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GEOMECHANICAL PRINCIPLES AND SPECIFICS OF MODELING A COMPLEX METHOD FOR DE-STRESSING GAS-DYNAMICALLY ACTIVE ROCK MASSIF

Purpose. To substantiate geomechanical principles for reducing stress concentration peaks during mining operations in gas-dynamic rock masses at great depths in coal mines.

Methodology. The methodology integrates theoretical, numerical, and experimental approaches. Computational modeling using the finite element method was performed to analyze the stress-strain state of the rock mass. Vertical and horizontal stresses, stress intensity, and their distribution isolines were evaluated. In parallel, acoustic emission measurements in the near-face zone were carried out to assess the degree of stress relief, with results compared against sections excavated using conventional technology. The synthesis of numerical and experimental data enabled the formulation of methodological principles for calculating the parameters of the proposed technology and assessing its resource-saving effect.

Findings. The study confirms that the application of a comprehensive stress-relief technology, combining pre-drilled boreholes with stress-relief slots, significantly enhances mine working stability in gas-dynamically active coal-bearing rock masses at great depths. Vertical rock pressure manifestations are reduced by 7.3 % and horizontal pressure by 10.2 %, leading to a decrease in cross-sectional area losses of up to 18.2 %. Acoustic emission measurements demonstrated weakening of the near-face rock mass, with a 7–28 % reduction in energy at 2.0–2.5 m from the excavation face and 32–58 % within 3.0–6.0 m. Energy consumption for rock fracturing decreased by 15–26 %, with an average of 19.5 %.

Originality. A geomechanical model was developed that, for the first time, accounts for the combined effect of boreholes and slots on the stability of mine workings. New correlations were established between stress redistribution and acoustic signal energy as indicators of stress relief in the near-face zone.

Practical value. A safe and resource-efficient method for constructing excavations in gas-dynamically active rock masses at great depths has been proposed, enabling a reduction in cross-sectional area loss by up to 20 %.

Keywords: *coal mine, coal-bearing rock massif, stress-strain state, pre-drilled borehole, stress-relief slot*

Introduction. In the context of energy independence and development of a long-term plan for revitalizing the country's energy sector [1, 2], a pressing issue for the coal industry is conducting mining operations in gas-dynamically active rock massifs at great depth (over 1,000 m) in coal mines [3, 4]. Multiple investigations [5, 6] indicate a continuous increase in the depth of mining operations [7], complications in mining-geological conditions [8, 9], and consequently the occurrence of various gas-dynamic phenomena (GDP) with the destruction of the bottom-hole zone of tunneling or stoping faces, intense gas emissions, and displacement of rocks.

Literature review. The problem of sudden outbursts has been considered for many years and is presented in fundamental [10, 11] and applied research [12, 13]. However, the majority of publications do not address the highly relevant issue of resource-saving during stoping and preparatory operations in gas-dynamically active rock massifs, namely the aspect of reducing the stress state, which is particularly important in coal mines at great depth [6, 14]. Thus, this study focuses on the combination of two key components: safety and resource efficiency.

The analysis of works in this direction [15] shows that authors are focused on methods and technical means for preventing gas and coal outbursts during mining operations in gas-bearing coal-rock mass. These studies are based on an analysis of literary sources, patent searches, and theoretical patterns. Reviewing local means and methods allows us to conclude that their application reduces the rate of mine working construction (sometimes several times) [16, 17], which leads to a decrease in coal mining [8, 19]. However, the technology of drilling pre-drilled de-stressing wells positively stands out due to a combination of beneficial factors for de-stressing the border rocks and the possibility of maintaining advancement [8, 20]. To enhance this effect, the authors propose combining the method for drilling pre-drilled wells with de-stressing slots, which will increase the level of stability and limit the gas-dynamic phenomena manifestations.

In previous studies [9, 21], a series of computational experiments using the finite element method were conducted, which are part of an algorithm for the targeted search, substantiation, and selection of rational parameters for the location of pre-drilled wells combined with de-stressing slots, allowing safe and resource-saving conduct of mine workings in gas-dynamically active rock mass at depths over 1,000 m.

In works [22, 23], the methodological foundations for conducting computational experiments are studied and geomechanical model parameters for calculating the stress-strain state (SSS) of the combined technology of preliminary de-stressing the bottom-hole mass with a combination of predrilled wells and de-stressing slots are substantiated [24, 25]. The significant influence of pre-drilled wells on changing the stress intensity of the enclosing mine working mass has been proven [9, 21]. However, the study of the combination of wells with de-stressing slots remains relevant. This solution will de-stress the area around the stoping face, thus forming a combination of two de-stressing methods.

Regarding the peculiarities of modeling the above-grounded comprehensive de-stressing method, they mainly involve changing the geometry of the bottom-hole mass – the form of the tunneling face becomes benched (stepped). Other model parameters remain constant and are taken from the work [9, 21]: model dimensions, its loading boundary conditions, the adjacent mass texture, and the mechanical properties of its lithotypes, mine working dimensions, and the parameters for the location of pre-drilled wells. As for the tunneling face geometry, the following parameters are accepted: $D = 0.8$ m, $L = 1.0$ m, $Xs = 1.0$ m. They correspond to the technical characteristics of most modern tunneling machines, and the spatial formulation of the problem allows for a complete reflection of the new form for the tunneling face, considering the implementation of the de-stressing slot in the lower part of the coal seam along the contact plane boundary with the immediate bottom.

