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# Rationale and modeling of technology for complex bottom-hole zone de-stressing of gas-dynamically active rock mass

Hennadii Symanovych [1*], Iryna Lisovytska [1], Mykola Odnovol [1], Ruslan Ahaiev [2], Serhii Poimanov [1]

[1] *Dnipro University of Technology, Dnipro, Ukraine*
[2] *M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine*
**Corresponding author: e-mail symanovych.h.a@nmu.one*

**Abstract**

**Purpose.** The research aims to substantiate the geological principles and peculiarities of modeling complex de-stressing of a stressed bottom-hole mass during the construction of mine workings at depths of more than 1000 m.

**Methods.** A comprehensive research methodology is proposed, which consists of conducting a computational experiment for calculating a complex de-stressing scheme and analyzing the stress-strain state (SSS) of the bottom-hole mass in the most informative mine working cross-sections, conducting experimental studies on the effectiveness of the method using the developed methodology for observing rock pressure manifestations and estimating energy consumption on the tunneling face rock destruction.

**Findings.** A combination of two methods for de-stressing a rock mass adjacent to the tunneling face using advance slots has been substantiated. A geomechanical model has been created that takes into account the specifics of the proposed method. The stress-strain state of the rock mass adjacent to the tunneling face has been calculated in a series of cross-sections and longitudinal section of mine working.

**Originality.** Three geotechnological principles of simultaneous de-stressing of both rocks adjacent to the face and rocks within the mass along the mine working route has been formulated and elaborated, embodied in the construction of a geomechanical model of complex adjacent rock mass de-stressing. Based on the obtained stress-strain state, five positions of have been developed for complex consideration of changes in the distribution fields of determining stress components. The methodological principle for assessing energy consumption for rock destruction has been substantiated, and an evidence base has been created to confirm the advantages of the proposed mine working construction technology at depths above 1000 m in a gas-dynamically active rock mass.

**Practical implications.** The method for complex de-stressing the rock mass adjacent to the tunneling face, using predrilled wells and de-stressing slots, is proposed. Experimental studies confirm the proposed method feasibility in three directions for safe and resource-saving construction of mine workings in a gas-dynamically active rock mass at great depths. Calculations have proven that energy consumption for bottom-hole rock destruction has decreased in the range of 15-26%.

***Keywords:*** *mine, gas-dynamic phenomena, predrilled wells, stress-strain state, field and in-seam working, de-stressing slot*

## 1. Introduction

According to research [1]-[4], the dynamics for coal mining growth is positive both in major coal-producing countries and globally (Fig. 1), despite the intensive development of renewable energy sources and the use of alternative energy [5]-[8]. Ukraine ranks among the top countries in terms of coal reserves and in the overall structure for organic fuel reserves worldwide. Therefore, the intensification of mining remains a top priority in the country's energy strategy [9]-[10].

The specifics of mining-geological and mining-technical conditions for mining coal seams in Ukraine indicate an increase in the depth of mining operations and, as a result, an increase in gas-dynamic phenomena manifestations, which involve sudden processes of destruction of the bottom-hole face zone with the displacement of rocks and intense gas emission [12]-[15]. The history of the emergence and resolution of gas-dynamic phenomena manifestations spans more than two centuries to substantiating its relevance based on modern concepts [16]-[22]. Currently, in Ukraine there are practical solutions for pre-venting these phenomena contained in normative documents [23]-[28].

At present, there is a database of industrial and experimental tests of new methods for preventing gas-dynamic phenomena (GDP) manifestations [29]-[32]. Various hypotheses and theories are proposed based on GDP concepts [33], [34]. Additionally, the formation of gas hydrates in mining operations is another significant factor that warrants attention. While the energy potential and rock pressure are primary considerations in the initiation of gas-dynamic phenomena, the role of gas hydrates cannot be overlooked.

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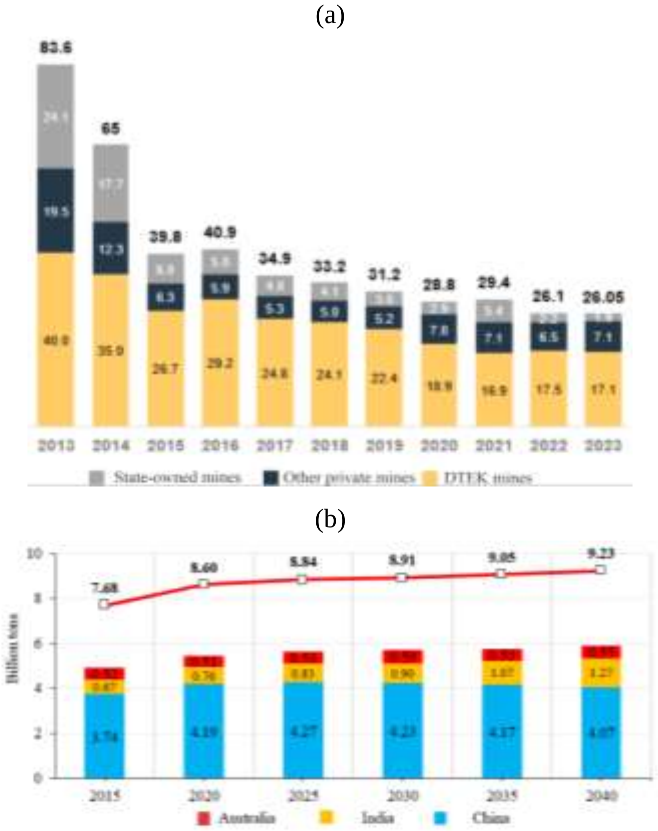


