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Principles of mining-geological classification for maintaining mine workings in conditions of weakly metamorphosed rocks

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Abstract

Purpose. The purpose of this research is to group the mining-geological conditions of a stratified mass containing weak rocks in the Western Donbas (Ukraine) and to substantiate recommendations for rational supporting and protecting system parameters for reused mine workings.

Methods. The research was conducted by combining analytical methods for studying the processes of rock mass deformation in the zone of stope operations with experimental measurements of rock pressure manifestations. As a connecting link, ideas about the development mechanism of the coal-overlaying formation shear process and its peculiarities for the mining-geological conditions of the Western Donbas were studied. The obtained patterns were taken into account in the calculation model as a component of load formation, as well as in supporting and protecting system for extraction drifts. A methodology for computer modeling was determined based on the condition of the maximum possible representation of the design peculiarities of frame and roof-bolting supports. The developed models were tested, which confirmed their adequacy to real objects.

Findings. The complex of conducted studies made it possible to develop an array of calculated texture variants that reflect the probability of dividing lithotypes by their thickness in the rock layers of the immediate and main roof and bottom. Based on the results of a number of computational experiments to study the effectiveness of the recommended options for supporting and protecting systems, the distribution of the stress-strain state in the load-bearing elements of the system has been determined. Principles of grouping of mine working maintenance schemes have been created, which cover most of the mining-geological conditions of mines in Western Donbas.

Originality. To achieve the reliability of the results, a complex of peculiarities and mutual influence of the geomechanical system elements has been studied. The patterns obtained as a result of multifactorial modeling have revealed the link between the strengthening of rock layers in the form of their discrete disturbance and the formation of a system of interacting plates, which intensifies the process of pressing-out a partially strengthened border mass.

Practical implications. The novelty of the research is in generalized principles of grouping structural-technological schemes for maintaining extraction drifts. As a result, three groups of mining-geological conditions for the operation of extraction drifts planned for reuse have been identified. Three variants of schemes for maintaining extraction drifts for the conditions of mines in the Western Donbas have been proposed and studied.

Keywords: *rock mass, mine working, supporting system, protecting system, loading mechanism, geomechanics*

1. Introduction

Minerals are the true basis of modern world economies and the development of civilization as a whole for the long term [1]. Effective mining is associated with many factors, the main of which are mining-technical, geomechanical, environmental, economic, etc. [2]-[4]. Successful consideration of the interconnection and mutual influence of these factors, as well as a meaningful resolution of the contradictions that have always existed in the mining industry, form the basis for further development of the economy with a careful attitude to the environment [5]-[9].

A key aspect of effective mining is understanding and managing the complex geomechanical processes that occur within the rock mass. The interaction between mining-technical and geomechanical factors plays a crucial role in ensuring the stability, and safety of underground operations [10], [11]. Given the inherent heterogeneity of the rock mass and its response to mining activities, a comprehensive approach is required to analyze and predict its behavior. This necessitates detailed research into both the mechanical properties of the rock mass and the technological solutions used to support mine workings, which are fundamental to maintaining the integrity of underground structures [12], [13].

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The rock mass is a very complex system characterized by a large number of texture parameters and mechanical properties that significantly influence the development of geomechanical processes in underground mining [14]-[18]. On the other hand, an interrelated component in solving geomechanics problems is a set of data and research on the behavior of mining-technological structures (the most common types of supporting and protecting structures of mine workings) that ensure the implementation of technological processes of mineral resource mining [19]-[24]. These are complex multiparametric structures that interact with an equally multiparametric heterogeneous rock mass and together constitute geomechanical systems with difficult-to-predict behavior under the influence of rock mass pressure.

Difficult mining-geological conditions significantly complicate the maintenance of mine workings, which leads to a decrease in their stability and the occurrence of dangerous frame support deformations [25]-[28]. In particular, in the area affected by stope operations, non-uniform load on the support causes its local destruction and overloading of individual structural elements.

As Figure 1 shows, a significant deformation of the frames is associated with the manifestations of the bearing pressure, which forms the stress-strain state of the surrounding rocks. Tangential stresses at contact points of layers exceed the ultimate strength values, which leads to their disturbance and additional mine working instability. Thus, the choice of the optimal scheme for supporting and protecting mine working is critical to ensure its safe operation [29]-[31].

Figure 1. Deformation of the extraction working support frames in difficult mining-geological conditions of the Western Donbas mines

Therefore, the wide variability of mining-geological conditions requires a certain generalization of the processes of interaction between a mining-technical facility and a rock mass. Thus, we are faced with the solution of the urgent task of substantiating the rational parameters of the supporting and protecting systems for each group of mining-geological conditions for maintaining mine workings. This issue is discussed for a weakly metamorphosed stratified rock mass on the example of Western Donbas mining enterprises (Ukraine).

2. Analysis of the grouping of mining-geological conditions of mining coal seams in Western Donbas

According to numerous geological prospecting works of the last century, Donbas coal-bearing deposits are mainly represented by terigenic rocks – sandstones, siltstones and argillites, among which there are coal seams and limestone layers in the form of low-thickness layers (Fig. 2).

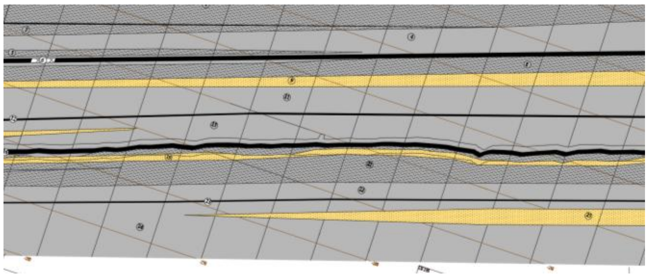

Figure 2. Fragment of a geological section of the coal-bearing stratum in Western Donbas

Terigenic rocks in the coal-bearing stratum make up 90-95%, besides, in some suites, argillites and siltstones predominate – up to 80%. Carbonate rocks are represented mainly by limestone, which plays a subordinate role among Donbas coal-bearing deposits, constituting 0.2-5.0% in the sections of individual suites. Coal and coal-clay rocks typically make up 0.5-2.0% of the total thickness of the suite. The above data show that the modeling of the coal-bearing stratum, consisting of coal seams and rock layers of argillites, siltstones and sandstones, is quite objective.

