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Substantiation of resource-saving technologies for supporting and protecting mine workings at their repeated use

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Abstract

Purpose. To determine the effective parameters of a resource-saving technology for supporting and protecting a panel entry during its repeated use based on experimental studies and multifactor computer modeling.

Methods. The study employed both experimental and numerical research methods. The experimental part included in-mine observations of rock pressure manifestations in repeatedly used extraction workings of the Western Donbas. The state of the workings was assessed by the displacement of the drift contour and parameters of frame support deformation in key cross-sections. Numerical modelling of the geomechanical state of the rock mass and support systems was performed using the ANSYS software package based on the finite element method (FEM), taking into account the texture of the coal-bearing stratum, physical and mechanical properties of lithotypes, moisture content, fracturing, rheological properties of rocks, and disruption of contacts between adjacent layers.

Findings. Based on experimental studies and numerical modelling, the effectiveness of using rope crown runners in combination with a combined roof-bolting system has been proven. It has been established that the proposed support scheme reduces the intensity of rock pressure manifestations and ensures significant savings in material and labour resources during the repeated use of mine workings. The feasibility of its application for supporting prefabricated drifts under complex mining and geological conditions of the Western Donbas has been confirmed.

Originality. The features of the formation of the stress-strain state of the rock mass surrounding an extraction working during its repeated use have been established, and the effectiveness of a combined roof-bolting system with rope crown runners for reducing rock pressure manifestations has been substantiated. New data on the redistribution of stresses in the roof and side rocks of the working have been obtained, explaining the mechanism of increasing its stability when using the proposed support system.

Practical implications. The results of the study can be used in the design and selection of resource-saving support schemes for repeatedly used drifts under conditions of weak surrounding rocks and increased rock pressure manifestations.

Keywords: *coal; rock mass; mine working; support system; computational experiment*

1. Introduction

The development of alternative and renewable energy sources is currently one of the most relevant areas of global energy policy, since it is directly related to strengthening energy independence, increasing the security and resilience of energy systems, and reducing environmental risks. At the same time, the transition to cleaner energy does not eliminate the role of traditional fossil fuels immediately. Among them, coal continues to occupy an important place in the global fuel and energy balance. This is confirmed by the positive dynamics of coal mining not only in the leading coal-producing countries, but also worldwide in general [1], [2]. Despite the active promotion of decarbonization strategies in many regions, coal remains a significant energy resource that supports the stable operation of power generation and industrial sectors.

Today, coal still provides a substantial share of the world's electricity generation and remains the basis of energy security for many countries with large reserves and established mining and energy infrastructure [3], [4]. In countries where energy demand is growing rapidly, coal continues to play the role of a relatively affordable and strategically important fuel [5]. For this reason, even under the conditions of active renewable energy development, the global coal market demonstrates considerable stability. According to recent studies, global demand for coal in 2025 remained at a consistently high level [6]-[8]. This situation is largely explained by the continued increase in coal production in Asia, especially in China and India, where production growth compensated for the reduction in coal consumption observed in the European Union and the United States [9]-[12].

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This issue is particularly acute for the energy sector of Ukraine, where the coal industry has been severely affected by the consequences of the full-scale war [13]-[16]. A significant part of Ukraine's coal mining capacity was historically concentrated in the eastern regions, primarily within Donetsk and Luhansk oblasts, which have experienced the most intense military impact. As a result, mining operations in many areas of these regions were suspended, disrupted, or completely lost, which substantially reduced domestic coal production and worsened the stability of fuel supply for the national energy sector. The situation became even more critical in January 2025, when the extraction of K-grade coal in the Pokrovsk area was stopped [17], [18]. Given the importance of this coal grade for metallurgical and energy-related needs, such losses further deepened the resource imbalance and increased the vulnerability of the national economy.

The scale of these negative changes is clearly illustrated by the dynamics of coal production in Ukraine shown in Figure 1. Compared with 2013, when total coal output reached 83.6 million tons, production volumes decreased sharply in subsequent years. In 2021-2024, coal mining remained several times lower than the pre-war level, and during the first eight months of 2025 the decline continued. In particular, coal production decreased from 17.82 million tons in the first eight months of 2024 to 10.83 million tons in the corresponding period of 2025, which corresponds to a reduction of 39.2%. Thus, the current state of the Ukrainian coal sector confirms not only the destructive effect of war on the mining industry, but also the urgent need to develop new technological approaches to the use of remaining coal resources and to justify alternative solutions for maintaining national energy security. In this difficult period, PJSC "DTEK Pavlohradvuhillia" remains one of the key coal-producing enterprises in Ukraine, maintaining stable operation under extremely challenging economic, logistical, and security conditions.

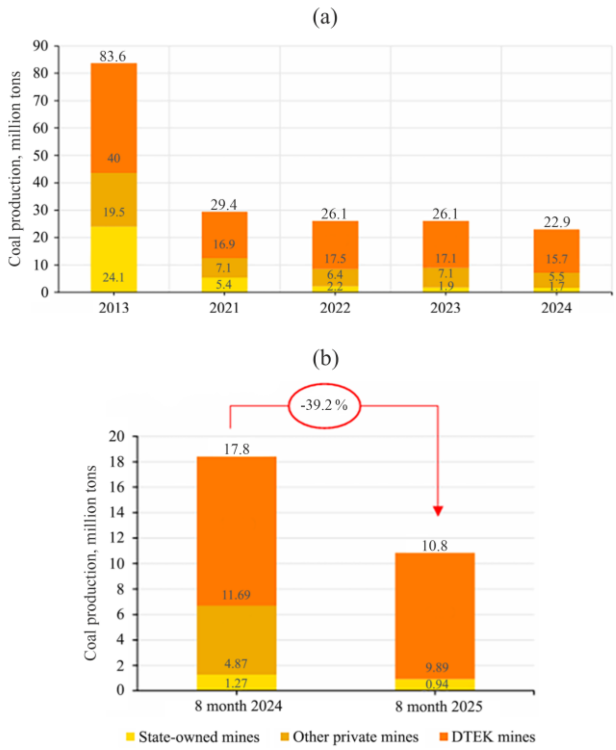

Figure 1. Dynamics of coal mining in Ukraine: (a) coal production in 2013 and 2021-2024; (b) coal production in the first eight months of 2024 and 2025

Its significance is determined not only by the scale of mining activity, but also by its role in sustaining the fuel base of the national energy sector during a time of sharp decline in coal production across the country. Operating in the Western Donbas, the company continues to extract both thermal and coking coal, which is of strategic importance for electricity generation as well as for metallurgical processes [19], [20]. Against the background of suspended or disrupted mining operations in other coal-producing regions, the effective functioning of PJSC "DTEK Pavlohradvuhillia" is particularly important, since it supports the preservation of domestic coal supply, industrial stability, and the overall resilience of Ukraine's energy system [21].

The modern development of mining systems requires not only maintaining production capacity, but also introducing approaches based on sustainable development, rational use of mineral resources, and improvement of technological planning in mining operations [22]-[24]. In this regard, attention is increasingly being paid to integrated concepts of coal mine development, ESG-oriented management, and the systematization of technological solutions in the mining sector [25], as well as the use of augmented and virtual reality tools in the training of mining engineers [26]. These approaches form an important general framework for substantiating resource-saving technologies in underground coal mining.

Within this long-term trend, one of the most important scientific and practical tasks has been and remains the development, substantiation, and implementation of resource-saving technologies for supporting and protecting mine workings during their repeated use [27]-[29]. The importance of this problem is determined by the need to ensure the long-term operational stability of mine workings, reduce the cost of maintaining underground infrastructure, and improve safety under conditions of complicated geomechanical influence. In deep and intensively mined coal deposits, repeated use of mine workings is accompanied by changes in the stress-strain state of the surrounding rock mass, deformation of support elements, deterioration of the contour condition, and a growing risk of local failure [30], [31]. Therefore, the search for effective technological solutions for maintaining mine workings in serviceable condition remains a relevant area of modern mining science.

A considerable number of studies by domestic and foreign researchers have been devoted to this issue. At the same time, these publications cover several interrelated scientific directions. In particular, a number of works address the technological and geomechanical foundations of underground coal mining and the conditions influencing the stability of mine workings during their operation [32]-[34]. Another group of studies focuses on the determination of rock mass properties, the identification of material parameters, and the numerical simulation of rock behavior under complex loading conditions [35]-[37]. Separate attention has been paid to monitoring, control, and assessment of the stress-strain state of the rock mass [38], as well as to the management of stability in mining structures under variable geotechnical conditions [39], [40]. In addition, a number of studies have addressed the development of methane monitoring systems and measuring instruments for underground conditions, including computer-integrated technologies for detecting unauthorized disturbances in methane sensor operation and optical methane concentration meters adapted to variable mine atmosphere parameters [41], [42].