*Figure 1. Tendency of coal mining in Ukraine (a) and world mining (b)*

However, the question of what initiates GDP – energy potential or rock pressure – remains unresolved. This ambiguity hinders the development of universally effective preventive measures.

When studying technologies to combat GDP, it should be noted that hydraulic influence methods are actively developed at the present stage [37], [38]. Hydrodynamic and hydro-pulse methods are the most developed [39]-[42]. It should be noted that the analysis of methods for preventing sudden coal, gas, and rock outbursts has shown that they lead to a decrease in the velocity of mining operations. In this sense, attention should be paid to the method of drilling de-stressing pre-drilled wells [43], [44]. Geomechanical studies of stress distribution around workings [45]-[50] allow for the search for rational parameters for the location of wells based on determining the most stressed zones [51]-[53].

In previous works [54]-[56], the significance of the influence of pre-drilled wells on the process of reducing stress levels in the rock mass adjacent to mine working was demonstrated: both the value of the SSS component maxima and the sizes of their spread areas decrease. To strengthen these positive tendencies, a technology for complex bottom-hole zone de-stressing was proposed, which involves adding de-stressing slots (in addition to the de-stressing wells) extending beyond the mine working boundaries to a distance $X_s$ (Fig. 2). This technical solution can be substantiated as follows.

De-stressing wells reduce the stress in the adjacent rock mass deep along the mine working route to a depth of up to 10-15 m, sometimes more. Thus, we have a component of partial de-stressing of rocks at a relatively far distance from the tunneling face plane [57].

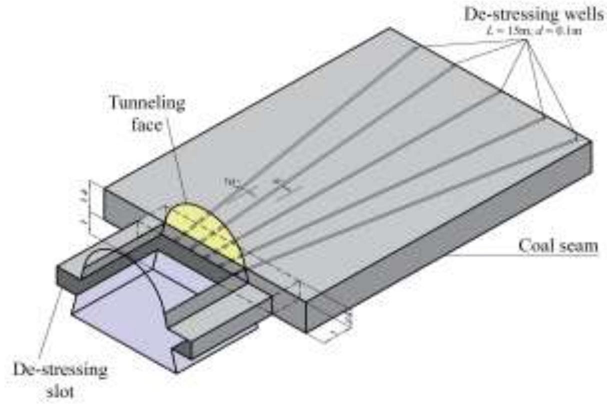


*Figure 2. Scheme for complex de-stressing the rock mass bottom-hole zone*

At the same time, maximum SSS component concentrations are observed near the tunneling face plane [58]-[60]; undoubtedly, they are influenced by pre-drilled wells, but it is desirable to enhance the restriction on the action of bottom-hole stress concentrations, for which an additional de-stressing slot can be applied. Thus, a combination of two methods for de-stressing (using wells and slots) has been formed, called "complex de-stressing" [61].

There is a need to lower the maximum stress concentrations located by the $Z$ coordinate a few meters from the tunneling face plane. This geomechanical problem can be fully addressed by de-stressing slot with a depth of up to 1.0 m: if the slot is near the face, the rock pressure has reduced value (although it gradually increases by the $Z$ coordinate) and intersects previously formed maxima in such a way that they ultimately decrease, leading to some leveling of SSS disturbances along the bottom-hole zone of the mine working route. This constitutes the first geotechnological principle of complex bottom-hole mass de-stressing.

The second geotechnological principle implements the requirement of reducing the rock pressure concentration outside the constructed mine working boundary. Therefore, the technical decision was made to extend the de-stressing slot to the maximum possible width $X_s$, limited only by the tunneling machine design characteristics. It is quite logical that the process of de-stressing the adjacent rock mass will extend beyond the mine working boundaries, which positively affects the rock pressure manifestations around it. Thus, a layer of de-stressed rocks is formed in the border rock mass, which will (in the future) transfer reduced rock pressure to the support of mine workings, while the main concentration of bearing pressure will be shifted into the depth of the side rocks. In other words, in both sides of the mine working, a protective structure resembling a protective strip is formed from the destroyed and caved rocks. From numerous studies [62]-[64], it is known that increased deformability of the gob pack (or any other protective structure with a yielding operating mode) contributes to reducing both vertical and lateral loads on the mine working support by forming a zone of reduced stress around it. In addition, such similarity to a protective structure will contribute to increasing the stability of preparatory in-seam workings in the zone of stope operations influence [65].

