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Optimization solution substantiation for resource-saving maintenance of workings

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Abstract

Purpose. Substantiate the expediency of optimizing decision-making in resource-saving maintenance of mine workings.

Methods. The concept of ensuring the conditions for the repeated use of mine working is based on modern methods of managing the rock pressure manifestations, conducting multifactorial computational experiments, experimental verification of the principles' implementation during effective use of resources in full-scale conditions.

Findings. The directions of improving the fastening and protection structures, which ensure the stability of reused mine workings, have been determined. In this case, the most lightweight protection structure is proposed, the functions of which are transferred to the collapsed and compacted rocks of the uncontrolled collapse zone.

Originality. The basic concept of repeated use of mine workings, taking into account resource-saving technologies, has been formulated and implemented. The stress-strain state of the "mass – support – protection elements" system has been studied, and its rational parameters have been optimized. An example of an optimization solution based on the stated methodology is presented.

Practical implications. The schemes have been developed for calculating the parameters of loading the fastening and protection structures in reused mine workings with a geomechanical substantiation of the adopted provisions and assumptions, which is the basis for issuing recommendations to ensure the mine working stability.

Keywords: *rock mass, reused mine working, efficient use of resources, fastening system, protection elements*

1. Introduction

The immediate and distant prospect of the energy independence in most countries of the world is associated with the technological processes intensification, including during underground mining of deposits.

When performing this task, an urgent and important scientific-technical problem is the preservation of the entire network of mine workings in an operational state, taking into account the issues of cost-effective use of resources [1], [2]. In this regard, the purpose of this research is to improve innovative fastening and maintenance technologies based on managing the state of enclosing mass with its maximum involvement in operation to resist the rock pressure manifestations. The results obtained are necessary to substantiate the possibility of reuse of mine workings, as well as for the geomechanical substantiation of the adopted provisions and assumptions.

2. Formulation of a research problem

The modern world economy requires new ways of the energy industry development based on the concepts of limiting the harmful emissions when using traditional types of carbohydrate fuels, which corresponds to the global strategy of enhancing environmental safety. At the same time, 41% of all electricity is produced in the world thanks to the coal sector [3] In addition, coal is used to smelt 70% of the global volume of steel [4]-[6]. Therefore, there are currently very contradictory trends in the coal industry. On the one hand, one of the components of environmental pollution is emissions of harmful gases into the atmosphere from coal combustion, and as a consequence, the task is set to reduce its consumption globally [7]-[9]. On the other hand, the volume of coal production is growing in some countries [10], [11]. And in this regard, the issue remains relevant – the use of high-performance purification equipment, operating efficiency of which provides for the reliability of functioning of mine workings. The high rates of mining the extraction sites require their timely reproduction, where the key issue is the resource-saving focus of technical policy, which indicates significant cost cut when reusing the mine workings [12], [13]. This way is recognized as the most promising. Thus, the problem of effective maintenance of mine workings in the zone of stope operations influence remains extremely urgent [14]-[16].

The main research concept is to provide conditions for reusing the mine workings with resource-saving technologies based on modern methods of managing the rock pressure manifestations [17], [18] and involving the border mass itself in resisting the geomechanical processes that company stope

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operations. The implementation of the principles for resource saving is performed in two directions: strengthening of the border rocks with roof-bolting systems with the creation of armored-rock load-bearing structures [19]-[21] control of the bearing pressure in the sides of mine working using protection systems of variable rigidity [22]-[24].

A generalized structural-logical diagram (Fig. 1) is proposed for the implementation of resource-saving concept in conditions of repeated use. It is based on the analyzed experience of maintaining the mine workings in various mining-geological conditions and identifying the disadvantages of the used fastening and protection systems.

