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Optimization Principles Implementation in the Innovative Technologies for Reused Extraction Workings Maintenance

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Abstract

This paper studies the main approaches to optimization principles implementation in innovative technologies for reused mine workings. Based on the experimental data processing and using the correlation analysis methods, the possibility of achieving the correspondence of the deformation-strength characteristics of the fastening structures to the optimal values of loads and displacement, at which the intensity of rock pressure manifestations is minimal, has been proved. A series of multivariate computational experiments with various mining-and-geological and mining-engineering factors have been conducted to determine the characteristics of the fastening structures in the conditions of the Western Donbass coal mines (Ukraine). Based on the comparative analysis of the experiment and analytical calculations, it is possible to represent recommendations for the use of the combined roof-bolting systems in difficult mining-and-geological conditions when maintaining reused extraction coal-mine workings.

Keywords*: Fastening structures; Geomechanical factors; Geomechanical index; Combined roof-bolting systems; Mechanism of the geomechanical deformation.*

1. Introduction

The previous research results [1–3] substantiate the principles and directions for optimizing the deformation-strength characteristics of fastening structures in reused extraction mine workings in accordance with the geomechanical conditions of their maintenance. The analysis of these directions [4–6] unambiguously indicates to a strong consistency between the fastening structure operating mode and the load it perceives from the side of the adjacent coal-bearing mass. This has been studied in detail in [7–10], but refers to mine workings maintained outside the zone of stope works influence, and without taking into account the impact of advanced combined roof-bolting systems on the adjacent mass behavior. The noted two fundamental differences not only reflect the essence of this paper novelty, but at the same time require a search for methodological approaches to experimental verification of the conformity degree of the analytical development results.

2. Experimental

2.1 Methodological principles for achieving the adequacy of comparing the results of mine research and analytical calculations

The complexity of experimental verification of the optimization decisions reliability and adequacy is in the following.

Each separate mine working or a group of adjacent mine workings is characterized by its own mining-and-geological conditions: depth H of location, structure and mechanical properties of the adjacent rock mass, which are expressed through an integral parameter R – the average calculated compressive resistance of adjacent lithotypes in accordance with the normative methodology [11]. The indicator H/R of the conditions for maintaining mine working is an initial parameter, which is constant for a particular case and does not depend on the fastening structure operating mode. The structure and mechanical properties of the adjacent rock mass are also classified as source data.

From the above, it follows the conclusion that the control of the rock pressure manifestation parameters towards minimizing the load is possible only with the help of the fastening system itself, by regulating its deformation-strength characteristics. This method in innovative technologies for the use of combined roof-bolting systems is performed by changing the fastening structure parameters.

The position of P_{max} adjustment by means of frame support is only partially expedient when the reaction P_{max} of a particular fastening structure significantly exceeds the required rational value P_p (Fig. 1). Then it seems logical to facilitate the frame support (as the most material-intensive structure), namely, to reduce the number of the special profile SCP and (or) to increase the step of setting the frames. If this is not enough, then the parameters of the combined roof-bolting system should be regulated. In the opposite geomechanical situation, when it becomes necessary to increase the reaction P_{max} of the fastening structure, it is inexpedient to increase the metal intensity of the frame support for technical and economic reasons. Here it is necessary to enhance the influence of the combined roof-bolting system: reduce the step of rope bolts setting or increase the number of resin-grouted rockbolts (with a change in the parameters of their setting) in the interframe space. When setting the rope bolts, it should be emphasized a certain limitation in changing the parameters only by the distance (step) between adjacent bolts along the length of mine working. This is due to the fact that other parameters of the rope bolts setting (the number and coordinates of the rope bolt tail joints location, their angle of gradient and length) are sufficiently fully presented and substantiated in the works [12–14] precisely for the conditions of the Western Donbass mines. As a result, there is a whole set of the fastening structure parameters, which can be adjusted to achieve the correspondence between its resistance reaction P_{max} and a rational value P_p at a specific value of the geomechanical index (Fig. 1).