The third geotechnological principle contains a simple technical solution related to the use of tunneling machines: there are no restrictions on the de-stressing slot construction conditioned by the actuating unit. The slot height $D$ equals the diameter of the actuating unit, its depth $L$ depends on the ability to feed the drill head by the machine boom hydraulic jack, and the width $X_s$ of the slot areas in the mine working sides is determined by the tunneling machine maneuvering capabilities, taking into account its dimensions and machine boom movement. Regarding in-seam workings, rock destruction usually starts from the weakest lithotype, that is, from the coal seam. This is a common practice in the construction of mine workings by the so-called mechanized method.

## 2. Methodology

### 2.1. Methodological peculiarities of border mass stress-strain state and patterns of its change

Main principles assessing the influence of complex de-stressing adjacent mass are as follows. Firstly, a database, reflecting the influence of the first complex de-stressing component – pre-drilled wells [66]-[68], has been created.

Secondly, the results of SSS calculations for the bottom-hole mass when applying the second component – de-stressing slot (according to the scheme in Figure 2), will be compared with database on the influence of the first complex de-stressing component.

Thirdly, for the purpose of specifying presentation of material, a comparative analysis is presented in isolines of the most informative stress components: vertical $\sigma_y$, horizontal $\sigma_x$ and $\sigma_z$, as well as stress intensity $\sigma$. Regarding the comprehensiveness of the comparative analysis, isoline graphs are provided in both cross-sections (plane *YX*) and longitudinal (plane *YZ*) sections of the mine working route.

Fourthly, the assessment of the adjacent mass SSS changes is mainly provided based on indicators of the spread distances of stress concentration components at a certain level and intervals of action of these concentration values.

Fifthly, information on the SSS component concentrations in the adjacent border rocks in the area of the already constructed mine working is quite important, since the reduction of stress concentrations in these areas positively affects the limitation of rock pressure manifestations and increase in the stability of preparatory workings. Using the example of the distribution of vertical stresses $\sigma_y$ along the length (coordinate $Z$) of the mine working route, the most informative cross-sections (plane *YX*) of the mine working have been selected for analyzing the de-stressing slot influence.

The first cross-section has been made in the already constructed mine working at a distance $Z_1$ = -10 m, where the influence of the tunneling face is almost insignificant. Here, the main task is to comparatively assess the change in the vertical stress $\sigma_y$ level specifically in the border rocks, where the load on the mine working support is formed. This is important because, according to existing concepts [69]-[72], the formation of a de-stressed rock layer around mine working contributes to reducing the rock pressure on the mine working support, including the area affected by stope operations when the future longwall face will advance nearby. After all, the important ultimate result is a satisfactory stability of extraction drifts for the stable conduct of stope operations and their possible reuse [73]-[75].

The second *YX* section is expedient to study at a distance $Z_2$ = 2.0-2.5 m from the tunneling face. Two important tendencies are observed here: firstly, there is a highest gradient of growth in $\sigma_y$ concentration spread distances at different levels (into the roof and bottom) formed by pre-drilled wells; secondly, at this distance, there is a maximum bearing pressure due to de-stressing slot action.

The third *YX* section is reasonable to make at a distance $Z_3$ = 11-12 m (from the tunneling face along the mine working route deep into the mass), where the maximum spread in the roof and bottom of different $\sigma_y$ concentrations is achieved due to the action of de-stressing wells.

These specified cross-sections in the *YX* plane are complemented by longitudinal sections *YZ*, when studying the change in $\sigma_y$ concentration spread along the mine working route. Similar mine working sections are examined by studying the patterns of change in stress intensity $\sigma$.

Regarding the horizontal stresses $\sigma_x$ and $\sigma_z$, the following should be noted. The $\sigma_x$ component can be studied only in the *YX* plane, which reflects the bending of rock layers specifically in the cross-section of the mine working route. Studying the $\sigma_x$ field in the $Z_1$ = -10 m section is reasonable due to significant influence of the de-stressing slot despite its somewhat distant location from the tunneling face. This occurs because the de-stressing slot extends beyond the mine working contour, and this area of border rocks undoubtedly "experiences" changes in the $\sigma_x$ field. Conversely, in the distant section $Z_3$ = 11-12 m along the mine working route, the influence of de-stressing slot is found to be insignificant. Therefore, the influence of de-stressing slot is studied in detail only in sections *YX* at distances $Z_1$ = -10 m and $Z_2$ = 2.0-2.5 m.

Horizontal stresses $\sigma_z$ are studied not only in the longitudinal section *YX* along the mine working route. We are interested not only in the *YZ* section by the central vertical coordinate of mine working, but also in the *YZ* section located at a distance $X_s$ along the horizontal coordinate $X$ of the mine working (Fig. 2). The reason for studying an additional *YZ* section is that the de-stressing slot endfaces will add certain bending stresses $\sigma_z$ in the border rocks outside the mine working. This requires studying the components $\sigma_y$ and $\sigma$ in the *YZ* section at the distance $X_s$ from the mine working contour, because this area generates oblique and lateral rock pressure on the mine working support.

Ultimately, the reasoned sections selected for study provide a comprehensive understanding of the de-stressing slot in-fluence on SSS of the rock mass adjacent to the tunneling face.

