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PREDICTING METHANE EMISSIONS FROM MULTIPLE GAS-BEARING COAL SEAMS TO LONGWALL GOAFS AT RUSSIAN MINES

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ABSTRACT

The purpose of the study is to improve methods for predicting methane emissions from adjacent coal seams to longwall goafs. To assess prediction efficiency, an analysis was carried out of the existing methods for calculating the parameters of gas emission zones in overlying and underlying coal seams. Different methodologies were analyzed that are used by both companies developing Russian coal basins and those operating in top coal-producing countries (China, the USA, and Australia). As a result of the analysis, it was concluded that the methodology described in one of the coal mining regulations currently in force in Russia does not take into consideration a number of important factors that have a significant impact on methane emissions to longwall goafs. The article demonstrates that it is necessary to take into account such parameters as panel width and the depth of cover. To confirm that the depth of cover affects the permeability of underlying and overlying coal seams in the zones of stress relief, numerical models describing such zones were developed using the finite element method. Numerical modelling was carried out using a 2D rock mass model that included three coal seams (underlying, overlying, and the one being developed), mine workings, and a goaf. The Mohr-Coulomb model was used to describe rock behaviour under stress. By comparing stress distribution patterns at depths of cover of 300, 500, and 900 m with a 300-m distance to the overlying seam and a 50-m distance to the underlying seam, it was concluded that the extent of the gas emission zone created by the underlying seam significantly exceeds the value specified in regulations (35 m) and depends on the depth of cover. It was also established that the effect of stress relief (i.e. an increase in the effective porosity and permeability of the seam) on the seam being overmined increases along with growth in the depth of cover. This dependence is explained by the fact that changes in stresses under the goaf become more significant at greater depths. The novelty of the study consists in identifying a significant effect of stress relief on permeability that manifests itself and great depths of cover and in providing a rationale for improving the methodology for predicting methane emissions from coal seams being overmined at Russian mines by taking into account changes in effective porosity that depend on the depth of cover.

Keywords: underground mining, longwall, multiple coal seams, mining height, methane emission, permeability, porosity, stress distribution.

INTRODUCTION

By using state-of-the-art high-performance mining equipment, Russian longwall mines have significantly improved their productivity [1, 2] and reduced production costs. As a result, this mining method has become widespread, driving out other underground coal mining methods. Currently, more than 90% of the total volume of underground coal production in Russia is accounted for by longwall mining. To improve equipment utilization, panel dimensions were increased, with panel lengths reaching 4 to 5 km and panel widths of up to 400 m, which helped to reduce both shearer downtime associated with the very nature of longwall mining operations (i.e. their cyclicity) and the number of long (from one to three months) and labour-intensive periods allocated for assembly and disassembly operations that are required before the next longwall panel is extracted [1-4]. This increase in longwall mining productivity and panel dimensions accompanied by steady growth in depths of cover has led to an increase in the gas emission rate, with values sometimes exceeding 200 or even 250 m^3/min [2]. It should be noted that more than 80% of Russian coal mines develop gas-bearing seams; in most cases, they have to face the issue of productivity becoming limited due to increased methane emissions. An analysis of methane flow distribution data collected at Russian mines showed that the major portion of methane (70 to 90%) accumulates in longwall goafs [5]. Thus, goafs act as man-made reservoirs for methane that comes from underlying and overlying coal seams as a result of both an increase in rock permeability in the zones of stress relief and intense fracturing. Predicting methane emissions to goafs and calculating the parameters of degasification systems are two tasks that are of vital importance to Russian coal mines [6-9]. Due to the intensification of underground coal mining operations in Russia (especially in the Kuznetsk Basin, which accounts for more than 70% of Russian coal production), mining depths are constantly increasing and the parameters of methane emissions are constantly changing, which requires high prediction accuracy in order to develop robust methane control measures. However, the approach outlined in one of the underground mining regulations currently in force in Russia [10] is based on methods that were developed back in 1989 [11]. Significant changes in longwall mining parameters, including an increase in longwall outputs (by 10 to 15 times), pillar dimensions (by 4 to 5 times), and gas emission rates (by 10 to 50 times), require reassessing methane control measures that have been used for a long time and, if needed, developing new methods for predicting methane emissions to ensure successful methane control at coal mines.

