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ASSESSMENT OF THE STATE OF THE ROCK MASS AROUND THE CROSSCUTS UNDER ADDITIONAL DEFORMATION DISTURBANCES

Purpose. Assessment of the level of disturbance of the stress state of the rock mass around the crosscut of the depth of 545 m when additional deformations occur during the mining of lower-lying coal pillars by southern longwalls of the k_5 layer and assessment of this impact on operational production in the mining-geological and mining-technical conditions of Krasnolymanska mine.

Methodology. Theoretical studies are based on the use of regulatory documents on the design of mining operations in coal mines and geomechanical models developed in accordance with the basic principles of solid mechanics, implemented in proven software products.

Findings. As a result of the research, it has been proven that the mining-geological and mining-technical conditions of the stressed-strained state of the rock mass around capital workings at a depth of 545 are not critical for their stability. The ability to mine coal pillars at lower depths has been substantiated, and a minimum distance limit between research objects has been established, below which the fastening must be strengthened to ensure the stability of the crosscuts.

Originality. For the first time, the stress-strain field in the rock mass around the basis workings has been studied as a result of the imbalance caused by previous mining during the excavation of underlying coal pillars under geological and technical conditions of Krasnolymanska mine based on geomechanical models. The regularity of the equivalent stress growth according to the Mohr-Coulomb criterion with a decrease in the distance between the research objects has been developed. Rational parameters of the technology for working out pillars are substantiated, under which the stress-strain state of the geomechanical system can be safely controlled.

Practical value. The possibility of increasing the productive coal reserves within the field of the mine Krasnolymanska due to the safe mining of pillars around the basis inclines on the underlying levels is justified.

Keywords: *capital crosscuts, coal pillars, capital slopes, stress-strain state, regulatory framework, geomechanical models*

Introduction. The global energy crisis has affected all types of fossil resources: gas, oil, coal. In today's conditions, there is relevance in nuclear energy. There is a trend in the world towards the construction of new nuclear power plants and units of existing ones. Mothballed coal mines and thermal power plants are reopening. The shortage of coal in Ukraine, which, in addition to crisis factors, has been largely caused by the war, which cut off most of the coal enterprises from the country, contributes to the search for new sites for its production in the mines of the Donbas, which have been operating for decades. At the same time, development depths are increasingly approaching 800–1000 meters, which contributes to an increase in catastrophic manifestations of rock pressure, sudden emissions of rock, coal and methane and a significant increase in the cost of mined coal.

Over time, the layers are mined, the depth of their development is constantly increasing, and engineers of coal enterprises are forced to look for additional opportunities to maintain its stable operation. At the same time, in the conditions of European integration, environmental requirements are a significant limiting factor.

One of these opportunities is the development of safety pillars of coal around capital workings. Millions of tons of coal are conserved in such elements of the development system. The problem is that as a result of pillar mining, the established equilibrium of the stress-strain state around the higher-lying capital workings is disrupted, which can lead to their destruction. This requires additional research to substantiate the possibilities of safe and effective mining of pillars around slopes.

Literature review. The review of recent scientific works showed that the problem of the effective use of mineral deposits, in particular coal, is dealt with by technologists, ecologists and economists [1, 2]. A coal mine as a natural resource contains, in addition to coal, water, methane, and subsoil heat [3]. This applies not only to operating mines, but also to those being closed in order to transfer them to another economic plane. This process is called Sinchro-mining [4, 5]. Much attention is paid to the use of coal mine methane, including from closed mines, water, and rock dumps [6, 7]. There are also known studies related to the use of rock mined during underground workings for their fastening, which made it possible in the mines of the Western Donbas to reduce the impact on the environment and reduce the cost of mined coal [8, 9]. A separate area of research is related to the discovery of new coal reserves in conditions of significant geological disturbances [10, 11].

Regarding the problems of mining coal pillars in mines whose operating life is approaching closure, there are few studies, and they were carried out at the end of last century, mainly with the aim of preserving nearby workings [12]. Scientific research in mines located in temporarily adjacent territories, as far as we know, is not carried out, which poses a threat from the point of view of environmental stability.