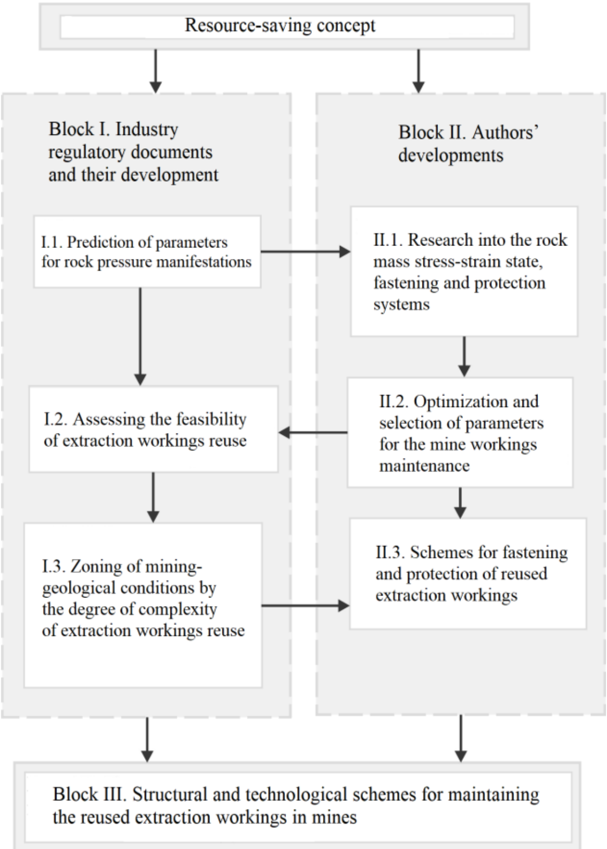


Figure 1. Structural-logical diagram of the extraction working reuse

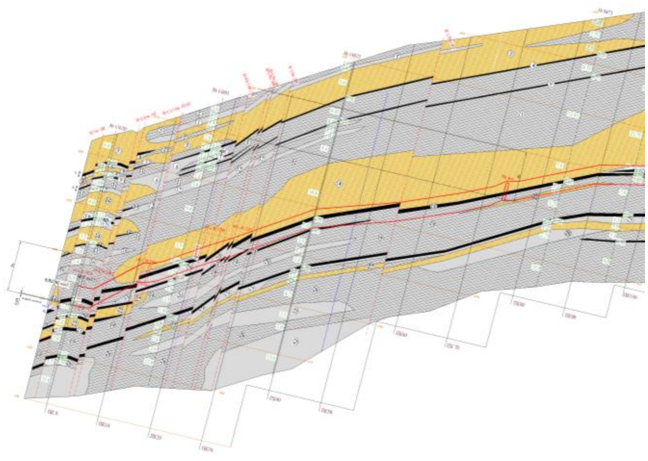
The structural-logical diagram consists of three main blocks, each of which is filled with specific computational and explanatory materials in the process of conducting research and experimental-industrial testing the effectiveness of the recommended parameters for fastening and protection systems. According to the stated methodology, let us study the process of optimizing the solution for resource-saving maintenance of mine workings using the example of mining-geological conditions of Western Donbas mines in Ukraine [25]-[27]. These mines are characterized as difficult due to mining in a stratified soft rock mass, which is partially flooded with water and has intense fractures. Under such conditions, the rock pressure manifestations are actively developing, especially in the zone of stope operations influence, where the sectional working is maintained for a long period until the second stope face is driven.

2. Mining-geological and mining-technical conditions

This problem is solved using the example of maintaining the mine workings in the Western Donbas mines of Ukraine. Let us study the seam C_5 at Heroiv Kosmosu mine.

According to the mining-geological prediction of driving the 501st prefabricated drift (Fig. 2), the coal seam C_5 has a predominantly simple structure, its geological thickness ranges from 0.62 to 1.42 m and on average is 0.92 m. The natural gas content of the seam C_5 is expected to be within the range of 13.2-25.2 m^3/t; the seam is hazardous in terms of dust and gas. The expected water inflow from coal interlayers and sandstone is up to 15-50 m^3/h.

(a)



(b)

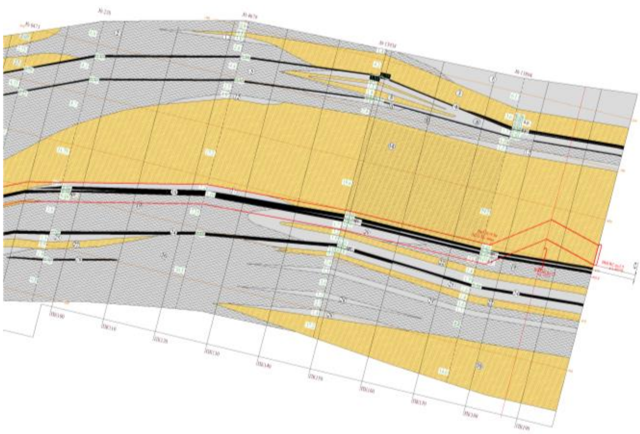


Figure 2. Mining-geological prediction of driving the 501st prefabricated drift of the seam C_5 with division along the mine working length into the lower (a) and upper (b) zones

The coal-bearing rock mass, enclosing the seam C_5, has a number of structural peculiarities that can significantly influence on the rock pressure manifestations in the 501st prefabricated drift, especially during the period of its predicted repeated use.

Firstly, the extraction site of the 501st longwall face is located at a fairly large depth *H* in terms of the mining-geological Western Donbas conditions. Mining operations are carried out at a depth of *H* = 485-540 m, which in itself implies the geostatic pressure *P* in the range of 11.64-12.96 MPa. Such an initial geostatic pressure (in a virgin mass) can provoke an intensive development of coal-bearing rock mass displacements and loads on the fastening and protection structures of the 501st prefabricated drift, especially in the zone of stope operations influence.

Secondly, it is necessary to use the structural peculiarity of adjacent roof rocks in terms of thick and relatively strong sandstone occurring either in the immediate roof of the seam

C_5, or at a height of up to 1.2 m above it. The thickness of the sandstone along the mine working length (according to mining-geological prediction in Figure 2) varies from 5.5 m to 19.6 m, and this makes it possible to assume that the roof rocks are sufficiently stable even in the zone of stope operations influence. Sandstone resistance to uniaxial compression in the sample is 13.7-48.2 MPa with an average value σ_{compr} = 31 MPa. Its texture is relatively homogeneous, and water-cut is the main weakening factor. According to regulatory document [28], such sandstone loses up to 30% of its strength and its calculated compressive strenght decreases to R = 21.7 MPa.

If to analyze the sandstone thickness distribution along the length of the 501st prefabricated drift, then when it is reused, the main or all thickness of the rocks of probable failure is represented by sandstone. This also makes it possible to assume moderate rock pressure manifestations from the side of the roof rocks.

However, on the other hand, in the rock mechanics, a pattern of withstanding an increased load with a more rigid and resistant lithotype is widely known [29]-[31]. Therefore, in thick sandstone, when the 501st longwall face is driven, rather high concentrations of lateral bearing pressure are expected. This should be taken into account when substantiating the ways and methods for maintaining the 501st prefabricated drift.

The next peculiarity of the rock mass structure around the coal seam C_5 is the texture and mechanical properties of the immediate and main bottom rocks. The expected water inflow from coal interlayers and sandstone is up to 15-50 m^3/h, and argillite and siltstone in the seam C_5 bottom are characterized as very unstable, swelling in water in 2-4 hours with a loss of load-bearing capacity. The compressive strength can be reduced up to 70% then, depending on the argillits mineral composition [32]. For this reason, these rocks are prone to intense heaving. Thus, the main danger of losing the operational state of the 501st prefabricated drift and the impossibility of its further reuse is associated with the intense heaving of the mine working bottom rocks and the convergence of its sides along the depth of ripping the seam C_5 bottom.