### 2.2. Vertical stress field changes

Following the provided algorithm, the patterns of change in the position of vertical stress $\sigma_y$ isolines under the influence of de-stressing slot have been sequentially analyzed.

In the first section ($Z$ = -10 m), the following results have been obtained (Fig. 3a). The main attention is paid to the adjacent rock de-stressing zone, which is formed around the mine working perimeter and is crucial in terms of reducing the rock pressure on its support. Thus, in the mine working roof, de-stressing zone ($K_y$ = 0.48-0.60) in the form of an arch spreads up to 3.1 m along the vertical axis $Y$ and occupies the central part of the arch up to 3.3 m wide. This size of the de-stressing zone is sufficient for a significant reduction in vertical rock pressure, and at the same time, it is capable of generating moderate loading from its own weight – up to a maximum of 80-100 kN per frame (with an installation step of 0.5 m). This is several times less than the load-bearing capacity of the support.

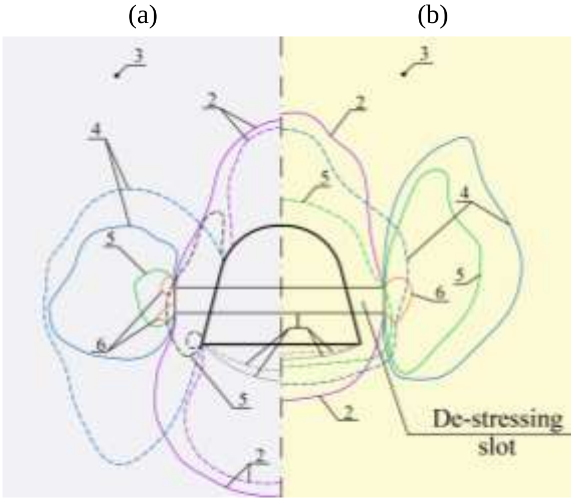


***Figure 3. Isolines of vertical stresses $\sigma_y$ in the mine working cross-section when using (——) de-stressing slot slot and without it (- - -): (a) at a distance of $Z_1$ = -10 m to the tunneling face plane; (b) at a distance of $Z_2$ = 2.0-2.5 m to the tunneling face plane; 1 – $\sigma_y$ = +(4-5) MPa; 2 – $\sigma_y$ = -(12-15) MPa ($K_y$ = 0.48-0.60); 3 – $\sigma_y = \gamma H$ = -25MPa ($K_y$ = 1.0); 4 – $\sigma_y$ = -(31-34) MPa ($K_y$ = 1.24-1.36); 5 – $\sigma_y$ = -(40-48) MPa ($K_y$ = 1.60-1.92); 6 – $\sigma_y$ = -(50-65) MPa ($K_y$ = 2.0-2.6)***

However, this applies only to the central arch contour area, because, when the advance is towards the mine working sides (beyond a width of 1.5 m from the central axis), the de-stressing zone disappears, and a zone of bearing pressure develops: initially, in an area up to 0.5 m wide, the geostatic pressure $\sigma_y = \gamma H$ of the undisturbed mass acts, and then (down to the mine working bottom), the bearing pressure increases up to a concentration of $K_y$ = 1.60-1.92 and in the mine working angle, the concentration $K_y$ = 2.0-2.6 acts. Therefore, in the mine workings sides, increased oblique and horizontal rock pressure should be expected.

Due to de-stressing slots, there is a displacement of the bearing pressure zone (of varying $K_y$ concentration levels) laterally from the mine working for a distance not less than $X_s$ size (Fig. 3a). Therefore, we can reliably predict an increase in the stability of extraction drifts both outside and within the zone of stope operations influence.

The second important cross-section of the mine working route is made at a distance $Z_2$ = 2.0-2.5 m into the mass from the tunneling face, and isolines of vertical stresses $\sigma_y$ are presented in Figure 3b.

The general tendency is the displacement of the bearing pressure zone deeper into the mass for a distance $X_s$, which reduces the border rock stress (to the future mine working) and somewhat contributes to limiting the risk of GDP occurrence. From this perspective, it should be noticed that due to de-stressing slot, even a zone of de-stressing of $K_y$ = 0.48-0.60 level is formed, which spreads along the entire contour of the future mine working. Thus, the safety of tunneling operations directly near the face and at a depth into the mass of more than 2.0-2.5 m increases. Such an effect is not achieved from the action of pre-drilled wells alone, hence their combination with the de-stressing slot is quite effective.

Regarding the comprehensive study of the de-stressing slot influence, changes in the vertical stress $\sigma_y$ field in the longitudinal direction along the mine working route by the coordinate $Z$ (Fig. 4) have been analyzed.