Unresolved issues of the problem. The problems of mining safety coal pillars around extended capital workings, such as slopes and bremsbergs (break incline), remain unresolved. The width of such security structures, depending on the thickness of the extracted layers, can reach fifty meters or more, with a length that can reach several kilometers.

They contain large reserves of coal, which is becoming especially in demand both in the context of the global energy crisis and military operations taking place on the territory of

Ukraine. The world price for this type of fossil fuel is constantly growing, which makes coal mining economically feasible. But the development of safety pillars can significantly disrupt the equilibrium stress-strain state that has developed over the years of previous operation of the coal mining enterprise.

Such careless technogenic influence can lead to catastrophic consequences, loss of life, and shutdown of the mine. Therefore, research related to the development and subsequent verification of models – graphical, geomechanical – is relevant, since it makes it possible to determine the parameters under which it is possible to effectively and safely work safety pillars around extended capital workings, and in the future will effectively affect the operation of the mine.

Research objective is to substantiate the possibility of safe mining of safety coal pillars around mine slopes and is achieved using standard methods adopted in surveying (the first stage of research), and modern methods of mechanics of solid deformed bodies, implemented in appropriate software products adapted for studying the stress-strain state of rock masses, significantly weakened by the system of underground workings developing in space and time (second stage of research).

Methodology. Methodologically, theoretical research consists of two parts. The first part is based on the use of regulatory documents regarding the procedure for designing mining operations in coal mines in conditions of undermined workings due to the extraction of coal reserves at depths lying below the objects under consideration. The second part consists of studying the stress-strain state that develops in time and space around capital workings as a result of mining the underlying pillars. The research is based on multi-stage geomechanical models developed in accordance with the basic principles of solid mechanics, which are implemented in proven software products such as Ansys.

Methods. The research to substantiate the stability of capital crosscuts when mining the underlying depths of safety pillars using the example of Krasnolymanska mine was methodically carried out in two stages. At the first stage, the research was carried out by analytical methods and was based on the use of government documents, taking into account regulatory methods for designing mining operations in coal mines, where most of the workings have been worked out and the extraction of coal reserves is carried out using safety pillars around underlying slopes.

The second stage of the study was carried out using a modern method on geomechanical models adapted to specific mining-geological and mining-technical conditions, which were developed in accordance with the structural and textural conditions of the rock mass and the basic principles of the mechanics of a solid deformed body and implemented in the Ansys software product [13]. The need for additional research is due to the fact that the regulatory documents on the basis of which the first stage research was carried out were developed for mining and geological conditions when workings in coal mines were located at shallower levels. Given that the depth of coal layer development has increased significantly over time, compliance with the outdated but still relevant regulatory framework requires additional verification using more modern methods.

The world-famous Ansys software package makes it possible to study the stress-strain state around holes in solids in general, including in rock masses around underground workings. Using the developed multi-stage geomechanical models, the evolution of the stress-strain state, concentrated around capital workings due to the gradual mining of underlying coal pillars, was studied. There are known similar studies in this direction in scientific teams in the USA, South Africa, Germany, Poland, China, and Kazakhstan [14, 15].

Characterization of the research object. Krasnolymanska mine, which was put into operation in 1958 with a working depth of 210 m and a design capacity of 1,200 tons per year at layers *l7* and *l3*, is critical from the point of view of mining coal reserves of enterprises.

Within the mine field, layers of mark Zh coal with a thickness of 1.2–3.0 meters are subject to development. The mine is one of the most mechanized and automated enterprises in the industry; it is dangerous due to the gas factor and the possibility of gas-dynamic manifestations of rock pressure, in particular sudden emissions of gas and coal [16, 17]. The analysis of data on coal reserves shows that in order to maintain sustainable production at the achieved level (2,500 thousand tons per year), timely reproduction of the working face line in promising layers m_4^2, l_3, k_5 is not enough.

This problem can be solved by mining pillars around capital slopes on the 740 m depth.

In order to obtain initial engineering-geological information, the mining-geological conditions and mining-technical situation around the safety pillars of slope of No. 1 "bis" coal layer k_5 were analyzed.