The 501st longwall face is prepared in the inclined drift area of the mine field eastern flank; the extraction panel length is 1020 m, the longwall face length is 250 m. The predicted spacing of the main roof caving is 18-20 m, the predicted primary caving is 20-25 m from the installation chamber (there are no analogues).

The 501st prefabricated drift is driven in with a cross-sectional area and dimensions for TSYS-14.4 frame support from SCP-27 with a spacing of setting L_{fr} = 0.8 m. In the middle of the interframe space, a set of resin-grouted rock bolts is installed with a spacing of setting $L_{r.-g.b.}$ = 0.8 m.

An improvement in the fastening and protection structures is seen in the creation (using a combined roof-bolting system) from the bottom of thick sandstone of an armored-rock load-bearing plate capable of protecting the frame support and the prop stays of the strengthening support from excessive vertical and oblique loads. It is assumed that the protection structure should be maximally lightweight due to the fulfillment of the main function of protecting the zone of uncontrolled collapse with rocks. Due to significant shrinkage, these rocks sharply reduce the concentrations of lateral bearing pressure and, accordingly, the heaving intensity of rocks in the mine working bottom.

4. The mechanism of the roof rocks displacement on the eastern flank of the seam C5 at Heroiv Kosmosu mine and substantiation of the principles for maintaining the extraction workings with their repeated use

According to the main research task, in order to substantiate the method for maintaining the sectional workings behind the stope face for their repeated use in the conditions of mining the seam C_5 on the mine field eastern flank, Heroiv Kosmosu mine, it is necessary to analyze modern ideas about the geomechanics of the displacement processes of coal-bearing mass on flat-lying thin and very thin seams of Donbas and, in particular, its western area.

The mechanism for loading the extraction working fastening system changes as soon as the studied section falls into the zone of bearing pressure ahead of the stope face; the rock pressure manifestations become more active, as evidenced by the results of measurements of displacements in the mine working abutment.

Summing up the modern concepts about the displacement processes in the coal-overlaying formation during the stope mining of coal seams in the mining-geological conditions of weakly metamorphosed rocks [29]-[31], it is possible to substantiate the mechanism of loading the fastening and protection structures of repeatedly used extraction workings on the example of the 501st prefabricated drift of the seam C_5. To illustrate the peculiarities of this process, a qualitative scheme of the surrounding mass deformation has been developed, which is shown in Figure 3.

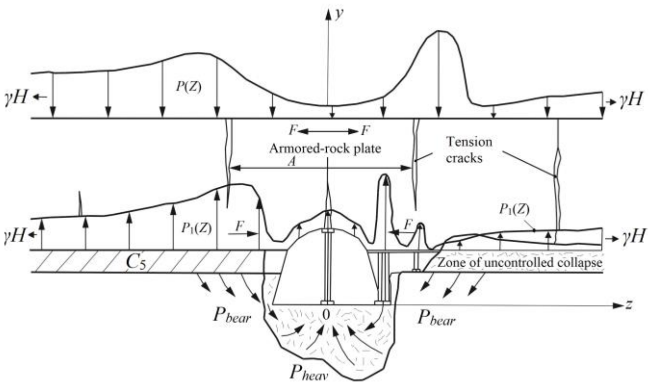


Figure 3. Schematic representation of the loading mechanism of the fastening and protection structures in the 501st prefabricated drift with its repeated use

As it was found earlier [33], [34] when the stope face is driven, various kinds of rock pressure anomalies are formed around the extraction working. In the mine working roof along its width, there is a de-stressing area. The damage zone range and its intensity can be easy checked with the help of endoscopic investigations [32]-[35]. There the vertical stresses σ_y are significantly lower than the initial geostatic pressure γH. In the sides of mine working, there are concentrations of compressive stresses σ_y in the form of lateral bearing pressure from the side of virgin mass and bearing pressure on the protection structure. Thus, the load in the area of the extraction working placement is extremely uneven and is represented in the scheme by a certain function $P(Z)$ that describes both the de-stressing area ($\sigma_y < \gamma H$), and the concentration area ($\sigma_y > \gamma H$). The existence of such a function is proven, for example, by studies [36], [37] of the mass SSS (in similar conditions of weakly metamorphosed rocks) around reusable extraction workings, which are performed on the basis of the finite element method (FEM) using various software such as SolidWorks Simulation and ANSYS.

The function $P(Z)$ of vertical rock pressure distribution on fastening and protection structures, as well as on adjacent rocks in the mine working sides is determined based on the results of computational experiments in similar mining-geological conditions.

One of the peculiarities is the formation of an armored-rock load-bearing plate of sandstone to protect mine working from excessive vertical and oblique load. This armored-rock plate is created with a combined roof-bolting system of rope bolts and resin-grouted rock bolts according to the scheme shown in Figure 4, and the principle of its formation is as follows.