In turn, foreign studies have also examined deformation and failure processes in coal-bearing strata, support performance, longwall mining conditions, and the risk of roof falls, which are directly related to the safe repeated use of mine workings [43]-[45].

Thus, the available scientific literature forms a substantial basis for understanding the regularities of rock mass behavior around underground excavations and for developing engineering solutions to maintain their stability. However, despite the significant number of studies, the issue of substantiating resource-saving technologies for supporting and protecting mine workings during repeated use cannot be considered fully resolved [46], [47]. This is due to the variability of mining and geological conditions, the diversity of support systems, and the need to adapt existing approaches to specific mining regions and operating conditions. Therefore, further research in this area remains relevant both from the scientific and practical points of view.

At the same time, despite the practical and scientific significance of these studies, a number of issues still remain insufficiently resolved. In particular, further substantiation is needed for modern structural and technological schemes aimed at the resource-saving maintenance of the junction between the longwall face and the extraction drift during its repeated use, especially under the specific mining and geological conditions of the Western Donbas [48]-[51].

The purpose of this study is to substantiate an effective resource-saving solution for maintaining the junction between the longwall face and the extraction drift during its repeated use under the mining and geological conditions of the Western Donbas. To achieve this, a multifactor computer model of the geomechanical system was developed to assess the stress-strain state of the rock mass and support elements in the junction area, as well as to determine the performance of the proposed innovative support method under specific operating conditions.

2. Materials and methods

2.1. Study area and mining-geological conditions

To substantiate and implement resource-saving technologies for supporting and protecting mine workings during their repeated use, the mining-geological conditions of the coal deposit in Western Donbas (Ukraine) were examined using the example of the "Samarska" mine, PJSC "DTEK Pavlohradvuhillia".

Analyzing the geological characteristics of the physical-mechanical properties of coal and host rocks, as well as the predicted mining-geological section along the prefabricated drift, an area (PK 90-PK 140) was identified where the most intense rock pressure manifestations are preliminarily predicted (Fig. 2).

Analysis of texture and physical-mechanical properties of the C_{10}^{u} seam coal-bearing stratum has previously shown the non-uniformity of possible rock pressure manifestations in the prefabricated drift, caused by the varying degree of influence of stope operations in the longwall face [52], [53]. Experience in supporting extraction drifts in Western Donbas indicates the formation of extensive zones of stratified and de-strengthened rocks around extraction drifts, all of which, without exception, belong to the category of weak rocks [54]-[57]. As for supporting the prefabricated drift with plans to reuse it, there are two possible geomechanical scenarios:

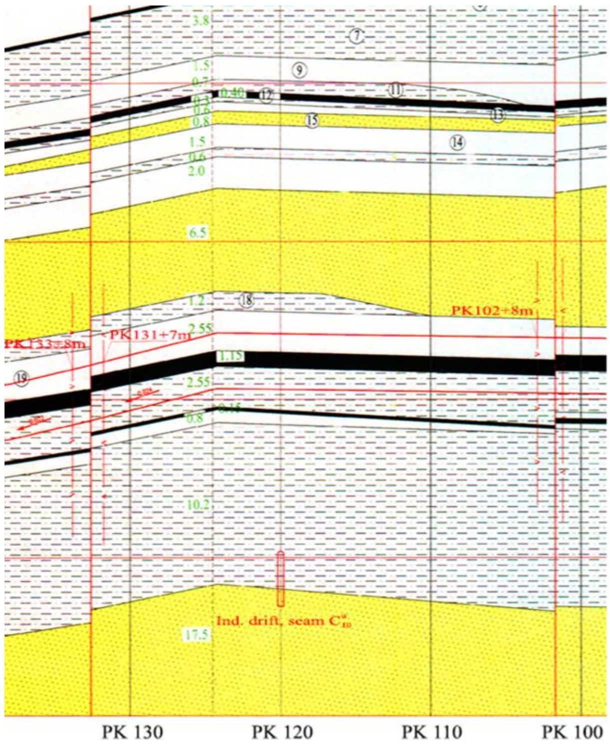

Figure 2. The most dangerous area of the prefabricated drift by the factor of previously predicted rock pressure manifestations

– first – thick sandstone of the main roof participates in the formation of the load on the supporting and protection systems of the mine working, and then the required resistance to rock pressure is at the level of 1000-1100 kN/m;

– second – the area of unstable state of the main roof lithotypes develops above the sandstone, presumably to the coal interlayer; then the load is predicted to be at the level of 1600-1800 KN/m.

In both cases, a radical strengthening of the supporting system is required, preferably using existing resource-saving means. These preliminary conclusions need to be substantiated on the basis of experimental studies conducted in Western Donbas on rock pressure manifestations in extraction drifts and modelling of geomechanical processes around the prefabricated drift using modern analytical finite element methods (FEM) [58]-[60].

2.2. Methodology for conducting experimental research

On the example of researches [50], [61], examine the main rock pressure manifestations in extraction workings that are used repeatedly in the conditions of the Western Donbas mines. As the object of mine research, 588 boundary, 590 prefabricated and 592 boundary drifts of the c_6 seam ("Yuvileina" mine) were selected as variants of different basic schemes for installing roof-bolts in the roof.

The state of the mine workings was assessed based on indicators of rock pressure manifestations in the form of drift contour displacements in key cross-section areas.

Regarding the specification of the measurements of the current drift dimensions, the corresponding scheme is shown in Figure 3. In time and space, the recording of the dimensions of mine workings was performed differentially. In the area outside the zone influenced by stope operations (at least 60-80 m from the stope face), measurements were taken once every 3-4 days.

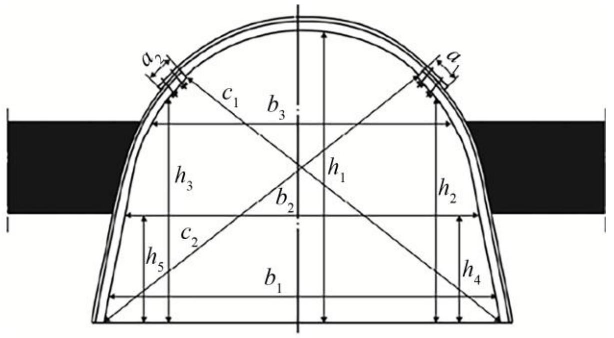

Figure 3. Scheme for measuring the current dimensions of extraction workings as the stope face advances

This method allowed for a more accurate reflection of the varying intensity of the development of the working contour displacements during the passage of the stope face through the intersection of the drift with the measuring station.

To provide a complete picture of the rock contour displacement curve of the extraction drifts and the peculiarities of the frame support deformation (Fig. 3), a sufficient number of measuring points are placed along its contour. Thus, the height h_1 of the mine working from the arch keystone to the bottom and its width b_1 (near the bottom) provide general information about the section loss when compared with the project dimensions of the drifts. No less important are the parameters b_2 and b_3 not only for assessing the drift section loss, but also for taking into account the convergence of its sides in the zone of movement of people. In addition, comparing the parameter $b_{1,2,3}$ change values makes it possible to identify areas of greatest deformation of frame prop stays, which are identical to areas of increased rock pressure in the mine working sides.

Measuring the height $h_{2,3}$ of the drift in the working and non-working walls makes it possible to assess two positions at once: the convergence of the roof and bottom in the zone of people movement with clarification of the mine working keystone height in this place; degree of the frame deformation asymmetry in opposite walls of the drift. Two additional parameters $c_{1,2}$ help to specify the degree of the frame deformation non-uniformity. These parameters measure the diagonal from the drift corner to the upper end of the frame prop stay in the opposite wall of the mine working. If initially identical values c_1 and c_2 have different lengths, then this indicates non-uniform loading on the frame. In addition to the specified parameters for assessing load asymmetry, the overlap value $a_{1,2}$ of the cap board and prop stay in the frame yielding joists was recorded; at $a_1 \neq a_2$, there is a load concentration from the side of increased overlap value. In addition, the performance of the frame support itself in the yielding mode is assessed by the values of $a_{1,2}$. Two dimensions $h_{4,5}$ determine the distance from the lower edge of the seam to the mine working bottom.