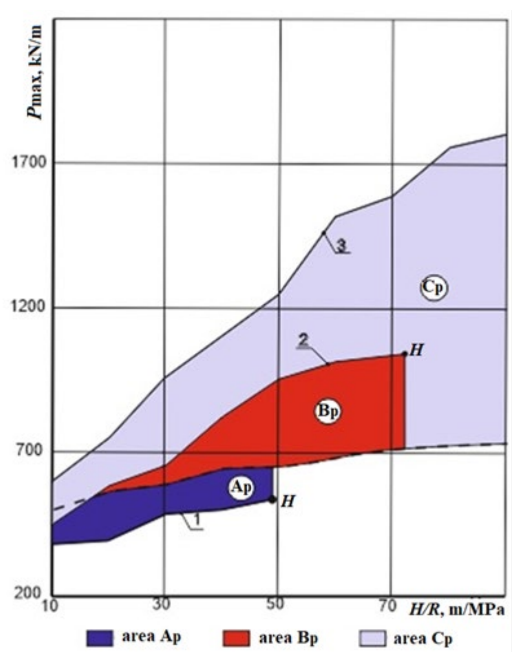

Figure 1. Comparative analysis of the instability P_{max} of the fastening structure

(- - - - - -) and its value P_p of rational resistance ( ) depending on the geomechanical index H/R: a variant of reduced (1), averaged (2) and increased (3) mechanical properties of rocks in a bolted roof

Regarding the varying yielding property of the fastening structure, the following can be noted. Firstly, there is a dependence between the yielding value u_{max} and the resistance reaction P_{max} of the fastening structure, which is explicitly shown in the graphs of Fig. 2, but implicitly has some reserves beyond the range of u_{max}values. This refers to the conditions of constrained deformation of quasi-plastic hinges in thrust structures made of strengthened rock blocks, when their yielding property increases substantially without significant resistance reaction loss. The graphs $P(u)$ flatten out, which indicates a predominant increase in the yielding property compared with an increase in reaction. That is, strengthened rock thrust structures have a certain internal margin of yielding property, which makes it possible to approach the rational deformation-strength characteristics $P_p(u_p)$ of the mass. This is clearly seen in the graphs in Fig. 3, where, in the areas of increased intensity of rock pressure manifestations (growth of the index H/R) the yielding property of a fastening structures as a whole approaches rational values.

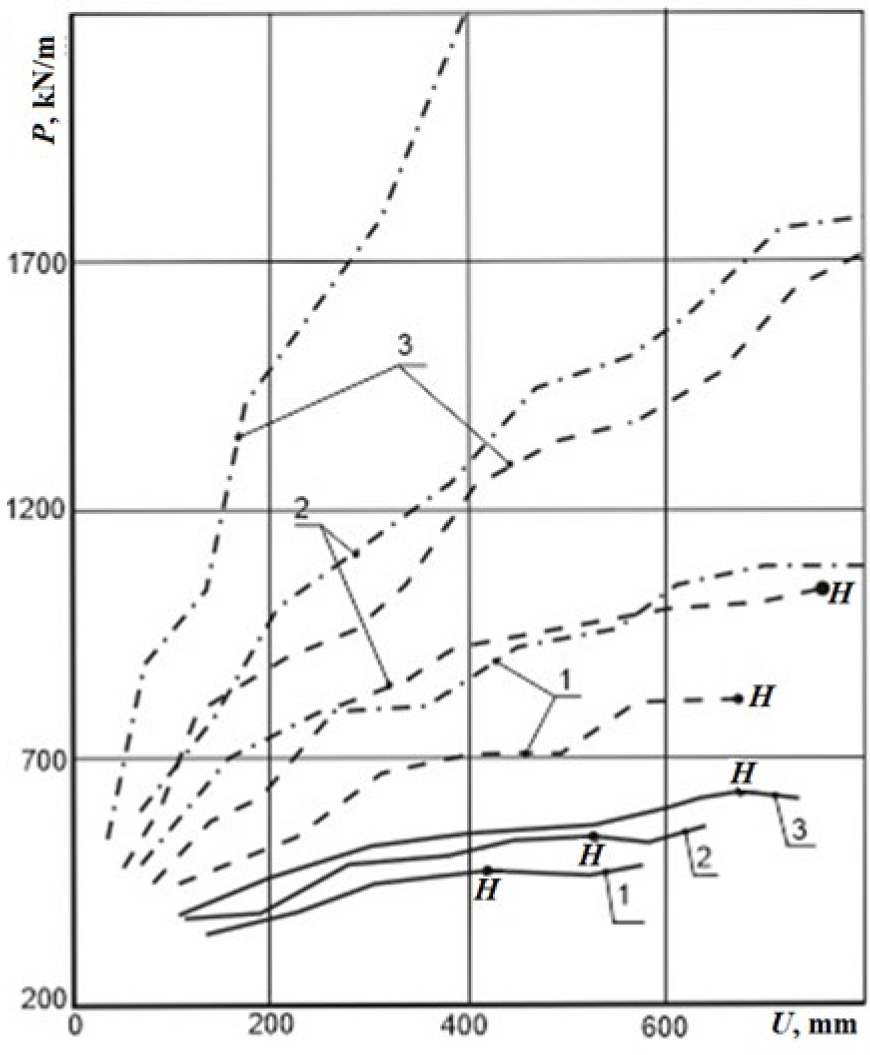

Figure 2. Deformation-strength characteristics $P(u)$ of the fastening structure, including the frame support and combined system (support), during strengthening the roof rocks by their structure groups: 1 – group I; 2 – group II; 3 – group III; variant of reduced mechanical properties;'basic' variant of the averaged mechanical properties; variant of increased mechanical properties

