity in the elements for maintaining the 148 prefabricated drift: the first – for the "ordinary" course of events; the second – for the case of unpredictable rock pressure manifestations.

(a)



(b)

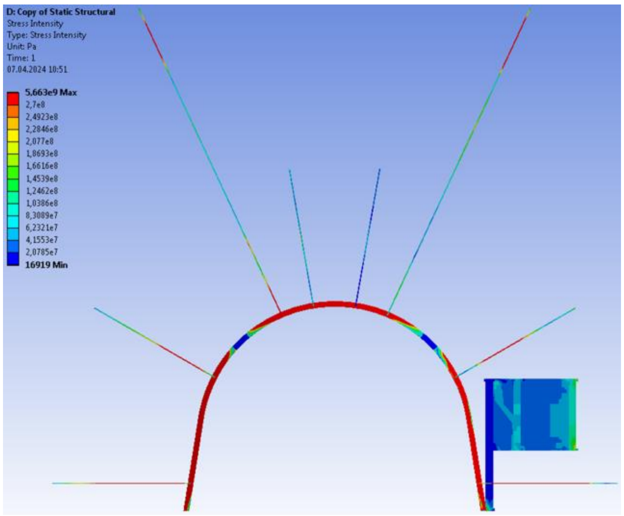


Figure 13. Stress σ intensity curves in the fastening and protection systems of the 148 prefabricated drift in case of geotechnical situations: (a) "ordinary"; (b) unpredictable rock pressure manifestations

The first variant of the geomechanical situation provides for the already analyzed stress σ intensity distribution curve with an underloaded frame cap board and more loaded its prop stays. In the event of unpredictable rock pressure manifestations (Fig. 13b), there are obvious changes in almost all fastening system elements:

– the frame cap board along the entire central part up to 2.7 m long is exposed to critical stresses σ , equal to or exceeding the calculated yield strength σ_s of St.5 steel; the cap board needs additional points of bearing from longitudinal binders connected to central resin-grouted rockbolts, or the use of a central prop stay of the strengthening support, but with a yielding mode of operation (for example, inventory hydraulic props), so as not to provoke plastic bending of the cap board at the point of contact with the prop stay;

– in the mine working sides, one more resin-grouted rockbolt should be added (Fig. 13b) and an additional row of side wooden prop stays for the strengthening support;

– the parameters of rope bolts and resin-grouted rockbolts remain constant, as they can fully withstand the increased load.

Thus, it is possible to provide stability of the 148 prefabricated drift even in the event of unpredictable rock pressure manifestations. A set of studies made it possible to substantiate and create a methodology for selecting rational parameters of fastening and protection systems of mine workings in case of unpredictable rock pressure manifestations.

4. Conclusions

A geomechanical model has been developed and substantiated of the behaviour of the coal-bearing mass, fastening and protection systems of the extraction working in the period after stope face advance, which is maintained for its reuse. The elastic-plastic formulation of the computational experiment (for each lithological variety and fastening materials) has brought the conditions of geomechanical system deformation closer to the real ones, as well as the reflection of the geometric parameters of the methods and means of fastening and protection in full compliance with the mine working passport. In conclusion, the SSS calculation results can be assessed as sufficiently adequate and reliable.

Comparative analysis of the SSS of the coal-bearing rock mass with different schemes for the prefabricated drift maintenance has created an evidence base for two new ideas about the probability of unpredictable rock pressure manifestations:

– changing the scheme for fastening and protection of mine working can significantly affect the distribution of stress components not only in the near-contour, but also in the rock volumes sufficiently distant from the mine workings;

– the combination of resin-grouted rockbolts and rope bolts plays a decisive role in transforming the stress field in the surrounding mass; their rational parameters make it possible to create an armoured and rock structure that is able to protect the mine working from excessive rock pressure.

The positive impact of the combined roof-bolting system is manifested in the rocks of the roof, sides and bottom of the drift: dangerous concentrations of stress components are reduced from 10-15 to 30-40%, and their areas of action are reduced to 50-80%, and in some zones – by up to 4.2-4.6 times.

A comparative analysis of the state of the basic and recommended fastening systems by the main stress components confirmed the feasibility of using a combination of resin-grouted rockbolts and rope bolts in combination with the used protection method for maintaining the prefabricated drift for the purpose of its reuse. An armoured and rock structure of high load-bearing capacity is created in the roof, and the side resin-grouted rockbolts provide reliable bearings for it.