Unsolved aspects of the problem. Despite a considerable number of fundamental and applied studies devoted to the prevention of gas-dynamic phenomena during mining operations at great depth, several critical issues remain unresolved. In particular, insufficient attention has been paid to the resource-saving aspects of roadway construction in gas-dynamically active rock massifs, as well as to the integrated application of the near-face zone under conditions of increased geostatic pressure. This highlights the necessity of developing a comprehensive approach the combines geomechanical modeling, in-situ experiments, and methodological substantiation of parameters for a new stress-relief technology, which would simultaneously improve safety and ensure the energy efficiency of mining operations.

The purpose is to substantiate the geomechanical principles of reducing stress concentrations and enhancing the stability of mine working in gas-dynamically active rock massifs at great depth through the application of comprehensive stress-relief technology that combines pre-drilled boreholes with stress-relief slots.

To achieve this purpose, the following research objectives were defined:

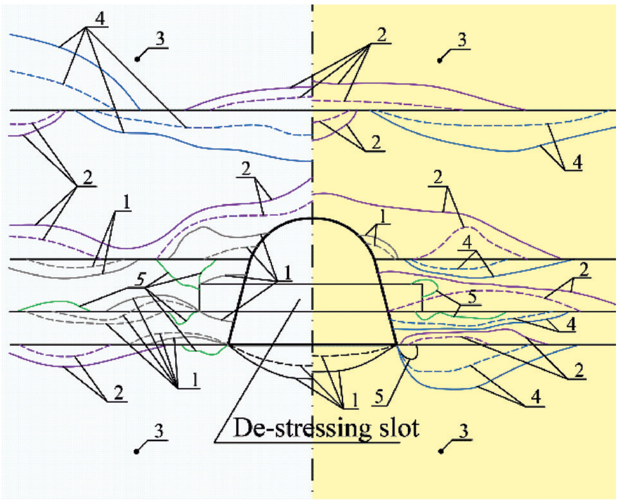
1. To analyze the SSS of the rock massif, taking into account the influence of pre-drilled boreholes and stress-relief slots.
2. To substantiate the parameters of the comprehensive stress-relief technology for near-face zone of the rock massif and to formulate methodological principles for its application.
3. To investigate the variation of acoustic signal energy in the near-face zone of mine workings under the new technology in comparison with the traditional one.
4. To assess the energy consumption for rock fracturing and determine the resource-saving effect of implementing the developed technology.

Methods. The methodological basis of the study was founded on a comprehensive combination of theoretical, numerical, and experimental approaches. To verify the effectiveness of the proposed technology, a series of computational experiments was carried out, aimed at analyzing the SSS of the rock massif. The most informative components were evaluated, including vertical and horizontal stresses, stress intensity, and isolines of their distribution in characteristic cross-sections. In parallel, laboratory and instrumental studies of acoustic emission parameters in the near-face zone were conducted to measure the energy associated with rock massif stress relief. The obtained values were compared with the results from sections where traditional excavation technology was applied. The generalization of numerical modeling results and experimental observations made it possible to formulate methodological principled for calculating the parameters of the comprehensive technology, as well as to correlate them with actual data on the condition of frame supports and the geometry of mine workings. In addition, an assessment of energy consumption for rock fracturing in the near-face zone was carried out, enabling the determination of differences between the specific indicators of traditional and proposed technologies and providing a quantitative evaluation of the resource-saving effect.

Research of the SSS of combined technology for de-stressing the bottom-hole mass. Methodologically, all data for conducting a computational experiment and visualizing the calculation results in the form of distribution curves of the SSS components in the space have been prepared.

Firstly, modeling and calculating the SSS concerning the influence of pre-drilled wells have been carried out. Secondly, using the example of horizontal stress isolines and stress intensity isolines, a comparison with the baseline data has been conducted.

Changes in the horizontal stress field. General trends in the influence of the de-stressing slot on the changes in the distribution of horizontal stresses are shown in Fig. 1.



a *b*

Fig. 1. Isolines of horizontal stresses σ_x in the mine working cross-section when using (——) de-stressing slot and without it (– – –):

a – at a distance of $Z_1 = -10$ m to the tunneling face plane; b – at a distance of $Z_2 = 2.0–2.5$ m to the tunneling face plane; 1 – $\sigma_x = +(3–5)$ MPa; 2 – $\sigma_x \approx 0$ ($K_x \approx 0$); 3 – $\sigma_x \approx \approx \lambda\gamma H \approx -(9–12)$ MPa (K_x = 1.9–2.8); 4 – $\sigma_x = = -(20–30)$ MPa (K_x = 1.9–2.8); 5 – $\sigma_x = -(50–65)$ MPa (K_x = 4.7–5.6)

In the cross-section $Z_1 = -10$ m, the following patterns in change of σ_x are observed, which most informatively demonstrate the bending processes of lithotypes in the *YX* plane. Thus, in the main roof of the seam (at a distance of more than 4.4 m from it), bending stresses σ_x with a bend towards the mine working cavity can still be observed over an area no less than its width and towards the roof in the lateral adjacent rock areas (Fig. 1). Evidence of such bending in the main roof is the formation of a complete de-stressing area ($\sigma_x \approx 0$) above the mine working, and in its lateral parts, there are areas of concentrated compressive horizontal stresses σ_x with a level of K_x = 1.9–2.8. It should be noted that the de-stressing slot influence is manifested in the increase of both the complete de-stressing zone and the compressive σ_x concentration areas. This indicates an increase in the deformation of the main roof bending of different signs, representing the overall de-stressing process of the adjacent rocks in the main roof when using the de-stressing slot. This is an entirely expected result, which does not contradict the existing concepts and confirms the adequate performance of the geomechanical model. The same observations apply to the immediate roof border rocks, but the influence of the de-stressing slot is more significant – even areas of tensile σ_x stresses of 3–5 MPa level appear, which are several times larger (in size) than those in the case of using the de-stressing slot.