The structure and texture of the rock mass was taken from well No. 2965 on 10.01.20. The physical and mechanical properties and characteristics of the host rocks and coal are accepted as those indicated in the fore-cast/actual geological section of the southern crosscut on the depth of 545 m for 2020. The geometric parameters of the spatial location of the complex of underground workings to be studied were adopted on the basis of the current mining plan.

Determination of the expected vertical deformations of the massif in the bearing pressure zone (stage I). The determination of expected vertical deformations is carried out according to the method [18] based on the initial shear parameters given in the state standard [19]. Determination of the boundaries of zones of vertical deformations of the massif above the edge of the formation is carried out on vertical sections along the strike and cross-strike, depending on the location of the object for which the predicted values are determined. A diagram for determining the zone of expected vertical deformations is shown in Fig. 1.

The magnitude L_0 will amount to the following: at the top of the part of coal layer $L_0 = 720 \cdot \mathrm{ctg}\,75 = 193$ m; at the bottom of the part of coal layer $L_0 = 802 \cdot \mathrm{ctg}\,75 \cdot \cos 9 = 217$ m. According to [19], the value of the boundary angles for the Donbas conditions is $\delta_0 = 75°$, $\gamma_0 = 75° + 0.2 \cdot 9 = 76.8$, $\beta_0 = 75 + 0.2 \cdot 9 = 76.8$. In accordance with the obtained initial data, a vertical section was constructed across the formation extension (Fig. 2).

The shaded triangles in Fig. 2 are zones of increased pressure and deformations. The zone of expected vertical deformations is located within the rectangular triangle B-1-5, and their

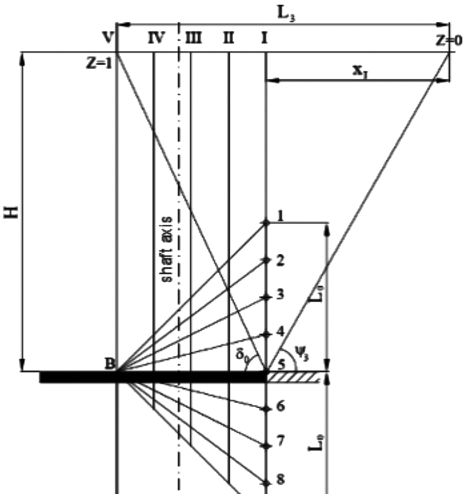

Fig. 1. Determination of the expected vertical deformations zone of the rock mass around capital crosscuts

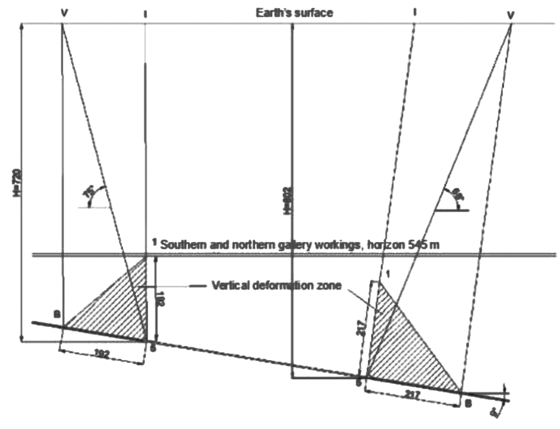

Fig. 2. Vertical section cross-strike of layer k_5 to determine the contour of the deformation zone

maximum values are observed at point 5 (minimum at points B and 1). The legs of this triangle are the width of the support pressure zone – L_0.

The magnitude L_0 is determined based on development depth H, limit angle δ_0 [19] and the dip angle of the layer α according to the formula: along the strike of the coal layer – $L_0 = H \cdot \mathrm{ctg}\,\delta_0$; into the cross of the coal layer – $L_0 = H \cdot \mathrm{ctg}\,\delta_0 \cdot \cos\alpha$.

In the conditions of development of pillars *1"bis"* and *2"bis"* by southern longwalls, their influence on the southern and northern sections located at a depth of 545 m should be taken into account in areas cross-strike of the developed coal layers.

Analyzing Fig. 2, we should note that the southern and northern crosscuts on depth of 545 m, according to the method [20], are located outside the vertical deformations in the zone of increased rock pressure. Consequently, further calculation of the vertical deformations of these workings is not required.

