

V. I. Bondarenko<sup>1</sup>,  
 orcid.org/0000-0001-7552-0236,  
 I. A. Kovalevska<sup>1</sup>,  
 orcid.org/0000-0003-2936-9680,  
 H. A. Symanovych<sup>1</sup>,  
 orcid.org/0000-0002-2121-1742,  
 M. V. Barabash<sup>2</sup>,  
 V. H. Snihur<sup>3</sup>

1 – Dnipro University of Technology, Dnipro, Ukraine,  
 e-mail: [y\\_domna@yahoo.com](mailto:y_domna@yahoo.com)

2 – “DTEK Energy” LLC, Kyiv, Ukraine

3 – MM “Heroiv Kosmosu”, PJSC “DTEK Pavlohrad-vuhillia”, Pavlohrad, Ukraine

## PECULIARITIES OF MINING THE PROTECTING PILLAR IN THE LAMINAL MASSIF OF SOFT ROCKS

**Purpose.** Increasing the completeness of mining coal reserves from protecting pillars located in a laminal massif of soft rocks in the roof and bottom in order to reduce the coal losses in mines and horizons in case when mining operations are at the stage of completion.

**Methodology.** A geomechanical model is developed for research into mining of protecting pillars influenced by stope works, taking into account the laminal massif and rheological processes of creep deformations and stress relaxation of the rock massif. Numerical modelling and analysis of the stress-strain state of the massif are conducted. Conclusions are drawn in terms of substantiation of the technical solutions for mining the protecting pillars.

**Findings.** New patterns have been determined of the stress-strain state of a laminal rock massif in the zone influenced by stope works. A geomechanical model has been developed for mining the protecting pillars with account of rheological processes in the rocks, and the technological parameters of mining the coal from longwall faces have been substantiated. A possibility is provided for repeated use of mine workings by introducing a resource-saving fastening system.

**Originality.** The patterns have been determined of the frontal bearing pressure zone displacement ahead of the longwall face during mining the protecting pillars, as well as the concentration factor  $K_y = 1.1-1.3$  at a height from the  $c_6$  coal seam up to 18–20 m, when contacting the thick siltstone. It was found that the calculated compressive resistance is by 4.2 times higher than the value of acting  $\sigma_y$  and, according to this factor, siltstone maintains continuity through all its thickness. When approaching the  $c_6^1$  seam, vertical stress concentration increases and is already  $K_y = 1.9-2.7$ . Based on the account and analysis of these factors, one can assert that the roof of the seam and the seam itself are not destroyed.

**Practical value.** Technological solutions have been developed for mining the protecting pillars to increase the completeness of coal reserves extraction while reducing its production costs and increasing the safety of stope operations by means of decreasing the rock pressure onto powered support.

**Keywords:** coal, rock massif, protecting pillar, stress-strain state, load, reserves extraction

**Introduction.** The technologies of mining a coal seam in a descending order are widely used not only in the Western Donbas conditions and in the geologically similar Lviv-Volyn Coal Basin, but also have a long history of application in other coal-mining countries. The relevance of studying this problem is differently vectored, for example, conditioned by the necessity to ensure mine workings stability during the period of stope works, conducted both in the overlying seams and underlying seams. That is, the influence of overworking and underworking of the mine rock massif should be taken into account. On the other hand, after the mine field section of the overlying seam is mined out, considerable coal reserves still remain in various kinds of the protecting pillars. Their extraction provides not only a more complete coal recovery, but also a significant reduction in cost for its output. This is facilitated by a number of factors:

- protecting pillars are partially or fully surrounded by mine workings, which sharply reduces the cost for their preparation to extraction;

- protecting pillars, previously planned for mining, have significant dimensions in order to reliably restrict the influence of stope works in the specific Western Donbas conditions (slightly metamorphized rocks occurring in the coal-bearing stratum); consequently, substantial coal reserves are concentrated in the pillars, and their mining in a number of mining-engineering situations is possible using traditional technologies;

- laminal coal-bearing massif of the Western Donbas soft rocks is characterized by an active flow of rheological processes (creep deformations and stresses relaxation), which contributes to “smoothing” the concentrations of bearing pressure and the consolidation of fully or partially broken rocks in the mined-out space (after previous stope works operation), which borders on the protecting pillar;

- in most cases, the preparatory mine workings that surround the protecting pillar are being filled, which eliminates the costs for their further maintenance; if it is necessary to preserve such mine workings, the conditions for their maintenance are improved by unloading the surrounding massif from the side of the previous periods of stope works operation and

partial relaxation of the lateral bearing pressure in the process of mining the protecting pillar;

- low mechanical characteristics of lithotypes of the laminal coal-bearing massif do not allow extended consoles overhanging and, thereby, they restrict the load on the powered support of the stope complex in case of appropriate velocities of the longwall face advance, which increases the operational safety. In addition, a partial weakening of the coal seam in the stope face enables intensification of coal mining process.

The above-mentioned and other factors of a predominantly geomechanical nature form a certain specificity of mining the protecting pillars in the slightly metamorphized Western Donbas rocks. This requires a more detailed research in terms of substantiating the current direction to increase the completeness of the coal reserves extraction while reducing its production costs [1]. A series of studies, conducted both in Ukraine [2] and abroad [3], are devoted to this direction. Particular attention is focused on mining and geological [4], hydrogeological [5] as well as mining-engineering conditions for mining the coal seams [6].

**Purpose.** Mining-and-geological and mining-engineering conditions for mining the protecting pillars are quite diverse even within the limits of a separate coal-bearing region – the Western Donbas [7]. Therefore, it is expedient to consider this geomechanical problem using a specific example (M.I. Stashkova Mine of the “Dniprovske” MM) to protect the underlying steep-dipping ventilation crosscut No. 1 (SVC No. 1) of the seam  $c_5$ , which is maintained in the bottom of the seam  $c_5 + c_5'$ . The issues of state of the SVC No. 1 of the seam  $c_5$ , influenced by overworking, will not be studied here. Moreover, according to the general expert assessment in the studies [8] for similar Western Donbas conditions and the computational experiment results, specifically for the conditions under consideration, a unified opinion has been formulated about the absence of stope works negative influence along the seam  $c_6$ . It is expedient (from an economic and technical point of view) to mine the reserves of a protecting coal pillar. The reserve volume is about 160 thousand tons, and the dimensions of the extraction area (576 m long and 165 m wide) fully allow it to be mined-out by traditional technology using a coal extracting complex).

The peculiarities of the geomechanical processes of the coal-overlying formation displacement should be studied using a rather complex research object – a laminal coal-bearing massif of soft rocks, the mechanical properties of which are additionally reduced under the negative influence of fracturing and moisture saturation of most lithotypes [9] constituting this massif.