Similar trends of intensified bending of lithotypes (under the influence of the de-stressing slot) are observed in the mine working sides and bottom: not only do tensile stress zones σ_x appear and grow, but local zones of compressive stress concentrations σ_x of K_x = 4.7–5.6 level also emerge. These examples confirm the trends of the de-stressing slot influence, characterized by the growth of areas under reduced compressive and even tensile stresses σ_x. These areas are the most affected by lithotype destruction since, according to existing rock strength theories, the difference in the stress components (in this case, vertical and horizontal) creates conditions for their destruction [26]. Conditions for the local coal seam destruction and its immediate bottom are created by compressive stress concentrations σ_x that exceed the compressive strength of the respective lithotypes. Thus, the de-stressing slot facilitates the formation and expansion of areas of partial weakening of the border rocks, acting as a damping layer and reducing the load on the mine working support. Simultaneously, this promotes the previously noted positive trends of reducing the energy required for the destruction of partially weakened rocks and limiting the probability of GDP occurrence.

The second cross-section under thorough study is located in the mass along the mine working route at a distance of Z_2 = 2.0–2.5 m from the tunneling face plane (Fig. 1, *b*). Despite being located in the mass and under high geostatic pressure ($\sigma_y = \gamma H = -25$ MPa), bending deformations with the emergence of de-stressing zones and compressive stress concentrations σ_x manifest themselves in the adjacent lithotypes. The general trend of the de-stressing slot influence remains unchanged: de-stressing and stress concentration areas σ_x expand, positively influencing the triune goal of enhancing mine working stability, reducing the energy required to destroy bottom-hole mass lithotypes and lowering the risks of GDP occurrence.

Another SSS component – horizontal stresses σ_z – are studied in the direction of coordinate *Z* in two *YZ* longitudinal section planes (Fig. 2): along the central vertical axis of the mine working (*X*–0) and along the planes of the de-stressing slot ends ($X = X_s$). In the central longitudinal section, the following trends of the de-stressing slot influence are observed (Fig. 2, *a*). The primary trend is the growth of de-stressing zones, which, according to existing theories, reduces the probability of GDP occurrence. Alongside this, compressive stress concentration areas σ_z increase, and their combined action with zones of reduced horizontal stresses σ_z (Fig. 1) facilitates the weakening of the rocks adjacent to the tunneling face. This is a positive aspect in reducing the energy required for the bottom-hole mass destruction. The maximum compressive stress concentrations σ_x of K_z = 3.27–4.67 level are located near the de-stressing slot face, a completely expected result indicating the adequacy of the geomechanical model to modern understandings.

On the peripheral ($X = X_s$) longitudinal sections (Fig. 2, *b*), the obtained patterns of σ_z distribution largely confirm the above mentioned results. It should be noted here that the de-stressing slot moves the compressive σ_z concentrations away from the contour of the mine working sides by at least the value of X_s. This reduces rock pressure in the lateral direction and contributes to the stability of extraction drifts.

The analysis of the SSS, by the factor of horizontal stresses σ_x and σ_z, confirms the trend of rock weakening

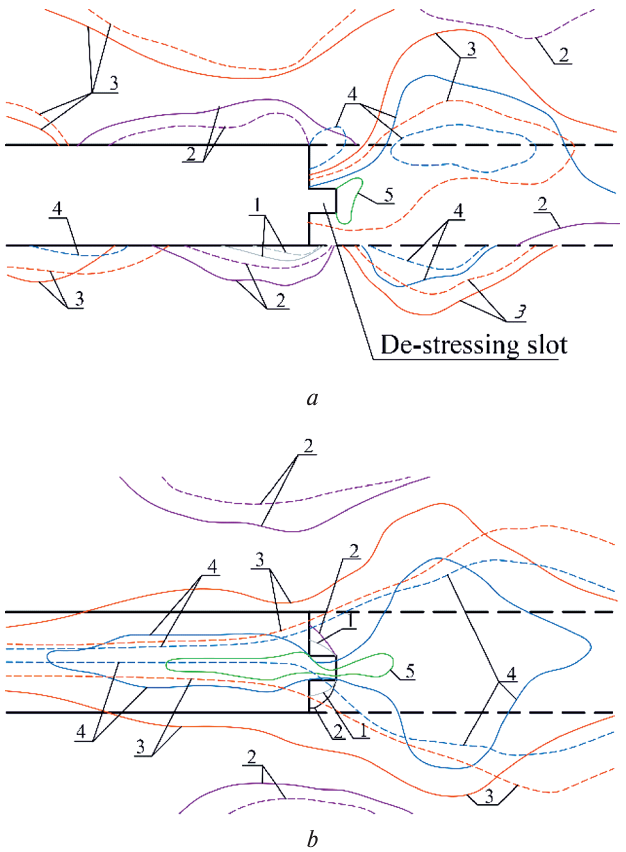


Fig. 2. Isolines of horizontal stresses σ_z in the mine working longitudinal section when using (——) de-stressing slot and without it (– – –):