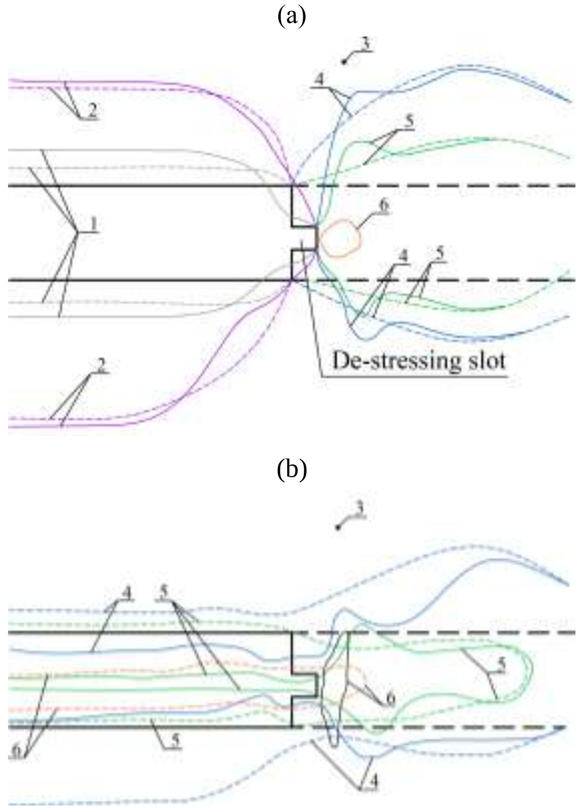


***Figure 4. Isolines of vertical stresses $\sigma_y$ in the mine working longitudinal section when using (——) de-stressing slot and without (- - -): (a) along the central vertical axis (X = 0); (b) along the peripheral vertical axes ($X = \pm X_s$); 1 – $\sigma_y$ = +(4-5) MPa; 2 – $\sigma_y$ = -(12-15) MPa ($K_y$ = 0.48-0.60); 3 – $\sigma_y = \gamma H$ = -25 MPa ($K_y$ = 1.0); 4 – $\sigma_y$ = -(31-34) MPa ($K_y$ = 1.24-1.36); 5 – $\sigma_y$ = -(40-48) MPa ($K_y$ = 1.60-1.92); 6 – $\sigma_y$ = -(50-65) MPa ($K_y$ = 2.0-2.6)***

Here, two longitudinal sections in the *YZ* plane are presented: along the central vertical axis of the mine working route and along the vertical axis (peripheral), located in the plane of de-stressing slot endface ($X = X_s$) in the side of the future mine working. Regarding the *YZ* section along the central vertical axis of the mine working route, the follo-wing can be stated.

At a depth $L$ of the de-stressing slot (Fig. 2), in its roof and bottom, there is a decrease in vertical stresses until they reach low tensile values of $\sigma_y$ = 4-5 MPa level. Starting from the mark $Z = L$ (de-stressing slot face plane), compression stress concentration $K_y > 1$ arises and spreads deep into the mine working route. By the $Z$ coordinate, the spread of $\sigma_y$ concentration increases rapidly both into the roof and bottom of the future mine working, and at a distance of 1.4-2.0 m (from the de-stressing slot face plane) it reaches its maximum, exceeding (in limited areas) the spread of corresponding concentrations in the absence of the de-stressing slot. However, further into the mine working route (by the $Z$ coordinate), the spread distances of $\sigma_y$ concentrations approach each other, and at $Z$ = 7-8 m, the difference between them is almost negligible, which means that the influence of the de-stressing slot disappears.

Conclusion from these results is as follows. Some exceedances of the distribution of $\sigma_y$ concentrations in a limited (by coordinate $Z$) area occur when using de-stressing slot, but this area of $\sigma_y$ concentrations is shifted towards the side rocks, and in the absence of a de-stressing slot, increased $\sigma_y$ ($K_y > 1$) concentrations spread around the entire perimeter of the future mine working and may provoke dangerous GDP. The second conclusion is that immediately adjacent to the tunneling face, to the depth of the entry way, the rocks are in a de-stressed state with the appearance of even tensile $\sigma_y$, actively strengthening them and contributing to energy savings in the mass destruction.

The second longitudinal section ($X = X_s$) also demonstrates the positive de-stressing slot influence on the distribution of vertical stresses $\sigma_y$ (Fig. 4b). Along the length of the already driven mine working, there is a significant decrease in the height of concentration distribution at the $K_y$ = 1.24-1.36 and $K_y$ = 1.60-1.92 levels against the background of their displacement deep into the side rocks. Additional concentrations of the $K_y$ = 2.0-2.6 level arise, but they have a very localized spread near the corners of the de-stressing slot endface. At $Z$ > 1.0 m, along the working route, anomalies of $\sigma_y$ with increased spread in height appear, but at $Z$ > 3.0-3.5 m, they quickly decrease, and at a certain distance, the influence of the de-stressing slot disappears.

The overall conclusion can be formulated as a positive influence of the combination of pre-drilled wells and de-stressing slots on the mass state in terms of the action of vertical stresses $\sigma_y$: firstly, the degree of de-stressing the adjacent mass bottom-hole zone is enhanced, reducing the risk of GDP; secondly, this part of the rocks surrounding the tunneling face is more intensively strengthened, reducing the energy needs for their destruction; thirdly, a layer of de-stressed rocks adjacent to the mine working (around its entire perimeter) arises, reducing differently directed rock pressure on the mine working support, thereby increasing its stability and substantiating the possibility of saving resources for support and maintenance of the mine working, including in the area of stope operations influence.