The research object complexity is demonstrated by a geomechanical sheet in the protecting pillar location, shown in Fig. 1. To illustrate the effect of the rock pressure anomalies development in the presented laminal massif of soft rocks, a

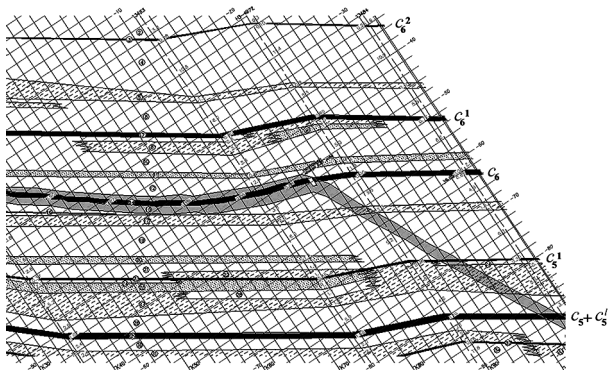


Fig. 1. Geological sheet in the area of the protecting pillar of the seam  $c_6$  to protect the SVC No. 1 of the seam  $c_5$  in M. I. Stashkova Mine

prediction scheme is constructed (Fig. 2). In the scheme, the propagation of the frontal bearing pressure zone with the concentration criterion  $K_y$  of vertical stresses  $\sigma_y$  ( $K_y = \sigma_y / \gamma H > 1$ ) and the unloading zone ( $K_y < 1$ ) is shown at a qualitative level. A widely used parameter  $\gamma H$  is applied here, which reflects the initial geostatic vertical pressure in the virgin massif:  $\gamma$  – weight-average unit specific gravity of rocks over the depth  $H$  of the protecting pillar location. These rock pressure anomalies are shown in the bottom of the seam  $c_6$  in order to simplify the visualization, but they also have a mirror reflection in the roof of the seam.

In general, the rock pressure anomalies development will be assessed beginning with the roof of the mined seam  $c_6$ . Its immediate roof is represented by argillite with an average thickness of about 2.4 m, which is characterized by the geological mine service in the range from rather unstable to very unstable, prone to collapse. There are several reasons for this: the argillite structure is laminal with weakened coherence between the layers, and the mica admixture shows signs of a “friable” roof; there is fracturing at the level of 6–8 fr./m; argillite occurs between two water-flooded lithotypes (seam  $c_6$  and sandstone), which reduces its average compressive resistance to  $\sigma_{comp} = 4.5$  MPa. The mentioned reasons suggest the argillite collapse straight behind the fencing of the powered support sections without formation of any extended rock cantilevers. Consequently, the argillite in the immediate roof is not able to create a significant concentration of vertical stresses  $\sigma_y$  and, most likely, the unloading zone will not propagate for a considerable distance towards the roof and bottom of the seam  $c_6$ .

The first rock layer of the main roof is represented by sandstone with a thickness of 0.9–1.2 m; its compressive resistance in a moisture-saturated state is  $\sigma_{comp} = 6.7$  MPa; fracturing intensity is 8–10 fr./m. All mentioned factors indicate an unstable sandstone state and its obligatory collapse without cantilevers hanging (behind the longwall face) for any significant distance. Therefore, the bearing pressure zone ahead of the stope face will be characterized by moderate stress concentrations with their restricted development ahead of the longwall face; behind it, collapsing sandstone creates, being weakened, a bearing to the overlying thick argillite, which leads to a reduced level of unloading and a moderate height (depth) of this zone propagation.

The second layer of the main roof is represented by argillite with thickness of up to 6.8 m. Despite the occurrence of

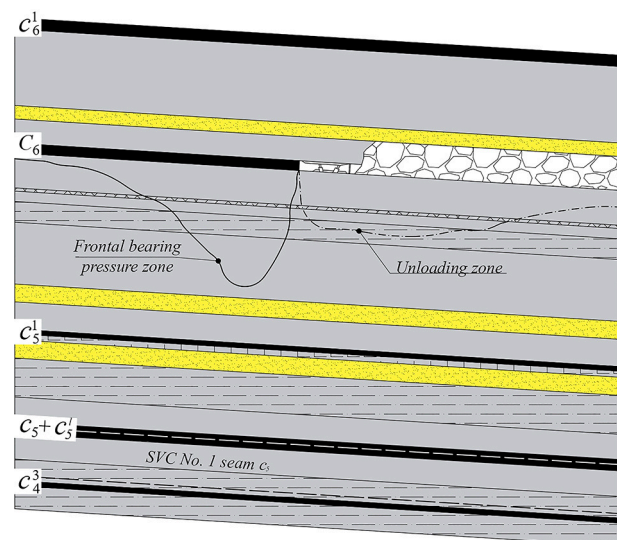


Fig. 2. Prediction scheme of the rock pressure anomalies development when mining the protecting pillar of the seam  $c_6$ : — frontal bearing pressure zone; - - - unloading zone behind the longwall face

argillite between two water-flooded lithotypes (below it – sandstone, above it – seam  $c_6^1$ ) and due to its thickness, it is exposed to local moisture saturation only in areas of contact with water-flooded lithotypes. Therefore, the mine surveying service characterizes basic state of argillite as naturally moist, in which most of its thickness has an average compressive resistance of  $\sigma_{compr} = 20.6$  MPa. On the other hand, the laminal and micaceous argillite structure, as well as the level of its fracturing of 6–8 fr./m does not, in our opinion, contribute to the formation of rock blocks with significant dimensions. Then, the zone of hinged-block displacement will be composed of relatively small rock partings with a limited length of the rock cantilever overhang over the mined-out space. This makes it possible to predict a considerable moderate stress concentration and dimensions of the frontal bearing pressure zone. Given the small depth of mining (at an average of 180 m), we consider that the zone of hinged-block displacement, as well as the entire area of active shifts of the coal-overlying formation, will propagate into the main roof to the seam  $c_6^1$  and in total will be of 10.5–11.2 m in height. At the same time, an increased deformability of rocks in this area leads to insignificant stress concentrations in the zone of frontal bearing pressure and a reduced degree of unloading in the area of mined-out space (Fig. 3).

Thus, the outlined concepts provide the basis for predicting a moderate development of the zones of frontal bearing pressure and unloading in the bottom of the seam  $c_6$  (Fig. 2); further on, the state of each adjacent lithotype will be studied in more detail.