Construction of zones of high rock pressure in the edge part of the coal layer. Danger category of high rock pressure (HRP) zones determined according to the method given in [20], in the following order. According to the nomogram in Fig. 3 [21], the width of the support pressure zone l is determined depending on the development depth H and the thickness m of the mined coal layer.

For specific conditions of development of a coal layer k_5 in a certain area with a thickness of $m = 2.25$ m at development depths of 720 and 802 m, according to the nomogram, the value of the width of the support pressure zone l will be 66 and 72 m, respectively.

According to [21, Table 6], we determine the dimensions of the HRP zones in the roof d_1, and the bottom d_2, from the edge part, depending on the size of the produced space a and the development depth H of the layer (in this case, the above-plot space is not considered, so only distances d_1 are given).

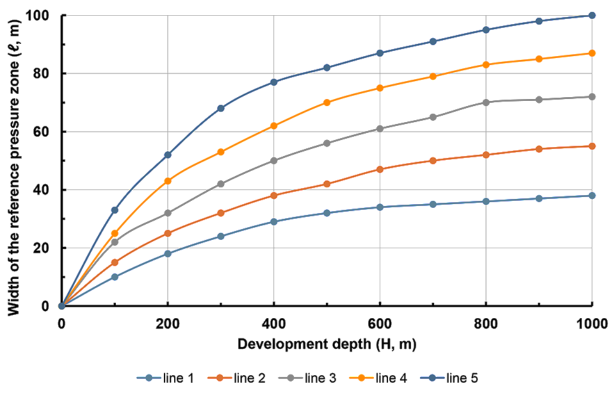

Fig. 3. Nomogram for determining the width of the support pressure zone [20]

Under certain mining and geometric development conditions at development depths of 720 and 802 m, the values of d_1 at $a = 250$ m will be equal to 150 and 157 m, respectively (Fig. 4).

In this case, the thickness of the interlayer h_1 is the distance on a vertical section from the formation plane to the bottom of the southern or northern crosscuts (located in the same horizontal plane).

The hazard category of HRP zones is established depending on the thickness of the interlayer h_1 and the size of HRP zones from the edge part h_1 (Fig. 4) according to data [21, Table 2].

Fig. 5 proves that the dangerous zone of high rock pressure above the edge of the k_5 layer within the planned development of pillars is below ($d_1 = 150$ m $< h_1 = 192$ m, $d_1 = 157$ m $< h_1 = 274$ m) the dangerous impact limit HRP.

Thus, according to the above calculations, based on the use of actually regulatory documents, the mining of safety coal pillars on the underlying depths will not lead to significant deformations in the rocks of the base and roof of the crosscuts and will not significantly affect their safe operation.

Selection of calculation method and calibration of the geomechanical model (stage II). Currently, the most effective method for solving problems of assessing the stress-strain state (SSS) of a rock mass, significantly weakened by a system of extended workings developing in space and time, is the methods of mechanics of a solid deformed body, implemented in the corresponding software products [10, 21].

It should be noted that not all software products are suitable for modeling geomechanical processes, but only those that are based on the ability to solve elastic-plastic problems based on the use of strength conditions suitable for describing the processes of destruction of specific rocks under dilatancy conditions. Taking into account the spatial complexity of the research object, it was decided to solve the problem in a three-dimensional formulation using the capabilities of the Ansys software package and the AutoCAD software environment. The task was to obtain the components of the field of stresses and displace-

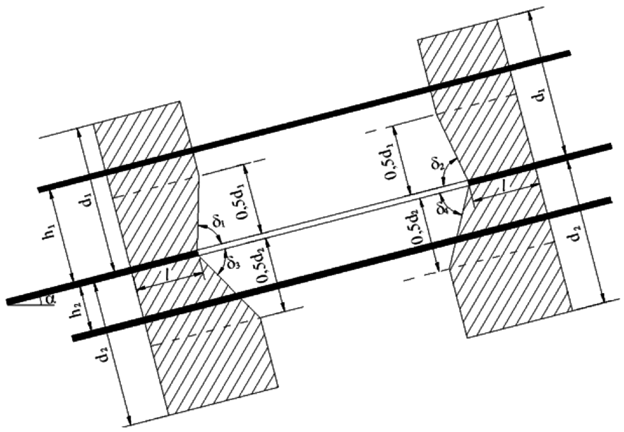

Fig. 4. Calculation scheme for determining zones of high rock pressure [21]