In general, the measurements provided allow for a sufficiently complete description of the actual rock pressure manifestations in the extraction drifts, which ensures the objectivity of the comparative analysis of various roof-bolt installing schemes in the mine working roof. The measurement results are presented in the form of graphs showing changes in a particular thrust depending on the distance Z to the stope face. Thus, there is a noticeable dynamics of the increase in the mine working contour displacements, covering all the most characteristic areas for its supporting.

2.3. Substantiation of the geomechanical model

Computational experiment based on the finite element method was performed for the prefabricated drift of the longwall face at "Samarska" mine using recommendations in [59], [62]-[64] for modelling the geomechanical processes of the coal-bearing mass shear around the extraction workings. More broadly, the growing role of mathematical and computer-based modelling in mining engineering is also confirmed by its application to other complex mining tasks, including mineral reserve assessment [65].

Modelling technology determines the synthesis of a general geomechanical system consisting of two components: a coal-bearing mass model and the supporting/protective structures of the extraction drift. The improved scheme for supporting the prefabricated drift (for its reuse) is based on research into rock pressure manifestations, analysis of the texture and mechanical properties of coal-bearing mass lithotypes, and experience in supporting reused extraction workings. To implement this scope of research, a geomechanical model and its components were created using the following basic provisions.

First – substantiation of the general model dimensions and conditions at its boundaries. For this purpose, a test calculation was performed for a general geomechanical model, which differs in its increased dimensions along the coordinates Y – height, X – width and Z – thickness along the axial coordinate of the mine working. This takes into account SSS disturbances caused by the construction of the preparatory and stope workings during coal mining, as well as by the impact of reused extraction drift. To determine the boundaries of the propagating SSS anomalies, they should be compared with the stress components for the undisturbed mass. The following initial conditions are:

$$\sigma_y = \gamma H \; ; \qquad (1)$$

$$\sigma_x = \sigma_z = \frac{\mu}{1-\mu}\gamma H \; , \qquad (2)$$

where:

H – depth of the mine working placement;

γ – the weight-average unit specific gravity of coal-overlaying formation rocks up to the earth's surface;

μ – Poisson's ratio of rocks.

According to the geological service data of the mine, the most dangerous areas of the prefabricated drift were selected and, in accordance with the coal-overlaying formation texture, its weight-average unit specific gravity was calculated. Then, using Formula (1), the initial vertical stresses of the undisturbed rock mass σ_y = 6.5 MPa were determined.

Horizontal stresses $\sigma_x = \sigma_z$ will differ for each lithotype due to different Poisson's ratio values. This was taken into account using the proven FEM by introducing the "symmetry" condition along the vertical boundaries of the model. In this case, the calculation of horizontal stresses $\sigma_x = \sigma_z$ is performed automatically according to the values of μ assigned for each lithotype. Information on the coefficient μ was taken from the geological service data of the mine, and the lacking information was obtained from the results of research on physical-mechanical properties of the Western Donbas rocks, which are presented in the works [66].

The lower horizontal surface of the model rests on a rigid base in accordance with the recommendations developed in [62], [67], [68].

Based on the above conditions, test calculations were performed on a model with the following dimensions: height $y = 60$ m, width $x = 70$ m, thickness $z = 8$ m (based on the calculation of modeling ten sets of frame support). The results of test calculations showed that a model height of $y = 45$ m and width of $x = 40$ m is quite sufficient, and in terms of the model thickness Z, the edge effects extend less than 1.0 m into the mass. Therefore, the model thickness is reduced to $z = 6$ m.

The second stage of the rock mass model fully corresponds to the texture of the coal-bearing stratum in the selected most dangerous area of the longwall face extraction column. To increase the accuracy of calculations, the model simulates real processes of contact disruption along the stratification planes of adjacent lithotypes.

The third stage of preparing a geomechanical model for conducting a computational experiment involves substantiating the physical-mechanical properties of each lithotype of the coal-bearing mass; they correspond to the data of the mining-geological prediction and experimental studies of the characteristics of the Western Donbas lithotypes [69]. The strength properties of the immediate/main roof and bottom rocks are incorporated into the model, taking into account moisture content [70]-[72]. For the remaining lithological varieties, the water content, fracturing and rheology of the rocks was taken into account in accordance with documents [73], and research work [66] which ensured the adequate representation of their deformation behavior.

All the lithotypes that compose the adjacent coal-bearing mass have low strength characteristics both in a naturally wet and waterlogged state. Therefore, these lithotypes are highly prone to plastic deformation, and a fairly adequate reflection of this state is provided by a bilinear diagram of rock deformation. The first linear section models the prelimiting stage of loading using the deformation modulus of each lithotype as a deformation characteristic. The limiting and superlimiting stages are simulated by the condition of plasticity with a constant elementary rock volume [74], [75].

When performing calculations, the effect of rock-weakening factors was taken into account: water content, fracturing and rheology by introducing known coefficients in accordance with the current normative document [73].

The calculated rock resistance to compression R and the calculated deformation modulus E_c are determined by the following formulas:

$$R = \sigma_{comp} \cdot K_c \cdot K_w \cdot K_t ; \quad (3)$$

$$E_c = E K_t^2 , \quad (4)$$

where:

K_c – coefficient that takes into account the "additional rock mass disturbance by surfaces of weakening without adhesion and low binding strength" is determined by [73];

K_w – coefficient that takes into account "de-strengthening of waterlogged rocks as a result of filtration through the mass of aquifer water" is determined by [73];

K_t – coefficient that takes into account the decrease in mechanical characteristics of rock under long-term loading is calculated using the Formula:

$$K_t = \sqrt{1 - \frac{x}{\beta}} , \quad (5)$$

where:

$\frac{x}{\beta}$ – rheological index, determined in accordance with [66] by the Formula:

$$\frac{x}{\beta} = 0.8 - 0.326 \lg \sigma_{comp} . \quad (6)$$

The third stage is the final stage in the complex of test calculations for creating a geomechanical model of the mass; based on their results, a model of the coal-bearing stratum around the prefabricated drift in the area of stabilization of rock pressure manifestations during its reuse is fully substantiated and prepared for a computational experiment.

The next (fourth) mandatory stage in preparing the computational experiment is to substantiate and test the second component of the general geomechanical model – the supporting and protection systems of the prefabricated drift in the area of rock pressure stabilization after the passage of the longwall face.

The proposed scheme for supporting the drift was modeled in full compliance with the developed recommendations, as shown in Figure 4 in the general plan.

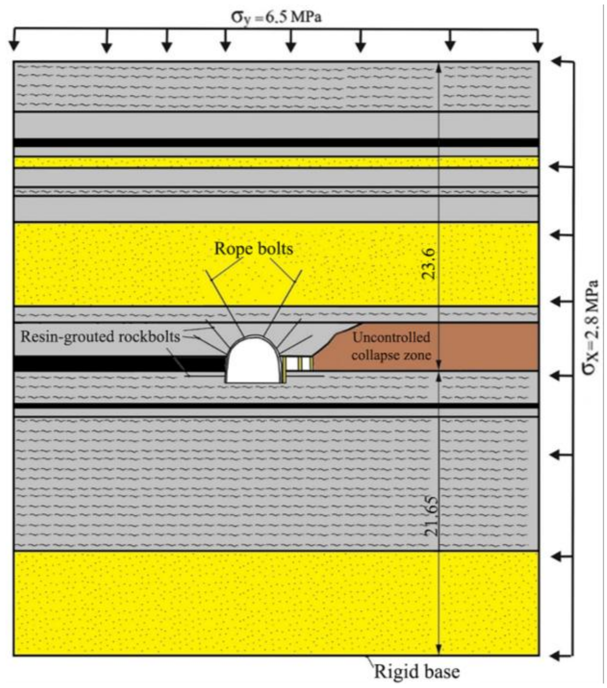

Figure 4. Geomechanical model of the rock mass around the extraction site in the area of stabilization of rock pressure manifestations in the prefabricated drift according to the recommended scheme of its supporting for reuse

Based on the developed geomechanical model, a computational experiment was performed to identify the main regularities of the stress-strain state formation in the rock mass and support system around the reused prefabricated drift. The analysis was focused on changes in the stress distribution near the longwall face junction, the degree of loading of the support elements, and the influence of the proposed supporting method on the stability of the drift under specific mining and geological conditions. This made it possible to evaluate the practical efficiency of the recommended support scheme and to substantiate its resource-saving advantages.

3. Results and discussion

Until now, not only a considerable experience of operating reused extraction workings has been accumulated, but also a sufficient volume of experimental research has been collected on rock pressure manifestations in many mines of Western Donbas [67], [76], [77]. The results of observations are of great importance for the awareness of geomechanical processes, in order to direct them towards substantiating the most expedient schemes for supporting reused mine workings, with the main criterion – resource saving [78], [79].