The immediate bottom of the water-flooded coal seam  $c_6$  is represented by argillite with a thickness of 3.5 m, mainly of a laminal structure, which is swelled in water for several hours and intensively heaved according to the geological prediction data. Even in a naturally moist state, it has a very low compressive resistance of  $\sigma_{compr} = 11.4$  MPa, and when water saturated –  $\sigma_{compr} = 3.6$  MPa. The underlying argillite layer with a thickness of up to 0.8–0.9 m, separated by a coal interlayer with a thickness of up to 0.2 m, has similar properties. The total thickness of adjacent bottom is about 4.5–4.7 m; its very low strength properties, especially in the water-saturated state, make it possible to suggest the active weakening of rocks under the influence of bearing pressure and acquisition of the properties of easily deformable medium. Such a state of both argillite layers leads to a damping effect development, which contributes to an intensive decrease in both the stresses concentration value and the area of the frontal bearing pressure zone propagation; such a visco-plastic medium very actively “absorbs” any rock pressure anomalies. Therefore, it is possible to predict a significant restriction of the frontal bearing pressure propagation both towards the bottom of the seam  $c_6$  and towards its roof.

Below, there is a siltstone layer (mainly of 2.0 m thickness), which is also characterized by low compressive resistance: in the naturally moist state  $\sigma_{compr} = 13.2$  MPa, and with account of stratification and fracturing (8–10 fr./m), its damping properties make a certain contribution to restricting the height (depth) of frontal bearing pressure zone propagation.

An argillite layer with a thickness of 5.8–6.0 m is located under siltstone. It also belongs to the category of very soft rocks – it has a low compressive resistance ( $\sigma_{compr} = 12.9$  MPa) in a naturally moist state and is quite easily deformable. In our opinion, due to its thickness, argillite finally “dampens” the frontal bearing pressure zone, which does not propagate deeper towards the seam  $c_5 + c_5^1$ .

The clearly observed damping properties of lithotypes in the bottom rocks of the seam  $c_6$  for a very significant total thickness make it possible to predict a restricted propagation of the unloading zone.

In general, according to the analysis results of the composition and mechanical properties of lithotypes, a conclusion has been made about the relatively favourable conditions for mining the protecting pillar of the seam  $c_6$ :

- the frontal bearing pressure zone ahead of the longwall face has a restricted propagation with predominantly reduced stress concentrations. This makes it possible to predict a moderate load on the sections of coal extracting complex and the support of extraction mine workings adjacent to the longwall face;

- the unloading zone behind the longwall face does not propagate for significant distances towards the roof and the bottom of the seam  $c_6$  due to the property of soft rocks free-collapsing in the immediate roof and, thereby, creating an active bearing to lowering the main roof; therefore, in case of necessity to maintain extraction mine workings behind the longwall face, a moderate development of rock pressure manifestations towards the bottom should be expected.

To confirm the preliminary conclusions, a computational experiment was performed to calculate the stress-strain state (SSS) of the rock massif, enclosing the protecting pillar of the seam  $c_6$ . A widely tested finite element method was used as a calculation technique.

The geomechanical model of the studied object was constructed in compliance with existing recommendations [10] and using the modelling experience [11] for the laminal massif conditions of the Western Donbas soft rocks.

The geometrical model dimensions were substantiated on the basis of the following considerations (Fig. 4). Model height (vertical coordinate  $Y$ ) is selected from the damping condition of the SSS components perturbations caused by stope works at the upper and lower boundaries. Here, the stresses components fluctuations are reduced to the level of 5–10 % of the value characterizing the initial state of the virgin massif; such a

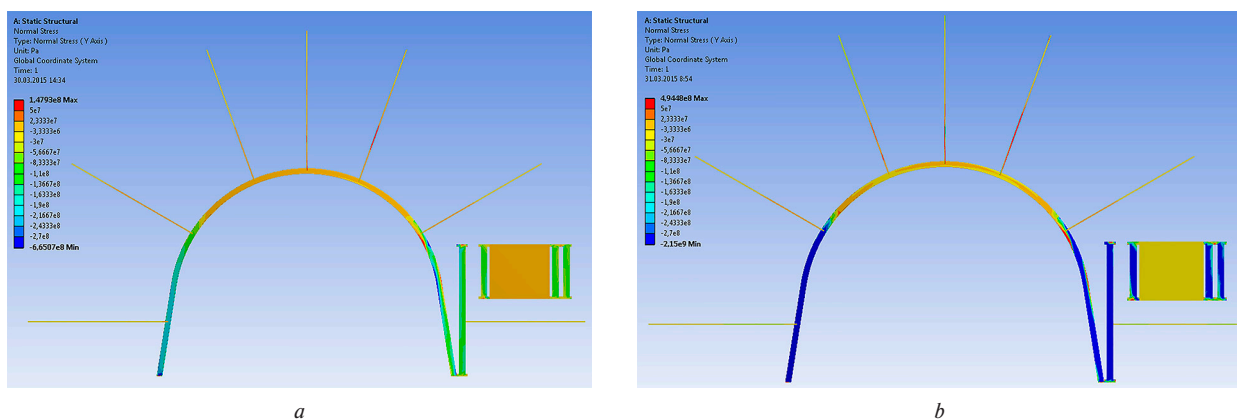


Fig. 3. Example of the vertical stresses  $\sigma_y$  distribution in fastening and security systems depending on the roof rocks structure: a – predominantly thick-bedded; b – predominantly thin-bedded

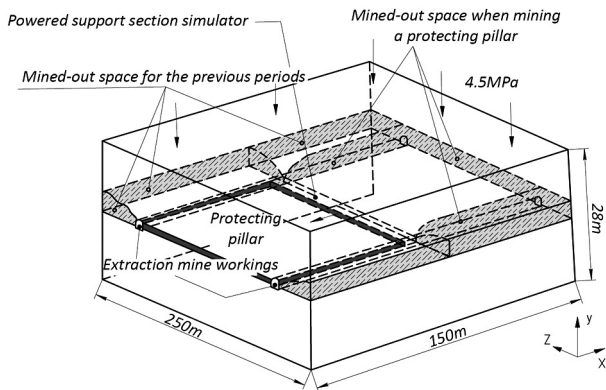


Fig. 4. Geomechanical model of mining the protecting pillar of the seam  $c_6$

state, for example, for vertical stresses  $\sigma_y$  is determined by the value of  $\gamma H$ . According to a preliminary assessment of the height (depth) of the rock pressure anomaly propagation towards the roof and bottom of the seam  $c_6$ , the model height  $Y = 28$  m is quite sufficient.

The model length in the coordinate  $X$  parallel to the longitudinal axes of the extraction mine workings and to the protecting pillar length is determined by the following conditions: to the rise of the seam  $c_6$  ahead of the longwall face, the frontal bearing pressure zone should disappear at the lateral boundary of the model; to the dip of the seam behind the longwall face, the unloading zone propagation should be stabilized towards the roof and bottom of the seam  $c_6$  at the opposite lateral boundary of the model. Based on mine instrumental observations and numerous computational experiments for the Western Donbas conditions, the total model length was adopted (with some safety factor) to the rise of the seam  $c_6$   $X = 150$  m.