Secondly, the above mentioned implicit margin of a yielding property as such is absent in the frame support, and the growth of u_{max} mainly occurs due to structural changes and partly deformation processes. The deformation-strength characteristics of a multi-element fastening structure are studied, which includes one of the most widespread components in the Western Donbass – a frame support of the TSYS series that has a vertical structural yielding property of up to 300 mm and a lateral yielding property of up to 100 mm from each side. From the graphs in Fig. 3, it can be seen that the yielding property value of 300 mm is sufficient only in favorable mining-and-geological conditions with a geomechanical index of H/R =10 – 15 m/MPa. The maximum difference between the optimal value of yielding property u_A and u_{max} of the basic fastening structure (with different structure of the adjacent mass and the strength properties of its lithotypes) is observed at the values of geomechanical index of H/R =20 – 35 m/MPa and is up to 300 – 350 mm; further increase in H/R reduces the level of discrepancy of u_A and u_{max} (Fig. 3) and at H/R >60 m/MPa the difference between u_A and u_{max} (both positive and negative sign) does not exceed 70 – 100 mm.

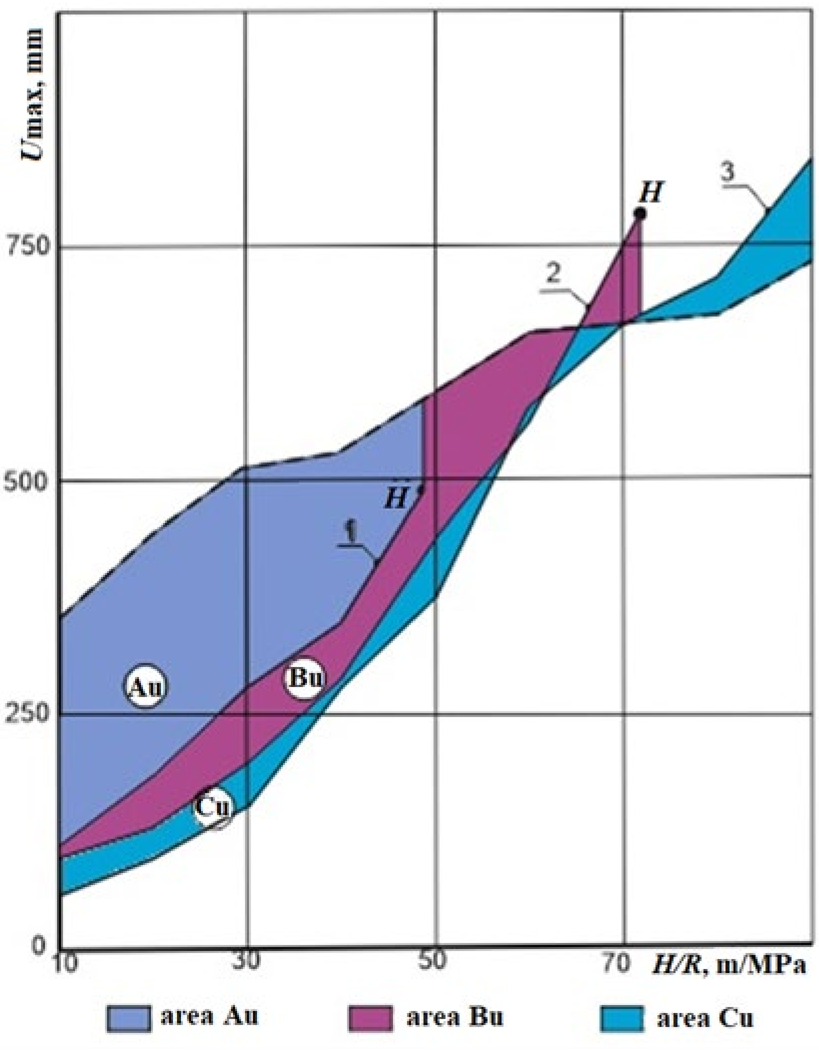

Figure 3. Comparative analysis of the fastening structure ( ) instability $u_{max}$and its optimal value u_A (-------) depending on the geomechanical index H/R: a variant of reduced (1), averaged (2) and increased (3) mechanical properties of rocks in a bolted roof

If to sum up the specified factors of additional yielding property, we get a value of the order of 350 – 500 mm, which is quite sufficient to compensate for the discrepancy between the parameters u_A and u_{max} in the frame support.