Based on the research performed, a methodology for selecting rational parameters of the fastening and protection systems of mine workings planned for reuse in conditions of unpredictable rock pressure manifestations has been developed.

Author contributions

Conceptualization: HS; Data curation: VK; Formal analysis: MO; Funding acquisition: MS; Investigation: HS; Methodology: HS; Project administration: IS; Resources: VK; Software: MO; Supervision: VK; Validation: MS; Visualization: MO; Writing – original draft: MS; Writing – review & editing: HS, IS. All authors have read and agreed to the published version of the manuscript.

Funding

The research results have been obtained as part of the scientific-research work on GP-514 "Development of geomechanical models of rock mass and innovative technologies for integrated mineral resource extraction in coal mines" (State registration No. 0123U10180).

Acknowledgements

The research was carried out within the framework of the Simons Foundation. Grant Maker: Simons Foundation International Program; PD-Ukraine: President Directed – Ukraine Support Grants Project "Mathematical Methods and Models in Engineering and Social Sciences Institution", Dnipro University of Technology – Record ID: SFI-PD-Ukraine-00014585.

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.

References

[1] Pochepov, V.M., Mamaikin, O.R., Sheka, I.V., Krukovskyi, O.P., Lapko, V.V., & Ashcheulova, O.M. (2024). Tool for management and planning of the fuel and energy complex taking into account the production potential of coal-mining enterprises. *IOP Conference Series: Earth and Environmental Science*, *1415*, 012045. https://doi.org/10.1088/1755-1315/1415/1/012045

[2] Nikitenko, I., Shevchenko, S., & Tereshkova, O. (2025). Mineral-resource potential of construction materials of Dnipropetrovsk region. *IOP Conference Series: Earth and Environmental Science*, *1481*(1), 012014. https://doi.org/10.1088/1755-1315/1481/1/012014

[3] Xu, Y., Yan, C., Liu, H., Wang, J., Yang, Z., & Jiang, Y. (2020). Smart energy systems: A critical review on design and operation optimization. *Sustainable Cities and Society*, *62*, 102369. https://doi.org/10.1016/j.scs.2020.102369

[4] Xu, Y., Tian, S., Wang, Q., Yuan, X., Ma, Q., Liu, M., & Liu, C. (2021). Optimization path of energy-economy system from the perspective of minimum industrial structure adjustment. *Energy*, *237*, 121650. https://doi.org/10.1016/j.energy.2021.121650

[5] Stukalo, N., Lytvyn, M., Petrushenko, Y., & Omelchenko, Y. (2020). The achievement of the country's sustainable development in the conditions of global threats. *E3S Web of Conferences*, *211*, 01029. https://doi.org/10.1051/e3sconf/202021101029

[6] Kulikov, P., Aziukovskyi, O., Vahonova, O., Bondar, O., Akimova, L., Akimov, O., & Akimov, O. (2022). Post-war economy of Ukraine: Innovation and investment development project. *Economic Affairs (New Delhi)*, *67*(5), 943-959. https://doi.org/10.46852/0424-2513.5.2022.30

[7] Yakovlev, Ye., Pyrikov, O., Anpilova, Ye., & Chumachenko, S. (2022). Assessment and forecast of changes in the ecological conditions of the underground and surface hydrosphere within Donbass at the post-mining stage. *Mineral Resources of Ukraine*, *1*, 43-51. https://doi.org/10.31996/mru.2022.1.43-51

[8] Mazaraki, A., Melnyk, T., & Banas, D. (2025). Impact of the EU Energy Markets Transformations on the Ukrainian Economy. *Strategic Planning for Energy & the Environment*, *44*(1), 133-166. https://doi.org/10.13052/spee1048-5236.4416

[9] Sribna, Y., Skakovska, S., Paniuk, T., & Hrytsiuk, I. (2023). The economics of technology transfer in the environmental safety of enterprises for the energy transition. *Economics Ecology Socium*, *7*(1), 84-96. https://doi.org/10.31520/2616-7107/2023.7.1-8

[10] Piwniak, G.G., Bondarenko, V.I., Salli, V.I., Pavlenko, I.I., & Dychkovskiy, R.O. (2007). Limits to economic viability of extraction of thin coal seams in Ukraine. *Technical, Technological and Economic Aspects of Thin-Seams Coal Mining International Mining Forum 2007*, 129-132. https://doi.org/10.1201/noe041543670a0.ch16