a – at a distance of $Z_1 = -10$ m to the tunneling face plane; b – at a distance of $Z_2 = 2.0–2.5$ m to the tunneling face plane; 1 – $\sigma_z = +(3–5)$ MPa; 2 – $\sigma_z \approx 0$ ($K_z \approx 0$); 3 – $\sigma_z = -(13–17)$ MPa ($K_z = 1.21–1.59$); 4 – $\sigma_z = -(20–28)$ MPa ($K_z = 1.87–2.62$); 5 – $\sigma_z = -(35–50)$ MPa ($K_z = 3.27–4.67$)

to the depth of the mine working route (up to 4–5 m) due to the de-stressing slot and the possibility of conducting mining operations in a gas-dynamically active mass at depths above 1,000 m.

Changes in the stress intensity field. As an example, Fig. 3 shows the stress intensity isolines σ in two cross-sections $Z_1 = -10$ m and $Z_2 = 2.0–2.5$ m.

In the first mine working cross-section ($Z_1 = -10$ m), the following trends in the de-stressing slot influence are observed (Fig. 3, *a*). In the coal seam main roof, a moderate lithotype bending is observed with the formation of de-stressing zones ($K_\sigma = 0.42–0.5$) and concentration zones σ (K_σ = 2.0–3.0). Both zones have increased propagation for the variant with the de-stressing slot, which is expected due to increased bending deformations of the rock layers. Thus, two conclusions can be drawn: first, some influence of the de-stressing slot extends to the main roof rocks; second, it contributes to the already indicated trends of de-stressing the rock mass and its weakening by increased σ concentrations.

More significant rock layer bending is observed in the immediate roof of the seam, even forming an arch of unstable rocks, but the trend of expanding de-stressing zones remains in this area of the border rocks. A similar de-stressing slot influence occurs in the mine working bottom.

In the mine working sides, the σ concentration areas extend with the application of the de-stressing slot. This extension occurs towards the adjacent mass while simultaneously moving away from the mine working side contour. That is, the bearing pressure moves deeper into the mass, and de-stressing zone is formed near the mine working, positively affecting its stability.

Regarding the second cross-section, in the mass along mine working route ($Z_2 = 2.0–2.5$ m), the following results can be highlighted. Despite the action of high geostatic pressure, de-stressing areas ($K_\sigma = 0.42–0.56$) are formed in the roof and bottom of the mine working, and their (although local) propagation is facilitated by the de-stressing slot (Fig. 3, *b*); a small de-stressing area even appears in the main roof of the coal seam.

In the mine working sides, the acting bearing pressure zone (concentration σ) moves away into the mass by 0.7–1.0 m, contributing to reduction of stress in the lateral border rocks and the risk of GDP occurrence.

Summarizing the directions of changes in the stress intensity field σ, the positive influence of the de-stressing slot can be emphasized on all three aspects of safety and resource-saving improvement during mine working construction at great depths in a gas-dynamically active rock mass.

Next, the situation regarding the de-stressing slot influence in the longitudinal central and peripheral sections of the already constructed mine working and its route is studied (Fig. 4). It should be noted immediately that the de-stressing slot influence on the stress intensity field σ fully corresponds to the previously noted trends. That is, in the section of the already constructed mine working, the propagation of de-stressing areas into the roof and bottom increases, as shown by both the central and peripheral *YZ* planes of longitudinal sections. Here, the peculiarity is the expansion of the de-stressing area to the bottom-hole mass to a depth of 1.2–1.4 m.

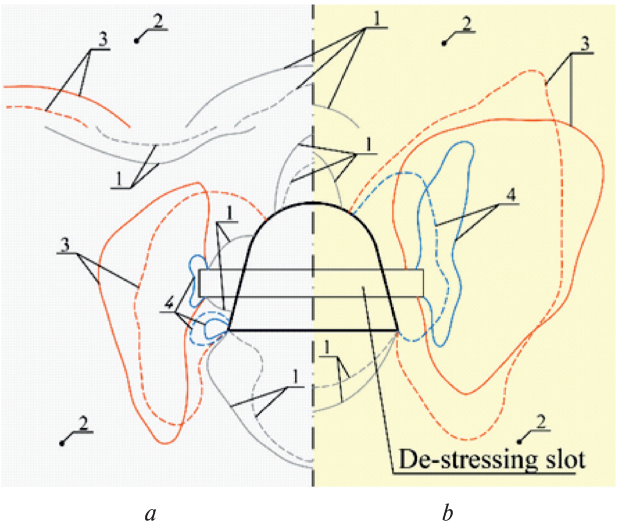


Fig. 3. Isolines of intensity stresses σ in the mine working cross-section when using (——) de-stressing slot and without it (– – –):

a – at a distance of $Z_1 = -10$ m to the tunneling face plane; b – at a distance of $Z_2 = 2.0–2.5$ m to the tunneling face plane; 1 – σ = +6–8 MPa ($K_\sigma = 0.42–0.56$); 2 – σ = 13–16 MPa ($K_\sigma \approx 1.0$); 3 – σ = 30–45 MPa ($K_\sigma = 2.0–3.0$); 4 – σ = 50–65MPa ($K_\sigma = 3.5–4.5$)

Along the mine working route deep into the still undisturbed mass at a distance of 2.5–4.0 m (from the tunneling face), disturbances in the stress intensity σ, caused by the de-stressing slot, can be observed. These disturbances are noted in both the central and peripheral *YX* sections and contribute to a more significant weakening of the rocks near the tunneling face, requiring less energy for their destruction.