3.1. Experimental analysis of rock pressure manifestations in extraction drifts

The results of visual and instrumental observations of the state of the extraction drifts were reviewed sequentially as the extraction columns were mined within the above-mentioned mine field area of the c_6 seam ("Yuvileina" mine).

The drift was reused. First as a drift during the mining of the 590 longwall face, and then as a boundary drift when conducting stope operations in the 592 longwall face. Therefore, two series of fixations of the mine working contour displacements were conducted at the measuring stations – when driving the 590 longwall face, and then, after a long period of time, during the approach and retreat from the measuring stations of the 592 longwall face. Thus, it was possible to assess the state of reused mine working over the entire period.

The results of the analysis are given in the form of graphs (Fig. 5) showing change in any fixed size depending on the distance Z of a given section from the stope face of the 590 longwall face. Since measurements were taken at several pickets, the results obtained were averaged.

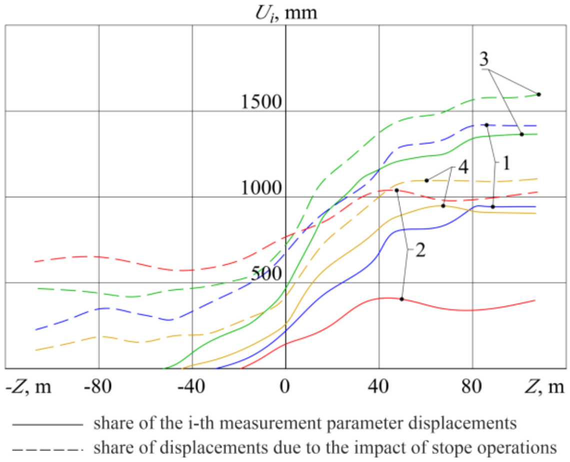

Figure 5. Dependences of the drift 590 contour displacements U_i on coordinate Z of the 590 longwall face position to measured section: 1 – U_{h1}; 2 – U_{b1}; 3 – U_{c1}; 4 – U_{c2}

Analysis of the vertical convergence U_{h1} of the roof and bottom made it possible to determine the following. Outside the zone of influence of stope operations, a decrease in the mine working height was recorded in the range of 420-470 mm; most of U_{h1} is due to the swelling development in the bottom rocks. Nevertheless, according to the degree of activation of yielding joists, as well as to the state of cap board and frame prop stays, the lowering of the roof rocks is assessed at the level of 120-180 mm. Therefore, we have concluded that even outside the zone influenced by stope operations, the supporting system of the 590 prefabricated drift does not fully cope with the load on the mine working roof.

As for the change in the auxiliary parameters of frame support displacements (as the stope face advances), the following should be noted. Corresponding graphs are given in Figure 6 and the first of them is the difference (h_2-h_3) of h_2 and h_3 heights from the side of non-working and working walls of the drift, which are measured vertically from the frame yielding joists to the mine working bottom. This parameter makes it possible to assess the degree of frame deformation asymmetry in the vertical direction.

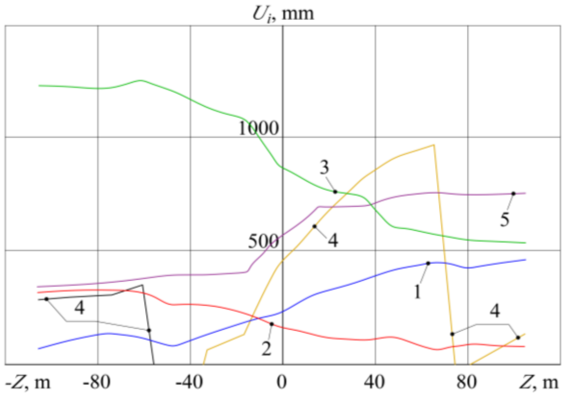

Figure 6. Patterns of change in auxiliary parameters for assessing the state of the 590 prefabricated drift during the period of mining the 590 extraction site: 1 – h_2 – h_3; 2 – b_1 – b_2; 3 – b_1 – b_3; 4 – U_{h4}; 5 – a_1

Outside the zone influenced by stope operations, there is a slight asymmetry in the vertical frame deformation in the range of 80-140 mm. Starting from the area Z = -(30-40 m) ahead of the longwall face, there is a steady increase in the difference h_2-h_3 with an approximately constant growth gradient up to Z = 45-50 m behind the longwall face. In the zone of stabilization of rock pressure manifestations, the difference in dimensions varies in a relatively narrow range of 420-460 mm.

Next, consider the following auxiliary parameters b_1-b_2 and b_1-b_3, which can be used to assess the degree of deformation of the frame prop stays and the change in their initial shape (graphs 2 and 3 in Fig. 6). The difference in dimensions b_1-b_2 in the area outside the zone influenced by stope operations varies in the range of 270-340 mm. Starting from a distance to the longwall face Z = -(30-35 m), this parameter gradually decreases to 11 mm (at Z = 35 mm). Further, in the stabilization zone of rock pressure manifestations, the variations in the value b_1-b_2 are in the range of 70-120 mm.

When mining the 592 extraction site, the 590 prefabricated drift was repeatedly used as a boundary drift. The measuring stations remained the same, as did the methodology for recording the mine working contour displacements.

Therefore, it will be more clear and expedient to assess the degree of influence of stope operations in the 592 longwall face separately, which will allow for clear systematization of patterns, conclusions and recommendations during the initial and repeated use of the extraction drift. Therefore, when determining and analyzing the patterns of change in the geometric parameters of the 590 prefabricated drift depending on the distance to the 592 longwall face, it is logical to represent only its influence, taking as a basis the constant dimensions of the drift after its initial use. The patterns of change in the contour displacements U_i (Z) of the 590 prefabricated drift are shown in the graphs in Figure 7.

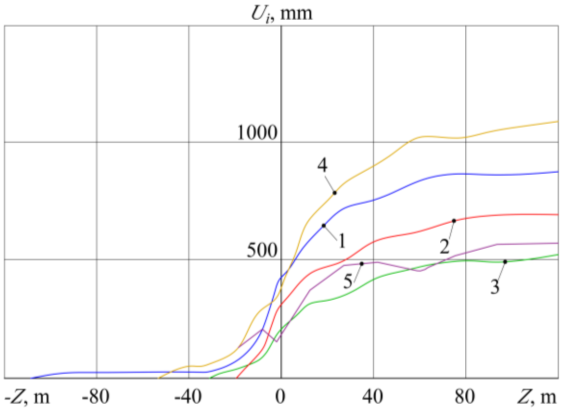

Figure 7. ***Dependences of the contour displacements of the 590 prefabricated drift on the distance Z to the 592 longwall face (repeated use of the drift): 1 – U_{h1}; 2 – U_{b1}; 3 – U_{c1}; 4 – U_{c2}; 5 – U_{c2} – U_{c1}***

The revealed patterns are quite logical, since numerous studies of the state of extraction workings indicate a predominant displacement of their contour from the side of the active longwall face. This fact is also confirmed by research data: the displacement U_{c2} exceeds U_{c1} by 560 mm, which significantly distorts the shape of the frame, deformed earlier during stope operations in the 590 longwall face. The patterns of change in auxiliary parameters (Fig. 8) complement the overall idea of the state of the 590 prefabricated drift when it is reused during the period of stope operations in the 592 longwall face.

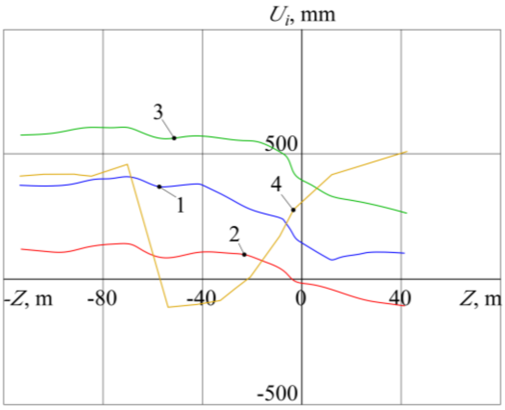

Figure 8. ***Patterns of change in auxiliary parameters for assessing the state of the 590 prefabricated drift during the period of mining the 592 extraction site: 1 – h_2 – h_3; 2 – b_1 – b_2; 3 – b_1 – b_3; 4 – U_{h4}***

To summarize the results of measurements of horizontal convergences of frame prop stays, it is necessary to point out their significant plastic deformations, which sharply reduce the load-bearing capacity of the frame support and the stability of mine working as a whole. Therefore, special attention should be paid to limiting the convergence of the mine working sides due to intense lateral bearing pressure.