Thirdly, the roof-bolt structures themselves (both rope and resin-grouted) have some yielding property when loaded with axial forces, which can be attributed to the category of additional yielding property.

Summarizing the studied factors influencing the deformation-strength characteristics of the fastening system, it is necessary to formulate generalizing conclusions:

- it is quite possible to achieve a satisfactory correspondence of the fastening structure deformation-strength characteristics to the minimized (rational) rock pressure manifestations in the specific conditions for maintaining extraction mine workings;
- the main condition for implementing the optimization solutions is the strength factor, which is regulated by the fastening structure parameters;
- the deformation factor performs a subordinate, but significant role and its implementation (in optimization solutions) is partly regulated by the rock pressure manifestations themselves, and in the other part – by the design parameters of the fastening system.

2.2. Specificity of comparing experimental and analytical results

Having considered the possibilities of implementing optimization solutions for controlling the fastening system deformation-strength characteristics, we proceed to substantiating the methodological principles for achieving the adequacy of comparing the results of mine research and analytical calculations.

The first peculiarity of comparing the experimental and analytical studies results is the possibility of only implicitly obtaining information about the rock pressure manifestations through the rock contour displacements U, the value of the mine working section loss ΔS and the state of its fastening structure.

The second peculiarity is the mutual influence of the two directions of optimization actions. On the one hand, the achievement of optimal parameters P_A and u_A does not happen by itself, but is controlled by the fastening structure deformation-strength characteristics $P(u)$. On the other hand, the fastening structure deformation-strength characteristics is also exposed to regulation by varying its parameters. Therefore, it is difficult to determine how rational a given fastening structure and its deformation-strength characteristics are. Obviously, in order to reveal the degree of rationality of the fastening structure operating modes in specific mining-and-geological conditions (from the geomechanical index H/R) it is necessary to compare at least several of their variants. And the function variants themselves $P(u)$ are determined by the variation of design parameters.

Therefore, a third peculiarity of the comparative analysis arises – the need for a fixed value of H/R to study the state of several fastening structure variants. There are two ways to implement the noted condition:

– a mine working (or several) is selected, where studies are carried out to assess its state and in advance (even outside the zone of stope works influence), several variants of structures of combined roof-bolting system are constructed in several places along the length of the mine working; the first method is quite labor-consuming and limited to only a few variants;

– the second method has wider possibilities and is in choosing a number of mine workings with approximately the same value of the geomechanical index H/R (deviations within 10%); however, mine workings (or their extended areas) differ from each other in the fastening structure parameters; this method is much less labor-consuming, provides only mine observations and is not limited by the number of studied mine workings; here, an extensive database of variants is searched for, both in terms of the values of the geomechanical index H/R, and in terms of various design solutions for fastening system in extraction mine working.

Taking into account the noted above peculiarities, a new methodology has been developed for assessing the degree of fastening structures rationality (from the point of view of minimizing the rock pressure manifestations) through the study and analysis of indicators of the mine working state, which are indirect in relation to the optimization solutions in terms of the deformation-strength characteristics $P(u)$ of the fastening system. For the source data base formation with its subsequent analysis, a series of tables of the following content has been compiled.

The method of filling in the source data of Table 1 has its own specifics. When the extraction mine workings are located to the rise (dip), the depth H of their placement changes in a relatively small range due to the small inclination angle of the seams. Nevertheless, the table contains the values of H, corresponding to the places for taking the readings about the displacements of the mine working contour and assessing the state of its fastening structure.

Table 1. Initial geomechanical factors for maintaining mine workings and parameters of their state

Mine working. Parameters of the fastening structure	Geomechanical factor Depth of placement H, mm Average calculated compressive resistance R, MPa Geomechanical index H/R, m/MPa Mass structure group Mine working section loss ΔS, % Convergence of the roof and bottom UR,B, mm Sides convergence Us, mm Bottom heaving UB, mm Pressing the prop stays into the bottom Upr.st, mm Vertical deformation of the cap board frame Δy, mm SCP overlap length in the yielding joist ly.j, mm

The structure of the adjacent rock mass is defined in accordance with the recommendations set out in the work [15].

The thickness and strength characteristics of the lithotypes that compose the adjacent coal-bearing strata are found according to the mining-and-geological prediction of the studied mine working, and the average calculated compressive resistance of rock is determined by the normative methodology [11]. Further, the value of the geomechanical index H/R is calculated using the known values of H and R.