According to the model width (coordinate  $Z$  along the strike of the seam  $c_6$ ), which is in parallel to the length of the longwall face, it is necessary to represent the following components: the extraction site width, two mine workings connected with longwall face and two areas of mined-out space adjacent from both sides to the protecting pillar of the seam  $c_6$ . In these areas, during previous periods of stope works operation, certain stress relaxation and collapsed rocks consolidation occurred. As a result, the influence intensity of the lateral bearing pressure zones decreased, and the residual rock pressure unevenness in the borders of the mined-out space acts within the limited area (along the coordinate  $Z$ ), which is adjacent to extraction mine workings. The width of these areas according to studies [12] for the Western Donbas conditions does not exceed 15–25 m. If to summarize the dimensions of all components with a certain margin, the model width is taken to be  $Z = 250$  m.

The mechanical characteristics of lithotypes that compose the model were chosen according to the Geological Survey data of mines, research of the Institute of Geotechnical Mechanics named by N. Poljakov of the NAS of Ukraine and works [2] on studying the physical-mechanical properties of the Western Donbas rocks. The influence of factors (stratification, fracturing, moisture saturation and rheology) weakening the rock was taken into account based on the methodology [13]. The mechanical properties of collapsed and consolidated rocks in the mined-out space were determined on the basis of research [14].

The model borderline conditions were specified on its surfaces in accordance with generally accepted principles for calculating the SSS of geomechanical objects using the finite element method. The geostatic pressure ( $\sigma_y = \gamma H = 4.5$  MPa) of the virgin massif acts on the upper surface at a depth of  $H = 180$  m. At the lower model boundary, the condition of a “rigid base” was used. The condition “symmetry” was applied

on all lateral surfaces, which reflects the rock massif effect beyond the model boundaries. It should also be noted that to eliminate some SSS distortion near the model surfaces (under the influence of borderline conditions), one extreme rock layer of argillite with a thickness of 10 m each was added in the roof and bottom. These extreme layers serve to compensate the possible frontier distortions of the SSS massif, and with its further analysis, they are excluded from consideration.

The final stage of the geomechanical model substantiation is reflecting the internal forces created by the reaction of the mechanized support of the stope complex and the support of the extraction mine workings. The experience of modelling the repulse of the powered support section to the rock massif, surrounding the longwall face, has substantiated a technological technique simple enough for conducting a computational experiment. This technique enables the simulator to reflect the reaction in the form of a rectangular prism with the dimensions of the powered support as a whole in both transverse and longitudinal sections of the longwall face [15]. The mechanical simulator properties are specified in accordance with the type of powered support in compliance with its technical characteristics: the maximum value of repulse (load-bearing capacity), the sliding ability of hydraulic prop stays of the sections, estimated yield limit of steel of its roofing. At the same time, the real deformation-strength characteristic of the powered support operation is reflected at the minimum costs of a computational resource. As for an error, as a result of such idealization, modelling of the real KD-90 powered support structure, which is widely used in the Western Donbas, showed moderate differences in the stresses components distribution only in the rocks of the immediate roof and bottom to a height (depth) of 0.8–1.5 m. In more remote areas of the massif, the error does not exceed 1–4 %.

In regard to the reaction of extraction mine workings support, it is not modelled at all for the following reason. The traditional structures reaction of frame supports is at least by 1–1.5 orders of magnitude lower than the value of the stress components in the rock massif. The works [16] indicate the insignificant effects of the support reaction on the SSS of even an adjacent massif with the exception of border rocks at a distance of 1.0–1.5 m. In addition, the lack of support reaction is added to a certain safety factor for predicting the stability of the studied massif [17].

The substantiation of the above assumptions and idealization against the background of its small error allows, as practical experience shows [18], ensuring the stability of the SSS calculation procedure, especially for such large-scale objects as the studied geomechanical system.

The developed geomechanical model was tested for consistency with existing concepts about the processes of coal-bearing massif displacement when conducting stope works [19]. Positive test results provided the basis to conduct a full-fledged computational experiment.

**Problem solving and analysis of the results.** Within the framework of a substantiated geomechanical model for mining the protecting pillar of the seam  $c_6$ , a computational experiment made it possible to determine the SSS of the laminal massif of soft rocks; through its analysis, a number of peculiarities of the vertical  $\sigma_y$ , horizontal  $\sigma_x$ , and stresses intensity  $\sigma$  components distribution has been determined; in such a sequence, the analysis results are presented with the use of indicators  $K_y$ ,  $K_x$ ,  $K_z$ , and  $K_\sigma$ , reflecting the value of the corresponding components with respect to the initial virgin massif state.

On the curve of vertical stresses  $\sigma_y$  (Fig. 5) in the roof of the seam  $c_6$ , the frontal bearing pressure zone is clearly observed ahead of the longwall face, when mining the protecting pillar. The following parameters of the frontal bearing pressure zone were determined. A very weak influence of the stope face (concentration criterion  $K_y$  of 1.1–1.3 level) can be observed at a height (from the seam  $c_6$ ) to 18–20 m, affecting thick siltstone.

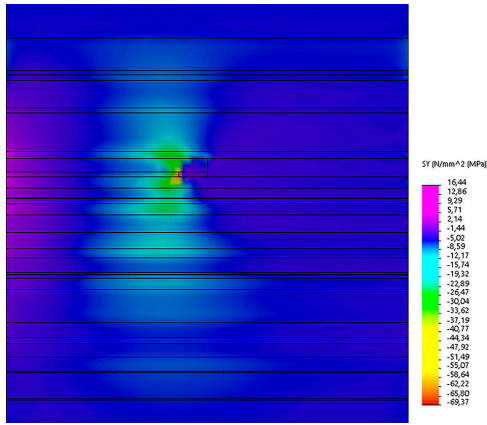


Fig. 5. Curves of the vertical stresses  $\sigma_y$  in the coal-bearing massif

Its calculated compressive resistance is many times greater than the acting stresses  $\sigma_y$ , and, by this factor, siltstone retains continuity over its entire thickness. When approaching to the seam  $c_6$ , the vertical stress concentration increases and at the height of the seam  $c_6^1$  occurrence it is already  $K_y = 1.9\text{--}2.7$ , which in absolute units is up to 12 MPa. Such a value of compressive stresses  $\sigma_y$  is significantly lower than the calculated compressive resistance of coal (by 2.56 times) and argillite (by 1.72 times) occurring in the roof of the seam  $c_6^1$ . It can be concluded that according to the factor of the vertical stresses  $\sigma_y$  action, the rocks in the roof of the seam  $c_6^1$  and the seam itself retain continuity.