The value U_{h4} of the bottom heaving after its previous dinting stabilized at the level of 420-460 mm outside the zone influenced by stope operations. Ahead of the frontal bearing pressure zone from 592 longwall face, the bottom rock dinting was performed to a depth of about 0.6 m, after which there was a gradual increase in the bottom heaving with a slight intensity from the mark of Z = -32 m ahead of the longwall face to the mark of Z =12 m behind the stope face. The bottom heaving was 520 mm.

3.2. Performance of combined roof-bolting system at the experimental site

We have analyzed the results of extensive experimental studies of rock pressure manifestations in reused extraction drifts, where basic schemes for installing resin-grouted rock-bolts (supporting – roof-bolting according to [80], [81]). These instrumental observation data serve as a basis for comparative analysis of the recorded values of the rock contour shear of the 594 prefabricated drift, supported by one of the variants of the combined roof-bolting system (Fig. 9).

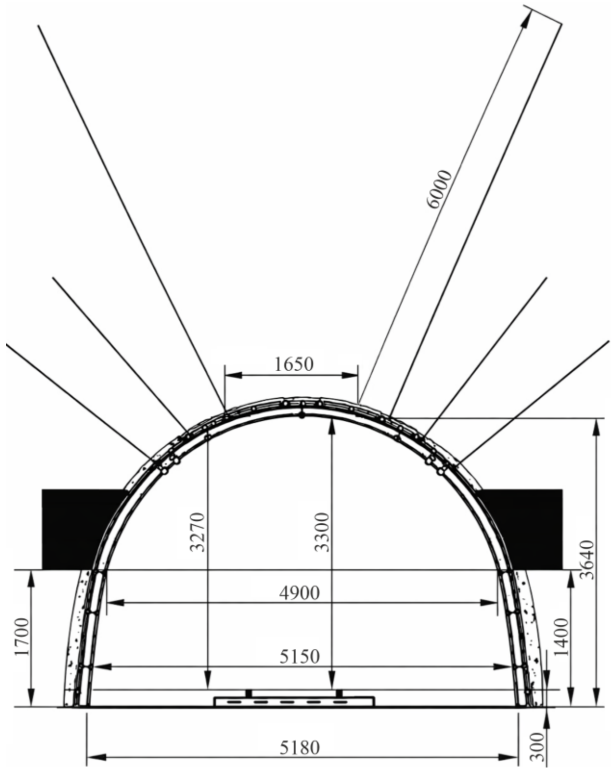

Figure 9. ***Scheme for supporting the 594 prefabricated drift at the experimental site (KShPU-15.0, S = 15.3 m²)***

The peculiarities of rock pressure manifestations are reflected by the corresponding graphs in Figure 10, characterizing the patterns of change in the geometric parameters of the 594 prefabricated drift depending on the distance Z to the stope face of the 594 longwall face.

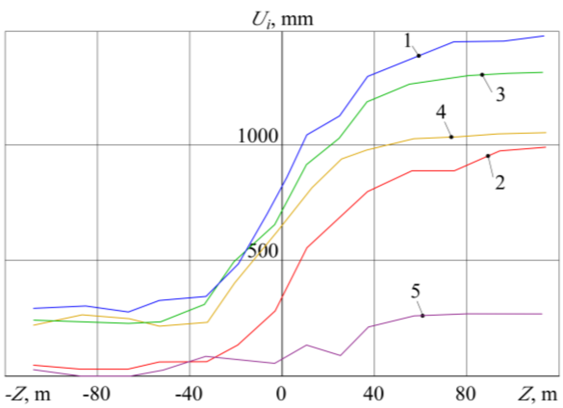

Figure 10. ***Dependences of the 594 prefabricated drift contour displacements U_i on the distance Z to the stope face at the experimental site: 1 – U_{h1}; 2 – U_{b1}; 3 – U_{c1}; 4 – U_{c2}; 5 – c_2 – c_1***

Summarizing the obtained results of mine observations, it should be noted the satisfactory state of the 594 prefabricated drift at the experimental site after driving of the 594 longwall face, which allows it to be reused without any repair or restoration work when mining the adjacent extraction site. The positive result was achieved due to the use of a combined roof-bolting system in the mine-working roof. The formulated conclusion is confirmed by the results of mine studies of the patterns of change in the so-called "auxiliary" parameters.

Analysis of the results of auxiliary parameter measurements confirmed the sufficient efficiency of the armoured-rock plate operation in the drift roof in terms of protecting its frame support from rock pressure manifestations. Compared to the state of the 594 prefabricated drift along the rest of its length (outside the experimental site), the following positive trends should be indicated:

– the roof and bottom rock convergence decreased by 2.47 times in the area outside the zone influenced by stope operations and by 35% in the zone of stabilization of the rock stratum shear after driving the 594 longwall face;

– convergence of frame prop stays (along the bottom of the drift) outside the zone influenced by stope operations is practically absent at the experimental site, and in the zone of stabilization of rock pressure manifestations, the decrease in horizontal displacements was 43%;

– the diagonal dimension from the side of the working wall of the drift is reduced by 49% outside the zone influenced by stope operations and by 34% in the area of stabilization of rock pressure manifestations; for diagonal thrust from the side of the mined-out wall of the drift, the reduction in displacements was 15 and 27%, respectively;

– for the above reasons, the asymmetry of the diagonal dimensions is reduced by 2 times, which resulted in the occurrence of only minor plastic deformations of the cap board and prop stays while maintaining the load-bearing capacity of the frame support as a whole;

– the reduction in horizontal deformations of lower part of the frame prop stays was 11% outside the zone influenced by stope operations and 40% in the zone of shear stabilization of coal-overlaying formation; the corresponding reduction in bending deformations of the prop stays along their entire height reaches 3% outside the zone influenced by stope operations and 34% in the zone of stabilization of rock pressure manifestations;

– the bottom heaving value was reduced by 2 times in the area outside the zone influenced by stope operations and by 41% in the zone of shear stabilization of coal-overlaying formation;

– the state of yielding joists and their operating mode is entirely satisfactory, with the exception of a limited number of individual violations.

As a result, the results of mine surveys of the 594 prefabricated drift state, when installing a combined roof-bolting system, made it possible to obtain multi-parameter evidence. The state of the experimental site of the 594 prefabricated drift fully complies with the operational standards and rules for its successful reuse as a boundary when mining the adjacent extraction site.

3.3. Stress-strain state of the rock mass around the prefabricated drift

For the study, an area of (reusable) prefabricated drift was identified where rock pressure manifestations reach their maximum values. By geomechanical model, shown in Figure 4, a computational experiment was performed and stress components were determined, the most informative of which are vertical σ_y, horizontal σ_x and generalized "stress intensity" indicator. Below, the results of the analysis of distribution fields σ_y, σ_x and σ in the rock mass adjacent to the mine working are given in this order.

The following field σ_y peculiarities are observed in the mine working roof (Fig. 11). In the immediate roof, represented by a weak argillite and siltstone, there is an arch of de-stressed rocks of a slightly asymmetrical shape:

– an arch limiting the tensile stresses σ_y, develops to a height of 0.7-0.8 m and occupies a width of 1.2-1.3 m;

– a little higher in the siltstone and in the lower part of the sandstone, there is a de-stressing zone of the level of $K_y = \sigma_y / \gamma H = 0.4\text{-}0.8$, up to 2.7 m high and 2.1 m wide; that is, the zone has an elongated shape into the roof of the mine working;

– deep into the sandstone thickness down to the coal interlayer (height from the mine working is 14.6 m), alternating arch-shaped areas with varying concentrations of vertical compressive stresses from $K_y \approx 1.0$ to $K_y = 2.0\text{-}2.3$ are observed in the roof.

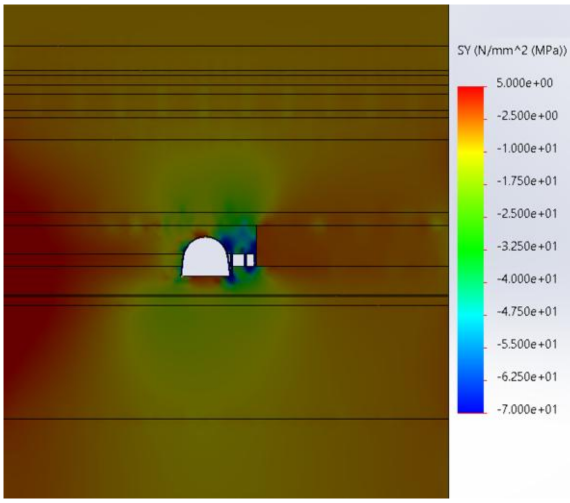

Figure 11. Curve of vertical stresses σ_y distribution in the rock mass around the prefabricated drift

As for the state of the prefabricated drift bottom, the active de-stressing zone with the occurrence of tensile stresses of $\sigma_y \leq 5.0$ MPa extends up to 3.2 m in width and up to 1.2 m in depth into the siltstone. In the main bottom, de-stressing zone (with the action of compressive stresses σ_y) gradually disappears until the initial state of the untouched mass is reached.