Many researchers [32]-[36] suggest that the development of rock pressure manifestations is influenced not only by the mechanical properties of rocks, but also by the structure (thickness ratio) of the adjacent rock layers of the coal seam roof and bottom. In addition, many experts believe that the intensity of rock pressure manifestations, for example, in the roof of a mine working depends to a certain extent on the rock texture in its bottom and vice versa. It is also believed that this mutual influence extends not only to the rocks of the immediate roof or bottom, but also covers more distant main roof and bottom layers. Some patterns of this relationship for the Western Donbas conditions are presented in [37]-[40].

The identified patterns of the actual coal-overlaying formation structure in Western Donbas are used for grouping adequate and reliable variants (Table 1) of the adjacent roof rock texture, which simultaneously satisfy the harmonious nature of the change in layer thickness throughout the height of the roof and the probability of thickness distribution within one layer. In addition, a set of variants should ensure sufficient reliability of further modeling of geomechanical processes in the zone of conducting stope operations, and its results should be adequate and reliable in predicting the state of the supporting and protecting systems for extraction drifts planned for reuse.

Table 1. Studied structure variants of the adjacent roof layers

Variants	m_1^{RR}, m	m_2^{RR}, m	m_3^{RR}, m,	m_4^{RR}, m
1	0.5	1.5	0.5	10.0
2	0.5	2.0	1.0	6.0
3	1.5	4.0	1.5	3.0
4	2.0	3.0	2.0	6.0
5	4.0	3.0	8.0	5.0
6	4.0	1.0	10.0	4.0

To model the most reliable coal seam texture, the structure of all the coal seams mined in Western Donbas has been analyzed based on the generalization of works [32], [41], [42] summarized in Table 2.

The coal seam texture was analyzed in three directions:

– probability of distributing the seam total thickness to identify the most characteristic interval of its change;

– thickness and lithotype of rock layers in complex-structure seams;

– the probability of distributing the thickness of coal bands and their number in seams with complex structure.

The next stage of the analysis is the assessment of the most probable variants of the structure of the adjacent bottom rocks based on the study of the data in [42], where it is proposed to divide the entire thickness variation range of rock layers into five intervals: < 1 m, 1-2 m, 2.1-4.0 m, 4.1-6.0 m, > 6 m. These intervals are used to determine the probability of their occurrence in each of the four rock layers of the studied bottom (Table 3).

Table 2. Parameters of coal seams mined in the Western Donbas mines

Mine	Seam index	Total thickness, m	Seam structure			
		change range	upper (middle) band, m	lower band, m	interlayer thickness, m	rock interlayer lithotype
Ternivska	C_5^b	0.70-1.01	–	–	–	–
	C_6^b	0.84-1.15	–	–	–	–
	C_8^b	1.59-1.60	0.75-0.85	0.80-0.87	0.02-0.03	argillite
Yuvileina	C_5	0.96-1.00	–	–	–	–
	C_6^1	0.73-0.86	0.13-0.18	0.58-0.66	0.02-0.03	argillite
Stepova	C_6	0.75-1.00	–	–	–	–
	C_6^1	0.56-0.74	0.02-0.08	0.47-0.64	0.03-0.04	sandstone, argillite
Pavlohradska	C_5	0.85-1.19	–	–	–	–
	C_6	0.95-1.26	–	–	–	–
Samarska	C_1	0.81-0.93	–	–	–	–
	C_4	0.79-0.92	–	–	–	–
	C_5	0.91-1.10	–	–	–	–
Heroiiv Kosmosu	C_9	1.02	–	–	–	–
	C_{10}^t	0.80-1.00	0.60-1.00	0.00-0.26	0.00-0.02	kaolin
	C_{11}	0.80-0.84	0.06-0.13 0.26-0.28	0.37-0.42	0.02-0.04 0.03-0.04	kaolin
Dniprovska	C_8^b	0.74-0.86	0.07-0.12	0.63-0.71	0.02-0.03	sandstone
	C_8^t	0.70-1.17	0.02-0.82	0.00-0.88	0.00-0.26	argillite
	C_{10}^t	1.05-1.25	–	–	–	–
Zakhidno-Donbaska	C_8^b	0.97-1.05	0.13-0.14	0.77-0.87	0.03	sandstone
	C_8^b	0.56-0.67	–	–	–	–
	C_{10}^t	0.75	–	–	–	–

Table 3. Distribution of adjacent layers of the coal seam bottom by their thickness

Layer No.	Layer thickness, m				
	< 1.0	1.0-2.0	2.1-4.0	4.1-6.0	> 6.0
m_1^b	43%	25%	21%	9%	2%
m_2^b	16%	32%	27%	14%	11%
m_3^b	22%	29%	24%	10%	15%
m_4^b	20%	26%	28%	11%	15%

Table 3 shows the designation of the bottom rock thickness m_i^b with the numbering of layers (i = 1, 2, 3, 4), beginning with the coal seam. It follows from Table 3 that if, during modeling, to take into account the first four intervals of m_i^b change (from < 1.0 to 4.1 – 6.0 m), then a very representative range of thickness variation of the adjacent coal seam bottom rocks will be covered: first rock layer – 98%, second rock layer – 89%, third and fourth rock layers – 85%. This solution provides a high degree of reliability in modeling the texture of the coal seam bottom rocks.

In addition to ensuring a high degree of model structure adequacy to the real coal-bearing mass texture, it is necessary to find a compromise of the multivariate combinations of thicknesses of the adjacent bottom rock layers:

– on the one hand, it is necessary to ensure that it is possible to identify the patterns of influence of the thicknesses m_i^{ad} of the adjacent bottom rock layers on the stress-strain state (SSS) of the "mass – in-seam working" system;

– on the other hand, a certain limitation of calculation variants is required to ensure a "reasonable" time frame for conducting computational experiments and further analysis of its results.