The mine working section loss ΔS is determined as a percentage in relation to the passport cross-sectional area in the clear S_{CB}

$$\Delta S = \frac{100\%}{S_{CB}}\left[U^{K,\Pi}\left(0{,}9B - U^{\delta}\right) + U^{\delta}h\right], \quad (1)$$

where $S_{\text{св}}$ – is the design cross-sectional area of the mine working in the clear to subsidence; it is determined according to the technical documentation for the construction of mine working; $U^{K,\Pi}$ and U^{δ} – convergence of the roof-bottom and sides of the mine working; it is determined by mine surveying data or by the results of measurements in the process of mine instrumental observations according to the standard methodology of VNIMI [16]; B and h – the design height and width of the mine working in the clear to subsidence.

The parameter of the working section lossΔS is partly generalizing its state and characterizes the general intensity of rock pressure manifestations and the degree of rationality of the fastening system operating mode. For the calculation of ΔS, it is necessary to determine and fill in Table 1 data on indicators $U^{K,\Pi}$ and U^{δ}.

The parameter the roof rocks subsidence U^K, which is compared with the optimal value u_A of the minimum load formation on the fastening structure, is more consistent with the tasks of comparative analysis. The value U^K is calculated using the obvious expression

$$U^K = U^{K,\Pi} - U^{\Pi}, \quad (2)$$

where U^{Π} – the mine working bottom heaving; it is determined according to the measurement data of the heaving value relative to the lower edge of the coal seam; in the absence of such data or the impossibility of performing measurements, the value U^{Π} is calculated by the normative methodology [11].

Comparison of the value U^K and u_A is one of two actions for a relatively direct assessment of the deformation-strength characteristics rationality degree of the fastening system.

The second action, which is almost directly related to assessing the conformity degree of the fastening system operating mode to the geomechanical conditions of mine working maintenance, is the calculation of the yielding property u_{max} of the fastening structure as a whole. For this, three parameters are fixed (Table 1): $U_{\text{ст}}$ – pressing of the frame prop stays into the rocks of mine working bottom; it is determined by increasing the distance from the end of prop stay to the lower edge of the coal seam; Δy – flattening out of the frame cap board shape in the vertical direction; it is determined by the difference between the design and current height of the arch rise; $\Delta l_{з.п}$ – an increase in the special profile SCP overlap length in the yielding joist.

The total yielding property of the fastening structure is calculated by summing the components
$u_{СТ_{з.п}} \sin \beta_{max}$ (3)
where β – the angle of gradient to the horizontal of SCP overlap area in the yielding joist.
In addition to these parameters, a general assessment of the mine working fastening structure state is made according to the visually observed deformations of the cap board and frame prop stays, the degree of yielding joists integrity, the tension level of roof-bolts in terms of the backing plates adherence to the rock surface of mine working, etc.

As a result, on the basis of the generated database, an analysis is performed by constructing a family of experimental graphs of the dependence of the fastening system yielding property u_{max}, generalizing the characteristics in the form of a section loss ΔS with a geomechanical index H/R. Further, a comparative analysis of the experimental graphs with the analytical ones is carried out. However, it should be remembered here that the existing analytical graphs are plotted for the so-called 'basic' fastening structure and to optimize its parameters, a set of variants for various fastening schemes using combined roof-bolting systems is required. This problem has been solved and its results are presented below.

The final position of the methodological principles is the systematization of recommendations for the use of innovative fastening systems, depending on the structure and properties of the surrounding mass, as well as the geomechanical index H/R.

3. Results

The necessity of performing calculations to determine the deformation-strength characteristics of various design solutions for fastening systems has already been substantiated [17]. Providing the possibility of choosing the rational fastening parameters is based on a series of calculations of the deformation-strength characteristics $P(u)$ of a number of fastening system structures, combined by two main conditions. Firstly, it is necessary to cover the widest possible range of actual design solutions. Thus, real fastening structures in real mine workings that are still in operation or have already been decommissioned, are exposed to calculation and analysis. And, there are mine surveying data for compiling Table 1. Secondly, as many mine workings as possible are studied where the combined roof-bolting system is still used (or has been used previously) as an integral part.

Guided by the above-mentioned approach for calculating the functions $P(u)$, a number of fastening structures that are actually used in mines have been selected. The choice of mine workings (according to the indicated methodological principles) provides for the widest possible range of changes in the values of the geomechanical index H/Rthat resulted in a need to assess the state of a large number of extraction drifts. A total of 43 mine workings has been surveyed. All of them are not chosen by chance, but meet the requirement for a significant variation in the parameters of deformation-strength characteristics of fastening structures, in which a roof-bolting support is a mandatory component.