It is well known that the horizontal stress curve σ_x provides very informative data (Fig. 12) on the bending processes of rock layers in the rock mass around the mine working. Against the background of the total sufficiently stable distribution of σ_x over most of the model plane at a level close to the undisturbed mass state ($K_x \approx 1.0$), there are still some component σ_x disturbances in both the tensile and compressive directions.

The curve σ_x peculiarities indirectly confirm the feasibility of installing a pair of resin-grouted rockbolts in the springs of the mine working arch on both its sides. The load value of de-strengthened rocks (from the action of σ_x) in the immediate roof does not exceed 100-110 kPa and does not pose a threat to the stability of the prefabricated drift. A slight bend can also be seen in the main roof of the thick sandstone, running from the prefabricated drift.

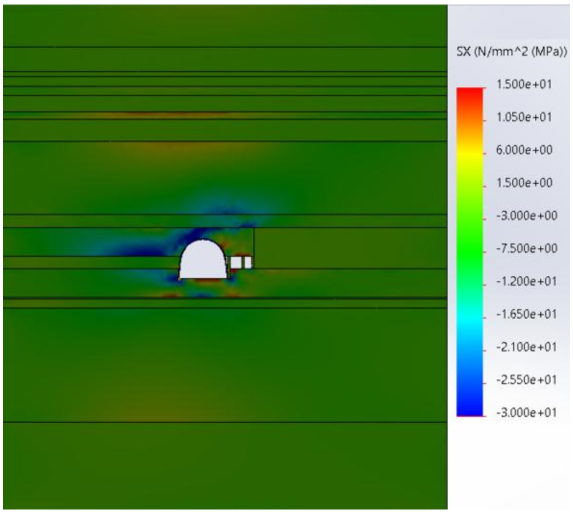

Figure 12. Curve of horizontal stresses σ_x distribution in the rock mass around the prefabricated drift

In the lower part of the sandstone, propagation-limited concentrations of compressive stresses σ_y = 15-20 MPa are formed, which are approximately equal to its compressive resistance in a sample of σ_{comp} = 19.0 MPa, so that the de-strengthening will also be local. In the upper part of the sandstone, at a distance of up to 1.0-1.2 m, there are small tensile stresses of σ_x = 1.5-6.0 MPa, which, given their limited area of action, are not capable of causing the loss of stability of such a thick (6.5 m) lithotype. Therefore, there are also indirect arguments for the formation of an armoured-rock structure in sandstone and siltstone with sufficient resistance to limit the shear of the main roof rock layers. Above the sandstone, in an unstable state up to 12 m wide, there is only thin siltstone above the mine working, but due to its small thickness of 0.6 m, it is not capable of disturbing the equilibrium of the main roof.

In the area of bearings of the frame prop stays at the height of the lower dinting, there are limited zones of compressive stress concentrations σ_x equal to the value of σ_{comp} of the siltstone in the immediate bottom. It would also be advisable to install one horizontal resin-grouted rockbolt on both sides of the mine working, which will increase the stability of the adjacent bottom rocks. Stress intensity σ is an indicator that summarizes the stress state of the studied object, and its value is used to assess the rock stability. The σ distribution curve is shown in Figure 13.

In the immediate roof from the side of the working wall of the mine working, maximum concentrations of $\sigma \leq 50$ MPa are present, extending over almost the entire thickness of the argillite, and in width – from the zone of uncontrolled collapse to approximately the middle of the width of the mine working arch. This concentration of σ is several times higher than that σ_{comp} of argillite, and therefore it is definitely destroyed; in order to at least partially preserve its residual strength, it is recommended to strengthen the specified zone with two resin-grouted rockbolts. The area of action of the maximum stresses σ in the middle part of the semi-arch, arch is strengthened with a rope bolt from the side of the working wall of the mine working. From the side of the non-working wall of the drift, a concentration of σ = 15-25 MPa acts in the immediate roof, which still higher than that σ_{comp} of the argillite. It is recommended here to install a pair of resin-grouted rockbolts and one rope bolt.

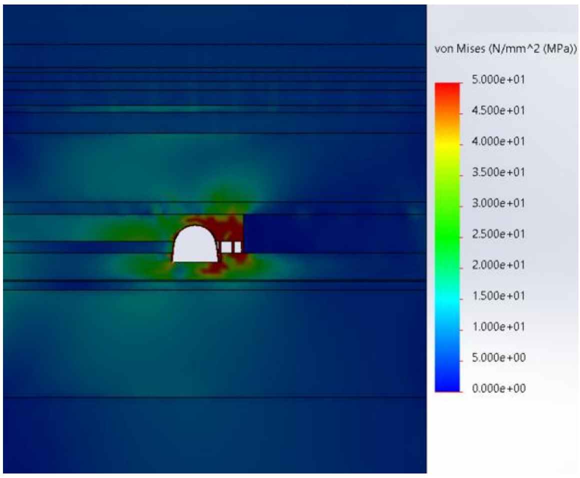

Figure 13. Curve of stress intensity σ distribution in the rock mass around the prefabricated drift

In the immediate bottom of the coal seam C_{10}^u, from the side of the non-working wall of the drift, concentrations of σ = 18-23 MPa act, which are at the level of (σ_{comp} = 27.4 MPa). This almost limiting state of the bottom argues for the expediency of installing horizontally positioned resin-grouted rockbolts along the height of the lower dinting of the drift. From the side of its working wall, such a measure is all the more expedient, because local zones have formed under the protective structure and in the corner part of the drift bottom, where the stress intensity σ is almost twice as high as that σ_{comp} of siltstones.

3.4. Stress-strain state of supporting and protection

The studied components of the prefabricated drift supporting scheme can be divided into three groups of elements: frame support (cap boards and prop stays), combined roof-bolting system (resin-grouted rockbolts and rope bolts), protective structure (side prop stay of the strengthening support, prop stays on the drift berm). The distribution of vertical σ_y and horizontal σ_x stresses is examined for a clear representation of the resistance effectiveness of elements in the vertical and horizontal directions of rock pressure action. The vertical stress σ_y curve is shown in Figure 14.

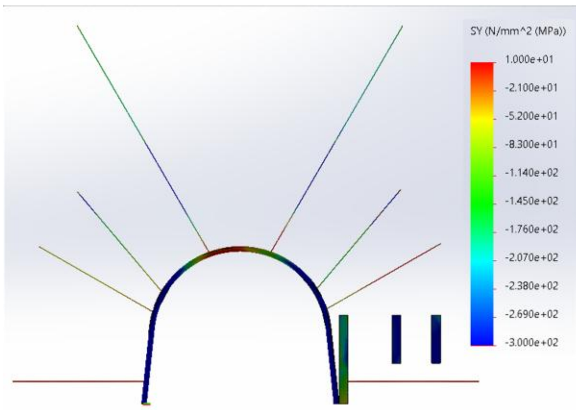

Figure 14. Curve of vertical stresses σ_y in the elements of the recommended scheme for supporting the prefabricated drift

The following peculiarities of σ_y action are observed in the frame support. The frame cap board undergoes sign-changing stresses ranging from compressive stresses σ_y = 200-280 MPa in the arch springs to tensile stresses

$\sigma_y \leq 10$ MPa in its keystone. However, there are no significant changes of σ_y in the cross-sectional area of the special concave profile (SCP), which proves the absence of any significant bending moment. No significant bending moment is observed in the frame prop stays either – the distribution of σ_y is relatively uniform both across the cross-sectional plane of the SCP and across the height of the prop stays. However, the value of compressive stresses σ_y is quite high and ranges from 270 to 300 MPa, which is equal to the yield strength of steel St.5 – $\sigma_{y.s.}$ = 270 MPa. That is, the frame support elements are exposed to the action of intense loads of mainly vertical direction.