The formulated principles are the basis for compiling variants of the coal seam bottom rock texture (Table 4).

There is another peculiarity of creating coal-bearing stratum texture variants for the Western Donbas conditions.

Table 4. Distribution of adjacent layers of the coal seam bottom by their thickness

Variants	m_1^{ad}, m	m_2^{ad}, m	m_3^{ad}, m	m_4^{ad}, m
1	0.5	1.5	0.5	4
2	3	4	4	6
3	2	1	6	3
4	1	0.5	2	1.5
5	3	2	3	2
6	2	6	4	6

By analogy with the roof texture (Table 1), by two variants with predominantly thin-, medium-, and thick-bedded textures are formed in the seam bottom (Table 4). This is done with the intention of identifying trends in the influence of the texture type on the parameters of rock pressure manifestations and the load value on the supporting and protecting systems of the extraction drifts.

The final stage in substantiating the texture of the adjacent coal-bearing stratum is to determine the most probable contact conditions of adjacent lithological varieties along the bedding planes. Therefore, there is a high probability of contact discontinuity between lithological varieties not only near the mine workings, but also at a considerable distance from them. In this sense, it is well known that rock layers with discontinuous contacts are less stable and intensify the rock pressure manifestations. Therefore, contact discontinuity between adjacent lithotypes should be taken into account in further analytical calculations of the SSS of the "mass – in-seam working" system.

3. Systematization of mechanical properties of the coal-bearing stratum lithotypes

After assessing the structure variations of the adjacent coal-bearing stratum in Western Donbas, it is necessary to determine the most characteristic range of changes in mechanical properties for each lithotype. The determining factors for this task are:

– distribution of lithotypes of terigenic rocks in the layers of the adjacent coal seam roof and bottom;

– choosing the most appropriate rock deformation model: elastic, elastic-plastic, limiting and superlimiting;

– determining the ranges of changes in mechanical properties of argillites, siltstones, sandstones and coal, which are generally characteristic not only of Western Donbas, but also of its particular areas; these properties should describe the rock behavior within the chosen model of its deformation.

Analysis made it possible to formulate such provisions:

– the coal seams mined in Western Donbas have a rather narrow range of strength changes;

– ultimate uniaxial compression strength of coal is σ_{com}^{c} = 30-40 MPa;

– the immediate roof rocks are represented mainly (88%) by weak argillites and siltstones, for which the most adequate interval of compression change is 5 MPa $\le \sigma_{com_i}^{RR} \le$ 20 MPa;

– siltstones (45%) are predominant in the main roof, which, together with sandstone (22%), slightly increase (on average) the strength characteristics; however, due to the presence of weak argillites (33%), the most objective range of changes in compression resistance is 10 MPa $\le \sigma_{com_i}^{RR} \le$ 40 MPa;

– the first bottom rock layer is represented by 76% weak argillite, which, together with weak siltstone (15%), determines its low compression resistance; thus, the most adequately reflected interval is 5 MPa $\le \sigma_{com_i}^{b} \le$ 20 MPa;

– the second, third and fourth bottom rock layers are characterized by a decrease in the probability of weak argillite occurrence (13-46%) and an increase in the probability of occurrence of stronger sandstones and coal interlayers (32-33%), which is accompanied by an increase (on average) in the strength properties of the main bottom rocks; thus, in our opinion, the most appropriate range for compression resistance changes is 10 MPa $\le \sigma_{com}^{b} \le$ 40 MPa.

The next component of the task is to select the most adequate ranges of changes in the mechanical characteristics of the Western Donbas rocks and to construct the required variant number of combinations of mechanical properties of rock layers in the adjacent coal-bearing stratum necessary for a reliable assessment. The whole variety of variants is divided into three positions: coal seam, roof and the bottom rock layers; in this case, the data used are from [37], [42].

For coal seams, the characteristics of prelimiting state are quite stable: σ_{com}^{b} = 30-40 MPa, E^b = (0.30-0.35)·10^4 MPa; the characteristics of the superlimiting state have been studied to a much lesser extent, but, given the results of individual experiments and the increased brittleness of coal, the variation intervals can be estimated as follows: $\left(\sigma_{com}^{c}\right)^3 / \sigma_{com}^{c}$ = 0.05-0.10, M^b / E^b = 2-3. Based on these intervals, three variants (Table 5) of the mechanical characteristics of coal were constructed and used for preliminary testing of the "mass – in-seam working" system model.

Table 5. Variants of coal seam mechanical characteristics

Variants	Mechanical characteristics			
	σ_{com}^{c}, MPa	$E^b \cdot 10^4$, MPa	$\left(\sigma_{com}^{c}\right)^3 / \sigma_{com}^{c}$	M^b / E^b
1	30	0.30	0.10	2.0
2	40	0.35	0.05	3.0
3	35	0.33	0.08	2.5

Analysis of data from a large number of rock sample tests made it possible to identify the most adequate ranges of changes in mechanical characteristics of prelimiting and superlimiting states of terigenic rocks in Western Donbas (Table 6).

Table 6. Ranges of changes in mechanical characteristics of coal-bearing rocks

Rock type	Mechanical characteristics			
	σ_{com}^{c}, MPa	$E^b \cdot 10^4$, MPa	$\left(\sigma_{com}^{c}\right)^3 / \sigma_{com}^{c}$	M / E
Argillite	5-25	0.2-11.0	0.10-0.25	0.5-1.7
Siltstone	10-35	0.4-1.5	0.08-0.20	1.0-3.0
Sandstone	25-45	0.8-2.0	0.05-0.15	2.0-5.0

Variants of combining the mechanical characteristics of the roof and bottom rocks (Tables 7 and 8) are intended for calculating the SSS of the "mass – in-seam working" system; in addition to covering the main range of changes in properties, these variants correspond to the probability of distribution of lithotypes through adjacent rock layers.