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LITERATURE REVIEW

Until 2011, the process of designing ventilation systems for coal mines and calculating potential gas emission rates in Russian coal mines was controlled by a regulation [11] containing various methods for calculating gas emission rates from coal seams being undermined and overmined. It should be noted that this article covers only longwall mining systems without backfilling and provides formulas for this particular method of development (which is the most widely used in coal mines). Gas contents per ton of coal (m^3/t) for seams being undermined in the biggest coal basins of Russia (except for the Karaganda Basin) were calculated using the following formula [11]::

$$q = \frac{m_o}{m}(x_o - x_{o1})(1 - \frac{M_o}{M}) \quad (1)$$

where m_o is the thickness of the overlying seam producing methane emissions, m; m s the thickness of the working seam, m; x_o is the natural gas content of the overlying seam, m^3/t; x_{o1} is the residual gas content of the seam, m^3/t; M_o is the distance to the overlying seam, m; M is the height of the gas emission zone in the goaf, m.

The methodology being discussed (1) is based on the relationship between the distance to the adjacent seam and the degree of degasification. It should be noted that this is a universally accepted methodology that is widely used around the world to assess gas emissions [12]. As can be seen from Figure-1 [12], most authors agree that the distance to the adjacent seam influences the process of degasification but the quantitative assessments of this influence differ by a factor of 1.2 to 2.

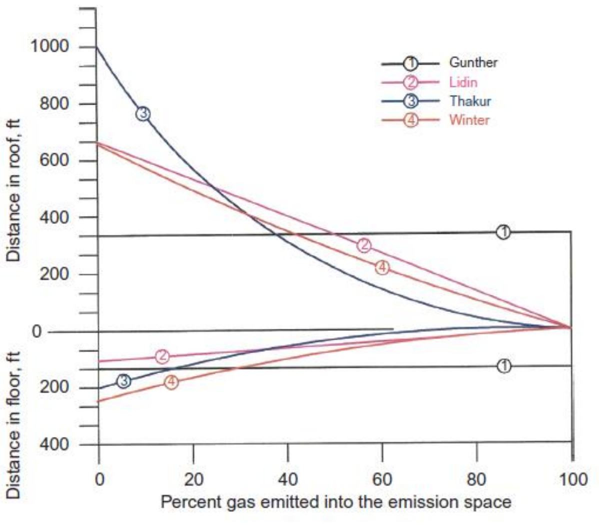

Figure-1. Vertical limits of the gas emission zone [12].

One of the main parameters influencing methane emissions from adjacent seams is the height of the gas emission zone (M, m). However, a different formula is applied to each coal basin. For the Kuznetsk Basin, the following one is used [11]:

$$M = 40m(1.2 + \cos\alpha) \quad (2)$$

where α is the angle of dip.

Thus, in the Kuznetsk Basin, the extent of the gas emission zone in the roof of the working seam depends mainly on the working height and decreases as the angle of dip increases.

For the Donetsk and Lvov-Volyn Basins (Ukraine), the extent of this zone is calculated using another formula [11]:

$$M = lk_p\sqrt{m} \quad (3)$$

where l is panel width, m; k_p is the coefficient taking into account the lithology of rocks in fracture zones.

In contrast to (2), not only working height but also panel width is taken into account in (3).

For the Pechora Basin, the extent of the gas emission zone was calculated using the following formula:

$$M = 4{,}9 \cdot m \cdot \sqrt{H - H_0} \quad (4)$$

where H is the depth of cover, m; H_0 is the depth of the upper boundary of methane distribution.

The formula above (4) does not account for panel width but it does for the depth of cover.

For other coal basins (those not specified here), M was calculated using (2) [11].