[11] Prokopenko, O., Chechel, A., Koldovskiy, A., & Kldiashvili, M. (2024). Innovative models of green entrepreneurship: Social impact on sustainable development of local economies. *Economics Ecology Socium*, *8*(1), 89-111. https://doi.org/10.61954/2616-7107/2024.8.1-8

[12] Barabash, M., Salieiev, I., & Symanovych, H. (2021). Technical and technological aspects of the coal mine closure based on the geomechanical component assessment. *Mining of Mineral Deposits*, *15*(3), 7-15. https://doi.org/10.33271/mining15.03.007

[13] Cha, J.M., & Grubert, E. (2024). Public control of coal resources of the United States' Powder River Basin for a managed decarbonization transition. *Progress in Energy*, *6*(4), 043004. https://doi.org/10.1088/2516-1083/ad756d

[14] Bazaluk, O., Slabyi, O., Vekeryk, V., Velychkovych, A., Ropyak, L., & Lozynskyi, V. (2021). A technology of hydrocarbon fluid production intensification by productive stratum drainage zone reaming. *Energies*, *14*(12), 3514. https://doi.org/10.3390/en14123514

[15] Saik, P., Rysbekov, K., Kassymkanova, K.K., Lozynskyi, V., Kyrgizbayeva, G., Moldabayev, S., Babets, D., & Salkynov, A. (2024). Investigation of the rock mass state in the near-wall part of the quarry and its stability management. *Frontiers in Earth Science*, *12*, 1395418. https://doi.org/10.3389/feart.2024.1395418

[16] Malashkevych, D., Petlovanyi, M., Sai, K., & Zubko, S. (2022). Research into the coal quality with a new selective mining technology of the waste rock accumulation in the mined-out area. *Mining of Mineral Deposits*, *16*(4), 103-114. https://doi.org/10.33271/mining16.04.103

[17] Sarycheva, L. (2003). Using GMDH in ecological and socio-economical monitoring problems. *Systems Analysis Modelling Simulation*, *43*(10), 1409-1414. https://doi.org/10.1080/02329290290024925

[18] Bondarenko, V., Symanovych, G., & Koval, O. (2012). The mechanism of over-coal thin-layered massif deformation of weak rocks in a longwall. *Geomechanical Processes During Underground Mining – Proceedings of the School of Underground Mining*, 41-44. https://doi.org/10.1201/b13157

[19] Ahaiev, R., Prytula, D., Kliuiev, E., Zhytlonok, D., Cabana, E., & Kabakova, L. (2020). The determination of the influence degree of mining-geological and mining-technical factors on the safety of the degassing system. *E3S Web of Conferences*, *168*, 00040. https://doi.org/10.1051/e3sconf/202016800040

[20] Bondarenko, V.I., Kovalevska, I.A., Podkopaiev, S.V., Sheka, I.V., & Tsivka, Y.S. (2022). Substantiating arched support made of composite materials (carbon fiber-reinforced plastic) for mine workings in coal mines. *IOP Conference Series: Earth and Environmental Science*, *1049*, 012026. https://doi.org/10.1088/1755-1315/1049/1/012026

[21] Bondarenko, V.I., Kovalevska, I.A., Symanovych, H.A., Sachko, R.M., & Sheka, I.V (2023). Integrated research into the stress-strain state anomalies, formed and developed in the mass under conditions of high advance velocities of stope faces. *IOP Conference Series: Earth and Environmental Science*, *1254*(1), 012062. https://doi.org/10.1088/1755-1315/1254/1/012062

[22] Bondarenko, V., Kovalevska, I., Symanovych, G., Sotskov, V., & Barabash, M. (2018). Geomechanics of interference between the operation modes of mine working support elements at their loading. *Mining Science*, *25*, 219-235. https://doi.org/10.5277/msc182515

[23] Bondarenko, V., Kovalevs'ka, I., & Ganushevych, K. (2014). *Progressive technologies of coal, coalbed methane, and ores mining*. London, United Kingdom: CRC Press, 534 p. https://doi.org/10.1201/b17547

[24] Bahrii, I., Riepkyn, O., Paiuk, S., Kryl, I., & Gafych, I. (2023). Scientific justification of spatial distribution and mapping of anomalous manifestations of white hydrogen – Energy raw material of the XXI century. *Mineral Resources of Ukraine*, *1*, 4-10. https://doi.org/10.31996/mru.2023.1.4-10