Methodologically, we have preliminarily divided the areas of expedient use of a particular fastening structure as follows.

Favorable mining-and-geological conditions for maintaining extraction mine workings. Medium rock pressure manifestations make it possible to keep the residual cross-sectional area at the level of 75 – 90% (in the area after the longwall face advance, taking into account the bottom ripping). Irreversible plastic deformations of the frame support are minimal and they insignificantly distort its original shape while maintaining the load-bearing capacity practically at the passport level. Favorable conditions are generally characterized by a range of changes in the geomechanical index of 10 m/MPa≤ H/R ≤30 m/MPa: here, according to our predictions (see Fig. 1 and Fig. 3), in order to reliably resist rock pressure, it is enough to set a frame support (with an appropriate step), and in the interframe space of a mine working arch – a set of resin-grouted rockbolts in the amount of 4 – 7 pieces (Fig. 4). Setting the rope bolts (with a stable roof) will increase a step of the frame support placement with a simultaneous decrease in the number of the special profile SCP used; in any case, the technical and economic aspects are of particular importance here, and the central and side prop stays of the strengthening support are an additional margin of load-bearing capacity in terms of ensuring the reuse of the extraction mine workings. Such a support scheme has found considerable distribution in the Western Donbass mines (Ukraine) and, in particular, in the 590 fabricated drift at Yubileynaya Mine, DTEK Pavlohradcoal PRJSC.

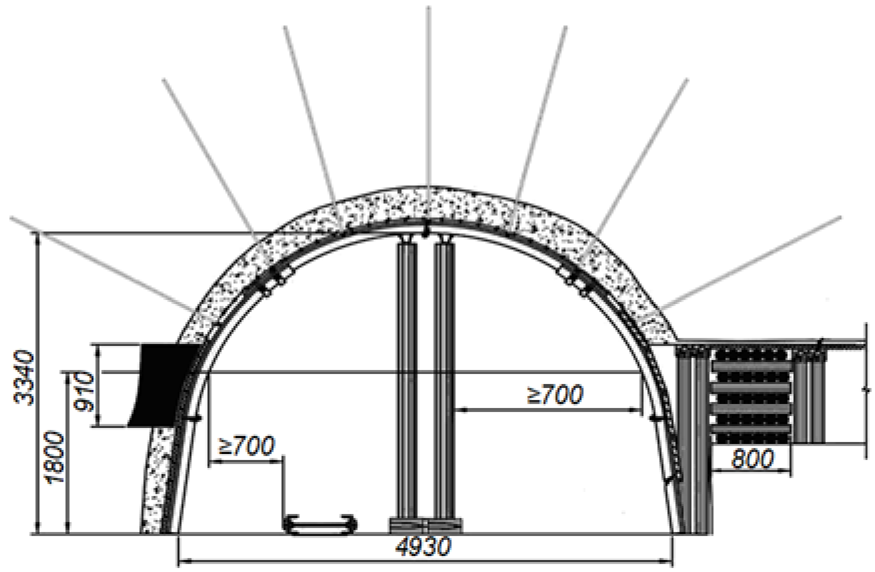

Figure 4. Basic scheme for extraction drifts maintenance in favorable mining-and-geological conditions

Joint substantiation of the mass displacement parameters in favorable mining-and-geological conditions and rational design solutions for fastening systems will allow to outline the range of geomechanical factors and identify the areas of their interdependence, where the use of combined roof-bolting systems as such is impractical. Thus, the lower limit of the area of rational combined roof-bolting system use is determined and this result is new in this direction of geomechanical research. As for the upper limit of the indicated area, in our opinion, it does not exist, since rope bolts, due to their length and load-bearing capacity, have the ability to effectively strengthen even the most unstable coal-bearing mass.

Conditions for rock pressure manifestations of medium intensity. In the first approximation, the range of geomechanical index variation 30 m/MPa≤ H/R ≤50 m/MPa corresponds to these conditions. After the longwall face advance, the value of the residual section remains at the level of 60 – 75% taking into account the periodic bottom ripping. The deformations of traditional fastening structures are more significant (after stope face advance) and to ensure the operational state of the extraction drifts during their reuse, it is expedient to use combined roof-bolting systems. Their resource-saving technologies for involving the adjacent rock mass in the work to resist rock pressure are distinguished by well-known advantages in comparison with the traditionally used fastening schemes. The basic scheme of the fastening structure is shown in Fig. 5 and, with some variations, it has been successfully tested on a number of extraction areas, for example, 861 fabricated drift (Zapadno-Donbasskaya Mine) and 594 fabricated drifts (Yubileynaya Mine).