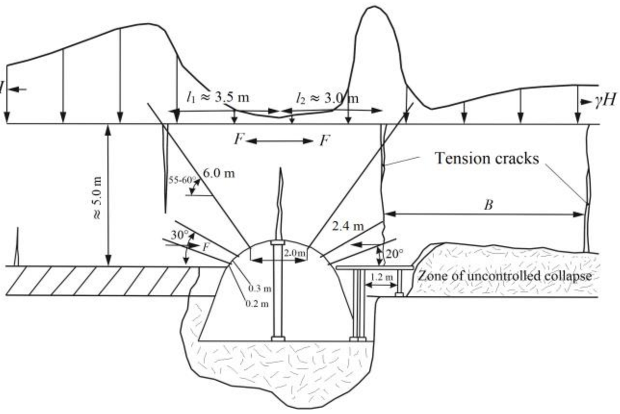


Figure 4. Basic diagram of the 501st prefabricated drift maintenance and some values of its parameters

Firstly, it is necessary to search for a compromise between the acting two factors:

– on the one hand, when moving the backing part of the plate as far as possible into the depths of the side rocks, the bearing pressure $P(Z)$ and the reaction of the underlying mass $P_1(Z)$ to it in Figure 3 can, to a lesser extent, contribute to the intensified development of the lateral loads (under bearing pressure P_{bear}) and the process of heaving of bottom rocks in the mine working, while creating the pressure P_{heav};

– on the other hand, with an increase in the span A of an armored-rock plate, its resistance to geostatic rock pressure of vertical and oblique action decreases in accordance with the classical concepts [38], [39].

Secondly, rocks by their nature are weakly resistant to tensile forces. Therefore, resistance to the process of developing vertical tension cracks is ineffective. On the contrary, the strengthening of sandstone in the armored-rock plate in the area of compressive stresses (during its bending) is considered very expedient; therefore, both resin-grouted rock bolts and rope bolts should be placed in such a way as to maximize the sandstone resistance in the area of acting compressive loads. In this case, the thrust forces increase F (Figures 3 and 4) between the two parts of armored-rock plate, which directly determine its load-bearing capacity.

In view of the indicated tendencies, setting of side prop stays of the strengthening support from the side of mined-out area is positively assessed. Their main task is to provoke the sandstone plate division into two blocks: the first is sufficiently stable due to thrust forces F, and the second is a rock cantilever from the side of mined-out area. When its stability is lost, it descends into the underlying collapsed rocks [40]. In this case, the load on the fastening and protection structures is sharply reduced, since the reaction of the collapsed rocks partially takes over the functions of the mine working protection.

In addition, two mutually opposite tendencies act here. On the one hand, the forced division into two blocks sharply reduces the load on the elements supporting the 501st prefabricated drift. On the other hand, the reaction impact of the side prop stays of the strengthening support on the bottom rocks provokes the development of their heaving process. In this regard, it is necessary to distress the drift berm from the bearing pressure in order to partially compensate for the intensive heaving process of bottom rocks from the side of mined-out area. Therefore, it is proposed to maximally lighten the protection structure by transferring its function to the collapsed rocks in the uncontrolled collapse zone, as shown in the schemes of Figures 3 and 4.

An important feature of the displacement process in the coal-bearing mass is the formation of weakened rock areas in the sides and bottom of the mine working. Partial or complete failure of the bottom rocks of the seam C_5 occurs up to a certain limited width into the mass under the influence of bearing pressure. As for the coal seam C_5, the mechanism of its weakening is alike the phenomenon of coal sloughing in a stope face. This weakening is quite limited and, according to our assessments, does not exceed 1.0 m on both sides of mine working, but it plays a positive role in moving away of the bearing pressure P_{bear} from the mine working abutment (see Figure 3). A de-stressed border area is formed, which promotes to limiting the heaving process development in the bottom rocks.

Summing up the complex of concepts on the displacement mechanism substantiation in the coal-bearing stratum and the principles of its resource-saving maintenance, it is necessary to note the following:

– it is expedient to create (with the help of a combined roof-bolting system) an armored-rock load-bearing plate that protects the mine working from excessive vertical and oblique rock pressure;

– a fundamental solution to the problem of increasing the load-bearing capacity of an armored-rock plate is to strengthen the zone of acting compressive stresses using the resin-grouted rock bolts and, in part, rope bolts, thereby increasing the thrust forces between sandstone blocks and the stability of the roof rocks in general;

– to move the zone of lateral bearing pressure deep away into the mass, the protection structure should be maximally lightened, while transferring its functions to the collapsed and compacted rocks in the zone of uncontrolled collapse; from the side of the virgin mass, the de-stressing zone is formed in a natural way;

– de-stressing zones in the mine working sides help to reduce the intensive heaving of its bottom rocks.

5. Calculation of parameters for loading and resistance of fastening and protection structures

On the basis of the developed mechanism for the development of the displacement processes in the coal-bearing stratum, representing the specific conditions for maintaining the 501st prefabricated drift and other sectional workings, the estimated provisions for determining the parameters for loading and resistance of fastening and protection structures have been substantiated, which are the basis of the appropriate recommendations.

Earlier, the expediency of forming an armored-rock load-bearing plate, using a combined roof-bolting system, has been substantiated (Fig. 4). Rope bolts prevent sandstone stratification to a height of about 5.0 m, which is determined by their 6.0 m length and a gradient angle of 55-60º to the horizontal. Taking into account the rather dense sandstone texture and its weak horizontal bedding, it is quite reasonable to consider this sandstone area as a holistic (along the vertical coordinate *Y*) plate with a thickness of 5.0 m.

The span *A* of an armored-rock plate is characterized by vertical tension cracks:

– from the side of a virgin mass, a vertical tension crack (extends only over the upper part of the thickness) is formed at a distance of approximately $l_1 \approx 3.5$ m, determined by coordinate *Z* of setting the side prop stays of the stren-gthening support.

Thus, the total span of an armored-rock plate is:

$$A = l_1 + l_2 \approx 6.5 \text{ m}, \tag{1}$$

but, the thrust structure itself is asymmetrical relative to the mine working central axis.