A different pattern is observed in the bottom rocks of the seam  $c_6^1$ , up to the seam  $c_6$ , which is being mined; this parting with a thickness of 10.4 m is significantly weakened by water-flooded lithotypes, the compressive resistance of which becomes many times less than the acting concentrations of  $\sigma_y$ .

Thus, in the argillite of the seam  $c_6^1$  bottom, the compressive stresses  $\sigma_y$  act in the main range of 9–14 MPa, and its compressive resistance in the water-saturated state is  $\sigma_{compr} = 3.1$  MPa according to the data of mining-and-geological prediction. In the lower part of the argillite thickness,  $\sigma_y$  increases to values of 17–23 MPa, and it is in contact with water-flooded sandstone and, most likely, is exposed to moisture saturation. This area of argillite propagates in height up to 2.5–2.8 m, and to the rise – up to 8–9 m and is definitely exposed to weakening with loss of stability. As a result, the stability of argillite throughout its thickness of 6.8 m is doubtful:

- in the upper part there is a moisture saturation from the seam  $c_6^1$  and the compressive resistance of argillite becomes by 2.9–4.5 times less than the compressive stresses  $\sigma_y$  acting here;
- in the middle part of the argillite thickness, the influence of moisture saturation is weakened, but  $\sigma_y$  grows, approaching the value  $\sigma_{compr}$  in a naturally moist state;
- the previously mentioned lower part of the argillite thickness is exposed to moisture saturation from the sandstone, and the  $\sigma_y$  acting here are by 5.5–7.4 times higher than the compressive resistance.

Thus, the collapse of weakened argillite behind the stope face is quite predictable.

The underlying water-flooded sandstone has a small thickness of 1.2 m, but the main factor of its instability is a low compressive resistance ( $\sigma_{compr} = 6.7$  MPa) in a water-saturated state. At the same time, compressive stresses  $\sigma_y = 19\text{--}27$  MPa act in sandstone, many times exceeding  $\sigma_{compr}$  and leading to its destruction.

Argillite with a thickness of 2.4 m is located under the water-flooded sandstone, which represents the immediate roof of the water-flooded coal seam  $c_6$ . Obviously, argillite is exposed to moisture saturation, in which its compressive resistance decreases to  $\sigma_{compr} = 3.1$  MPa. The vertical stresses  $\sigma_y$ , acting in

argillite near the stope face (to the rise of the seam in the area of up to 4–5 m long) reach 23–48 MPa, which unambiguously weakens the immediate roof (ratio  $\sigma_y/\sigma_{compr} \approx 7.4\text{--}15.5$ ) even before the longwall face approach.

In the coal seam  $c_6$  being mined, on its border (0.7–1.2 m wide), the highest concentrations of  $\sigma_y = 50\text{--}60$  MPa are formed, which are by 1.63 times higher than the coal compressive resistance ( $\sigma_{compr} = 30.7$  MPa) and create the so-called zone of its pressing-out.

In general, the following conclusions can be made about the state of the roof rocks in the seam  $c_6$  under the action of vertical stresses  $\sigma_y$  in the zone of frontal bearing pressure ahead of the longwall face:

- the roof rocks weakening is predicted up to a coal seam  $c_6^1$  to a height of 10.4 m; in this case the vertical pressure from the unstable rocks weight will be approximately 250 kPa;
- the load-bearing capacity of sections of the applied powered supports is approximately by 2 times higher than the predicted vertical rock pressure, which could ensure trouble-free longwall face operation;
- very unstable water-flooded and weakened immediate roof of the seam  $c_6$  does not allow any significant areas of outcropping and requires the powered support sections to be closed immediately after the shearing machine passage;
- for the above reason, collapse of the immediate roof rocks will occur near the section fencing and “heave” the overlying layers of the main roof due to the sufficient thickness (2.4 m) of argillite in the immediate roof; due to this process the main roof layers rest upon the collapsed rock straight behind the longwall face, which leads to a decrease in the load on the sections of the powered support;
- the phenomenon of intense pressing-out of coal in the stope face contributes to a sharp decrease in the power intensity of its destruction, which allows the shearing machine to operate with higher speeds of supply; the latter circumstance favourably affects the reduction of vertical rock pressure on the powered support.

In the border parts of the protecting pillar, adjacent to the extraction mine workings, the concentration criteria  $K_y$ , the frontal bearing pressure zone are slightly reduced, which is conditioned by the repulse of consolidated rocks of the mined-out space for the previous periods of stope works. The most significant influence of about 25–40 % was recorded for increased concentration  $K_y$  levels in the rock layers adjacent to the mine workings. The revealed peculiarity of  $\sigma_y$  distribution is favourable in terms of reducing the load on mine workings support and increasing, thereby, their stability.

The field of horizontal stress  $\sigma_x$  distribution indicates the formation of a concentration  $K_x = 2.6\text{--}5.7$  in the immediate roof of the seam  $c_6$ . This concentration in the absolute measurement is not so significant (5–11 MPa), but destructive, if compared with a very low compressive resistance  $\sigma_{compr} = 3.1$  MPa of the water-saturated argillite. This area propagates over the entire argillite thickness, and to the rise it has an extent of up to 20–23 m, including straight over the entire width of the longwall face. Thus, according to the factor of horizontal stress  $\sigma_x$  action, the total destruction of argillite in the immediate roof is predicted, which, due to its thickness (2.4 m), “heaves” the overlying layers of the main roof straight behind the fencing of the powered support section; the repulse reaction of the collapsed rocks reduces the displacement activity of the coal-overlying formation and the load on the longwall face support.

The nearest lithotype of the main roof – water-flooded sandstone – is also characterized by low compressive resistance of  $\sigma_{compr} = 6.7$  MPa. For comparison, for the most part of the concentrations  $\sigma_x$  area extent (up to 40–48 m), their level of 6–13 MPa causes either the limiting state of sandstone or its weakening. Directly above the longwall face and behind the support section, the concentrations act  $K_x = 13\text{--}18$  of compressive stresses  $\sigma_x = 25\text{--}35$  MPa at a distance of 2 m. They

definitely destroy sandstone, supplementing (in height) the zone of uncontrolled collapse and enhancing repulse reaction against the overlying main roof layers.

Above the water-flooded sandstone, a thick argillite occurs, which is in contact with the water-flooded coal seam  $c_6^1$ . Obviously, not all argillite experiences moisture saturation due to its thickness of 6.8 m, but its parts that are in contact (above and below) with water-flooded lithotypes will surely lose compressive resistance to a value of  $\sigma_{\text{compr}} = 3.1$  MPa. At the same time, two areas with increased  $\sigma_z = 4-6$  MPa are formed along the entire argillite thickness: the first area with a width (to the rise) up to 9–10 m is located at a distance of 8–9 m from the stope face; the second area with a width of 17–20 m is located above the longwall face and in the mined-out space. Argillite in the noted areas is exposed to partial weakening and some part of it is involved in the formation of the load on the powered support.