Substantiation of optimization solutions for the parameters of fastening structures for medium intensity of rock pressure manifestations (Fig. 5), as well as for favorable mining-and-geological conditions (see Fig. 4) is based on determining the deformation-strength characteristics $P(u)$ of the presented fastening systems.

Difficult mining-and-geological conditions. They mainly correspond to the values of the geomechanical index of H/R >50 m/MPa and are characterized by intense rock pressure manifestations; if certain repair and restoration works are not carried out, then the section loss of the order of 50 – 60% no longer makes it possible to reuse the mine working in compliance with safety rules [18]. For these conditions, we reasonably indicate the high efficiency of using the combined roof-bolting systems, which is based on the analytical research results [19–21]. The basic scheme of the combined roof-bolting system is shown in Fig. 6.

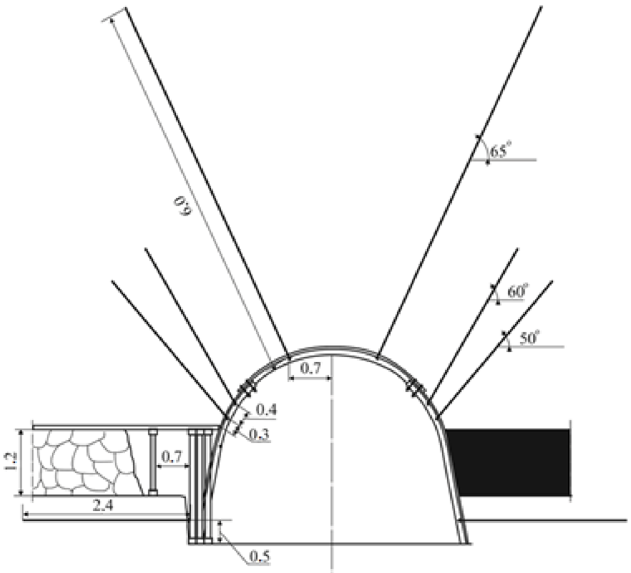

Figure 5. Basic scheme for extraction drifts maintenance in conditions of rock pressure manifestations of medium intensity

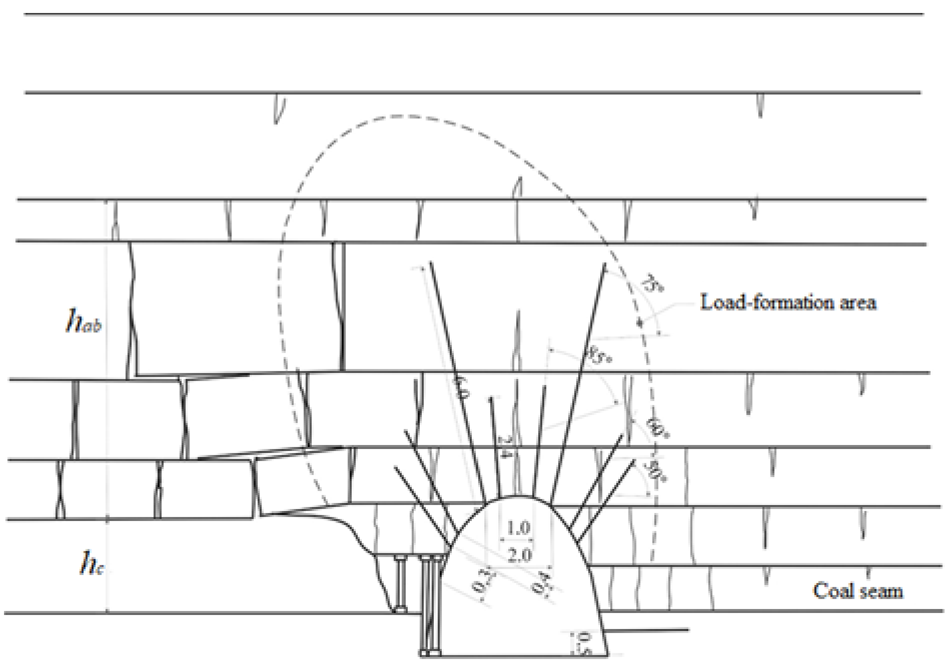

Figure 6. Basic scheme for extraction drifts maintenance in difficult mining-and-geological conditions

From the point of view of the search for optimization solutions, variations in the fastening structure parameters have already been substantiated in order to achieve rational deformation-strength characteristics $P(u)$ in difficult mining-and-geological conditions. Referring to the graphs of comparative analysis (see Figs. 1 and 3) of the correspondence to rational resistance P_p and yielding property u_p, a significant margin of P_{max}can be noted in most cases, and with very low strength of adjacent lithotypes, there are ways to increase P_{max} to the required value of P_p. As for the fastening system yielding property, it is in difficult mining-and-geological conditions (H/R >60 m/MPa) that the conformity degree increases of rational u_p and constructive u_{max} values.