In conclusion, the research confirms a reduction in the risk of gas-dynamic phenomena and the energy required for the destruction of bottom-hole zone rocks, as well as an increase in the mine working stability. The effectiveness of the method for complex bottom-hole zone de-stressing is studied using a mine experiment.

The level of influence of complex de-stressing method is assessed using values of the displacement of the mine working contour into its cavity. Using standard measurement methods employed by the mine surveying service of PJSC "Mine Management "Pokrovske", two parameters are regularly determined: the current mine working height h_w as a distance between the center of its arch and the bottom, that is, along the central vertical axis of the mine working; the current width B at the level of rolling stock and passage of people. When measuring these distances, the mine working section is fixed relative to the corresponding pickets. As a result, objective information is collected on the change in the dimensions of the mine working, which is crucial for criteria such as effective ventilation and adherence to clearances and distances regulated by safety rules.

In addition to this instrumental information, a visual assessment is also made of the frame support state and its irreversible damages: bending of the frame cap board under excessive vertical rock pressure; bending and torsion of special profile of the prop stays under excessive lateral rock pressure; loss of the initial shape of the frame support under oblique rock pressure; the condition of the frame joists and their yielding property value.

The experimental section, where the complex de-stressing method is applied, is over 100 m long. The schemes for summarizing and analyzing the values of rock pressure manifestations are shown in Fig. 5.

The range of variation of current values is outlined by two graphs shown with dotted lines (on the example of the value h_w), which reflect the minimum ("min") and maximum ("max") deviations of the mine working height from the nominal value under the influence of rock pressure. Thus, the outlined range of change in the current mine working height is the most objective parameter reflecting the consequences of rock pressure in the vertical direction (Fig. 5, *a*).

When comparing the two technologies for mine working construction (Fig. 5, *b*), it is very convenient and illustrative to show their advantages and disadvan-

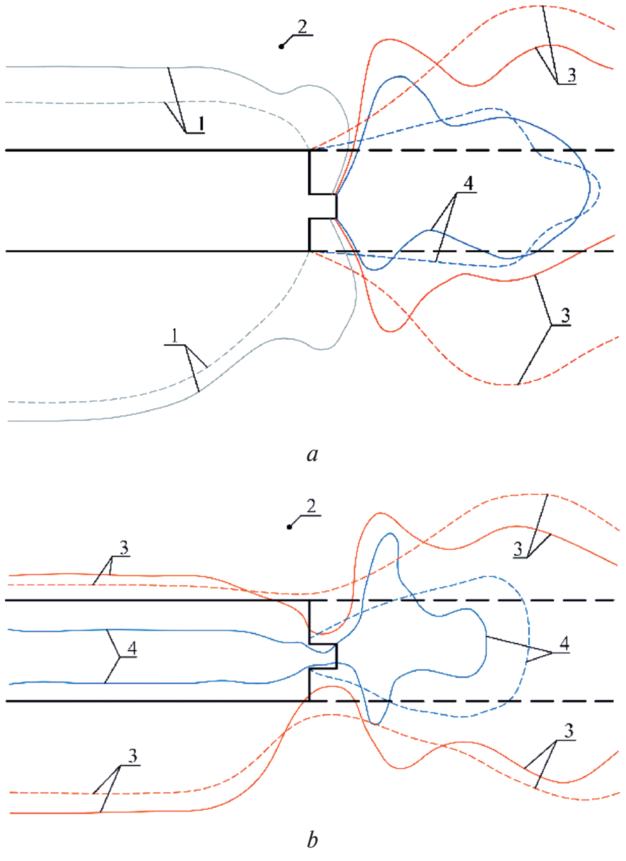


Fig. 4. Isolines of stress intensity in the mine working longitudinal section when using (——) de-stressing slot and without it (– – –):

a – along the central vertical axis ($X = 0$); b – along the peripheral vertical axes ($X = \pm Xs$); 1 – σ = 6–8 MPa (K_s = 0.42–0.56); 2 – σ = 13–16 MPa ($K_\sigma \approx 1.0$); 3 – σ = 30–45 MPa (K_σ = 2.0–3.0); 4 – σ = (50–65) MPa (K_σ = 3.5–4.5)