Since methane emissions from the floor are mainly associated with an increase in the permeability of mine floor rocks and that of the underlying seam due to stress relief, the extent of this zone in the floor of the working seam is insignificant compared to that in its roof, where an important role is played by the height of the fracturing zone and that of the caving zone.

According to the methodology under consideration [11], the extent of the emission zone in the floor is accepted to be equal to 60 m for the Donetsk and Lvov-Volyn Basins and 35 m for the Kuznetsk Basin and other basins (except for the Pechora Basin). Only for the Pechora Basin is the extent of this zone calculated taking into account the depth of cover:

$$M_p = 2{,}8 \cdot \sqrt{H - H_0} \quad (5)$$

Some works [13] highlight that a fracturing zone develops in the floor (at the edges of the zones where the seam is compressed and extended) as the panel face advances. It is proposed to use the following formula to find the height of this zone:

$$h = 0.0113H + 6.25\ln(\frac{L}{40}) + 2.52\ln(\frac{m}{1.48}) \quad (6)$$

where h is the height of the fracturing zone, m; H is the depth of cover, m; L is panel width, m; m is working height, m.

Since 2011, a single methodology for assessing methane emissions [10] has been applied to all Russian coal basins. It uses (2) to find the extent of the gas emission zone in the roof, with its extent in the floor being taken equal to 35 m. Thus, the regulation currently in force in Russia [10] does not take into account the impact of panel width and the depth of cover.

In terms of studying the permeability of rock layers that have been undermined, of considerable interest are methods that have been developed based on the results of numerous observations on water drainage in mines. The height of the zone of full drainage above the goaf can be found using the following formula [14]:

$$H = 1438 ln\left(4.315 \cdot 10^{-5} u + 0.9818\right) + 26 \quad (7)$$

$$u = wt^{1,4} d^{0,2} \quad (8)$$

where H is the height of the zone of full drainage above the goaf, m; u is the parameter that depends on panel width (w, m), working height (t, m), and the depth of cover (d, m).

Thus, panel width and the depth of cover are among the main factors that should be taken into account when calculating the parameters of the zone of drainage in the roof of the working seam.

Since the effect of stresses on the permeability of the seam is a commonly accepted fact [15-17], the use of methodological approaches that do not account for this effect [10, 11] does not make it possible to yield correct results when calculating the parameters of the gas emission zones in the roof and floor of the working seam.

MATERIALS AND METHODS

A literature review showed that panel width and the depth of cover are among the factors that have the greatest impact on methane emissions in multiple coal seams. Since stress distribution around the longwall goaf depends on a number of factors (working height, depth of cover, stress-strain behaviour, and panel width), the finite element method can be successfully used to take into account all these parameters as it is able to factor in the complex configuration of mine workings and the stress-strain characteristics of rocks. In the course of the study, a 2D rock mass model was developed that included three coal seams (underlying, overlying, and the one being developed), mine workings, and a goaf (with a cave-in height equal to 6*m*). The model layout is shown in Figure 2. The depth of cover for the working seam varied from 300 to 900 m, the distance to the overlying seam was taken as equal to 300 m, and the distance to the underlying seam varied from 35 m to 50 m. Panel width was taken as equal to 200 m. The distance from the goaf to the panel workings was 30 m. The initial conditions in the model were set using the weights of the elements. The relationship between stresses and deformations was described using the Mohr-Coulomb model.