Summing up the presented ideas, the following tasks are formulated to implement the optimization solutions:

– the first one is to calculate the deformation-strength characteristics of the fastening structures (see Fig. 4), where there are no rope bolts; the structure variation and the adjacent mass properties will allow to determine the lower limit of the area of rational combined roof-bolting system use;
– the second is to carry out the calculation of $P(u)$ in the fastening structures according to the scheme in Fig. 5 with varying the step of rope bolts settings $L_{к.а}$ to achieve satisfactory compliance with the rational deformation-strength characteristic $P_p(u_p)$;
– the third is to assess the influence of the parameters variation of the combined roof-bolting systems (see Fig. 6) on the function $P(u)$ in terms of achieving its rational operating modes in difficult mining-and-geological conditions.

The listed tasks have been implemented in full: for three selected adjacent mass textures groups and variations in the strength characteristics of the constituent lithotypes. Changes in the step of rope bolts settings are modeled by varying their reaction value. Changes in the step of settings the frame support are taken into account through the load-bearing capacity of the frame per one running meter of the mine working. The connection between the rope bolts and the frame cap board (through the pliable binders) is taken into account by the action of an additional reaction on it [22]. All calculations are performed by the algorithm and in accordance with the developed mechanism of the geomechanical system deformation described in the work [23]. Thus, the methodological principles for the implementation of optimization solutions for calculating the deformation-strength characteristics of variants for fastening structures with combined roof-bolting systems have been determined. Control of the deformation of the mountain range and fastening structure can be carried out by fixing its acoustic activity [24].

4. Conclusions

Based on the results of the research performed, a number of conclusions have been formulated that have scientific and practical significance.

1. On specific examples, the possibility of achieving a completely satisfactory correspondence of the deformation-strength characteristics of fastening structures to the optimal values P_A and u_A, at which the rock pressure manifestation intensity is reduced to a minimum, has been proved. It has been substantiated that it is the operating mode of the fastening structure, close to the optimal one, that allows, on indirect indicators (mine working contour displacement, the value of its cross-sectional area loss, the overlap growth in the frame support joist joints), determined experimentally, to assess the degree of adequacy and reliability of the developed methods for optimizing the parameters of the mass interaction with the support and to calculate its rational deformation-strength characteristics. This new methodological principle for performing mine research has been comprehensively substantiated with the identification of three main peculiarities and implemented when carrying out large-scale measurements of the rock pressure manifestation parameters in various mining-and-geological and mining-engineering conditions of maintaining the reused extraction mine workings in mines.

2. In accordance with large-scale mine research, both in terms of mining-geological and mining-engineering factors, a series of multivariate computational experiments have been conducted to calculate the deformation-strength characteristics of a number of fastening structures actually used in the Western Donbass coal-mines. And on this basis, an extensive database has been created for a comparative assessment of the results of mine experiments

and analytical calculations. In this regard, two subproblems have been formulated and implemented for all selected groups of adjacent mass structure and variations in the strength characteristics of the constituent lithotypes:

– the first is to calculate the deformation-strength characteristics of fastening structures, where there are no rope bolts; the structure variation and the adjacent mass properties allow to determine the limits of the area of rational combined roof-bolting system use;
– the second is to calculate the fastening structures with combined roof-bolting systems when changing their parameters depending on the purpose – to achieve satisfactory compliance with the optimal values of interaction with the coal-bearing mass; these results are the basis for recommendations on the use of combined roof-bolting systems in difficult mining-and-geological conditions and in conditions of average complexity for maintaining reused extraction mine workings.

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Symbols

H – depth of location, placement;
R *– the average calculated compressive resistance;*
H/R *– Geomechanical index – indicator of the conditions for maintaining mine working;*
P_{max} *– position of adjustment;*
P_p *– required rational value;*
U *– rock contour displacements;*
ΔS *– working section loss;*
UR – convergence of the roof and bottom;
Us – sides convergence;
UB – bottom heaving;
Upr.st – pressing the prop stays into the bottom;
Δy – vertical deformation of the cap board frame;
ly.j – SCP overlap length in the yielding joist.

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