Table 7. Variants of mechanical characteristics of adjacent rock layers of the coal seam roof

Layer No., i	Variants	Mechanical characteristics			
		σ_{com_i}, MPa	$E_i \cdot 10^4$, MPa	$\sigma^3_{com_i} / \sigma_{com_i}$	M_i / E_i
First, $i = 1$	1	5	0.3	0.2	0.5
	2	10	0.6	0.2	1.0
	3	30	2.0	0.08	3.0
Second, $i = 2$	1	5	0.2	0.25	0.5
	2	20	1.0	0.15	2.0
	3	40	2.0	0.05	5.0
Third, $i = 3$	1	10	0.6	0.15	1.5
	2	20	1.0	0.20	2.0
	3	30	2.0	0.08	3.0
Fourth, $i = 4$	1	10	0.8	0.20	1.0
	2	10	0.3	0.25	0.5
	3	40	2.0	0.05	5.0

Table 8. Variants of mechanical characteristics of adjacent rock layers of the coal seam bottom

Layer No., i	Variants	Mechanical characteristics			
		σ_{com_i}, MPa	$E_i \cdot 10^4$, MPa	$\sigma^3_{com_i} / \sigma_{com_i}$	M_i / E_i
First, $i = 1$	1	5	0.2	0.25	0.5
	2	10	0.8	0.20	1.0
	3	20	1.0	0.15	1.5
Second, $i = 2$	1	10	0.6	0.15	2.0
	2	10	1.0	0.15	1.5
	3	20	1.5	0.20	3.0
Third, $i = 3$	1	5	0.3	0.25	0.5
	2	10	0.8	0.15	1.5
	3	30	2.0	0.08	3.0
Fourth, $i = 4$	1	10	1.0	0.15	1.5
	2	20	1.5	0.15	2.0
	3	40	2.0	0.05	4.0

Systematization should provide a limited number of groups of mining-geological conditions, because structural-technological solutions for maintaining reused mine workings should be universal to a certain extent, which can help improve the quality of the relevant technical documentation.

4. Loading mechanism of support and protection systems in reused workings

Proper fulfillment of the main task – substantiation of the parameters of supporting and protecting systems for each group of mining-geological conditions for maintaining extraction workings – is impossible without analyzing the peculiarities of the mechanism of coal-overlaying formation shear in Western Donbas, since any grouping of conditions depends on the predicted parameters of deformation, stratification, fracture formation, water-cut and other texture transformation components and mechanical properties of lithotypes in the zone influenced by stope operations.

As for the geomechanical conditions of the Western Donbas mines, the ideas about the development of the so-called anomalous zones of the coal-bearing stratum near the longwall face have been developed in [42]-[44].

Summarizing the above trends, it is necessary to note the following positions of loading the supporting and protecting systems:

– firstly, there is a large load P non-uniformity along the mine working perimeter, which negatively affects its stability;

– secondly, a rigid protecting structure provokes the formation of increased bearing pressure on it, and, as a result, lateral pressure on the frame;

– thirdly, due to the above, the asymmetry of load distribution on the extraction working support is further enhanced, which is confirmed by analytical studies and mine experiments;

– fourthly, the high bearing pressure on the mine working berm (from the protecting structure) contributes to its weakening and the creation of lateral load concentrations in the area of the frame stand bearing;

– fifth, intensive lateral load does not correspond to the frame support structural peculiarities and its operation under such conditions is inefficient.

The presented general peculiarities of the mechanism of loading the supporting and protecting systems of the extraction workings in the Western Donbas mines have certain differences depending on the coal-bearing stratum texture and mechanical properties of the lithotypes composing it. Thus, the schemes for maintaining extraction workings are grouped based on the following geomechanical factors.

Firstly, the development of rock mass disturbances into the mine working roof depends on the stability of the thrust load-bearing rock formations in the hinged-block shear zone. The load-bearing capacity, and therefore the level of resistance to rock pressure of such thrust rock structures, largely depends on a number of the following main factors: lithotype thickness, where the thrust structure is formed; the value of its compression strength, taking into account the effects of rock-weakening phenomena; length of the rock blocks (slabs) that make up the thrust structure.

Secondly, the coal-bearing mass texture and the mechanical properties of its lithotypes influence the formation of lateral rock pressure, which the traditional frame support does not resist very effectively.

Numerous studies [43] have revealed a direct relationship between the intensity of rock pressure manifestations in the vertical and lateral directions. Consequently, there is a general decrease in multi-vector rock pressure due to the support of mine working in the predominantly thick-bedded mass with increased strength properties of its lithotypes.

Thirdly, a decrease in vertical rock pressure has a positive effect on the stability of extraction working bottom rocks [37], [45], [46].

Positive trends in increasing the stability of the extraction working bottom rocks are as follows:

– thick-bedded roof texture with high-strength lithotypes reduces vertical and lateral rock pressure on the coal seam and, consequently, on the bottom rocks;

– the thick-bedded bottom rock texture limits its heaving due to the formation of the same thrust structures of increased stability;

– side roof bolts set to the height of the lower bottom dinting also limit its movement into the mine working cavity.

Fourth, it is necessary to take into account the influence of geomechanical factors on the load of the protecting system and to respond constructively to changes in the shear parameters of the coal-overlaying formation depending on its texture and mechanical properties of its lithotypes.

Summarizing the stated principles of grouping structural-technological schemes for maintaining extraction workings according to the trends of influence of the coal-bearing mass texture and the mechanical properties of its lithotypes, it is possible to propose rather universal conditions, taking into account the existence of other geomechanical factors.

It is quite clear that under the conditions of placing an extraction working in a predominantly thick-bedded mass with reduced mechanical properties of its lithotypes, the opposite trends will occur – an increase in rock pressure in all directions, and the mechanism of this process has already been revealed earlier. The group of mechanical conditions occupying an intermediate position will be characterized by moderate multi-vector rock pressure manifestations, which are consistent with certain structural-technological solutions to maintain the extraction working in proper operating condition.