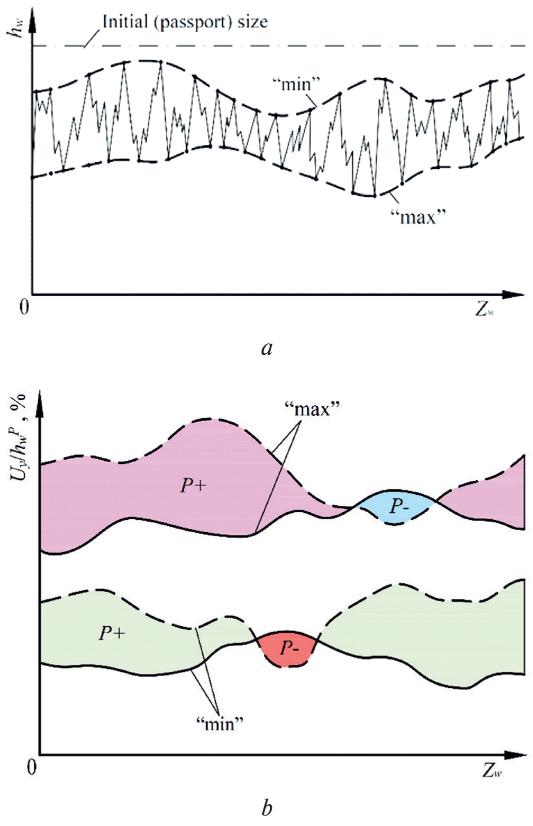


Fig. 5. Schemes for generalization and analysis of rock pressure value in the mine working:

a – determining the graphs of changes in the minimum ("min") and maximum ("max") deviations of the current mine working dimensions from the initial (passport) values on the example of its height h_w; b – change in the relative value U_y/h_wP of the reduction in the mine working height using the complex unloading method (——) and the traditional technology (– – –) of the mine working construction tages. For this purpose, a generalized value P is proposed, which is a specific physical value – the area between the two lines representing the proposed complex de-stressing method and the existing mine working construction technology

Trends in acoustic signal energy changes. It is well-known that the seismic-acoustic response to any forceful action characterizes not only the deformation properties of the mass lithotypes, but also the degree of its disturbance. In this context, it is important to have a physical value that can be measured and used to assess the degree of disturbance of the mass adjacent to the tunneling face of the mass. This property exists and is called the energy of the acoustic signal. This parameter W can be reasonably used for indirect assessment of the degree of stratification and weakening of the surrounding mass.

Methodologically, this stage of experimental research involves the ongoing recording of W, primarily in the mine working section, where complex de-stressing of the bottom-hole mass is conducted. The results obtained are compared with the W parameter values in the mine working sections with approximately the same texture of the surrounding mass, serving as a basis for comparative analysis.

The analysis itself is visually represented in graphs of the change in acoustic signal energy W over the length Z (into the mass) to the tunneling face plane. The informativeness of the comparative analysis results is improved by using the relative value W_r, calculated as the ratio of W in the experimental section of the mine working (application of the complex de-stressing technology) to the averaged W_r value in the baseline sections, but at the same distance Z to the tunneling face plane.

As a result, $W_r(Z)$ graphs are constructed, showing changes in relative energy W_r along the distance coordinate Z to the tunneling face (Fig. 6). Since W values are somewhat stochastic, to enhance their reliability, it was decided to outline the range of W_r changes at each fixed Z with two values – minimum (“min”) and maximum (“max”) deviations. Consequently, we obtain two graphs that fully reflect the variation range of the relative decrease in W_r acoustic signal energy with the proposed technology for complex de-stressing of the bottom-hole rock mass.

The analysis of graphs has revealed the following experimentally observed characteristics of lithotypes weakening in the bottom-hole mass.

Firstly, in the bottom-hole zone up to 2.0–2.5 m in length, active lithotype weakening occurs, which is fully consistent with stress intensity isolines σ (Fig. 4) and is explained by active rock stratification near the de-stressing slot. Here, the relative value fluctuates within $W_r = 7–28$ %, demonstrating high efficiency of the complex de-stressing method.

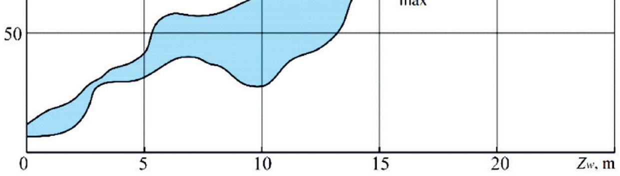


Fig. 6. Graphs of the relative decrease in energy W_r of the acoustic signal in the bottom-hole part (by Z coordinate) of the mine working route under the complex rock mass de-stressing compared to the traditional technology of its construction

Secondly, at a distance of $Z = 3.0–6.0$ m, an increase in W_r to 32–58 % is observed, which can be interpreted as an action of bearing pressure from the de-stressing slot with partial preservation of mass continuity.

Substantiation and selection of parameters for complex bottom-hole zone de-stressing technology during the construction of mine workings at depths above 1,000 m. Based on the formulated purpose, the objectives for conducting the necessary analytical experimental studies are substantiated. The obtained results require synthesis and practical application in the form of an appropriate methodology for selecting rational parameters of complex bottom-hole zone de-stressing technology for highly stressed bottom-hole rock mass during the construction of mine workings at depths above 1,000 m. This synthesis of research results is based on the substantiation of a series of methodological principles that are interconnected and united by the triunity goal of reducing stress intensity in the bottom-hole mass:

- limiting the probability of GDP occurrence using existing prevention methods;
- creating a zone of de-stressed rocks around the mine workings to prevent excessive rock pressure;
- saving energy resources during tunneling face rock destruction.