[25] Bondarenko, V., Symanovych, H., Kicki, J., Barabash, M., & Salieiev, I. (2019). The influence of rigidity of the collapsed roof rocks in the minedout space on the state of the preparatory mine workings. *Mining of Mineral Deposits*, *13*(2), 27-33. https://doi.org/10.33271/mining13.02.027

[26] Bazaluk, O., Kuchyn, O., Saik, P., Soltabayeva, S., Brui, H., Lozynskyi, V., & Cherniaiev, O. (2023). Impact of ground surface subsidence caused by underground coal mining on natural gas pipeline. *Scientific Reports*, *13*, 19327. https://doi.org/10.1038/s41598-023-46814-5

[27] Sailygarayeva, M., Nurlan, A., Rysbekov, K., Soltabayeva, S., Amralinova, B., & Baygurin, Z. (2023). Predicting of vertical displacements of structures of engineering buildings and facilities. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *2*, 77-83. https://doi.org/10.33271/nvngu/2023-2/077

[28] Petlovanyi, M., Medianyk, V., Sai, K., Malashkevych, D., & Popovych, V. (2021). Geomechanical substantiation of the parameters for coal auger mining in the protecting pillars of mine workings during thin seams development. *ARPN Journal of Engineering and Applied Sciences*, *16*(15), 1572-1582.

[29] Kostenko, V., Bohomaz, O., Kostenko, T., & Kutniashenko, O. (2024). Improvement of microclimatic working conditions for miners in deep mines. *Rudarsko Geolosko Naftni Zbornik*, *39*(3), 145-152. https://doi.org/10.17794/rgn.2024.3.11

[30] Dang, P.T., Malanchuk, Z., & Zaiets, V. (2021). Investigation of resistance and air leakage of auxiliary ventilation ducting in underground mine in Quang Ninh. *E3S Web of Conferences*, *280*, 08002. https://doi.org/10.1051/e3sconf/202128008002

[31] Kuandykova, A. (2024). Production of Composite Cement Clinker Based on Industrial Waste. *Journal of Composites Science*, *8*(7), 257. https://doi.org/10.3390/jcs8070257

[32] Zeqiri, I., Brahimaj, F., Zeqiri, R., & Gashi, J. (2022). Comparability of microclimate in the horizons of the Trepça Mine in Stantërg. *Rudarsko Geolosko Naftni Zbornik*, *37*(4), 83-90. https://doi.org/10.17794/rgn.2022.4.7

[33] Vergelska, N., Vergelska, V., & Skopychenko, I. (2024). Peculiarities of using man-made reservoirs of coal-bearing massifs of the Donets Basin. *Mineral Resources of Ukraine*, *3*, 54-60. https://doi.org/10.31996/mru.2024.3.54-60

[34] Kovalevska, I., Symanovych, G., & Fomychov, V. (2013). Research of stress-strain state of cracked coal-containing massif near-the working area using finite elements technique. *Annual Scientific Technical Collection – Mining of Mineral Deposits 2013*, 159-163. https://doi.org/10.1201/b16354-27

[35] Symanovych, H., Salieiev, I., Shyshov, M., & Odnovol, M. (2022). Substantiating the optimization solutions for the mine working fastening system interaction with the enclosing rock mass. *Mining of Mineral Deposits*, *16*(3), 54-60. https://doi.org/10.33271/mining16.03.054

[36] Symanovych, G., Ganushevych, K., & Chervatyuk, V. (2010). Researches of influence of depth of an in-seam working on displacement field of rocks in its vicinity. *New Techniques and Technologies in Mining – Proceedings of the School of Underground Mining*, 121-125. https://doi.org/10.1201/b11329-19

[37] Bondarenko, V.I., Kharin, Ye.N., Antoshchenko, N.I., & Gasyuk, R.L. (2013). Basic scientific positions of forecast of the dynamics of methane release when mining the gas bearing coal seams. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *5*, 24-30.

[38] Bondarenko, V.I., Sheka, I.V., Khorolskyi, A.O., Salieiev, I.A., Kovalevska, I.A., & Stoliarska, O.V. (2025). Substantiation of rational parameters for composite support in mine workings. *Naukovyi Visnyk Natsionalnoho Hirnychogo Universytetu*, *3*, 30-36. https://doi.org/10.33271/nvngu/2025-1/030

[39] Gornostayev, S.S., Crocket, J.H., Mochalov, A.G., & Laajoki, K.V.O. (1999). The platinum-group minerals of the Baimka placer deposits, Aluchin horst. *Canadian Mineralogist*, *37*(5), 1117-1129.