Therefore, the following grouping of mining-geological conditions for the operation of reused extraction workings is proposed:

– predominantly thick- and medium-bedded texture with increased mechanical characteristics of the adjacent mass lithotypes;

– predominantly medium-bedded texture with averaged mechanical characteristics of lithotypes;

– predominantly thin- and medium-bedded texture with reduced mechanical characteristics of lithotypes.

Thus, the principles of grouping structural-technological schemes for maintaining extraction workings wee summarized according to the trends in the influence of coal mass texture and the mechanical properties of its lithotypes. As a result, three groups of mining-geological conditions for the operation of the extraction workings that are planned for reuse have been identified.

5. Results and discussion

5.1. Geomechanical modeling results by mining conditions

The accumulated experience [22], [36], [37] of conducting computational experiments using modern methods of calculating the SSS of geomechanical systems proves the feasibility of gradually approximating the model to a real object with simultaneous implementation of cycles for assessing the reliability and adequacy of the results obtained.

Step-by-step modeling:

1. Modeling of the rock mass mechanical properties in several successive stages: elastic and elastic-plastic deformation in the prelimiting state; deformation in a superlimiting state, given the rock weakening and loosening.

2. Modeling the texture of the mass surrounding the mine working: stratified coal-bearing mass represented by rocks with different mechanical properties; a mass with discontinuous contacts between rock layers with modeling of the main natural fracture systems within each layer.

3. Modeling of the support is performed in relation to typical sections of mine workings in the direction of consistent approximation to its real structural-technological peculiarities: support with interframe fencing and a backfilled grouting space; spatial (third coordinate – the axis of the mine working) modeling of a group of frames with structural idealization of the yielding nodes (locking joints) and interframe fencing; spatial modeling in elastic setting (mandatory for discrete types of supports set along the mine working): frame, roof-bolting, frame-roof-bolting, etc.) with structural idealization of the most geometrically complex nodes while preserving the principle of their operation; spatial modeling in an elastic setting with full indication of the geometric parameters of all support units; spatial modeling of all real structural peculiarities of a particular type of support based on the full deformation diagram of materials (steel, concrete, wood, etc.).

4. Stage-by-stage substantiation of the initial modeling provisions: at the first stage, the texture and properties of the rock mass surrounding the mine working, the support structure, initial and boundary conditions for its interaction with the surrounding rocks, the dimensions of the spatial model, etc. are substantiated (most typical for a particular mining-geological and mining-technical situation); at the second stage, the most typical ranges of changes in the texture and properties of the coal-bearing mass, intervals of variation of typical mine working sections with the corresponding support structures and its standard sizes, variants of support operating modes with the corresponding boundary conditions are selected; at the third stage, the behavior of the “mass – frame – roof bolt” system is studied relative to the extreme values of the selected ranges of changes in its parameters; at the fourth stage, the ranges of changes in the main influencing parameters of the system, variants of initial and boundary conditions of its deformation, and the expedient dimensions of the geomechanical model for a particular mine working, mine or geological-industrial area are substantiated.

5. Assessment of the geomechanical model reliability and adequacy:

– sequential assessment of each of the idealizations and assumptions adopted in the model separately for the geometric, mechanical and force parameters of the “mass-frame – roof bolt” system based on the relevant calculations and subsequent analysis of its SSS for each of the stress and displacement components;

– analysis of the degree of error in assumptions and idealizations of the created geomechanical model and its correction based on the analysis results;

– verification of the adequacy and reliability of modeling results for compliance with available analytical, laboratory and mine studies and adjusting the model based on the conclusions obtained.

The research algorithm is presented in the form of a sequential execution of the following stages:

A. Mine working location depth.

B. Mine working orientation relative to the coal seam.

C. Coal-bearing stratum texture.

D. Mechanical characteristics of the rock mass adjacent to the mine working in the prelimiting state.

E. Typical mine working section.

6. Structural-technological characteristics of support.

The six stages covered concern the substantiation of the initial data for computer modeling; the following stages are aimed at improving the model, assessing the adequacy and reliability of the research in accordance with the proposed methodology for modeling geomechanical processes.

7. Estimating the dimensions (in Y, X, Z coordinates) of a spatial geomechanical model. The task of this stage is to determine the minimum permissible dimensions of the model, at which the boundary conditions on its surfaces do not significantly affect the disturbance of stress fields and displacements around the mine working. To do this, it is sufficient that the SSS components at the model boundaries approach the initial state of the virgin mass with an error of up to 10%. In this case, the SSS calculation is performed in the elastic setting, which, on the one hand, is the most sensi-

tive to disturbances in the stress fields and displacements, and, on the other hand, the relative SSS error on the model boundaries is not related to the mining depth.

8. Assessment of compliance of the SSS calculation results (in the elastic setting) with the classical provisions of the mechanics of underground structures. The analysis of the SSS calculation results of the models at stage No. 7 is performed for each stress component, during which the presence or absence of contradictions to the provisions of the mechanics of underground structures in general, or to known studies (in this area) in particular, has been found.

It has been determined that the tangential stresses along the rock-coal bedding planes, as a rule, significantly exceed (sometimes by an order of magnitude) the adhesion forces (or net shear resistance) between the layers. Therefore, there is a contact discontinuity between the adjacent rock layers around mine working, which should be incorporated into the geomechanical model to improve its adequacy.

9. Consideration of discontinuous contacts between the layers of coal-bearing stratum around the mine working. The task of this stage is to model the discontinuous contacts between adjacent layers in an elastic setting (a fact determined in the studies at stage No.8), which makes it possible to predict them relative to each other when bending towards the mine working cavity.

10. Estimating model dimensions with account of discontinuous contacts between rock layers. By analogy with the studies at stage No. 7, the minimum permissible model dimensions are determined. The necessity of this stage is caused by an increase in the intensity of bending of rock layers when interlayer contacts are disturbed, which is proven by an increase in the minimum required width of the model along the X coordinate to 60 m. The model dimensions remain constant along the vertical coordinate Y and the axial coordinate Z of the mine working length.