The general tendencies of de-stressing slot influence on changes in the distribution of horizontal stresses $\sigma_x$ confirm the previous conclusions regarding vertical stresses $\sigma_y$.

In general, by the factor of cumulative action of horizontal stresses $\sigma_x$ and $\sigma_z$, it is possible to assert that the de-stressing slot develops a tendency to weaken rocks up to 4-5 m deep into the mine working route and is expedient when solving the set triunique task of safe and resource-saving conduct of a mine working at a depth of more than 1000 m in a gas-dynamically active rock mass.

Regarding the tendencies of de-stressing slot influence on changes in the stress intensity field $\sigma$, it can be argued that there are consistent patterns of mainly extending de-stressing areas in the rocks adjacent to the tunneling face.

Summarizing the analysis results of the tendencies in the de-stressing slot influence on the fields of the most effective SSS components, it can be stated (based on finite element modeling) the expediency of a comprehensive de-stressing of the bottom-hole rock mass for the implementation of the triunique task: reducing the risks of GDP and the energy spent for bottom-hole rock destruction, while increasing mine working stability.

## 3. Experimental studies on the effectiveness of complex bottom-hole mass de-stressing

### 3.1. Results of observations of rock pressure manifestations

The main task of this research stage is to assess the reliability of finite element modeling (FEM) results of the technological solution for complex bottom-hole de-stressing of high-stress bottom-hole mass during the construction of mine working at a depth above 1000 m and even in conditions of gas-dynamically active adjacent rocks. The necessity of conducting these experimental studies lies in verifying a new technological solution involving the combination of two known methods for de-stressing (pre-drilled wells and de-stressing slots), considering that the de-stressing slot extends beyond the mine working side contours by a certain distance $X_s$ from them. When filling this cavity with destroyed lithotypes (coal seam and rocks of its immediate roof), something similar to a protective gob pack is formed, which displaces the bearing pressure from the mine working due to its own yielding mode of operation. Therefore, it is crucial to determine the extent to which the proposed technological solution contributes to enhancing the stability of extraction drifts even at the stage of their maintenance beyond the zone of stope operations influence.

To perform a comparative analysis, an experimental mine working area with a length of at least 100 m is created, where the method of complex bottom-hole mass de-stressing is applied. The basis for comparison are all other mine working areas with approximately the same adjacent rock mass texture.

As for enhancing the degree of in formativeness and objectivity of the comparative analysis, the following methodological approaches are proposed.

Firstly, we are more interested not in the absolute values of the mine working contour displacements in the vertical $U_y$ and horizontal $U_x$ directions (although they are also important for compliance with operational safety rules), but in the relative improvement (or deterioration) of the mine working state when applying the method of complex bottom-hole mass de-stressing. Such relative indicators vertically $\Delta_x$ and horizontally $\Delta_y$ immediately substantiate the evidence base regarding the effectiveness of the proposed method in terms of increasing the stability of mine workings.

Secondly, the experience of analyzing the surveying results indicates the complexity of their perception when reproducing the full volume of observations over a relatively large area of the mine working.

More informative are the values of mine working contour displacements vertically $U_y$ and horizontally $U_x$, which are calculated as the difference between the initial (passport) height $h_b^{in}$ and width $B^{in}$ values and the current $h_b$ and $B$ values:

$$\left.\begin{aligned} U_y &= h_b^{in} - h_b; \\ U_x &= B^{in} - B. \end{aligned}\right\} \tag{1}$$

The change in the mine working state under the proposed complex bottom-hole de-stressing method will be assessed based on the parameters $U_y$ and $U_x$.

Thirdly, the “rapid” change in the mine working dimensions along its length complicates comparative analysis, so the next proposed step is to somewhat “smooth” the graphs of distribution of the measured current indicators $h_b$ and $B$.

Fourthly, we need to reflect the change in two parameters of the mine working cross-section, so it is most expedient to do this in relative values of $\Delta_y$ and $\Delta_x$:

$$\left.\begin{aligned} \Delta_y &= \frac{U_y}{h_b^{in}}; \\ \Delta_x &= \frac{U_x}{B^{in}}. \end{aligned}\right\} \tag{2}$$

Since there may be discrete advantages of one technology over another, the planes $P$ are marked as positive $P_+$ and negative $P_-$, and their result will be equal to:

$$P = P_+ - P_- . \quad (3)$$

In addition, we have two pairs of lines ("min" and "max"), so the generalized result $P_{n.gen}$ is calculated as the average value of the two $P$ values, and the averaged deviation $\Delta_{y,x}^{av}$ is equal to:

$$\Delta_{y,x}^{av} = \frac{P_{n.gen}}{Z_{ar}}, \quad (4)$$

where:

$Z_{ar}$ – is the length of the observation area.

In our opinion, such a methodological approach will be the most objective in assessing the effectiveness of the proposed complex bottom-hole de-stressing method in terms of improving the operational condition of the mine workings.