An active load *P*(*Z*) acts on the armored-rock plate, causing its deformation and the occurrence of vertical tension cracks in the center of mine working and in its sides. This load *P*(*Z*) is determined from the results of calculating the vertical stresses σ_y by the finite element method (Fig. 5) at a height of 5.0 m from the coal seam C_5. The degree of armored-rock plate stability is determined by the reactive forces *F* acting on the ends of both rock blocks both from the side of the virgin mass and from the side of the mined-out area.

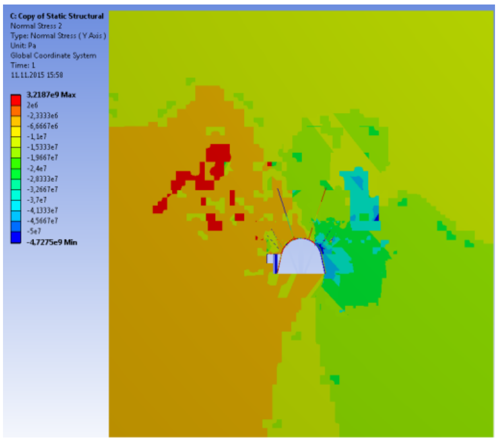


Figure 5. Curve of vertical stresses σ_y in a rock mass of weakly metamorphosed rocks

The parameters of the lightweight protection structure are determined taking into account the formation of a rock block from the side of mined-out area with a thickness of at least 4.0 m, which for the most part of length of its span *B* rests on the collapsed rocks of uncontrolled collapse zone.

The value of heaving U^b of the mine working bottom rocks is calculated according to the regulatory industry methodology [28] for the depth of its placement *H* = 500 m and the maintenance section – after the second longwall face advance.

Deformation of the armored-rock plate in the roof of the 501st prefabricated drift is considered as the work of a three-hinged load-bearing structure (Fig. 6). Taking into account the previously made assumptions (in favor of increasing the reserve of load-bearing capacity), the active load *P*(*Z*) in the form of vertical rock pressure $\sigma_y(Z)$ and reactive thrust forces *F* at the ends of the two rock blocks, which compose the considered load-bearing structure, act on the plate.

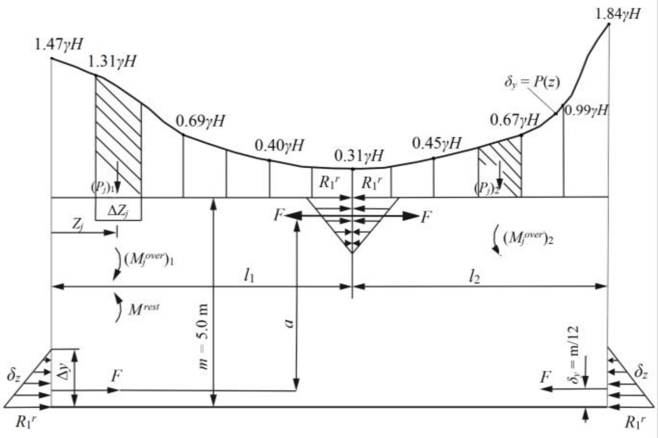


Figure 6. Scheme for calculating the stability of the armored-rock plate in the roof of the 501st prefabricated drift

The active load $\sigma_y(Z)$ is determined in the section of the mine working maintenance before driving the second longwall face for the external surface of the armored-rock plate, located at a height of *y* = 5.0 m from the seam C_5. When analyzing the curve $\sigma_y(Z)$, obtained on the basis of a computational experiment by the finite element method, it is convenient to represent the distribution of vertical forces in fractions γH of the geostatic pressure of a virgin mass. Such a curve of vertical rock pressure $\sigma_y(Z) = P(Z)$ has been obtained and shown in Figure 6; since it has asymmetry and there are different span lengths for the left (l_1) and right (l_2) sandstone blocks, their stability is calculated for each of the blocks.

The vertical load *P*(*Z*) tends to disturb the stability of an armored-rock plate due to the action of the so-called overturning moment $M_{1,2}^{over}$. To determine it, the entire length of the spans l_1 and l_2 is divided into small sections ΔZ_j, for each of which the overturning moment is determined by the Formula 2:

$$M_j^{over} = P_j \Delta Z_j \cdot Z_j, \tag{2}$$

where:

P_j – average load over the width ΔZ_j of the sections into which all block lengths $l_{1,2}$ are divided, N/m;

Z_j – distance from the bearing of the blocks to the middle of the *j*-th section, where the overturning moment component is calculated.

The total overturning moment $M_{1,2}^{over}$ is determined as the sum of all sections of the curve *P*(*Z*):

$$M_{1,2}^{over} = \sum_{j=1}^{n} M_j^{over}. \tag{3}$$

In this calculation, the left rock block is divided into 7 sections with a length of 0.5 m, that is, $n_1 = 7$, and the right rock block – into 6 sections ($n_2 = 6$) with a length of 0.5 m each. The calculation results are as follows (per 1 long meter of the mine working length):

$$M_1^{over} = 41.02 \text{ MN·m}; \; M_2^{over} = 36.73 \text{ MN·m}. \tag{4}$$

The so-called restoring moment M^{rest}, which is generated by the action of a pair of thrust forces *F*, resists to the overturning moment:

$$M^{rest} = F \cdot a. \tag{5}$$

The thrust force *F* is the result of the cumulative action of horizontal stresses σ_z in the compression areas:

$$F = \frac{1}{2} \Delta y \cdot \sigma_z, \tag{6}$$

where:

Δy – the height of propagation of the compressive stresses along the thickness m of the armored-rock plate.

According to studies in [41], the value Δy is a quarter of the rock plate thickness m due to different rock deformation characteristics during compression and tension, that is:

$$\Delta y = \frac{1}{4} m, \tag{7}$$

where:

m = 5.0 m – armored-rock plate thickness.