11. Substantiation of the model texture of the adjacent coal-bearing stratum. The task of this stage is to assess two interrelated factors: firstly, to determine the extent of influence of thickness of the rock layers and the coal seam; secondly, whether it is possible to describe the structure of the adjacent coal-bearing stratum throughout the entire mine working length with one model. This intention is conditioned by the peculiarities of the finite element method, which involves constructing a new model every time any of its geometric parameters change; on the other hand, it is necessary to limit the number of variants of the mass texture around the mine working to a smaller number (if possible), while maximally covering the real structure of the coal-bearing rock stratum in Western Donbas.

12. Assessment of the influence of deformation characteristics of adjacent rock layers on the SSS of model elements. The task of the stage includes three components: firstly, to identify the patterns of influence of deformation characteristics of rock layers on the system SSS in general and, in particular, on the size of the bearing pressure zones of de-stressing (around the mine working) as factors determining the intensity of rock pressure manifestations; secondly, to assess the compliance of modeling results with the provisions of the mechanics of underground structures and existing knowledge of geomechanical processes around the mine working; thirdly, to identify the quantitative patterns of growth of the bearing pressure and de-stressing zones with deepening of the mine working location.

Having made an intermediate summary, we note that stages 7-12 gave a positive assessment of the adequacy of the modeling results (in the elastic setting) to the basic principles of the mechanics of underground structures and modern ideas about geomechanical processes in the stratified mass surrounding the extraction working. The next stages are aimed at improving the model to take into account the full deformation diagram of all system elements and to assess the adequacy and reliability based on the results of existing analytical, laboratory and mine research in this area.

13. Substantiation of mechanical characteristics of complete deformation diagrams of materials of model elements. In accordance with the idealization generally accepted in geomechanics, the complete rock-coal deformation diagram is modeled by three linear sections with the following characteristics: ultimate uniaxial compression strength σ_{com}, relative residual strength $\sigma^3_{com} / \sigma_{com}$ at the loosening stage, strain modulus, strain modulus E at the elastic-plastic stage and relative modulus of decay M / E at the stage of weakening. Modern studies of the superlimiting rock state in Western Donbas have made it possible to substantiate the most objective ranges for changing the above characteristics $0.05\text{-}0.10 \le \sigma^3_{com} / \sigma_{com} \le 0.20$; $0.5 \le M / E \le 3$.

The characteristics of the prelimiting state are specified earlier (stage D); here it should be noted that it is necessary to take into account rock weakening factors, which are most reasonably considered according to the recommendations of industry normative documents. The frame support is exposed to very significant stresses and strains, so the real diagram of steel St.5 loading is modeled, taking into account the yield point when the ultimate state σ_T = 270 MPa is reached (σ_T – is the yield strength of steel).

14. Calculating the model SSS based on the full deformation diagram of its elements.

15. Assessment of the adequacy and reliability of the model SSS calculation results based on the full material deformation diagram. The adequacy of the results is assessed in two directions: analysis of the peculiarities of stress fields and displacements, as well as analysis of the patterns of influence of a particular geomechanical model parameter.

The reliability of the results is assessed by constructing a number of dependences of the displacement development of the mine working contour with increasing mining depth H with the variation of a particular model parameter. These dependences are compared with the results of mine observations and recommendations of industry normative documents, for which additional calculations are performed for specific mining-geological conditions of the mine experiment.

16. Development of recommendations for maintaining extraction workings in the conditions of Western Donbas mines.

According to the research results of the effectiveness of the recommended variants of supporting and protecting systems for extraction workings, it has been determined:

– the greatest danger to the extraction working stability is the bearing pressure zone from the side of the mined-out space; here, large rock volumes of the roof are expected to be weakened to width of 2.0-2.2 m and the bottom to 1.8-2.0 m;

– in terms of the impact of vertical stress σ_y factor, the greatest danger to the supporting system stability is posed by the frame stand, especially from the side of the mined-out space, which need to be strengthened with lateral lagging; to prevent bending of the cap board and bending of the stand of the strengthening support, it is necessary to specify a structurally yielding operating mode;

– the protecting system is quite stable due to the crushing of timber and pressing into the rocks of the roof and bottom, although this reduces its height and, accordingly, the height of the extraction working;

– the stress intensity field σ development as the longwall face retreats, is more actively manifested from the side of the mined-out space in such load-bearing elements as frame stands, side roof bolts, strengthening support and the protecting structure; this fact emphasizes the need for stability of the border rocks, supporting and protecting systems of mine workings from the side of the operating extraction site.

5.2. Recommendations for maintaining reused workings

All the available variety of supporting and protecting systems is to some extent subordinated to consideration of peculiarities of rock pressure manifestation in specific mining-geological conditions. In this regard, when analyzing the schemes for maintaining the reused extraction workings, their compliance with the mining-geological conditions of the mine working operation was assessed and the conditions were grouped according to the degree of feasibility of using various supporting and protecting systems. Three averaged conditions for the texture and state of the coal-overlaying formation rocks, as well as the schemes for maintaining site workings recommended to them, have been identified.

Group I, which characterizes the so-called "difficult" mining-geological conditions: predominantly thin-bedded texture of weak rocks (strength coefficient $f < 1.5$); argillite with a thickness of 1.0 m and more with average distance between weakening surfaces less than 1.0 m; argillite and siltstone layers (f = 1.5-2.5) of medium thickness are periodically separated by watered coal interlayers of thickness 0.1-0.3 m. Figure 3a shows the supporting scheme: step of setting frames and resin-grouted rockbolts is $L_f = L_{rg.b}$ = 0.8 m; step of setting rope bolts is $L_{s.r.b}$ = 1.6 m.