Using the provided methodology, indicators of vertical $U_y$ and horizontal $U_x$ displacements are measured, the obtained dataset is processed, and graphs (Fig. 5) of changes in relative indicators along the experimental and nearly "identical" base mine working areas are constructed.

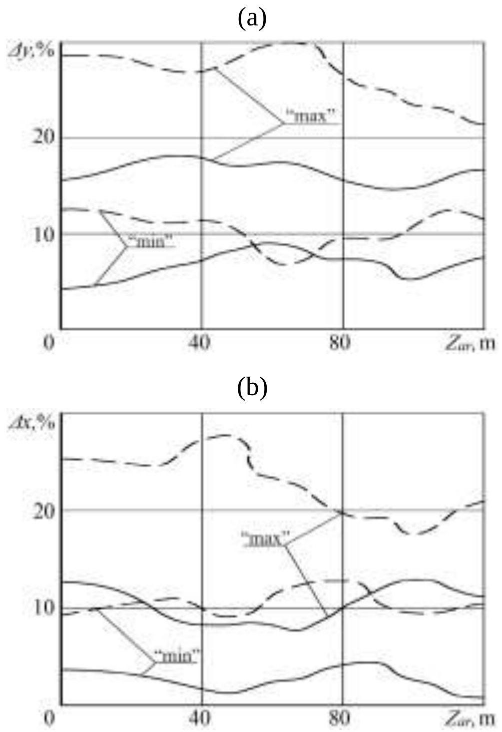


***Figure 5. Graph for comparative analysis of the limitation degree of vertical (a) and lateral (b) mine working contour displacements when using the technology of complex de-stressing of the bottom-hole mass***

As a result, a limitation can be determined on a decrease in the mine working height by 7.3% and a convergence of its sides by 10.2%. Thus, the positive influence of the technology for complex bottom-hole mass de-stressing on the stability of preparatory workings has been experimentally proven. This results (ultimately reducing the loss of cross-sectional area by 18.2%) in one of the arguments for the expediency of applying the proposed technology for the construction of mine workings at depths above 100 m.

### 3.2. Assessing the energy consumption for tunneling face rock destruction

Experimental results demonstrate partial weakening of lithotypes in the bottom-hole zone, especially along the mine working entry way. Such weakening is expected to influence the energy consumption for tunneling face rock destruction.

The methodological specifics of this experimental stage is as follows. The existing traditional method for constructing mine workings using a tunneling machine provides a basis for further comparative analysis; for this purpose, the mine working areas with approximately similar textures of surrounding rocks are selected compared to the experimental area where the proposed complex bottom-hole mass de-stressing technology is applied. The energy $G$ spent for rock destruction is determined by current and voltage indicators (in real-time mode) during the tunneling machine boom motor operation. That is, the design of tunneling machines with separate drives for their main mechanisms allows isolating the energy spent solely for tunneling face rock destruction from other technological processes.

For the traditional method of conducting mine workings, the basic energy value $G_b$ for destruction of lithotypes (per linear meter of its length) is determined as an averaged value over an area up to 100 m long. Such length for averaging allows for "absorbing" small-amplitude lithotype thickness fluctuations (within the mine working plane), some unpredictable disturbances of their continuity, changes in mechanical properties when encountering so-called "inclusions" of other rocks, and so on.

The same approach to averaging is used in the experimental area when determining the energy values $G$ spent for rock destruction, but the mine working length for averaging is reduced to 5 m to assess the entire spectrum of $G$ fluctuations for the reliability of comparative analysis.

Also, towards enhancing reliability, a methodological approach is used, which involves dividing the recording of energy spent for rock destruction into the following operations: $G_1$ – drilling pre-drilled wells; $G_2$ – formation of the de-stressing slot; $G_3$ – destruction of the bottom-hole rock volume along reduced planes.

The total energy $G$ spent for rock destruction using the proposed technology is determined as the sum of components:

$$G = G_1 + G_2 + G_3 , \quad (5)$$

recalculated per 1 linear meter of mine working.

It is considered expedient to use the most informative relative indicator $G_b$, which positions energy $G$ as a fraction of energy $G_b$. Thus, the following ratio is considered:

$$G_r = \frac{G}{G_b}, \quad (6)$$

as a clear evidence of energy savings during bottom-hole rock destruction using the proposed mine working technology, as shown in Figure 6. Analyzing the obtained graph, a minimum indicator of $(G_r)_{min}$ = 74% and a maximum value of $(G_r)_{max}$ = 85% can be obtained; in general, the averaged value of energy resource savings is 19.5%.

The summary of the conducted experimental research is unequivocally positive – all three directions confirm the advantages of the proposed mine working construction technology at depths above 1000 m in a gas-dynamically active rock mass.