The thrust forces F are at their maximum when the horizontal stresses σ_z on the outer plate surfaces are equal to the ultimate compressive strength of the sandstone σ^r_{compr1} According to [28] and taking into account the weakening factors, namely the influence of structural disturbance (decrease of σ^r_{compr1} by 10%) and moisture saturation (decrease of σ^r_{compr1} by 20%), average calculated compressive resistance of sandstone is:

$$R_1^r = \sigma^r_{compr_1} \cdot 0.9 \cdot 0.8 = 22.32 \text{ MPa}. \tag{8}$$

Thus, thrust forces act on the ends of the rock blocks:

$$F = \frac{1}{2} \cdot \frac{1}{4} m R_1^r = \frac{1}{2} \cdot \frac{1}{4} \cdot 5 \text{ m} \cdot 22.32 \text{ MPa} = 13.95 \text{ MN/m}. \tag{9}$$

The restoring moment according to Formula 5 is directly proportional to the shoulder a of the thrust forces F. In accordance with the classical provisions [38], [39], taking into account [41], the shoulder of acting thrust forces is:

$$a = \frac{5}{6} m, \tag{10}$$

then, according to Formulas 5 and 10, we have:

$$M^{rest} = 581.2 \text{ MN} \cdot \text{m}. \tag{11}$$

As a result, comparing the restoring and overturning moments, the following conclusion can be drawn about the stable state of the armored-rock plate: for the left sandstone block, the safety factor is $K_{s.f.}$ = 1.42; for the right block – $K_{s.f.}$ = 1.58. The main conclusion: despite the fact that the reactions of the elements in fastening structures and roof-bolt strengthening are not taken into account, the armored-rock plate is in a stable state with a safety factor of at least 1.42. This substantiates the effective resistance to rock pressure in the roof of the 501st prefabricated drift with the proposed type of its fastening structure.

The specific conditions for thick and relatively hard (for Western Donbas) sandstone occurrence in the roof of the 501st prefabricated drift should be taken into account when substantiating the protection structure parameters for the repeated use of extraction working. This substantiation is determined by the process of forming the load on the protection structure after the first longwall face advance.

With the method of managing the roof with complete caving, the studies [42], [43] previously conducted in Western Donbas, note the rock pressure development on the rocks of the uncontrolled collapse zone and their active compaction in the section up to 40-70 m behind the stope face; further, the reaction of the collapsed rocks stabilizes at the level of 10-11.3 MPa (in the experimental conditions, γH = 4.5-5.0 MPa), which makes it possible to resist not only the geostatic weight of rocks in the coal-overlaying formation up to the earth's surface, but also the concentrations of the lateral bearing pressure. Consequently, at the noted distance behind the longwall face, the defining role is played by the resistance of rocks in the uncontrolled collapse zone, and the protection structure mainly prevents the spillage of collapsed rocks into the mine working cavity from the side of the mined-out area.

In view of the noted patterns, the most active loading of the protection structure occurs in the immediate vicinity of the longwall face, when a rock block of sandstone with a length B (Fig. 4) collapses. Its weight is taken up by the prop stays of the protection row and the collapsed rocks in the area adjacent to mine working.

Thus, the task set is to calculate the load P_{prot} on the prop stays of a lightweight protection structure during the period of the sandstone block collapse from the side of mined-out area in the immediate vicinity of the longwall face. For this purpose, a scheme has been developed (Fig. 7), which provides for the sequential solution of two problems:

– determining the length B of a sandstone block at the time of its collapse;

– calculating the load P_{prot} on a row of protection prop stays from the weight of the collapsed sandstone block.

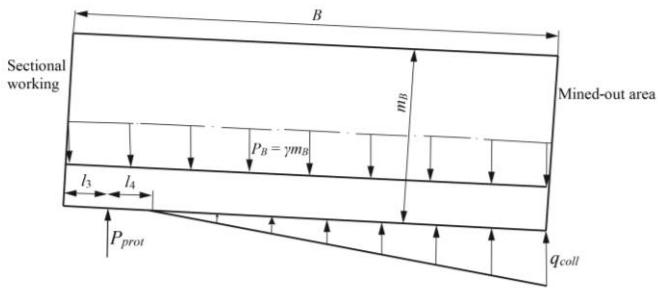


Figure 7. Scheme for calculating the load on the prop stays of the protection structure

To solve the first problem, schematic constructions in Figure 6 are used: the sandstone block is collapsed when the overturning moment M^{over} is determined by the weight of the collapsed sandstone block and is:

$$M^{over} = \frac{1}{2} B^2 P_B \cdot K_{s.f.} = \frac{1}{2} \gamma B^2 m_B \cdot K_{s.f.}, \tag{13}$$

where:

$K_{s.f.}$ – safety factor, which takes into account the coal-mined load on the sandstone block in the lateral bearing pressure zone; here, in the block length B section closest to the mine working, the load on it can exceed its own weight many times; therefore, we take approximately $K_{s.f.}$ = 5.

The ultimate equilibrium condition of a sandstone block has the form:

$$M^{over} = M^{rest}, \tag{14}$$

on the basis of which, using Expressions 12 and 13, we obtain the Formula 15 for calculating the maximum block length:

$$B = \frac{1}{2} \sqrt{\frac{5 m_B R_1^r}{6 \gamma K_{s.f.}}}. \tag{15}$$

For the previously specified initial data ($m_B = 4.0$ m, $R_1^r = 22.32$ MPa, $\gamma = 25$ kN/m^3, $K_{s.f.} = 5$) by the Formula 15, $B = 12.2$ m is determined.