Group II, reflecting the "moderate" rock pressure manifestations: thin- and medium-bedded texture of water-free rocks with a strength coefficient of argillite and siltstone f = 1.5-25; medium- to thick-bedded structure of water-cut rocks with $f \geq 1.5$ with sandstone occurring up to 3.0 m thick. Figure 3b shows the supporting scheme: step of setting frames and resin-grouted rockbolts is $L_f = L_{c.a}$ = 0.8 m; step of setting rope bolts is $L_{s.r.b}$ = 2.4 m.

Group III, characterizing "favorable" mining-geological conditions: medium- and thick-bedded texture of water-cut rocks ($f \geq 2.5$) with sandstone occurring over 3.0 m thick; medium- and thick-bedded texture of water-free rocks ($f \geq 2.5$). Step of setting frames and resin-grouted rockbolts is $L_f = L_{rg.b}$ = 0.8; step of setting rope bolts is $L_{s.r.b}$ = 3.2 m (Fig. 3c).

The reliability of the correctness of using the proposed systems has been confirmed by conducting mine experiments. The analysis of the results of visual and instrumental observations, shown in Figure 4, proved that the choice of rational parameters for supporting and protecting systems of reused mine workings should be based on groups of mining-geological conditions with the above-studied classification peculiarities.

The conducted research and mine experiments have confirmed the effectiveness of the proposed supporting and protecting systems for maintaining reused extraction workings under different mining-geological conditions. The classification of conditions into three groups – difficult, moderate, and favorable – ensures a systematic approach to selecting appropriate support schemes.

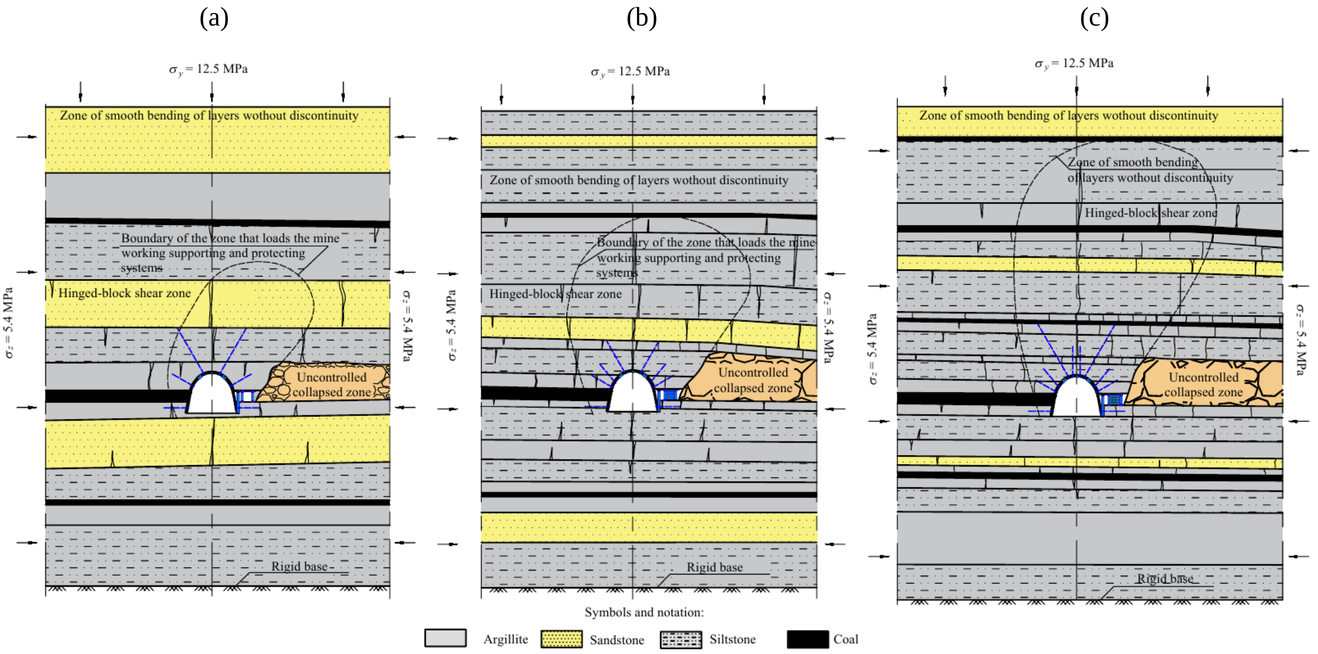

Figure 3. Scheme for supporting extraction drift: (a) in difficult mining-geological conditions; (b) with moderate rock pressure manifestations; (c) in favorable mining-geological conditions

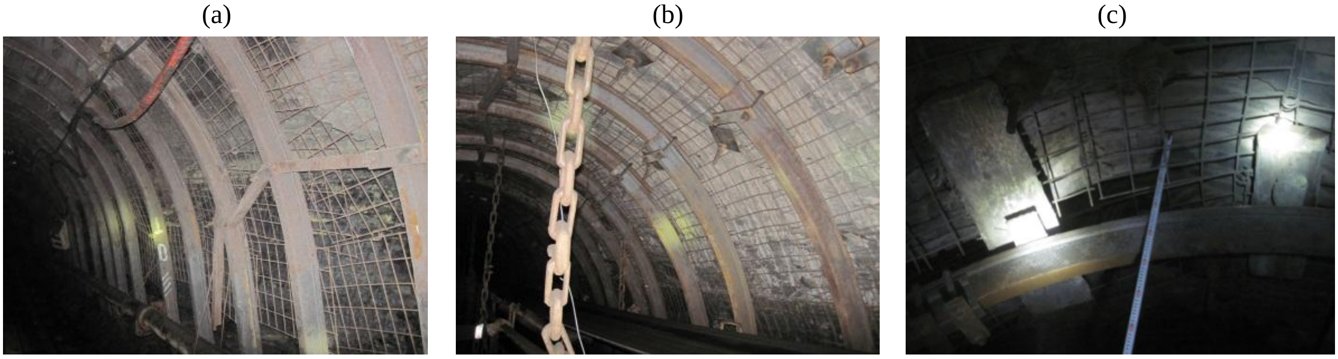

***Figure 4.** Prefabricated drift 1047 condition in the frontal bearing pressure zone with the proposed supporting scheme (Zakhidno-Donbaska Mine): (a) from the side of the 1047 longwall face; (b) from the side of the mined out 1045 longwall face; (c)checking the state of the mine working roof using a measuring rai*

The results of visual and instrumental observations demonstrated that properly chosen support parameters significantly enhance the stability of mine workings and mitigate the risks associated with rock pressure manifestations. The implementation of these re-commendations in real mining operations, as exemplified in the Zakhidno-Donbaska Mine, contributes to improving the safety and efficiency of underground extraction processes.