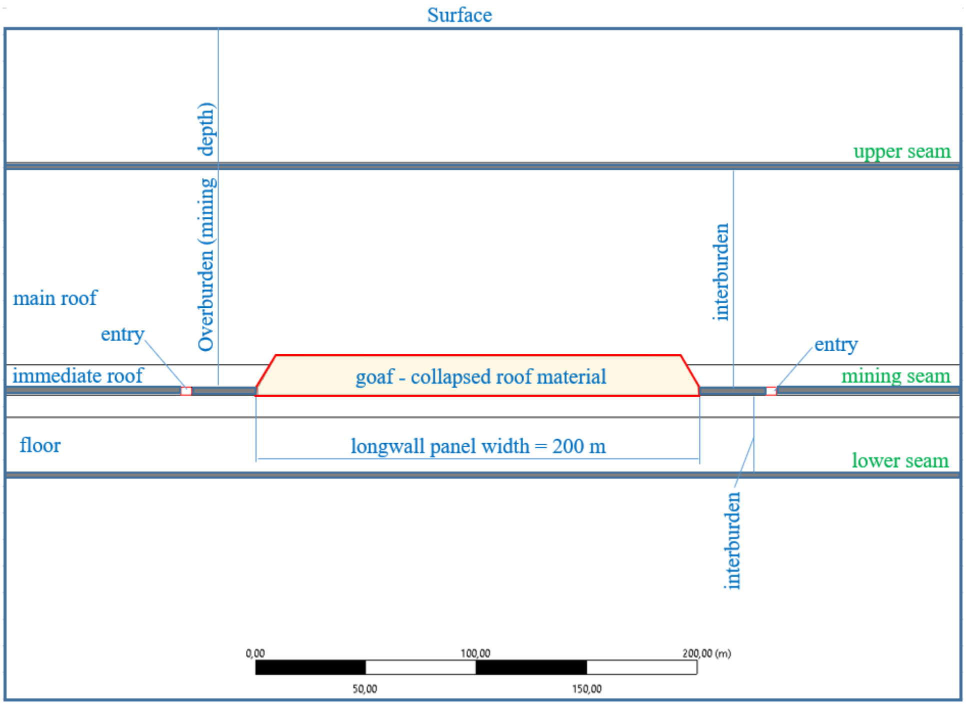

Figure-2. Model layout.

The 2D model that was developed makes it possible to analyze stress distribution in the zones affected by the goaf. The subsequent quantitative assessment of changes in the filtration properties of rocks in different zones of the overlying and underlying seams will be carried out based on the relationship between stresses and

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permeability. It is estimated that effective porosity (n) is ~3%. The relationship between effective porosity and stresses can be presented in the following form [19]:

$$n = n_0^{-b|\sigma|} \tag{9}$$

where n_0 is the effective porosity of coal that is free from stress; b is the empirical coefficient; σ is the stress acting on the rocks, MPa.

The author of [19] points out that (9) can be replaced by a simplified version:

$$n = n_0 - C|\sigma| \tag{10}$$

where C is the empirical parameter (dimension: 1/σ) for the depths under consideration that is estimated to be equal to C = 52·10-4 (1/MPa).

Using (10), the porosity parameters of the underlying and overlying seams can be numerically evaluated.

RESULTS AND DISCUSSIONS

As an example of the results of numerical modelling, Figure-3 shows stress zones at a depth of cover of 900 m. As can be seen from Figure-3, abutment pressure zones (high-stress zones) emerge at the edges of the working seam, and zones with low stresses emerge above and below the goaf. The zone with low stresses in the roof of the working seam is significantly bigger than the one in the floor. Sections of the interburden (a distance of 300 m to the upper seam and a distance of 50 m to the lower seam) also experience stress relief but their extent is much smaller than panel width.