To solve the second problem (determining the load P_{prot} on a row of protection prop stays), based on the calculation scheme (Fig. 7), two Equations are composed of the block's equilibrium under the influence of active load $P_B = \gamma m_B$ and unknown reactive forces P_{prot} and q_{coll}. In this case, we take the reaction q_{coll} of the collapsed rocks as distributed according to a triangular law, taking into account the different degree of their deformation from zero (at the beginning of the block contact) to the maximum q_{coll} at remote (from the mine working) end.

The first Equation characterizes the balance of vertical forces:

$$\gamma m_B \cdot B = P_{prot} + \frac{1}{2} q_{coll} \left(B - l_3 - l_4 \right), \tag{16}$$

where it is designated, according to the design diagram in Figure 7:

l_3 – the distance from the sandstone block end closest to the mine working to the row of protection prop stays set on the drift berm; we take approximately $l_3 \approx 1.0$ m according to the scheme in Figure 4;

l_4 – the distance from the protection prop stays to the beginning of the sandstone block contact with the underlying collapsed rocks; the value of l_4 we take approximately as equal to the extraction thickness of the seam based on the formation of a natural slope at an angle of 30º; then l_4 is approximately equal to 1.0 m.

The second Equation determines the equilibrium of bending moments relative to the remote sandstone block end:

$$\frac{1}{2} \gamma m_B B^2 = P_{prot} \left(B - l_3 \right) + \frac{1}{6} q_{coll} \left(B - l_3 - l_4 \right)^2 . \tag{17}$$

The simultaneous solution of two Equations 16 and 17 allows determining two unknown parameters, but the value P_{prot} of the load on a row of protection prop stays remains a priority:

$$P_{prot} = \gamma m_B \cdot B \frac{0.5B - l_3 - l_4}{2B + 2l_3 - l_4}. \tag{18}$$

Substituting the initial data and the obtained calculated data into the Formula 18, the load P_{prot} (per 1 long meter of the mine working length) is determined, acting on the prop stays of the lightweight protection structure:

$$P_{prot} = 197 \text{ kN/m}. \tag{19}$$

According to this load value, the number of prop stays is selected (per 1 long meter of the mine working length) with their known diameter d_{prop} (usually $d_{prop} = 10\text{-}12$ cm). For this purpose, the document [42] is used with some transformations [31].

Another way is to determine the minimum permissible diameter of a wooden prop stay according to the load P_{prot} value, which is performed using the Formula 20:

$$d_{prop} \ge 10^{-2} \times \left(1.7 h_{prop} + \sqrt{2.89 h_{prop}^2 + \frac{L_{prop} P_{prot}}{1.79} K_{s.f.}} \right), \text{ m}, \tag{20}$$

where:

h_{prop} – the height of a wooden prop stay; approximately, it can be taken as equal to the extraction thickness of the seam, that is, $h_{prop} \approx 1.0$ m;

L_{prop} – the spacing of setting the prop stays along the mine working; prop stays can be erected on a continuous basis or with a certain gap;

$K_{s.f.}$ – safety factor.

There may be alternatives. For example, at $L_{prop} = 0.8$ m (the spacing of setting the frame support) and $K_{s.f} = 1$, the minimum permissible prop stay diameter, according to the calculation is 0.1123 m = 11.23 cm; we take $d_{prop} = 12$ cm. But, in order to ensure reliable operation of the prop stays, we take $K_{s.f} = 2$, and for 1 long meter of the mine working ($L_{prop} = 0.25$ m) we set four prop stays; then, using Formula 20, we determine $d_{prop} \ge 9.31$ cm, that is, the prop stays should be set with a diameter of 10 cm in the amount of 4 pcs per 1 long meter with a safety factor of $K_{s.f} = 2$.

This lightweight protection structure ensures the secure maintenance of the 501st prefabricated drift with its repeated use.

6. Substantiating the parameters of the method for maintaining the sectional workings in the conditions of the eastern flank, seam C_5 at Heroiv Kosmosu mine

Based on the performed research, recommendations have been formulated for the resource-saving maintenance of sectional workings planned for repeated used.

To ensure the stability of roof rocks due to the strength properties of the sandstone, a thick armored-rock plate is created using a combined roof-bolting system (Fig. 8). It is thanks to setting of rope bolts, it becomes possible to strengthen the sandstone to a height of about 5.0 m. Rope bolts with a length of 6.0 m are set in the central part of the mine working arch at a distance of 1.0 m from its vertical axis. The so-called checkerboard arrangement of rope bolts along the sides of mine working is used. The bolts are installed at a gradient angle of 55-60º to the horizontal axis, due to which their joist parts go beyond the mine working dimensions and form a load-bearing plate with a width exceeding the width of mine working. Rope bolts are set in 3.2 m spacing when installing the TSYS-14.4 frame support from SCP-27 in 0.8 m spacing, which means that the rope bolts are placed in a checkerboard pattern in the middle of every fourth interframe gap. To increase the efficiency of restricting the sandstone stratification, it is recommended to install rope bolts when driving mine working with a lag of up to 30-40 m from the drifting face.

Figure 8. Armored-rock plate creation using a combined roof-bolting system

In the area of the mine working spring, on each side of it, two resin-grouted rock bolts with a length of 2.4 m are erected: the tail joint of the lower bolt is placed at a distance of 0.2 m from the coal seam edge, the tail joint of the upper bolt is at a distance of 0.5 m; the gradient angle of the lower bolt is 20º, of the upper one – 30º to the horizontal axis. Such an arrangement of the resin-grouted rock bolts significantly strengthens the areas of the armored-rock plate, where the thrust forces act, thereby ensuring its high load-bearing capacity (Fig. 9). In addition, the deepened part of the resin-grouted rock bolts provides stable bearings for the armored-rock plate, and at the same time moves their location away from the mine working abutment.