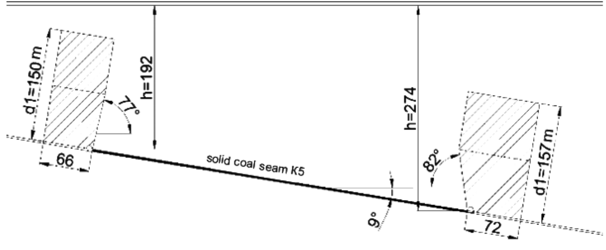

Fig. 5. Scheme for determining the dangerous category of HRP zones depending on the size of the produced space

ments around capital workings during the gradual development of safety pillars of coal around the slopes located below, that is, during the development of mining operations in space and time.

The process of gradual development of pillar reserves is subject to modeling *1“bis”* and *2“bis”* southern longwalls of the coal layer k_5 with an assessment of the influence on the stability of the southern and northern crosscut on depth of 545 m in the mining and geological conditions of Krasnolymanska mine. To implement this process, a special step-by-step modeling technique was developed, which took into account the evolution of the stress and deformation field around the research objects.

Solution to the problem. The studied geomechanical models are spatial, 3D-measuring. They include a complex of workings of those objects that are subject to study according to the mining development plan and lithology at Krasnolymanska mine. The heterogeneity of the structure of the rock mass due to its layering and the presence of a system of workings was taken into account by introducing into consideration the coefficient of structural weakening, which was equal to $k_c = 0.6$.

The Mohr-Coulomb criterion was adopted as a strength criterion as the most tested in practice modeling of the available geomechanical criteria, integrated into the Ansys software. Calculation parameters that were not included in the forecast geological section were taken from the “Reference book (cadaster) of physical properties of rocks”.

Parameters of geomechanical models are given in the Table.

Below we consider the mining and technical situation of mining the safety pillars of the slope of the k_5 layer with the southern longwalls *1“bis”* and *2“bis”* with the impact on the operational condition of the Southern and Northern crosscuts of the mountains, 545 m, when the minimum and maximum vertical distances are 192 and 274 m, respectively.

The following power and graphical restrictions were adopted at the boundaries of the model:

- ban of movements along the *X*, *Y*, *Z* axes along the bottom edge;
- ban movements along the *X*, *Y* axes and allowed movements along the *Z* axis along the side edges;
- uniformly distributed load along the base of the longwall from the pressure of the open sections on the base and scales of the technological equipment – a total of 2.2 MPa;
- uniformly distributed load from the above layer, equal to 15.7 MPa, along the upper edge of the model;
- the finite element mesh of the model is assembled from tetrahedral elements with a number of 53,567 units;

Table

Parameters of the studied geomechanical models

Name	Model
Geometric parameters of the model $B \times H \times L$, m	550 × 500 × 710
Boundaries of the model along the contour of the region, m	50
Type and number of finite elements	Type –Tet10, Number – 53,567
Side size of working elements, m	112 m for large; 1 m for condensed
Vertical load on the outer boundary of the model γH, MPa	15.7
Additional load from machines and mechanisms, MPa	2.2
Weighted average tensile strength of host rocks, MPa	48
Elasticity modulus, MPa	9,800
Poisson’s ratio	0.3
Specific gravity of rocks, kN/m^3	2.5

- the dimensions of the finite elements varied from 112 m at the model boundary to 1 m in the deformation analysis zones.

The modeling problem was solved in six stages (Fig. 6). Each stage corresponded to a situation when part of the pillar was mined and the primary collapse of the roof rocks in the longwall occurred.

The considered geomechanical situation in the three-dimensional model corresponded to the conditions for excluding part of the finite elements from consideration, which led to a corresponding change in the stress-strain state of the rock mass around the crosscuts. In this case, the preliminary stress-strain state of the geomechanical model was taken into account. After the longwall face moved to a distance corresponding to the collapse of the roof rocks, some number of finite elements were again connected to the working model with a change in the physical and mechanical characteristics that match to the properties of the destroyed rock mass.