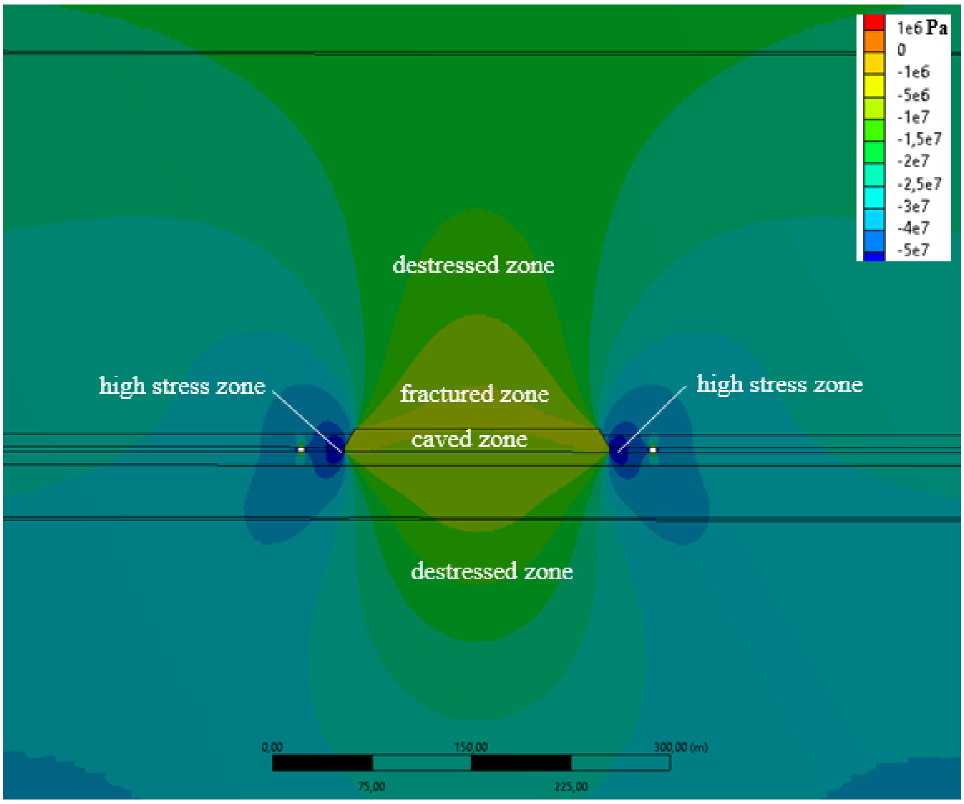

Figure-3. Stress distribution around the goaf (a depth of 900 m).

For a detailed study of stress relief in the upper and lower seams, stress distribution was plotted (Figure-4) and the results were converted into effective porosity distribution graphs taking into account (10). As the distance to the overlying seam is 300 m, changes in its stress-strain behaviour do not affect the working seam and can be viewed as insignificant. However, changes in the stress-strain behaviour of the working seam and the underlying seam are significant (Figure-4).

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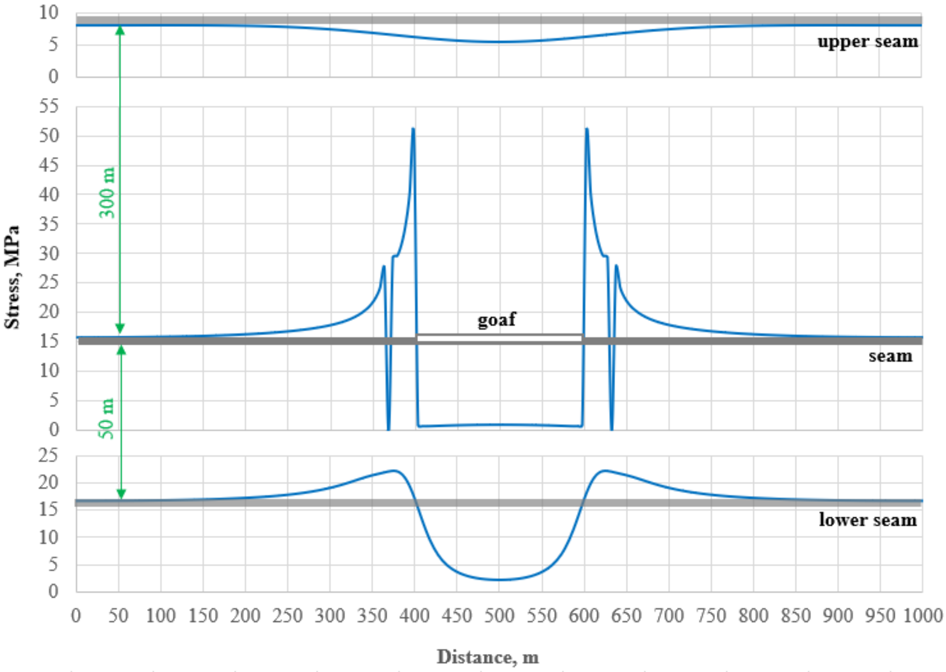

Figure-4. Stress distribution demonstrated by the three seams.