The overlying lithotypes, beginning with the seam  $c_6^1$ , are in a stable state due to the compressive resistance which significantly exceeds the value of acting stresses  $\sigma_x$ .

Thus, according to the criterion of influence of the horizontal stresses, it can be stated that the weight of stable rocks above the longwall face is less than half of the powered support load-bearing capacity. This is facilitated by the formation straight behind the sections fencing of a sufficiently thick zone of uncontrolled collapse, which creates an active bearing to lowering the overlying layers of the main roof.

In the coal seam  $c_6$  being mined, the maximum concentrations of  $\sigma_x = 20-30$  MPa ( $K_x = 10.4-15.5$ ) are concentrated ahead of the stope face at a distance of up to 3.0–3.5 m. They do not exceed the compressive resistance of coal, even in a water-flooded state, which indicates the stability of the seam  $c_6$  by the factor of  $\sigma_x$  action.

In the rocks of the seam  $c_6$  bottom, weakening from the action of horizontal stresses  $\sigma_x$  propagates to a depth of 6.0–6.5 m. As noted earlier, this area develops a “damping effect”, which restricts the value and area of concentration  $\sigma_x$  propagation in the frontal bearing pressure zone. This is positive in addition to its manifestations in the form of a load on the sections of powered support in the longwall face.

A similar positive effect is observed in the areas of massif surrounding the extraction mine workings. But here the influence of the mined-out space of collapsed and consolidated rocks after the previous periods of stope extraction of the seam  $c_6$  is also added. This influence of the “yieldable environment” is totalized with the previous “damping effect”, as a result of which the maxima  $\sigma_x$  in the adjacent rock massif are reduced by 1.3–2.1 times for various levels of horizontal stresses concentration. Therefore, it is possible to predict a decrease in the intensity of rock pressure manifestations in the extraction mine workings based on the factor of the component  $\sigma_x$  action.

Another horizontal component, representing stresses  $\sigma_z$ , is more interesting near the extraction mine workings, since across the main width of the protecting pillar it varies in a rather limited range without formation of significant  $\sigma_z$  perturbations.

Around the extraction mine workings in their roof a zone of moderate unloading is formed, while in the sides – an area of increased rock pressure.

In the unloading zone, the lithotype bending is directed into the mine workings cavity. Therefore, in the central part of an arch in each adjacent rock layer, an area of reduced (up to  $\sigma_z = 0$ ) stresses is formed in the lower (by thickness) rock bands, and in the upper rock bands – a small concentration of compressive stresses  $\sigma_z$  of  $K_z = 1.5-3.5$  level. In the lateral arch parts, the areas of unloading and  $\sigma_z$  concentrations interchange within the lithotype thickness. Weakening of rocks in the mine working arch under the action of  $\sigma_z$  can be predicted only in the immediate roof of the seam  $c_6$ , represented by very soft argillite. If we consider the upper ripping of the extraction mine workings, the height of the unstable rocks arch does not

exceed 1.6–2.0 m, and the load from their weight is 200–250 kN/m; this value approximately corresponds to the working resistance of the frame support made of the special profile SCP-22(27), being set along the mine working with a step of 1.0 m. Therefore, the vertical load on the support can be expected of quite a moderate value.

In the sides of the extraction mine workings of the increased rock pressure zone, they have an asymmetric (with respect to the vertical axis) pattern of  $\sigma_z$  distribution. Ahead of the longwall face in the frontal bearing pressure zone, the concentration of  $\sigma_z$  is higher from the side of the coal pillar, and behind the longwall face – from the side of the mined-out space after the previous periods of the stope extraction of the seam  $c_6$ . But, in both of the noted areas, weakening of the side rocks is quite limited: in the sides of mine workings – 1.2–2.7 m, towards the roof – up to 2.4 m, towards the bottom – up to 3.5 m. It should be taken into account that the weakened rocks displacements in the sides partially “absorb” the collapsed and consolidated rocks themselves. This allows suggesting the development of a moderate lateral load on the frame support of the extraction mine workings.

In general, two conclusions can be drawn by the factor of horizontal stresses  $\sigma_z$  action:

- the component  $\sigma_z$  does not induce the development of roof rocks weakening in the longwall face above the seam  $c_6^1$ , thus, the load on the powered support still does not exceed 50 % of its load-bearing capacity;
- around the extraction mine workings, a moderate differently vectored rock pressure is predicted at the level of working resistance of traditional frame support structures.

In the final part of the SSS analysis of the soft rocks laminal massif, the peculiarities of the stresses intensity  $\sigma$  distribution field are studied; it should be recalled that this parameter is the most informative when assessing the rock state: prelimiting or superlimiting.

The upper rock layers of the studied coal-bearing stratum, representing the roof of the seam  $c_6^1$ , are characterized by a moderate distribution of  $\sigma$  in the main interval of 3–10 MPa. On this background, a thick siltstone stands out, in the upper part of which the stresses intensity increases to  $\sigma = 14-18$  MPa. However, the compressive resistance of siltstone  $\sigma_{\text{compr}} = 25.9$  MPa in the naturally moist state exceeds the level of  $\sigma$  concentrations, and, therefore, it is necessary to predict the maintenance of its continuity throughout this lithotype thickness.

The rest of lithotypes in the roof of the seam  $c_6^1$  and the seam itself are influenced by  $\sigma$ , the level of which is many times lower than the corresponding values of compressive resistance of these rocks. This leads to the conclusion about the stability of rocks in the roof, including the seam  $c_6^1$ .

Thick argillite occurs in the bottom of the seam  $c_6^1$ , which, when being water-saturated, sharply reduces its compressive resistance to  $\sigma_{\text{compr}} = 3.1$  MPa. This process is enhanced by the location of argillite above the water-flooded sandstone and under a water-flooded seam  $c_6^1$ . Given the significant argillite thickness of 6.8 m, it is possible that not all of its thickness will be saturated with moisture. Although, we should take into account the average level of fracturing, which intensifies the penetration of mine water into the middle part of the argillite thickness. Therefore, with a high degree of probability and with some safety factor of prediction, it is expedient to consider the strength characteristic  $\sigma_{\text{compr}} = 3.1$  MPa of water-saturated argillite.