[40] Bazaluk, O., Sadovenko, I., Zahrytsenko, A., Saik, P., Lozynskyi, V., & Dychkovskyi, R. (2021). Forecasting underground water dynamics within the technogenic environment of a mine field: Case study. *Sustainability*, *13*(13), 7161. https://doi.org/10.3390/su13137161

[41] Lousada, S., Delehan, S., & Khorolskyi, A. (2024). Application of dynamic programming models for improvement of technological approaches to combat negative water leakage in the underground space. *Water*, *16*(14), 1952. https://doi.org/10.3390/w16141952

[42] Absametov, M.K., Murtazin, E., Kulagin, V.V., Makyzhanova, A., & Ismagulova, A. (2024). Infiltration and colmatation dynamics on physical models' study by infiltration basins at artificial groundwater recharge. *Water Conservation & Management*, *7*(1), 45-54. http://doi.org/10.26480/wcm.01.2023.45.54

[43] Mirlas, V., Kulagin, V., Ismagulova, A., & Anker, Y. (2022). Field experimental study on the infiltration and clogging processes at Aksu research site, Kazakhstan. *Sustainability*, *14*(23), 15645. https://doi.org/10.3390/su142315645

[44] Ismagulova, A., & Mirlas, V. (2019). Research of hydrodynamics of infiltration and colmatations processes in basins of daily regulation under artificial replacement of groundwater reserves. *News of the National Academy of the Science of the Republic of Kazakhstan, Geology and Technical Sciences*, *3*(435). https://doi.org/10.32014/2019.2518-170X.72

[45] Erzhan, K., Vitaly, K., Elmira, K., Medetkhan, Z., & Aida, I. (2015). Field studies of artificial ground water spreading processes in the boundary conditions of the infiltration basin physical model (by the example of the Karatal area of experimental studies in the South-East Kazakhstan). *Ecology, Environment and Conservation*, *21*, S121-S130.

[46] Simanovich, G., Serdiuk, V., Fomichov, V., Bondarenko, V., & Kovalevska, I. (2007). Research of rock stresses and deformations around mining workings. *Technical, Technological and Economic Aspects of Thin Seams Coal Mining*, 47-56. https://doi.org/10.1201/noe0415436700.ch6

[47] Usachenko, B.M., Cherednichenko, V.P., & Golovchanskiy, I.Ye. (1990). *Heomekhanika okhorony vyrobok v slabometamorfizovanykh porodakh*. Kyiv, Ukraina: Naukova dumka, 144 s.

[48] Bondarenko, V., Kovalevska, I., Sheka, I., & Sachko, R. (2023). Results of research on the stability of mine workings, fixed by arched supports made of composite materials, in the conditions of the Pokrovske mine administration. *IOP Conference Series: Earth and Environmental Science*, *1156*(1), 012011. https://doi.org/10.1088/1755-1315/1156/1/012011

[49] Pivnyak, G., Bondarenko, V., Kovalevs'ka, I., & Illiashov, M. (2012). *Geomechanical processes during underground mining*. London, United Kingdom: CRC Press, 300 p. https://doi.org/10.1201/b13157

[50] Vinogradov., V.V. (1989). *Geomekhanika upravleniya sostoyaniem massiva vblizi gornykh vyrabotok*. Kyiv, Ukraina: Naukova dumka, 192 s.

[51] Krukovskyi, O., Krukovska, V., & Kostrytsia, A. (2024). Numerical study of time-dependent stresses in the floor of the stope with powered support. *IOP Conference Series: Earth and Environmental Science*, *1348*(1), 012030. https://doi.org/10.1088/1755-1315/1348/1/012030

[52] Bondarenko, V., Kovalevs'ka, I., & Fomychov, V. (2012). Features of carrying out experiment using finite-element method at multivariate calculation of mine massif – combined support system. *Geomechanical Processes During Underground Mining – Proceedings of the School of Underground Mining*, 7-13. https://doi.org/10.1201/b13157-3

[53] Kovalevs'ka, I., Fomychov V., Illiashov, M., & Chervatuk, V. (2012). The formation of the finite-element model of the system "undermined massif – support of stope". *Geomechanical Processes During Underground Mining – Proceedings of the School of Underground Mining*, 83-90. https://doi.org/10.1201/b13157-14