The first methodological principle summarizes the influence of pre-drilled wells on the de-stressing process of the rock mass along a specific section of the mine working route. Significant limitation of excessive stress intensity σ propagation zones in the bottom-hole part of the rock mass has been set, both on the sides of the already constructed mine working part and along its route into the mass. For instance, excessive (and therefore hazardous due to GDP occurrence) concentration zones σ propagate along the mine working route at distances up to 9.5–12.2 m (by Z coordinate) from the tunneling face plane of the field working. Beyond its contour, the distance of excessive concentration action towards the roof is up to 5.2–7.5 m, towards the bottom it is up to 7.7–8.2 m, and towards the side rocks it is up to 4.1–4.3 m. Drilling just three wells in the field working contributes to an average 45–55 % reduction in excessive concentration σ propagation distances. As for in-seam workings (typically extraction drifts), the propagation of excessive concentrations σ (compared to field workings) towards the sides is stable at 25–40 %, vertically at 20–25 %, and along the working route into the mass at 50–75 %. However, the effectiveness of limiting these σ concentrations remains approximately the same, with its enhancement depending on the number of de-stressing wells and the rational parameters of their placement.

The second methodological principle concludes that de-stressing the mass should be expedient not only along the mine working route, but also beyond its boundaries in adjacent rocks. This approach simultaneously achieves two objectives: reducing the risks of GDP occurrence and limiting excessive manifestations of rock pressure by forming a layer of de-stressed rocks, which positively affects the mine working stability. For this purpose, wells should be drilled at a specific angle towards the mine working contour, and to ensure the most complete de-stressing of stressed mass volume along the mine working route, it is advisable to drill new wells in the tunneling face when the previous wells are (as the face advances) beyond the mine working contour, with their residual length not exceeding the propagation zone of hazardous concentrations σ by Z coordinate of its route. This ensures de-stressing of the stressed rocks both in the plane of the mine working face and beyond its contour in adjacent mass.

The criterion for starting the drilling of a new group of wells in the tunneling face is the condition that (as the face advances) the deepened part of the pre-drilled wells reaches the contour of the mass-hazardous zone propagation (Fig. 7). Together with the accepted length of wells (based on technological processes and technical characteristics of drilling equipment), this condition determines the frequency of the operation to drill new wells.

The contour of the hazardous rock zone propagation is determined by the degree of its stress due to the geostatic pressure, which depends on the ratio of the stress intensity σ and the calculated compressive strength of the rock R [27, 28]. The first component (the level of stress in hazardous rocks) is determined by calculating the SSS of the rock mass adjacent to the mine working using FEM. The second component is provided in the geological documentation of PJSC "Mine Management "Pokrovske" (Ukraine) based on rock characteristics: ultimate compressive strength σ_{comp} in a sample, fracture intensity and moisture content; considering these data and the influence of the rheological factor [29], the calculated value R of rock compressive strength is determined according to the normative methodology [30].

The third methodological provision concerns the selection of appropriate parameters for the placement of pre-drilled wells. It is recommended to separate the schemes of their placement separately for field and in-seam workings. The unifying factor is that the central well is drilled perpendicular to the tunneling face plane (parallel to Z axis coordinate), while the mentioned peripheral wells are drilled with a slight inclination to the Z-axis, or there is a requirement to de-stress the rock mass outside the mine working contour.

Field workings are driven through more robust lithotypes (usually sandstones and siltstones), characterized by increased stiffness (greater thickness and Young modulus) relative to the coal seam. This causes several differences. The first is that to achieve effective de-stressing of the mass outside the mine working contour, it is necessary to distribute the wellheads more or less uniformly along the mine working contour, that is, a greater number of peripheral wells are predominantly required. The second difference is some limitation in σ concentration propagation, but a simultaneous increase in the peaks of these concentrations compared to in-seam working. The third difference is that, for these reasons, the inclination of peripheral wells should be both vertically Y and horizontally X in the ZY and ZX planes.

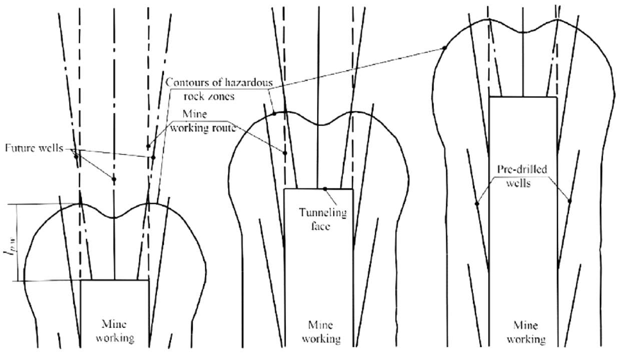


Fig. 7. Principal scheme for drilling wells in the overstressed mass around the tunneling face of a mine working at the stages of its advance

In-seam workings have a coal seam in the cross-section YX plane, which, due to its texture (cleavage, systematic fracturing, etc.) and low deformation properties, contributes to some de-stressing of the roof and bottom rocks of the seam, which not only fall within the cross-section plane, but also extend beyond the mine working contour. Therefore, it is recommended to place pre-drilled wells in the plane of the coal seam in quantities of 3–5 units: the central well is drilled perpendicular to the face plane, and the peripheral wells are inclined in the ZX plane.