Based on the above considerations, the field of the stress intensity  $\sigma$  distribution in the argillite of the seam  $c_6^1$  bottom and the main roof of the mined seam  $c_6$  was analysed. In the upper part of the argillite thickness (about 2.5–2.8 m),  $\sigma = 10-13$  MPa act, which propagate to the rise at a distance of up to 8–9 m. The indicator  $\sigma/\sigma_{\text{compr}} = 3.2-4.2$  clearly evidences the process of weakening in the upper part of the argillite

thickness. In its lower part, the concentration  $\sigma$  increases to the level of 15–33 MPa and, thereby, contributes to the argillite destruction. Thus, a significant rock volume in the main roof of the seam  $c_6$ , represented by argillite, is in an unstable state over the entire thickness and up to 8–10 m to the rise.

The indicated unstable rocks volume (in the frontal bearing pressure zone) induces weakening of the underlying lithotypes: of water-flooded sandstone in the main roof and water-saturated argillite in the immediate roof of the seam  $c_6$ . This process is promoted by the following circumstances:

- in water-flooded sandstone with a compressive resistance of  $\sigma_{\text{compr}} = 6.7$  MPa to the rise at a distance of 27–29 m,  $\sigma = 9$ –15 MPa act; across the width of 18–20 m,  $\sigma = 17$ –33 MPa are propagated, and over an area with a length of 3.0–3.5 m, the stresses intensity reaches a maximum of 35–40 MPa;

- in the water-saturated argillite of the immediate roof with a compressive resistance of  $\sigma_{\text{compr}} = 3.1$  MPa, the area of breaking stresses  $\sigma$  is reduced, occupying to the rise the width of: up to 6.5–7.0 m for  $\sigma = 9$ –15 MPa; up to 5–6 m for  $\sigma = 17$ –33 MPa and up to 1.0–1.5 m for  $\sigma = 35$ –45 MPa.

The data presented indicate a definite collapse (in the frontal bearing pressure zone) of sandstone in the main roof and argillite in the immediate roof. In such a way, the total thickness of unstable rocks in the roof of the seam  $c_6$  is 10.4 m, which forms a vertical load of about 230–250 kPa. The powered support of the stope face has a maximum resistive reaction exceeding approximately twice the specified vertical rock pressure. Thus, with an appropriate performance of technological operations there is no danger to set the stope complex onto a “rigid base”.

The second conclusion concerns the formation of uncontrolled collapse zone straight behind the fencing of the powered support sections. It is proved by the fact that in the argillite of the immediate roof, the indicator  $\sigma/\sigma_{\text{compr}}$  reaches 10.6–14.5; in the sandstone of the main roof it is 4.9–6.0; in the overlying thick argillite of the main roof, it is 3.2–10.6. With such ratios of acting  $\sigma$  and compressive resistance  $\sigma_{\text{compr}}$  of lithotypes, any extended rock cantilevers are not formed. Moreover, the process of uncontrolled collapse begins straight near the fencing of the powered support section and develops to a considerable height towards the roof. In this case, the collapsed rocks immediately create reliable bearing to the overlying massif of coal-overlying formation; for example, at a distance of 0.5–1.0 m behind the longwall face, the value  $\sigma$  is stabilized at the level of 80–90 % of the state of the virgin massif. Consequently, the practical absence of significant rock cantilevers reduces the load on the powered support, and with the rhythmic advancing the stope face, the reliable operation of the support will be ensured.

The third conclusion is based on a study on the state of the coal seam  $c_6$  border part. Despite its significant hardness, even in a water-saturated state ( $\sigma_{\text{compr}} = 30.7$  MPa), the border part of the seam with a width of 0.7–1.2 m experiences weakening  $\sigma = 35$ –45 MPa. This leads to active pressing-out of coal, a decrease in the power intensity of its destruction and the shearing machine operation with higher speeds of supply.

In the area of extraction mine workings location, the following peculiarities of the stress intensity  $\sigma$  distribution are observed. An unloading zone  $\sigma$  with relatively limited dimensions is formed above mine workings – its height does not exceed 1.5–2.0 m with an unloading level of  $K_\sigma = 0.3$ –0.7. This fact, in our opinion, is conditioned by the influence of low deformation characteristics of collapsed and consolidated rocks in the mined-out space after the previous periods of stope works in the seam  $c_6$ . Such a volume of unloaded rocks in the roof in case of loss of its stability is able to create a vertical load onto a support of moderate size, which does not pose a danger to the stability of extraction mine workings. In their sides, the parameters of  $\sigma$  distribution vary depending on the position of the mine working site relative to the stope face.

Ahead of the longwall face in the frontal bearing pressure zone, significant concentrations of  $\sigma$  act from the side of the coal pillar; however, due to the repulse reaction of collapsed and consolidated lateral rocks from the opposite side of mine working, the main level of these concentrations ( $K_\sigma = 2.9$ –5.6) is, even so, lower than in the central part of the protecting pillar width. Here, rock destruction is predicted, mainly in the immediate roof, with partial weakening of the sandstone in the main roof. The depth of destructive  $\sigma$ , penetrating into massif varies over a wide range: from 1.3–2.0 m in the beginning of the bearing pressure zone to 3.0–4.5 m near the stope face. This is the most dangerous (in terms of formation of the oblique load on the support) mine working area, which is temporarily strengthened by traditional means of fastening, since after the longwall face passage in the collapsed rocks of the newly formed mined-out space, an unloading zone ( $K_\sigma < 1$ ) is set with reduced lateral and oblique pressure on the frame support. This reduction of load is mainly caused by the action of two factors: firstly, the soft rocks of the adjacent roof during their collapse immediately straight behind the longwall face, create a bearing to the more distant layers of the main roof, receiving the most part of bearing pressure; secondly, collapsed and consolidated rocks from the opposite side of mine working also actively resist to the lowering of the overlying rock layers in the main roof. As a result, after the longwall face passage, the extraction mine workings are surrounded by an easily deformable, weakened massif, which is not able to create any significant concentrations of  $\sigma$ . Here we face with a geomechanical situation close to the conditions for maintaining mine workings in collapsed rocks, and studies on such conditions [20] prove a significant increase in the stability of mine workings for various purposes (Fig. 6).

From the above information, the fourth conclusion is drawn about the satisfactory state of extraction mine workings (with the temporary use of traditional prop stays for the strengthening support) in case of arising necessity for their further exploitation as part of the underground mine complex.

**Practical value** of the research performed has several directions of implementation in the conditions of soft rocks laminal massif occurrence:

- substantiating the engineering decisions expediency for mining the protecting pillars in order to increase the completeness of the coal reserves extraction while reducing costs of its output;

- increasing the safety of stope works by reducing rock pressure on the powered support of the coal extracting complex and the fastening structures of extraction mine workings adjacent to the longwall face (Fig. 7);

- providing resource-saving maintenance of extraction mine workings for their further use in the technical complex of the mine (Fig. 8).