Figure 9. The state of mine working, fastened by the combined roof-bolting system

Calculations show that the armored-rock sandstone plate, by itself, is capable of withstanding vertical rock pressure. Nevertheless, in order to increase the mine working stability (in the zone of stope operations influence), it is recommended to erect central and side prop stays of the strengthening support with a spacing of 0.8 m. For the central prop stays, a diameter of 20-22 cm is recommended, for the side prop stays – 16-18 cm. The side prop of the strengthening support are erected in two rows and their second task is to ensure the forced collapse of the sandstone block hanging from the side of mined-out space. This makes it possible to sharply reduce the load on the fastening structure and limit the oblique rock pressure development.

As a protection, a lightweight construction is recommended, consisting of one row of wooden prop stays with a diameter of 10-12 cm, set on the drift berm at a distance of 1.2 m from the side prop stays of the strengthening support. Such deepening of wooden prop stays into the mined-out space allows to prevent the rock berm from chipping and to move the zone of lateral bearing pressure away from the mine working abutment.

The presence of collapsed zones in the sides of mine working reduces the intensity of heaving, however, weak and water-flooded bottom rocks require their periodic dinting in order to ensure the norms and rules of accident-free operation of sectional workings.

7. Conclusions

The main scientific and practical conclusions can be summarized as follows.

1. Analysis of the mining-geological and mining-technical conditions for mining and maintaining the 501st prefabricated drift and other adjacent mine workings on the mine field eastern flank of the seam C_5 has revealed that the structure and properties of lithotypes in the surrounding coal-bearing mass suggest the development of moderate rock pressure from the side of roof rocks, increased lateral movements along the height of the seam C_5 bottom ripping, as well as intensive heaving of bottom rocks in the mine workings.

2. An improvement in the fastening and protection structures is seen in the creation (using a combined roof-bolting system) from the bottom of thick sandstone of an armored-rock load-bearing plate capable of protecting the frame support and the prop stays of the strengthening support from excessive vertical and oblique loads. It is assumed that the protection structure should be maximally lightweight due to the fulfillment of the main function of protecting the zone of uncontrolled collapse with the collapsed rocks. Due to significant shrinkage, these rocks sharply reduce the concentrations of lateral bearing pressure and, accordingly, the intensity of heaving of rocks in the mine working bottom.

3. Analysis of modern ideas about the mass displacement processes in the coal-overlaying formation in the conditions of weakly metamorphosed rocks during the stope operations has substantiated the resource-saving principles of ensuring the stability of repeatedly used extraction workings at depths of about 500 m.

A decrease in the intensity of lateral rock pressure manifestations and restriction of the heaving process of bottom rocks in a repeatedly used extraction working is conditioned by the preservation of natural and the creation of artificial zones of de-stressing on its sides, including through the use of the most lightweight protection structure with the transfer of its functions to collapsed and compacted rocks of the uncontrolled collapse zone.

4. Schemes have been developed for calculating the parameters of loading and resistance of fastening and protection structures of repeatedly used extraction workings with a geomechanical substantiation of the adopted provisions and assumptions. Sufficient reliability of the calculations is ensured by the reservation in the safety factor of the fastening structure of such factors as the strengthening effect of the combined roof-bolting system, the resistance reaction of the frame support, central and side prop stays of the strengthening support. Nevertheless, calculations have proven that an armored-rock sandstone plate successfully resists vertical rock pressure with a safety factor of at least 1.42. This makes it possible to substantiate a resource-saving technical solution on the use of a combined roof-bolting system in the specific conditions of mining the mine field eastern flank of the seam C_5 at Heroiv Kosmosu mine.

5. The expediency of using a lightweight protection structure, where the main protection function is performed by the backing of the collapsed rocks in uncontrolled collapse zone, has been substantiated and confirmed with calculations. A low-material-consuming protection structure from one row of wooden prop stays is potentially capable of increasing the rate of advancing the stope faces by reducing the time required for its construction in the general technological cycle of coal mining.

6. The developed recommendations for the choice of parameters and protection structures ensure the proper stability of sectional workings with their repeated use.

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Обґрунтування оптимізаційного рішення ресурсозберігаючої підтримки гірничих виробок

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Мета. Обґрунтування доцільності прийняття оптимізаційних рішень ресурсозберігаючої підтримки гірничих виробок.

Методика. Концепція забезпечення умов повторного використання виробок основана на сучасних методах управління проявами гірського тиску, проведенні багатофакторних обчислювальних експериментів, експериментальної перевірки реалізації принципів ресурсозбереження в натурних умовах.

Результати. Визначено напрями вдосконалення кріпильних та охоронних конструкцій, які забезпечують стійкість виробок, що повторно використовуються. При цьому запропонована максимально полегшена охоронна конструкція, функції якої передані зруйнованим та ущільненим породам зони безладного обвалення.

Наукова новизна. Сформульовано та реалізовано основну концепцію повторного використання виробок ресурсозберігаючими технологіями. Досліджено напружено-деформований стан системи "масив – кріплення – охоронні елементи" та оптимізовано її раціональні параметри. Наведено приклад оптимізаційного рішення щодо викладеної методології.

Практична значимість. Розроблено схеми для розрахунку параметрів навантаження кріпильних та охоронних конструкцій виробок, що повторно використовуються, з геомеханічним обґрунтуванням прийнятих положень і припущень, що послужило основою для видачі рекомендацій, які забезпечують стійкість виробок.

Ключові слова: *гірський масив, виробка, що повторно використовується, ресурсозбереження, кріпильна система, охоронні елементи*