6. Conclusions

The adjacent rock layers around the coal seams mined in Western Donbas are composed mainly of weak argillites and siltstones and to a lesser extent of weak sandstones; in this sense, the patterns of their texture are presented and analyzed. On this basis, an array of calculated texture variants has been developed that reflect the probability of lithotype classification by their thickness in the rock layers of the immediate and main roof and bottom, which maximally approximates geomechanical models to the real mining-geological conditions for maintaining extraction drifts in the Western Donbas mines.

Recommendations have been developed on the principles of creating geomechanical models of mass shear and loading of supporting and protecting systems in the zone of influence of stope operations.

Two directions of modern structural-technological solutions, which have already been tested at the Western Donbas mines, contribute to the implementation of resource-saving prospects for the reuse of extraction drifts:

– use of combined roof-bolting systems to form powerful reinforced rock structures of high load-bearing capacity in the roof;

– use of spatially yielding rope lagging of frames and roof bolt tail joints to increase resistance to rock pressure, especially in the sides of the extraction drifts.

The principles have been generalized of grouping structural-technological schemes for maintaining extraction drifts according to the trends in the influence of the coal-bearing mass texture and the mechanical properties of its lithotypes. As a result, three groups of mining-geological conditions for the operation of extraction drifts planned for reuse have been identified.

Based on the results of a number of computational experiments performed to study the effectiveness of the recommended variants of supporting and protecting systems of extraction drifts, it has been determined:

– the greatest danger to the stability of extraction drifts is the zone of bearing pressure from the side of the mined-out space; here, large rock volumes of the roof are expected to be weakened to a width of 2.0-2.2 m and the bottom – to 1.8-20 m;

– frame stands, especially from the side of the mined-out space, need to be strengthened with side roof bolts with spatially yielding lagging;

– to prevent bending of the cap board and bending of the stand of the strengthening support, it is necessary to specify a structurally yielding operating mode;

– the protecting system is quite stable due to the crushing of timber and pressing into the rocks of the roof and bottom;

– the stress intensity field development up to 10-20% is observed as the longwall face retreats, but only in such load-bearing elements as frame stands, side roof bolts, strengthening support and the protecting structure.

The generalization of the performed studies is given in a convenient form of three variants of schemes for maintaining extraction drifts, while covering most of the mining-geological conditions of the Western Donbas mines.

Author contributions

Conceptualization: VB; Data curation: IK; Formal analysis: RG; Investigation: IS, DM; Methodology: VB; Project administration: IK; Resources: DM; Supervision: VB; Validation: IS; Visualization: RG; Writing – original draft: IK, DM; Writing – review & editing: IS, VB, RG. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

Authors VB and IK declare that they were editorial board members of the Mining of Mineral Deposit journal at the time of submission, which had no impact on the peer review process or the final decision. Author IS was employed by DTEK Energy BV. The remaining authors declare no conflict of interest.

Data availability statement

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

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Принципи гірничо-геологічної класифікації підтримання виробок в умовах слабометаморфізованих порід

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Мета. Мета даної роботи – провести групування гірничо-геологічних умов шаруватого масиву, який вміщує слабкі породи Західного Донбасу (Україна) та обґрунтувати рекомендації щодо раціональних параметрів систем кріплення та охорони виробок, що повторно використовуються.

Методика. Дослідження проводились при поєднанні аналітичних методів вивчення процесів деформування гірського масиву у зоні ведення очисних робіт з експериментальними вимірами проявів гірського тиску. Як зв'язуюча ланка вивчались уявлення про механізм розвитку процесу зсуву надвугільної товщі та його особливості для гірничо-геологічних умов Західного Донбасу. Отримані закономірності враховані в розрахункову модель як складова формування навантаження та системи кріплення і охорони виїмкових штреків. Визначена методологія комп'ютерного моделювання за умовою максимально можливого відображення конструктивних особливостей рамного і анкерного кріплень. Проведено тестування розроблених моделей, що підтвердило їх адекватність реальним об'єктам.

Результати. Комплекс проведених досліджень дозволив побудувати масив розрахункових варіантів текстур, які відображають ймовірність поділу літотипів за їх потужністю по породних шарах безпосередньої та основної покрівлі й підошви. За результатами виконання низки обчислювальних експериментів щодо вивчення ефективності рекомендованих варіантів кріпильних та охоронних систем встановлено розподіл напружено-деформованого стану у вантажонесучих елементах системи. Створено принципи групування схем підтримання виробок, які охоплюють більшість гірничо-геологічних умов шахт Західного-Донбасу.

Наукова новизна. З метою досягнення достовірності результатів досліджено комплекс особливостей та взаємовпливу елементів геомеханічної системи. Закономірності, отримані в результаті багатофакторного моделювання, виявили зв'язок зміцнення породних шарів у вигляді їх дискретної порушеності з формуванням системи взаємодіючих плит, яка інтенсифікує процес видавлювання часткового зміцненого приконтурного масиву.

Практична значимість. Узагальнені принципи групування конструктивно-технологічних схем підтримання виїмкових штреків. У підсумку виділено три групи гірничо-геологічних умов експлуатації виїмкових штреків, що плануються до повторного використання. Запропоновано та досліджено три варіанти схем підтримання виїмкових штреків для умов шахт Західного Донбасу.

Ключові слова: *гірський масив, виробка, система кріплення, система охорони, механізм навантаження, геомеханіка*

Publisher's note