The load level of rope bolts from the working and non-working walls of the drift differs from each other. From the working wall of the drift, the distribution of σ_y along the length of the rope bolt is 6.0 m:

– in the zone adjacent to the mine working, tensile stresses of σ_y = 2-8 MPa act over a length of up to 0.5 m;

– further into the roof along the length of the roof-bolt, σ_y change to compressive stresses of a fairly significant value of 180-220 MPa with a decrease only at the buried end (bolt lock) to 70-100 MPa.

Similar σ_y distribution trends occur in the rope bolt from the non-working wall of the drift, but with slightly less intensity:

– tensile stresses of $\sigma_y \leq$ 8-10 MPa act in the area up to 0.25 m;

– further into the roof of the mine working, at a length of 1.7-1.9 m, compressive stresses of σ_y = 200-240 MPa occur;

– at the buried end of the roof-bolt with a length of 3.8-4.0 m, compressive stresses are reduced to 70-90 MPa.

The data presented indicate that, with the exception of the near-contour areas of the rope bolt lengths, they perform their function of preventing the roof rock stratification by compression poorly, which can only occur when the rope bolt is tensioned. The reason for this, in our opinion, is the incompatibility of the frame cap board deformation and armored rocks, especially if, as is usually the case, the rope bolt is located in the interframe gap between several frames (usually 3-4 frames).

On the other hand, a rope bolt can have a direct strengthening effect on the frame by connecting it to the cap board through the installation of rope crown runners. Figure 15 shows a fragment of the installation of rope crown runners at the experimental site of the 594 prefabricated drift, "Yuvileina" mine. Effective formation of a protective armoured-rock plate occurs when the rope bolts exposed to tension from their connection to the frame cap board.

Figure 15. Fragment of the installation of rope crown runners at the experimental site of the 594 prefabricated drift, "Yuvileina" mine

To argue the advantages of using rope crown runners and the clarity of evidence of the expediency of this resource-saving direction, the most informative curves are examined for vertical stresses σ_y and stress intensity σ.

Examine the curve of vertical stresses σ_y (Fig. 16) in the supporting elements of the prefabricated drift when using the rope crown runners of the frame cap boards by means of their connection with the tail joints of rope bolts in the combined roof-bolting system for forming a protective armoured-rock plate.

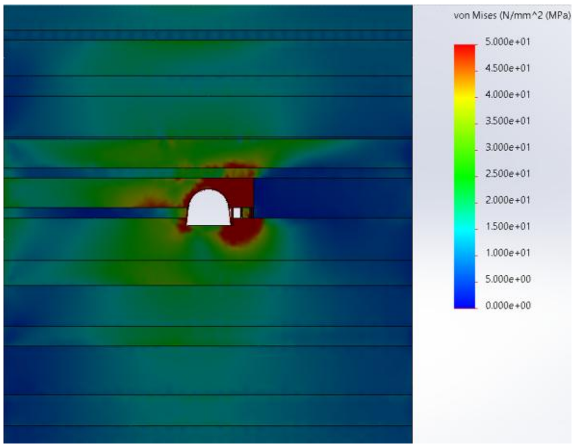

Figure 16. Curve of vertical stresses σ_y in the elements of the scheme for supporting the prefabricated drift when using rope crown runners

The frame cap board also experiences sign-changing stresses σ_y, but they are several times, and in some cases an order of magnitude, smaller than in the variant of supporting the prefabricated drift without the use of rope crown runners. Thus, with the exception of limited areas in the vicinity of yielding joists, the frame cap board is exposed to influence of moderate values σ_y ranging from tensile stresses of 30-40 MPa to compressive stresses of no more than 60 MPa. Moreover, such a value of compressive stresses σ_y occurs only in a limited area (0.20-0.25 m long) where the rope crown runners are located. Over the rest of the cap board length, the value σ_y varies in the range from tensile stresses of 30-40 MPa to compressive stresses of 10-35 MPa. Thus, vertical stresses in the cap board decrease by no less than 3.3-4.7 times, and this is easily explained by the creation of additional bearings with a large resistance reaction (not less than 200 kN according to the technical characteristics of rope bolts).

From a resource-saving perspective, the given results show that replacing the SCP-27 profile with the SCP-22 profile can save 18.5% of rolled metal, or 25% when increasing the frame installation step from 0.8 to 1.0 m.

The use of rope crown runners (when using a combined roof-bolting system) provides significant savings in material and labour resources in the area of the drift near the "window" of the longwall face and immediately behind it, where a protective structure is built for the reuse of the mine working.

The traditional technology for supporting extraction drifts as the longwall face approaches involves installing central wooden prop stays of the strengthening support ahead of the frontal bearing pressure zone at a distance of at least 20-40 m. These prop stays require certain resource expenditures, significantly interfere with the implementation of technological operations in the area where the longwall face joins the drift, and also worsen the ventilation regime.

It is proposed to completely abandon the central prop stays of the strengthening support and replace their action with rope crown runners. To substantiate this proposal, the most dangerous area near the "window" of the longwall face was modeled, where, according to the existing technology, it is necessary to dismantle and then restore the frame prop stay from the side of the working wall of the drift. Regarding the evidence of the feasibility of using rope crown runners, we analyzed the fields of vertical stresses σ_y and stress intensities σ for two compared variants: installation of a central wooden prop stay of the strengthening support and the proposed use of rope crown runners in a combined roof-bolting system.

First, two curves of vertical stresses σ_y in the elements of the schemes for supporting the prefabricated drift are examined. When using a central wooden prop stay of the strengthening support (Fig. 17), the following σ_y distribution pattern is observed in the absence of a prop stay from the side of the working wall of the drift.

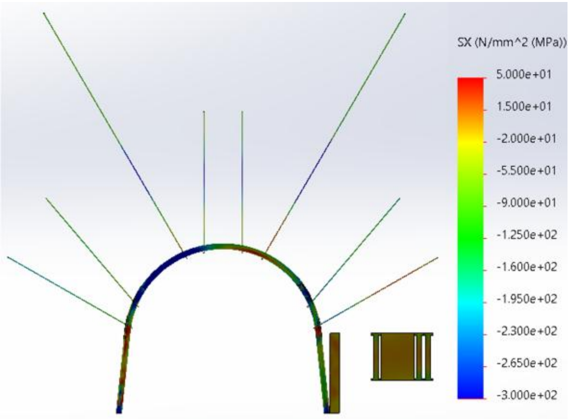

Figure 17. Curve of vertical stresses σ_y in the elements of the scheme

Vertical stresses of different signs act in the cap board of the frame. At the end of the cap board, from the side of the non-working wall of the drift (frame lock area), a concentration of compressive stresses of σ_y = 220-280 MPa is formed, where the SCP is close to the limiting state, or equal to the value of the calculated yield strength of St. 5 steel. When moving towards the central part of the frame arch, the compressive stresses σ_y almost disappear (0-5 MPa), and then increase to 20-30 MPa. In the arch keystone (up to 1.0 m long), tensile stresses of $\sigma_y \leq$ 50 MPa appear, but it is important to note that a significant bending moment acts here and coincides with the contact of the wooden prop stay.

The frame prop stay from the side of the non-working wall of the drift is exposed to compressive stresses σ_y at the level of the calculated yield strength of SCP steel, which is also a negative factor in the loss of the mine working stability. In this case, the rope bolt moderately helps support the frame prop stay, but the tensile stresses of $\sigma_y \leq$ 50 MPa only act in the near-contour zone over a length 1.2-1.3 m of the rope bolt.

The central wooden prop stay of the strengthening support is loaded to 70-75% of its load-bearing capacity and can be considered to fully perform the functions assigned to it. The side wooden prop stays and protective structure elements operate at maximum load at the limit of their load-bearing capacity. Compare the identified peculiarities of the σ_y curve with those related to the variant using rope crown runners and abandoning the central prop stay of the strengthening support (Fig. 18).

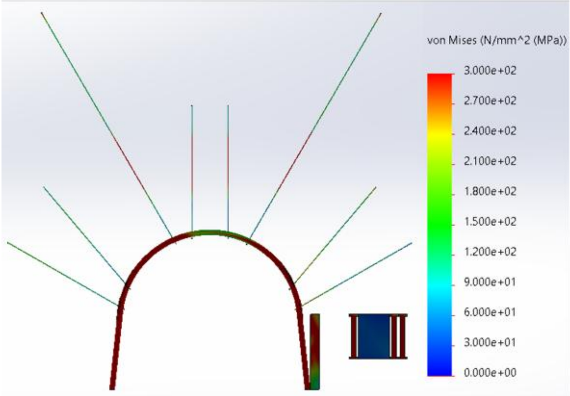

Figure 18. Curve of vertical stresses σ_y in the elements of the scheme

In the frame cap board, vertical stresses decreased dramatically to almost complete de-stressing in the central part of the frame arch: an interval σ_y from tensile stresses of up to 2 MPa to compressive stresses of less than 3 MPa. However, tensile stresses of σ_y = 20-50 MPa act near the locations of the rope crown runners, but they do not pose a threat, as they are 5.4-13.5 times less than the calculated yield strength of SCP steel.