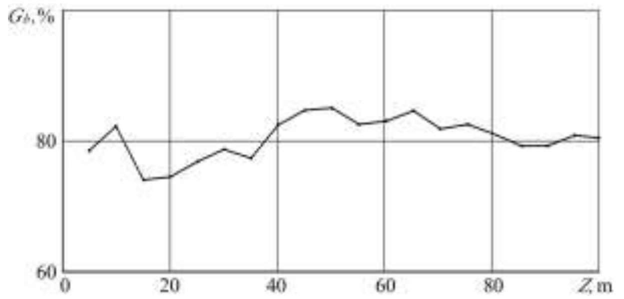


***Figure 6.** Graph of relative decrease in energy $G_b$ spent for the bottom-hole rock mass destruction along the length Z of the experimental area of mine working constructed using the proposed technology*

## 4. Conclusions

1. Regarding the increased effectiveness of achieving the research purpose, a combination of two methods for de-stressing the rock mass adjacent to the stoping face using pre-drilled wells and de-stressing slots, which is called "complex de-stressing", has been substantiated. For this purpose, three geotechnological principles have been formulated and disclosed for simultaneous de-stressing of both the rocks adjacent to the face and the rocks deep in the mass along the mine working route. To create an evidence base for expedient complex de-stressing, a geomechanical model has been constructed, taking into account the peculiarities of the proposed method.

2. Methodological principles have been developed for comprehensive investigation of the de-stressing slot influence patterns on the SSS of the rock mass adjacent to the tunneling face. For this purpose, five positions of comprehensive consideration of changes in the distribution fields of determining stress components have been developed: vertical $\sigma_y$, horizontal $\sigma_x$ and $\sigma_z$, as well as stress intensity $\sigma$. A number of cross-sections and longitudinal sections of the mine working have been substantiated, which fully reflect the tendencies of the de-stressing slot influence.

3. A positive influence on the mass state of a combination of pre-drilled wells with a de-stressing slot has been identified, confirmed by the analysis of the fields of distribution of the main, most informative stress components. The technical solution under study allows developing rational directions for solving three interconnected tasks: first – to enhance the degree of de-stressing the adjacent mass bottom-hole zone, thus reducing the risks of GDP; second – this part of the rocks surrounding the tunneling face is strengthened more intensively, thus reducing the energy intensity for their destruction; third – a layer of de-stressed rocks adjacent to the mine working (around its entire perimeter) is formed, which reduces differently directed rock pressures on the mine working support, thereby increasing its stability and substantiating the possibilities of resource savings when fastening and maintaining mine working, including in the area of stope operations influence.

4. Experimental research of the proposed method for complex de-stressing has confirmed its expediency in three directions for the safe and resource-saving construction of mine workings in a gas-dynamically active rock mass at great depths.

## Author contributions

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


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## Conflicts of interests

The 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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## Обґрунтування та моделювання технології комплексного розвантаження привибійної частини газодинамічно активного гірського масиву

Г. Симанович, І. Лісовицька, М. Одновол, Р. Агаєв, С. Пойманов

**Мета.** Обгрунтування геологічних принципів й особливостей моделювання комплексного розвантаження напруженого привибійного масиву при спорудженні виробок на глибинах понад 1000 м.

**Методика.** Запропоновано комплексну методику проведення досліджень, яка складається з проведення обчислювального експерименту з розрахунку комплексної схеми розвантаження й аналізу напружено-деформованого стану привибійного масиву в найбільш інформативних поперечних перерізах виробки, проведення експериментальних досліджень ефективності способу за розробленою методикою спостережень за проявами гірського тиску та оцінкою витрат енергії на руйнування порід прохідницького вибою.

**Результати.** Обґрунтовано комбінацію двох способів розвантаження прилеглого до прохідницького вибою гірського масиву за допомогою випереджаючих щілин. Створено геомеханічну модель, яка враховує особливості запропонованого способу. Розраховано напружено-деформований стан прилеглого до прохідницького вибою масиву гірських порід у низці поперечних та поздовжніх перерізів виробки.

**Наукова новизна.** Сформульовано і розкрито три геотехнологічні принципи одночасного розвантаження як прилеглих до вибою порід, так і в глибині масиву по трасі виробки, які втілено в побудову геомеханічної моделі комплексного розвантаження прилеглого гірського масиву. На базі отриманого напружено-деформованого стану розроблено п'ять позицій комплексного врахування змін у полях розподілу визначальних компонент напружень. Обґрунтовано методичний принцип оцінки витрат енергії на руйнування порід і створено доказову базу підтвердження переваги запропонованої технології спорудження виробки на глибині понад 1000 м у газодинамічно активному гірському масиві.

**Практична значимість.** Запропоновано спосіб комплексного розвантаження прилеглого до прохідницького вибою гірського масиву за допомогою випереджаючих свердловин і розвантажувальних щілин. Експериментальні дослідження підтвердили дослідження запропонованого способу в трьох напрямах безпечного та ресурсозберігаючого спорудження виробок у газодинамічно активному масиві гірських порід на великих глибинах. Розрахунками доведено, що знизилися витрати електроенергії на руйнування привибійних порід у діапазоні 15-26%.

***Ключові слова:*** *шахта, газодинамічні явища, випереджаючі свердловини, напружено-деформований стан, породний масив, розвантажувальна щілина*

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