At subsequent stages of modeling the process of working out the safety pillars and analyzing the evolution of the displacement field around the crossbar, the calculation algorithm was repeated six times until the three-dimensional model was completely completed.

Analysis of rock movements at the base of the crosscuts at a depth of 545 m was carried out at each stage of numerical modeling. At the same time, equivalent Coulomb-Mohr stresses were analyzed in order to assess the possibility of point failure of the carbon rock mass. The qualitative picture of changes in the stress-strain state and the quantitative values of displacements and stress in the coal-rock mass around the modeled workings were analyzed.

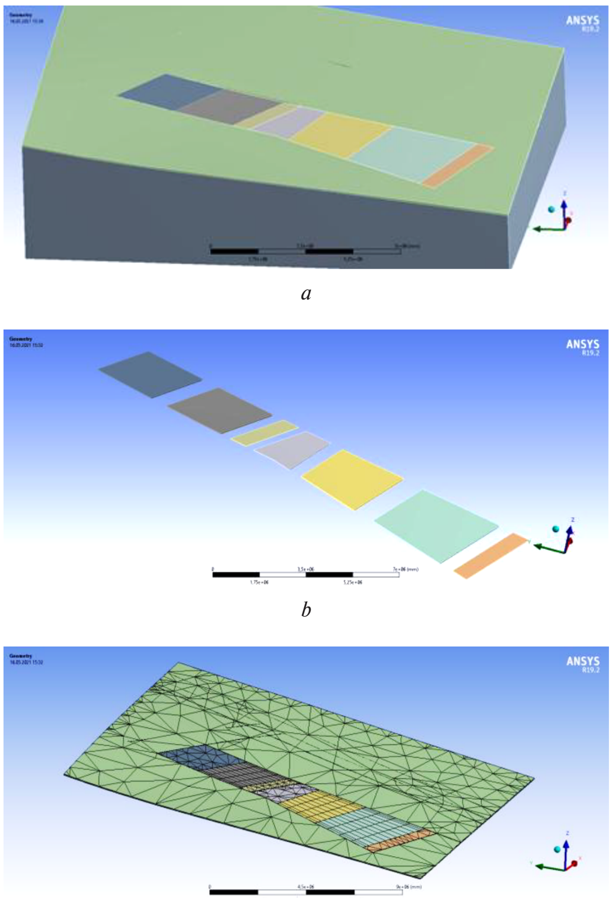

Fig. 6. Models for studying the field of displacements around crosscuts when testing safety pillars:

a – general view of the 3D model; b – detailed view of the plots; c – approximation by finite elements

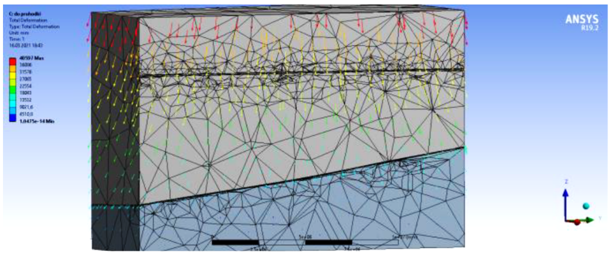

Fig. 7. Qualitative picture and movement direction of finite elements under the next load

A qualitative picture of the movements and their direction is shown in Fig. 7.

In the following models, the probable vertical distance between the mined safety pillars and crosscuts within the geological section of the deposit changed: minimum – 180, 170 and 140 m; maximum – 262, 252 and 232 m. The procedure for studying these modeling options is similar to that described above.

Fig. 8 shows the resulting graph of the second stage of research.

The graph shows the dependence of equivalent stresses on the small distance between the crosscuts and safety pillars. It follows from this that if the distance between them is reduced to 145 meters, the stability of the cross-cuts may be impaired and strengthening of the fastening will be required to ensure their operational capabilities. When the distance between the research objects increases, threatening deformations of the cross-cuts are not expected.

Conclusions.

1. An assessment of the hazardous impact of clearing operations during the mining of pillars *1*“bis” and *2*“bis” by southern longwalls on the southern and northern crosscuts at a depth of 545 m along the k_5 layer was carried out using current documents [18, 20]. Thus, at a depth of 545 m, no dangerous impact of the treatment work on the crosscuts during the mining of safety pillars by southern longwalls along the k_5 layer is expected and their operation will be safe.

2. Calculations of geomechanical models for mining safety coal pillars around slope No.1 “bis” of layer k_5 showed that the redistribution of stresses in the rock mass along the length of the northern and southern crosscut, located at a depth of 545 m, occurs naturally for each modeling stage.

3. The results of numerical modeling of the stress-strain state using geomechanical models adapted to specific mining-geological and mining-technical conditions showed a significant impact of pillar mining on the excavations under study can only occur if: the minimum distance between them is reduced to 145 m vertically; their resistance is strengthened by metal strengthen. Under the specified mining conditions, the influence of pillar mining on crosscuts is not dangerous.

4. Recommendations for ensuring the operational capability of the crossbars, located at a depth of 545 m in the mining

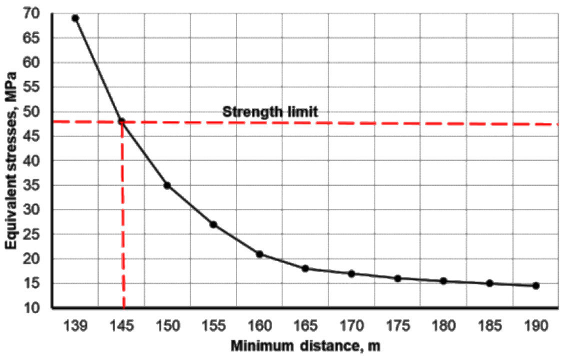

Fig. 8. Graph of equivalent stresses versus the minimum distance between crosscuts and pillars

technical and geological conditions of Krasnolymanska mine, come down to the implementation of standard regulatory, industry and production documents and do not require the development of additional special measures [20, 21].

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Оцінка стану породного масиву навколо квершлагів при додаткових збуреннях деформацій

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Мета. Оцінка рівня збурення напруженого стану породного масиву навколо квершлагів на гор. 545 м унаслідок виникнення додаткових деформацій при відпрацюванні нижче розташованих ціликів вугілля південними лавами пласта k_5 і оцінка характеристики такого впливу на експлуатаційний стан виробок у гірничо-геологічних і гірничотехнічних умовах шахти «Краснолиманська».

Методика. Теоретичні дослідження базуються на використанні нормативних документів щодо проєктування гірничих робіт на вугільних шахтах і геомеханічних моделях, розроблених відповідно до основних положень механіки твердого деформованого тіла, що реалізовані в апробованих програмних продуктах.

Результати. Доведено, що гірничо-геологічні й гірничотехнічні умови напружено-деформованого стану породного масиву навколо капітальних виробок гор. 545 не є критичними з точки зору їх стійкості. Обґрунтована можливість відпрацювання вугільних ціликів на нижче розташованих горизонтах, і встановлена межа мінімальної відстані між об'єктами досліджень, нижче якої для забезпечення стійкості квершлагів потрібно підсилювати кріплення.

Наукова новизна. Уперше для гірничо-геологічних і гірничотехнічних умов шахти «Краснолиманська» на основі нормативних документів і геомеханічних моделей вивчено напружено-деформаційне поле в породному масиві навколо капітальних виробок, як результат порушення рівноваги, що склалась унаслідок додаткових деформацій при відпрацюванні нижче розташованих ціликів вугілля. Встановлена залежність зростання еквівалентних напружень за критерієм Мора-Кулона при зменшенні відстані між об'єктами досліджень, обґрунтовані раціональні параметри технології відпрацювання запобіжних ціликів, за яких можливо безпечно керувати напружено-деформованим станом геомеханічної системи.

Практична значимість. Обґрунтування можливості збільшення продуктивних запасів вугілля в межах поля шахти «Краснолиманська» за рахунок безпечного відпрацювання ціликів навколо капітальних ухилів на нижче розташованих горизонтах.

Ключові слова: *капітальний квершлаг, цілик вугілля, капітальний ухил, напружено-деформований стан, геомеханічна модель*

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