**Conclusions.** Using a specific example of mining the protecting pillar of the seam  $c_6$ , the development of a number of favourable geomechanical factors is predicted that ensure



Fig. 6. Fragment of a fabricated drift



Fig. 7. State of the powered support of the coal extracting complex



Fig. 8. State of the extraction mine working in M. I. Stashkova Mine (Western Donbas)

trouble-free coal extraction in compliance with the relevant technological regulations:

- vertical rock pressure is approximately by 2 times lower than the load-bearing capacity of the powered support section, which excludes the possibility to set it on a “rigid base”;
- the collapse of a very unstable immediate roof with sufficient thickness creates an active bearing to the main roof layers straight behind the section fencing and reduces the load on the powered support;
- the maintenance of extraction mine workings at the border with the mined-out space of the previous periods of stope works has a positive effect on their stability due to combining the function of active resistance to rock pressure by collapsed and consolidated rocks with the function of “smoothing” the concentrations of SSS components caused by their increased deformability;
- extraction mine workings can successfully function while being maintained in the mined-out space for solving other mining-engineering tasks of the underground mine complex;
- the combination of mentioned favourable factors contributes to resource saving while increasing the completeness of the coal reserves extraction.

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### Особливості відпрацювання охоронного цілика в шаруватому масиві слабких порід

В. І. Бондаренко<sup>1</sup>, І. А. Ковалевська<sup>1</sup>, Г. А. Симанович<sup>1</sup>,  
М. В. Барабаш<sup>2</sup>, В. Г. Снінгур<sup>3</sup>

1 – Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна, e-mail: [v\\_domna@yahoo.com](mailto:v_domna@yahoo.com)

2 – ТОВ «ДТЕК Енерго», м. Київ, Україна

3 – ШУ «Імені Героїв Космосу» ПраЕ «ДТЕК Павлоградвугілля», м. Павлоград, Україна

**Мета.** Підвищення повноти виймання запасів вугілля із охоронних ціликів, що розташовані у шаруватому масиві слабких порід покрівлі й підшви для зниження втрат вугілля на шахтах і горизонтах, де гірничі роботи наближаються до свого завершення.

**Методика.** Створена геомеханічна модель дослідження відпрацювання охоронних ціликів в умовах впливу очисних робіт з урахуванням шаруватого масиву та реологічних процесів повзучості деформацій і релаксації напружень гірського масиву. Проведено чисельне моделювання та аналіз напружено-деформованого стану. Зроблено висновки щодо обґрунтування технічних рішень з відпрацювання охоронних ціликів.

**Результати.** Встановлені нові закономірності напружено-деформованого стану шаруватого гірського масиву у зоні впливу очисних робіт. Створена геомеханічна модель відпрацювання охоронних ціликів з урахуванням реологічних процесів у породах та обґрунтовані технологічні параметри видобутку вугілля із лав. Забезпечена можливість повторного використання виробок за рахунок упровадження ресурсозберігаючої кріпильної системи.

**Наукова новизна.** Встановлені закономірності переміщення зони фронтального опорного тиску попереду лави, що відпрацьовує охоронні цілики, коефіцієнт концентрації  $K_y = 1,1-1,3$  на висоті від вугільного пласта  $c_6$  до 18–20 м, зачіпаючий потужний алевроліт. Встановлено, що розрахунковий опір стисненню у 4,2 раза переважає величину діючих  $\sigma_y$ , і за цим фактором алевроліт зберігає цілісність по всій своїй потужності. Із наближенням до пласта  $c_6^1$  концентрація вертикальних напружень зростає та становить уже  $K_y = 1,9-2,7$ . Урахування та аналіз цих факторів дає підставу стверджувати, що покрівля пласта й сам пласт не руйнуються.

**Практична значимість.** Розроблені технологічні рішення з відпрацювання охоронних ціликів для підвищення повноти вилучення запасів вугілля з одночасним зниженням собівартості видобутку й підвищенням безпеки очисних робіт за рахунок зниження гірського тиску на механізоване кріплення.

**Ключові слова:** вугілля, гірський масив, охоронний цілик, напружено-деформований стан, навантаження, вилучення запасів

### Особенности отработки охранный целика в слоистом массиве слабых пород

В. И. Бондаренко<sup>1</sup>, И. А. Ковалевская<sup>1</sup>,  
Г. А. Симанович<sup>1</sup>, М. В. Барабаш<sup>2</sup>, В. Г. Снингур<sup>3</sup>

1 – Национальный технический университет «Днепро-ская политехника», г. Днепр, Украина, e-mail: [v\\_domna@yahoo.com](mailto:v_domna@yahoo.com)

2 – ООО «ДТЭК Энерго», г. Киев, Украина

3 – ШУ «Имени Героев Космоса» ЧАО «ДТЭК Павлоградуголь», г. Павлоград, Украина

**Цель.** Повышение полноты выемки запасов угля с охранных целиков, расположенных в слоистом массиве слабых пород кровли и почвы, для снижения потерь угля на шахтах и горизонтах, где горные работы близятся к своему завершению.

**Методика.** Создана геомеханическая модель исследования отработки охранных целиков в условиях влияния очистных работ с учетом слоистого массива и реологических процессов ползучести деформаций и релаксации напряжений горного массива. Проведено численное моделирование и анализ напруженно-деформированного состояния массива. Сделаны выводы по обоснованию технических решений по отработке охранных целиков.

**Результаты.** Установлены новые закономерности напруженно-деформированного состояния слоистого горного массива в зоне влияния очистных работ. Создана геомеханическая модель отработки охранных целиков с учетом реологических процессов в породах и обоснованы технологические параметры добычи угля из лав. Обеспечена возможность повторного использования виробок за счет внедрения ресурсосберегающей крепежной системы.

**Научная новизна.** Установлены закономерности перемещения зоны фронтального опорного давления впереди лавы, отработывающей охранные целики, коэффициент концентрации  $K_y = 1,1-1,3$  на высоте от угольного пласта  $c_6$  до 18–20 м, затрагивающей мощный алевролит. Установлено, что расчетное сопротивление сжатию в 4,2 раза превосходит величину действующих  $\sigma_y$ , и по этому фактору алевролит сохраняет целостность по всей своей мощности. С приближением к пласту  $c_6^1$  концентрация вертикальных напряжений растет и составляет уже  $K_y = 1,9-2,7$ . Учет и анализ этих факторов дает основание утверждать, что кровля пласта и сам пласт не разрушаются.

**Практическая значимость.** Разработаны технологические решения по отработке охранных целиков для повышения полноты извлечения запасов угля с одновременным снижением себестоимости добычи и повышением безопасности очистных работ за счет снижения горного давления на механизированную крепь.

**Ключевые слова:** уголь, горный массив, охранный целик, напруженно-деформированное состояние, нагрузка, извлечение запасов

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