[54] Krukovskyi, O.P., Kurnosov, S.A., Makeyev, S.Y., & Stadnychuk, M.M. (2023). Determination of the reliability of mine support equipment considering its deformation risks. *Strength of Materials*, *55*(9-30), 475-483. https://doi.org/10.1007/s11223-023-00540-5

[55] Bondarenko, V., Kovalevska, I., Husiev, O., Snihur, V., & Salieiev, I. (2019). Concept of workings reuse with application of resource-saving bolting systems. *E3S Web of Conferences*, *133*, 02001. https://doi.org/10.1051/e3sconf/201913302001

[56] Pivnyak, G., Bondarenko, V., & Kovalevska, I. (2015). *New developments in mining engineering 2015: Theoretical and practical solutions of mineral resources mining*. London, United Kingdom: CRC Press, CRC Press, 616 p. https://doi.org/10.1201/b19901

[57] Dychkovskyi, R., Tabachenko, M., Zhadiaieva, K., & Cabana, E. (2019). Some aspects of modern vision for geoenergy usage. *E3S Web of Conferences*, *123*, 01010. https://doi.org/10.1051/e3sconf /201912301010

[58] Prykhodko, V., Ulanova, N., Haidai, O., & Klymenko, D. (2018). Mathematical modeling of tight roof periodical falling. *E3S Web of Conferences*, *60*, 00020. https://doi.org/10.1051/e3sconf/20186000020

[59] Haidai, O., Ruskykh, V., Ulanova, N., Prykhodko, V., Cabana, E.C., Dychkovskyi, R., & Smolinski, A. (2022). Mine field preparation and coal mining in Western Donbas: Energy security of Ukraine – A case study. *Energies*, *15*(13), 4653. https://doi.org/10.3390/en15134653

[60] Bondarenko, V., Kovalevska, I., Svystun, R., & Cherednichenko, Yu. (2013). Optimal parameters of wall bolts computation in the united bearing system of extraction working frame-bolt support. *Annual Scientific-Technical Collection – Mining of Mineral Deposits 2013*, 5-9. https://doi.org/10.1201/b16354-2

Оптимізація раціональних параметрів кріпильної та охоронної систем гірничих виробок в умовах виникнення непрогнозованих проявів гірського тиску

Г. Симанович, В. Красник, М. Одновол, М. Снігур, І. Шека

Мета. Розробка та обґрунтування раціональних параметрів кріпильної та охоронної систем підтримання гірничих виробок в умовах можливих непрогнозованих проявів гірського тиску із забезпеченням їх стійкості для повторного використання виробок після відпрацювання очисного вибою.

Методика. Дослідження ґрунтується на геомеханічному моделюванні в пружно-пластичній постановці з відображенням білінійної діаграми "напруження – відносна деформація" для кожної літологічної різниці та кріпильного елементу. Розрахунки проведено із урахуванням фізико-механічних властивостей порід. Моделювання включало варіанти стандартного та комбінованого кріплення із застосуванням канатних анкерів (довжина 6.0 м) та сталеполімерних анкерів (довжина 2.8 м), із розміщенням додаткового кріплення в зоні можливого вторинного обвалення.

Результати. Запропонована комбінована система з канатними та сталеполімерними анкерами дозволила створити армопородну плиту високої несучої здатності. Порівняльний аналіз напружено-деформованого стану показав зниження небезпечних концентрацій напружень на 10-40%, а площі їх впливу – до 4.2-4.6 разів. Рекомендована схема ефективно протидіє гірському тиску навіть за умов непрогнозованих геотехнічних ситуацій.

Наукова новизна. Вперше обґрунтовано взаємозв'язок між структурною побудовою комбінованої анкерної системи й просторовим розподілом напружень у породному масиві, що забезпечує перехід від рамної до армопородної несучої системи. Запропоновано методику вибору параметрів кріплення з урахуванням комплексного впливу тріщинуватості, обводнення та реології порід.

Практична значимість. Отримані результати дозволяють підвищити надійність і безпеку експлуатації гірничих виробок у складних геотехнічних умовах, а також забезпечити їх повторне використання при мінімальних витратах на ремонт.

Ключові слова: *вугілля, шахта, гірський тиск, гірничі виробки, кріпильна система*

Publisher's note

All claims expressed in this manuscript are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers.