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THE RELATIONSHIP BETWEEN LOWERING THE EARTH'S SURFACE AND BEARING PRESSURE ABOVE THE ADVANCING LONGWALL FACE

This work aims to develop a method for determining the increase in stresses above an advancing longwall face of Western Donbas mines. The paper presents a solution to the problem. It is based on the analysis of geodetic instrumental observations of the earth's surface lowering and rock mass deformation above the advancing longwall face. Length and propagation in the roof and floor of the extracted seam are the main geometrical parameters of the zone of high rock pressure. Currently, the quantitative parameters of this zone are not considered. And its length under the conditions of Western Donbas is determined with an accuracy of 50%. Thus, research in this direction is relevant. The experimental basis for the research includes the results of observations performed at two vertical borehole extensometers and the results of data processing obtained at more than 30 observation stations on the Earth's surface. Thus, the research specified the geometrical parameters of the zone of high rock pressure and the nature of the vertical stress distribution within this zone. The paper introduces a method to determine a coefficient of stress increase above the advancing longwall face of Western Donbas mines. We also established the empirical coefficients of the vertical stress distribution function within the abutment pressure zone. There is a relationship between the lowering of the earth's surface and the values of the stress increase in the borehole edge part. The reliability of the obtained results is confirmed by geophysical studies in Western Donbas, as well as by the results of field observations.

Key words: Earth's surface; subsidence; high rock pressure; rock pressure increment; surveying instrumental observations; borehole extensometer.

Introduction

During the extraction of coal seams, a zone of high rock pressure, which spreads into the roof and the floor of the extracted seam, is formed along the boundary of the longwall panel. High rock pressure is formed as a result of hanging rock layers over the goaf. The magnitude of the hanging depends on the extraction height of the coal seam, the strength of rocks [Location, security …., 2001] and the rate of the longwall face advance [Nazimko, 2008]. The distance where the high rock pressure is manifested at the edge part of the extracted seam is called the width of the abutment pressure zone and is denoted by l. The value of l depends on the depth of mining and the extraction height of mined seam and is the main initial parameter for designing high-rock pressure zones. Within the zone of the abutment pressure, rocks are exposed to vertical stress whose value exceeds the stress in the undisturbed rock mass.

The zone of high rock pressure propagates into the strata at a distance that depends on the mining depth and the coal seam extraction height. The maximum stress in the roof of the coal seam is concentrated at a certain distance from the boundary of the longwall panel. According to the results of various studies [Khalymendyk et al., 2013; Junker, 2006], this distance is taken from the panel border and is equal to 3–16 extraction heights of the coal seam. This is due to the destruction of the edge part of the coal seam and the overlying rocks, and further sloughing of the rock mass towards longwall. The existing methods of calculating the value l give a variation in its prediction up to 100 % for the same conditions. So far, there have not been any methods for assessing the quantitative parameters of the increase in rock pressure at the edge of the extracted seam.

This work aims to study the objective laws of rock pressure distribution based on mine surveying instrumental observations in boreholes and on the Earth’s surface.

To study the displacement of the earth's surface in the mines of the Western Donbas, 35 observation stations were installed. They consisted of 76 profile lines and 4030 ground benchmarks. The stations made 498 series of observations, including the short-term (frequency) ones. Observations were made using both classical measuring instruments (level, steel tape measure) and modern geodetic equipment (electronic tacheometers, GNSS receivers).

Research methods

The behavior of the underworked rock mass can be studied using both laboratory and theoretical methods, as well as in-situ instrumental observations. The first method provides only qualitative information about the processes taking place and a general idea of the subsidence of the rock mass. Theoretical methods are very diverse, but they depend on the assumed hypothesis, the mathematical apparatus, and the number of accepted assumptions.

The most reliable results in predicting the rock mass subsidence and deformation can be obtained by a simultaneous analysis of the results of in-situ instrumental observations on the Earth’s surface and in the strata in combination with theoretical models of the underworked rock mass [Kuchin, 2011; Elashiry et al., 2009; Chen et al., 2018]. In this case, the priority method includes in-situ instrumental observations, based on the results which, for example, calibrate mathematical models [Sdvyzhkova et al., 2016; Kuchin et al., 2017; Shahsenko et al., 2017; Tereschuk et al., 2014]. Mine surveying instrumental observations at special observation stations is the basic in-situ method of studying the rock mass deformation and the Earth’s surface subsidence [Lee, Abel, 1983; Subsidence Monitoring Program, 2007]. Instrumental observations of the rock mass deformation are less numerous than the observations of the Earth’s surface subsidence. In addition, the interpretation of such observation results is often associated with the difficulty of considering various external factors. However, their contribution to the development of the science of rock mass deformation is indisputable. Based on the foregoing, the mine surveying observations of the benchmark displacement on the Earth’s surface and of the anchors in borehole extensometers were taken as a research technique [Subsidence from coal mining activities, 2014; Holla, Barclay, 2000].

The subsidence curves go through initial, accelerated, and slow subsidence stages. They are S-shaped and can be adequately fitted with logistic regression [Yang et al., 2022].

Coal mining subsidence theory is applied to analytically separate vertical and horizontal components [Chen et al., 2020].

The research [Sepehri et al., 2017] shows that the numerical predictions of the mining-induced surface subsidence are consistent with the Gaussian distribution.

The author`s numerical modeling strategy [Zhao, Konietzky, 2020] is proposed to predict uplift during the flooding process of an excavated coal mining area under complex geological conditions. The model considers elastoplastic material behavior including faults represented by interfaces. The measured subsidence up to 17 m was reproduced as well as the uplift within the last 10 years with values between 0.5–2.0 mm/year. Our instrumental observations in the Western Donbas did not reveal such phenomena.

According to the study [Ma et al., 2022], the upper and the lower critical support pressures are 1.43 and 1.06 times of lateral earth stress at the tunnel crown, respectively. These results are consistent with the results of our studies. The differences are explained by various coal mining technologies and specific geological conditions of the Western Donbas.

The authors [Zheng et al., 2021] agree that forecasting tunnel displacement is difficult due to the uncertainty of rock mass properties.

A subsidence prediction model [Dai et al., 2022] based on the variation of mining influence propagation angle can be used to evaluate the surface movement and deformation.

The analysis of publications showed the main directions of modern research into the process of rock deformation. They include the determination of rock mass and the earth's surface displacements; modeling the process of the thickness displacement; vertical and horizontal projections of the displacement vector; determination of loads and displacements on the contour tunnels and mine workings; studies of thickness displacements after the mining completion. At the same time, the question of the relationship between the earth's surface subsidence and the reference rock pressure at the boundary of the stope is poorly understood. The establishment of this relationship will make it possible to solve the inverse problem: determining the values of the support pressure in the edge part of the stope (pillar) based on the established values of the earth's surface subsidence.

By now, the instrumental observations of the rock mass deformation have been performed in conditions of the Western Donbas mines. The rocks are soft thin-laminated clayey siltstones and mudstones with UCS 15–30 MPa, and the depth of mining is from 100 to 550 m. The observations involve using the following methods:

- mine surveying observations at observation stations consisting of lines of benchmarks placed in underworked roadways (2 case studies);
- mine surveying observations of the displacement of anchors of borehole extensometers (2 borehole extensometers, 10 anchors in each borehole);
- a geophysical survey in vertical boreholes drilled from the Earth’s surface (1 observation station, 2 boreholes);

– mine surveying observations of the support deformation of the underworked roadways.

The first two methods are of practical interest, in terms of the quantitative assessment of the values of the rock mass displacement and deformation.

To identify the patterns of the rock mass deformation during the longwall face advances at the Stepna mine in Western Donbas, extensometer anchors were set up in boreholes No. 35 and No. 2. Mine surveying observations were conducted simultaneously at the borehole extensometers No. 35 & No. 2 and on-surface observation stations No. 13 & No. 12 respectively. The depth of mining was 100–110 m. In borehole extensometer No. 35, anchors were installed at a depth of 56–82 m with an interval of 5–6 m. In borehole extensometer No. 2, anchors were set up at a depth of 57–77. The time interval between observations was 1–7 days. A total of 96 observation series were performed.

Investigation of the geometrical parameters of the high rock pressure zone in front of the advancing longwall face.

The process of the rock mass deformation can be divided into two stages:

– rock mass deformation in front of the advancing longwall face within the high rock pressure zone;

– rock mass deformation over the goaf within the de-stressed zone.

Let us consider the high rock pressure zone that is formed ahead of the advancing longwall face. The boundaries of this zone in strata are rather arbitrary and are often defined in various methods using the angle of draw (above the undisturbed coal seam) and the internal angle of draw (above the goaf) [Location, security …., 2001, KD 12.01.01.503-2001. Roof control…, 2001]. Using instrumental observations on anchor displacement in borehole extensometers can help determine the position of the high rock pressure zone boundary. The method of determination of the boundary position is presented below.

The first signs of the Earth's surface subsidence appear at the position of the longwall face at a distance d (Fig. 1) from the borehole.

When the face approaches the borehole at a distance of d_1, the anchor 6 at a depth of H_6 starts to subside. Consequently, the distance $\Delta d = d - d_1$ characterizes the declination of the boundary of the high rock pressure zone from the vertical line at a level H_6 (Fig. 1, line BD). The angle δ_2 that characterizes this declination can be calculated by the equation:

$$\delta_2 = \mathrm{arctg}\left(\frac{H_1}{\Delta d}\right), \text{ deg.} \qquad (1)$$

Considering that the Earth's surface subsidence reflects the one of the rock masses qualitatively, the angle δ_2 can be obtained from recorded values of the Earth's surface subsidence and borehole extensometer anchors. Such a method of determination of boundaries of high rock pressure zone can only be used when the borehole is located above an undisturbed rock mass during observations.

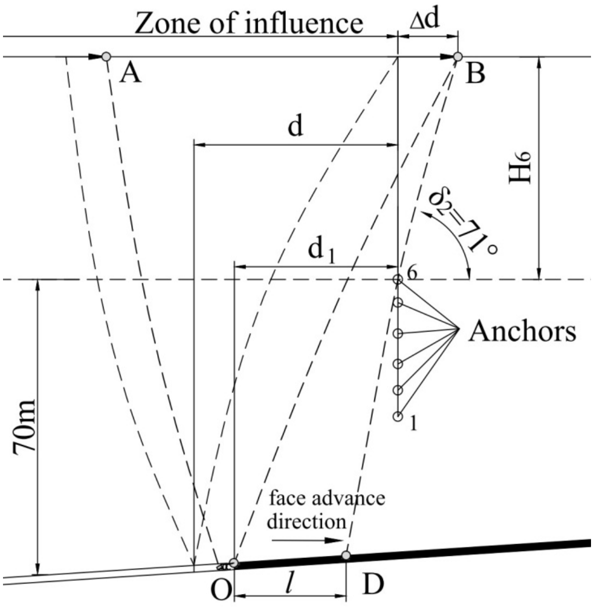

Fig. 1. Model of determination of high rock pressure boundary on the side of undisturbed rock mass.

The analysis of the results of 8 observations at two borehole extensometers that meet the abovementioned requirements allowed us to establish that the value of angle δ_2 is about 71º (in the conditions of advancing longwall face). The range of variation of δ_2 values is 70–73º, and the standard deviation is 0.75º. With sufficient accuracy for practical use, the boundary BD (Fig. 1) can be replaced with a line that connects the boundary of the longwall influence zone on the Earth's surface and the point in the roof of the coal seam. At this point, the vertical stresses correspond to the ones in the undisturbed rock mass (zero-value subsidence).

The boundary of the zone of high rock pressure OA on the side of the goaf can be determined similarly. The criterion for determination of the boundary position is the moment when the rock mass vertical stresses change from the loaded to the unloaded state. This moment is marked by a drastic decrease in vertical compressions and further intensive development of tensile deformations due to the bending of rock layers and their sagging into the goaf. This is illustrated in Fig. 2.

For the lower anchors of the borehole extensometer No. 35, this moment occurred when the longwall face was at a distance of 12 m from the borehole axis, and for the upper ones – at 17 m. Note: in Fig. 2, the position of the advancing longwall face is fixed for the convenience of representation. The position of the extensometer anchors in the borehole is shown twice, representing the results of two observations. The distance between the observations is Δ*d* = 5 m, which is the distance the face has advanced.

The zone OAB on the Earth's surface is characterized by a point where horizontal strain is zero and tilt is at its maximum (point A). Linear elements can be used to represent the boundary of the high rock pressure zone, which can be plotted from the longwall face (point O) towards the goaf (as shown in Fig. 2).

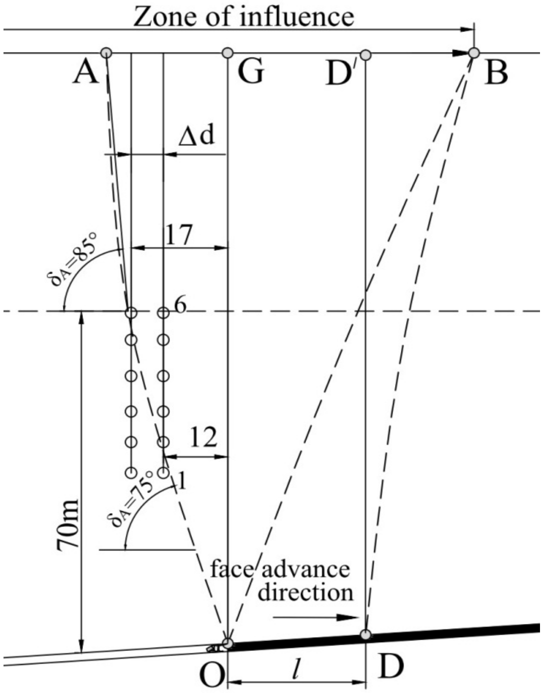

Fig. 2. Model of determination of high rock pressure boundary on the side of the goaf.

Fig. 2 shows that the boundary OA of zone OAB consists of two lines that form the angles δ_A with the horizontal line: the angle of the lower line is 75º and of the upper one – 85º. Similar results were obtained from geophysical research at a depth of 360 m and observations over the deformation of the 2nd Western Main Haulage Roadway at Blagodatna mine at a depth of 290 m. The total value of angle δ_A above the longwall face depends on the speed of its advancement and can vary from 72º to 85º, but after face advancement is stopped, the value of δ_A is 85º. Thus, the dependencies were obtained from the processing of the results of instrumental observations during the underworking of borehole extensometers. They are well-correlated with the results of the analysis of distinguished points' position at the subsidence profile of the Earth's surface.

The weight of the rock mass within the OAG zone forms high rock pressure at the interval OD. Under conditions of an undisturbed rock mass, the weight of rocks loading the coal seam within the interval OD is determined by the area of the quadrilateral $S_{ODD'G}$ and the bulk density of rocks γ. The extraction of a coal seam results in an increase in vertical stresses in the abutment pressure zone. It is due to the volume of rocks within the contour OAG, which is also determined by the area S_{OAG} and the rock density. Consequently, the total increment in rock pressure (vertical stress) ΔP at the interval OD can be determined by the equation:

$$\Delta P = \frac{S_{\mathrm{OAG}} \cdot \gamma^{av}_{\mathrm{OAG}}}{S_{ODD'G} \cdot \gamma^{av}_{ODD'G}}. \qquad (2)$$

Because the bulk density of rocks γ in adjacent zones is identical, the total increment in rock pressure will be equal to the ratio of the areas $S_{OAG} / S_{ODD'G}$. Under the conditions of the borehole extensometer No. 35, the ratio of these areas was ΔP = 1.550/2.970 = 0.52 (52 %). However, the ratio was 0.38 under the mining conditions of the Heroyiv Kosmosu mine at a depth of 360 m.

Investigation of vertical stress increment distribution within the zone of abutment pressure.

The value of ΔP is nonuniformly distributed within the abutment pressure zone. When examining how rock mass subsidence and high rock pressure are related, it can be concluded that the distribution of abutment pressure is equivalent to the distribution of subsidence along the edge of a seam.

Let us analyze the principle of surface subsidence distribution within the longwall influence zone limited by points G and B (Fig. 2). In this case, the values of the Earth's surface subsidence are not as interesting as their distribution in the examined area. Our study uses the results of instrumental observations on the Earth's surface obtained at observation stations No. 5, 8–10, and 13 (Western Donbas), as well as the results of lowering anchors into borehole extensometers No. 35 and No. 2. We use a scaling factor equal to 1/LGB), to bring the subsidence plots to unified plan sizes, LGB is the length of an interval GB obtained from instrumental observations. The limit of the subsidence profile from the side of the undisturbed rock mass (point B) is determined by existing criteria [Kuchin, 2011]. Because only the distribution is of interest, the scaling of the graphs along the subsidence axis is made by the concurrence of curves obtained from different observations. A total of 11 observations were analyzed, and the obtained distribution of subsidence is shown in Fig. 3, *a*. The coefficients of the typical sediment function were determined according to the method [Rules for undermining …, 2003].

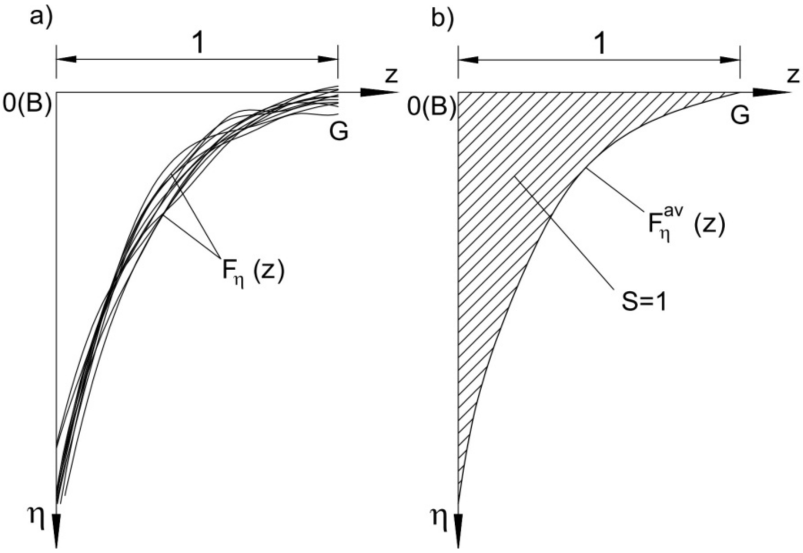

Fig. 3. The function of subsidence distribution above the edge part of the coal seam: a – according to the results of observations, b – averaged.

The averaged curve is scaled along the subsidence axis to make the value of area *S* equal to 1 (Fig. 3, *b*). As a result of such transformations, the function $F\eta^{av}(z)$ describes the increase in vertical stress within the abutment pressure zone due to the weight of rocks in the OAG zone. The coefficients of this function are presented in the table.

The coefficients of the function $F_\eta^{av}(z)$

z	$F_\eta^{av}(z_i)$	z	$F_\eta^{av}(z_i)$
0	3.651	0.6	0.428
0.1	2.587	0.7	0.293
0.2	1.868	0.8	0.185
0.3	1.297	0.9	0.090
0.4	0.886	1	0.000
0.5	0.615		

The distribution of the relative rock pressure increment at a random point of the OD interval can be obtained by the equation:

$$\Delta P_i = F_\eta^{av}(z_i) \times \frac{S_{OAG}}{S_{ODD'G}}, \qquad (3)$$

where $z_i = x_i / l$ (Fig. 4), $F_\eta^{av}(z_i)$ – coefficients of the function of vertical stress increase (see Table).

For the conditions of the borehole extensometer No. 35 (observation station No. 13), the maximum value of the relative rock pressure increment calculated by equation (3) was ΔP_0=3.651·1.550/2.970=1.90. Due to the redistribution of rock pressure, the load on the edge part of the coal seam increased 2.9 times relative to the load under conditions of an undisturbed rock mass. This value corresponds to the classical concept of the maximum stresses in the abutment pressure zone, which are 2–5 times greater than the stresses in the undisturbed rock mass. For the conditions of the coal seam extraction at a depth of 360 m, the maximum value of ΔP_0 was 1.47.

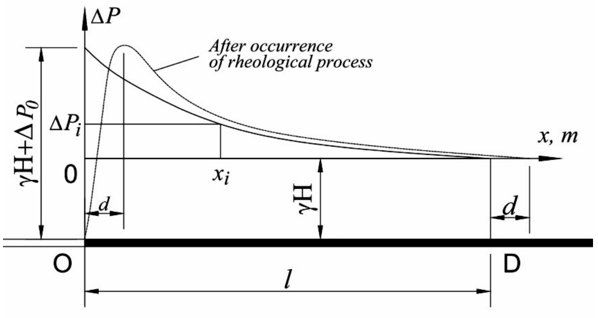

Fig. 4. Model for the determination of vertical stress increment Δ*P* in the abutment pressure zone

The decrease in the value of the rock pressure increment is associated with an increase in the volume of rocks within the limits of the OAG contour, which have a greater volumetric weight. It is possible to determine the values of the function Δ*P* more objectively by considering the density of rocks within the boundaries of the OAG and ODD′G contours.

$$\Delta P_i = F_{\mathrm{h}}{}^{av}(z_i)\times\frac{S_{\mathrm{OAG}}\cdot\gamma_{\mathrm{OAG}}^{\mathrm{av}}}{S_{ODD'G}\cdot\gamma_{ODD'G}^{\mathrm{av}}}. \qquad (4)$$

The method that considers the volumetric weight of rocks, implemented in equation (3), allows for increasing the reliability of the calculated ΔP values. However, at the same time, it significantly increases the complexity of mathematical operations for the determination of the weighted average value of γ^{av}.

The function of the ΔP values distribution (4) is valid under the conditions of an advancing face and at a low level of manifestation of rheological processes. As noted previously, a decrease in the rate of face advancing or its stoppage leads to the disintegration of the rocks in the coal seam edge part. It also causes overlying strata and, consequently, a decrease in vertical stresses and the formation of a de-stressed zone. In this case, the point of the maximum value of the abutment pressure shifts by a distance ***d*** (Fig. 4) from the boundary of the goaf. The total length l of the abutment pressure zone increases. Interestingly, when the rate of face advance is high, the point of the maximum value of the vertical stress shifts towards the goaf. This is supported by the observation that the values of Earth's surface subsidence ($\eta3$) above the longwall face change as the rate of advance (v) increases, as reported by Kuchin in 2011. As v increases, the subsidence above the face decreases and the inflection point of the subsidence profile moves towards the goaf.

Thus, the distance d can be determined by the dependence of the position of the subsidence profile inflection point on the longwall face advance rate. For example, when the rate is 60 m/month, the subsidence profile inflection point is at $0.22H$ distance from the face. After stopping, this distance is reduced to $0.11H$. With a mining depth H = 360 m, the distance d will be (0.22–0.11) ·360 = 39 m. According to the study of the rock pressure manifestation [Monitoring the state of workings…, 2011] in the ventilation roadway No. 3 of the c10 seam of Heroyiv Kosmosu mine (mining depth H = 360 m), the distance from the boundary of the goaf to the point with the maximum value of abutment pressure was 30–40 m. This agrees well with the abovementioned result.

To use equation (3) in the conditions of the completed subsidence process, the origin of coordinates (Fig. 4) must be shifted towards undisturbed rock mass by the distance of $0.11H$ from the coal seam edge part.

The value of the rock pressure increment decreases proportionally with the distance from the roof of the extracted seam. At the same time, the size of the high rock pressure zone increases. The previously obtained geometrical parameters of this zone can be used (Fig. 5) to determine the length of the high rock pressure zone at a height of h from the roof of the extracted seam.

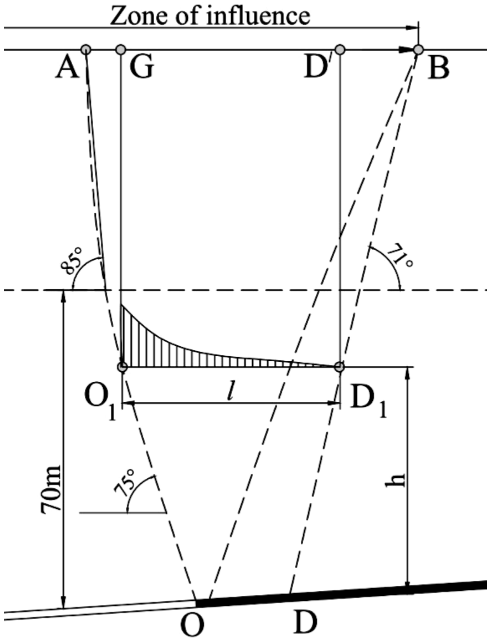

Fig. 5. Model for determination of the rock pressure increment ΔP at the height h from the roof of the extracted coal seam.

Based on the data gathered from borehole extensometer No. 35 and on-surface observation station No. 13, the maximum rock pressure increment $\Delta P0$ was 0.36 at a height of 50 m from the top of the extracted coal seam. However, at a height of 70 extraction coal seam capacities, the value of ΔP_0 dropped to 0.1, indicating that there was almost no further increase in rock pressure under these mining and geological conditions. It is important to note that the calculation model and angular parameters are only applicable to the cross-section of the panel that runs parallel to the longwall face advance direction.

Originality

Empirical coefficients of the vertical stress distribution function within the bearing pressure zone are established.

Practical significance and future work

The study refined geometric parameters of the zone of increased rock pressure, based on the analysis of surveying instrumental observations of the displacement of the undermined massif, The paper also introduced the technique for determining the stress growth coefficient over a moving stope of Western Donbas mines.

Conclusions

1. The study analyzed the results of geodesic observations of the earth's surface and rock mass displacement.
2. The paper established the relationship between the lowering of the earth's surface in front of the advancing longwall face and stress increase magnitude in the edge part of the developed stope.
3. The reliability of the results obtained is confirmed by geophysical research in the Western Donbas, as well as the field observation findings.
4. Future research aims to develop a methodology for determining the stress growth coefficient from the excavation drifts` side and its dynamic changes during the longwall passage.

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ВЗАЄМОЗВ'ЯЗОК МІЖ ОПУСКАННЯМ ЗЕМНОЇ ПОВЕРХНІ ТА ОПОРНИМ ТИСКОМ НАД ОЧИСНИМ ВИБОЄМ

Мета дослідження – розробити методику визначення приросту напруги над рухомим очисним вибоєм шахт Західного Донбасу. У роботі наведено варіант вирішення поставленого завдання на основі аналізу результатів інструментальних спостережень за деформацією масиву гірських порід над очисним вибоєм, що рухається. Основними геометричними показниками зони підвищеного гірського тиску є її ширина (довжина) і дальність поширення в покрівлю і підошву пласта, що відпрацьовується. Кількісні показники цієї зони поки що не розглянуто, а її ширину (довжину) в

Західному Донбасі визначено з точністю 50 %. Отже, дослідження у цьому напрямі актуальні. Експериментальною основою для досліджень є результати інструментальних вимірювань деформацій у двох вертикальних свердловинах, що розташовані попереду рухомого очисного вибою та результати опрацювання геодезичних спостережень на 30 спостережних станціях, розташованих на земній поверхні. На основі аналізу геодезичних інструментальних спостережень за зсувом масиву, що підробляється, уточнено геометричні параметри зони підвищеного гірського тиску. Запропоновано методику визначення коефіцієнта приросту напруги над очисним вибоєм шахт Західного Донбасу, що рухається. Встановлено емпіричні коефіцієнти функції розподілу вертикальної напруги в межах зони опорного тиску. Встановлено взаємозв’язок між опусканням земної поверхні попереду очисного вибою, що рухається, і приростами напруг у крайовій частині розроблюваної очисної виробки. Достовірність отриманих результатів підтверджено геофізичними дослідженнями у Західному Донбасі, а також результатами натурних спостережень.

Ключові слова: опускання земної поверхні; осідання; підвищений гірський тиск; приріст гірського тиску; геодезичні інструментальні спостереження; екстензометри свердловинні.

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