Thus, there is a division of schemes for the placement of pre-drilled wells in the tunneling face and determination of their rational parameters by the type of preparatory workings – field or in-seam.

The fourth methodological principle determines the requirements for the de-stressing slot parameters. Firstly, the slot is made along the least strong lithotype with a height equal to the diameter of the cutting head of the tunneling machine, taking into account the extension of the rock-breaking tool. Secondly, the depth L of the de-stressing slot depends on the stroke of the hydraulic jack rod of the tunneling machine boom and usually does not exceed 1.0 m. Thirdly, the length of the de-stressing slot extends from both sides beyond the mine working contours by a value X_s, which is determined by the capabilities of the tunneling machine design and its maneuverability in the mine working, but usually, the length X_s should be at least 1.0 m. Fourthly, when conducting in-seam working, the de-stressing slot is made in the lower part of the seam thickness along the plane of its bedding with the immediate bottom.

The four presented methodological principles for selecting the appropriate parameters for the technology of complex bottom-hole zone de-stressing are fundamental and will allow the effective implementation of the triunique research objectives.

Thus, the research formulates the geomechanical principles and peculiarities of modeling the complex method for de-stressing a gas-dynamically active rock mass.

Conclusions. Based on numerical modeling and in-situ studies, a new technology for comprehensive stress relief of the rock massifs has been proposed, which combines pre-drilled boreholes with stress-relief slots.

It has been proven that the application of this technology enhances the stability of mine working by limiting the effects of rock pressure by 7.3 % in the vertical direction and by 10.2 % in the horizontal direction, thereby reducing cross-sectional area losses by up to 18.2 %.

The studies showed an increased degree of weakening of the near-face rock massif, confirmed by a relative decrease in acoustic signal energy of 7–28 % at a distance of up to 2.0–2.5 m from the excavation face. In the range of 3.0–6.0 m along the working, the reduction level reached 32–58 %. At a distance of $Z \geq 10$–13 m, the energy decreased to 70–85 %, and further along the working route the weakening process ceased due to the effect of the comprehensive stress-relief technology. As a result, energy consumption for rock fracturing in the near-face zone was reduced within the range of 15–26 %, with an average of 19.5 %.

The geomecanical principles underlying the study include the limitation of excessive stress concentrations in the near-face zone of the rock massifs, the creation of partially stress-relief zones to reduce rock pressure manifestations, ensuring the stability of mine workings under complex mining and geological conditions, and the integration of borehole drilling with slot cutting as a single comprehensive approach to stress relief of the coal-bearing massif.

The practical significance of the study lies in the possibility of safe and resource-efficient excavation in gas-dynamically active coal-bearing rock massifs at depths exceeding 1,000 m.

Future research prospects are associated with refining the optimal parameters for the placement of pre-drilled boreholes and the geometry of stress-relief slots for different rock types, as well as expanding the practical implementation of the technology under production conditions in the Western Donbas coal mines and other coal basins.

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Геомеханічні принципи й особливості моделювання комплексного методу розвантаження газодинамічно активного гірського масиву

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Мета. Обґрунтувати геомеханічні принципи зменшення максимумів напруженого стану під час ведення гірничих робіт у газодинамічних масивах на великих глибинах вугільних шахт.

Методика. Методика досліджень ґрунтується на поєднанні теоретичного, чисельного й експериментального підходів. Для аналізу напружено-деформованого стану вуглепородного масиву було застосоване чисельне моделювання методом скінченних елементів. Оцінювалися вертикальні й горизонтальні напруження, інтенсивність напружень та ізолінії їх розподілу. Паралельно у привибійній зоні виконувалися вимірювання акустичної емісії для визначення ступеня розвантаження, результати яких порівнювалися із даними для ділянок, пройдених за традиційною технологією. Узагальнення результатів чисельних та експериментальних досліджень дозволило сформувати методичні принципи розрахунку параметрів запропонованої технології й оцінити її ресурсозберігаючий ефект.

Результати. Дослідження підтвердило, що застосування комплексної технології розвантаження, яка поєднує буріння випереджальних свердловин і створення розвантажувальних щілин, суттєво підвищує стійкість гірничих виробок у газодинамічно активних вуглепородних масивах на великих глибинах. Прояви гірського тиску знижуються на 7,3 % у вертикальному та на 10,2 % у горизонтальному напрямках, що зменшує втрати площі поперечного перерізу до 18,2 %. Вимірювання акустичної емісії засвідчили знеміцнення привибійного масиву: зниження енергії становило 7–28 % на відстані 2,0–2,5 м від вибою та 32–58 % у межах 3,0–6,0 м. Витрати енергії на руйнування порід зменшилися на 15–26 %, у середньому на 19,5 %.

Наукова новизна. Розроблена геомеханічна модель, що вперше враховує сумісний вплив свердловин і щілин на стійкість гірничих виробок. Встановлені нові залежності між перерозподілом напружень та енергією акустичного сигналу як індикатором ступеня розвантаження привибійної зони.

Практична значимість. Запропоновано безпечний і ресурсозберігаючий метод спорудження виробок у газодинамічно активних масивах гірських порід на великих глибинах, що дозволяє знизити втрати площі поперечного перерізу до 20 %.

Ключові слова: *вугільна шахта, вуглепородний масив, напружений стан, випереджаюча свердловина, розвантажуюча щілина*

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