It is noteworthy that the frame prop stay (from the side of the non-working wall of the drift) was significantly de-stressed by 18-32%, which occurred due to the action of rope crown runners in the system of combined roof-bolt support. Indeed, the rope bolt (from the side of the non-working wall of the drift) has recorded the occurrence of several areas of action of tensile stresses σ_y, which indicates increased load and a corresponding reaction to the frame cap board. The rope bolt experiences even greater load from the side of the working wall of the drift: here, tensile stresses σ_y act along most of the roof-bolt length, which prevents the cap board branch from bending into the mine-working cavity.

As a result of a comparative analysis of vertical stress σ_y curves, significant advantages were identified in using rope crown runners in the scheme for supporting the prefabricated drift in the area of the longwall face "window".

In addition to the technological advantages mentioned above, we have:

– almost complete de-stressing of the central part (2.1-2.3 m wide) of the frame cap board;

– no bending of the cap board at the point of contact with the central wooden prop stay of the strengthening support;

– de-stressing of the frame prop stay (from the side of the non-working wall of the drift) by 18-32%, which will increase its stability or reduce metal consumption.

To confirm the conclusions made, a comparative analysis of stress intensity σ distribution curves was performed for both variants of the schemes for supporting the prefabricated drift.

Thus, the effectiveness of using rope crown runners in combination with the installation of a combined roof-bolting system is confirmed, and in specific figures, it can be expressed in savings of SCP rolled metal products by 15-22%.

In general, the conducted series of computational experiments provides an evidence base for the feasibility of implementing recommendations for supporting the prefabricated drift, based not only on the results of computational experiments, but also on testing the recommended scheme in the conditions of the Western Donbas mines.

As a result of performing a series of studies, the scheme for supporting the prefabricated drift has been substantiated, which provides significant savings in material and labour resources when reusing the mine working. The scheme parameters are shown in Figure 19. Therefore, the conducted computational and field-based studies make it possible to consider the proposed scheme for supporting the prefabricated drift as a practically justified and geomechanically efficient solution for its repeated use. The use of rope crown runners in combination with the roof-bolting system provides unloading of the frame support, improves the stress distribution in the junction zone of the longwall face and the extraction drift, and creates conditions for reducing material and labour consumption.

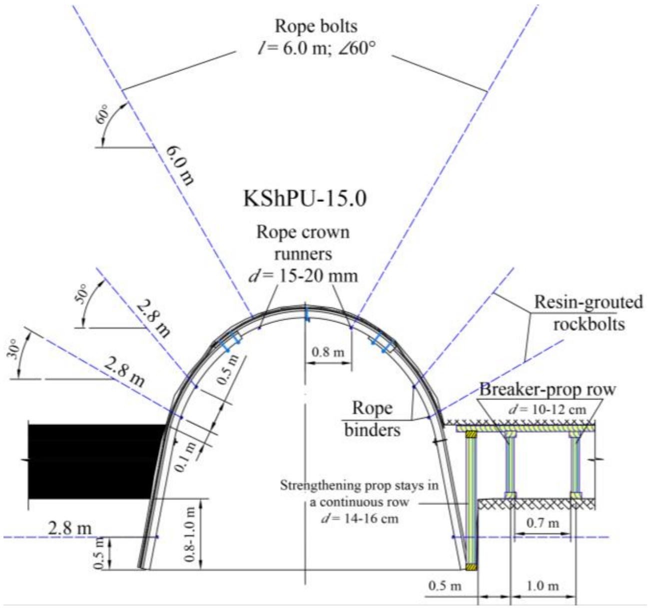

Figure 19. Recommended scheme for supporting the prefabricated drift of the C_{10}^{u} seam at the "Samarska" mine

The agreement of these results with recent foreign publications indirectly confirms the correctness of the adopted geomechanical approach and the practical relevance of the proposed support concept for repeated roadway use [46], [47], [82]-[85]. Consequently, the recommended scheme can be regarded as an effective resource-saving approach adapted to the specific mining and geological conditions of the Western Donbas mines.

4. Conclusions

Experience in supporting extraction drifts in Western Donbas indicates the formation of extensive zones of stratified and de-strengthened rocks around them, all of which, without exception, belong to the category of weak rocks. The parameters of the supporting and protection systems were substantiated on the basis of experimental studies of rock pressure manifestations in extraction drifts and modelling of geomechanical processes around the prefabricated drift using modern analytical FEM.

Mine observations of the state of the prefabricated drifts, supported for reuse in the conditions of the Western Donbas mines, have substantiated the idea of the critical importance of limiting the convergence of the mine working sides by reducing the intensity of lateral bearing pressure when forming an armoured-rock structure of high load-bearing-capacity above the mine working. This is achieved through a combination of rope bolts and resin-grouted rockbolts: its high load-bearing capacity is achieved by maintaining horizontal thrust forces even when the roof layers are broken into rock blocks and the plate has a considerable total thickness (several metres).

In accordance with the mining-geological conditions for mining the extraction site of the Samarska mine, a geomechanical model was substantiated, which as adequately as possible reflects the interaction of the adjacent rock mass with the supporting and protective structures, taking into account: loss of adhesion between adjacent rock layers, their partial de-strengthening, formation of a zone of uncontrolled collapse and elastic-plastic deformation of all constituent elements of the model.

In the area of the longwall face "window", the effectiveness of using the rope crown runners in combination with the installation of a combined roof-bolting system has been confirmed: the frame cap board is de-stressed by 2.5-3.0 times, and for the prop stays, it is possible to save 15-22% on rolled metal. The conducted complex research has created an evidence base for the feasibility of implementing recommendations for resource-saving supporting the prefabricated drift of the Samarska mine during its reuse.

Author contributions

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

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Conflicts of interest

Author VB served as Editor-in-Chief of the *Mining of Mineral Deposits* journal at the time of submission, and author

IK served as Deputy Editor-in-Chief. Neither of them was involved in the handling, peer review, or decision-making process for this manuscript. The manuscript was handled independently by an editor with no conflict of interest. Author MS was employed by LLC "DTEK Energy". The remaining authors declare that they have 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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Обґрунтування ресурсозберігаючих технологій кріплення та охорони виробок при їх повторному використанні

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Мета. Визначити ефективні параметри ресурсозберігаючої технології кріплення та охорони збірного штреку при його повторному використанні на основі експериментальних досліджень і багатофакторного комп'ютерного моделювання.

Методика. У роботі використано експериментальні та чисельні методи дослідження. Експериментальна частина включала шахтні спостереження за проявами гірського тиску в повторно використовуваних виїмкових виробках Західного Донбасу, які оцінювали за зміщеннями контуру штреків і параметрами деформування рамного кріплення на ключових ділянках поперечного перерізу. Чисельне моделювання геомеханічного стану масиву та систем кріплення виконано у програмному комплексі ANSYS на основі методу скінченних елементів із урахуванням текстури породної товщі, фізико-механічних властивостей літотипів, вологості, тріщинуватості, реології порід та порушення контактів між суміжними шарами.

Результати. За результатами експериментальних досліджень і комп'ютерного моделювання доведено ефективність застосування канатних підхватів у поєднанні з комбінованою анкерною системою кріплення. Встановлено, що запропонована схема підтримання знижує інтенсивність проявів гірського тиску та забезпечує суттєву економію матеріальних і трудових ресурсів при повторному використанні виробок. Підтверджено доцільність її застосування для підтримання збірних штреків у складних гірничо-геологічних умовах Західного Донбасу.

Наукова новизна. Встановлено особливості формування напружено-деформованого стану масиву навколо виїмкової виробки при її повторному використанні та обґрунтовано ефективність комбінованої анкерної системи з канатними підхватами для зниження проявів гірського тиску. Отримано нові дані щодо перерозподілу напружень у покрівлі та бокових породах виробки, які пояснюють механізм підвищення її стійкості при застосуванні комбінованої анкерної системи з канатними підхватами.

Практична значимість. Результати роботи можуть бути використані під час проєктування та вибору ресурсозберігаючих схем підтримання штреків, що повторно використовуються, в умовах слабких бокових порід і підвищених проявів гірського тиску.

Ключові слова: *вугілля; гірський масив; виробка; система кріплення; обчислювальний експеримент*