The results of assessing stress distribution and permeability in different zones of the lower seam are shown in Figure-5. The analysis showed that in the zone of stress relief, which has a length of 100 m, porosity changes from 2.91% (300-m depth) to 2.84% (900-m depth) after mining operations have been conducted. However, relative to the initial (natural) state, effective porosity changed by 18% (300-m depth), 34% (600-m depth), and 68% (900-m depth).

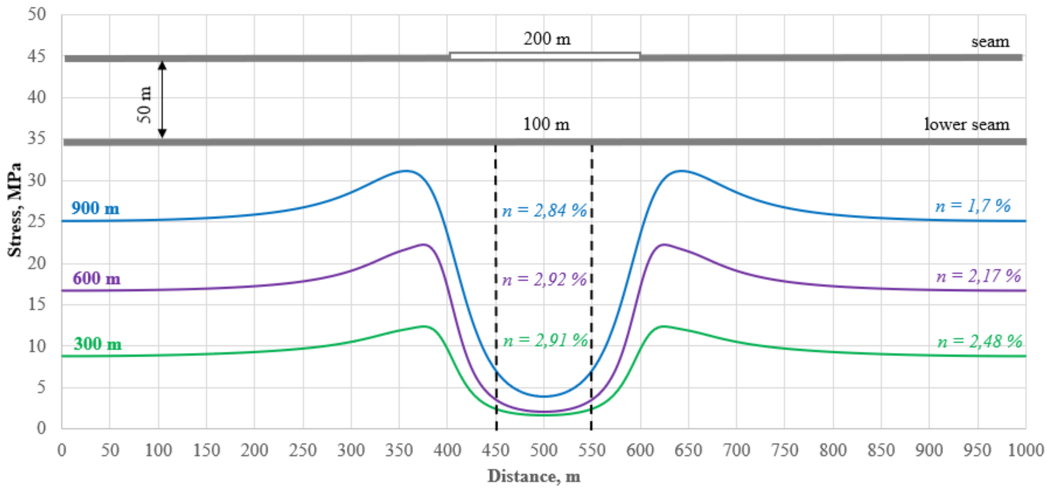

Figure-5. Influence of mining depth on stress distribution and effective porosity in the overworked (lower) layer.

Thus, the results of numerical modelling confirmed that with an increase in the depth of cover, the permeability of the lower seam located at a distance of 50 m from the working seam changes significantly. This significant change is a result of great changes in stress distribution demonstrated by the zones of stress relief. The difference between stresses before and after mining operations increases as the depth of cover grows.

At the same time, according to the methodology described in the regulation [10] and currently used in Russia, the extent of the gas emission zone in the floor should be taken as equal to 35 m regardless of the depth of cover. Such a limitation can be explained only by the fact that the methodology was developed quite long ago (in 1989) [11] and that mining conditions in Kuzbass at that time were different. Depths of cover did not exceed 300 m; these are depths where stress relief does not have a great impact on permeability. The fact that the depth of cover does not affect the extent of the gas emission zone in the roof can be explained by a decrease in natural gas contents with depth, which makes it meaningless to assess methane emissions from seams with low gas contents that are located at big distances from the working seam. These facts explain why the extent of the gas emission zone in the floor is limited to only 35 m while that in the roof reaches 300 m. However, using the formula (2) from the regulation currently in force [10] leads to the accumulation of errors in predicting methane emissions as the depth of cover increases.

CONCLUSIONS

The analysis of the methods for predicting methane emissions that are used in Russia [10, 11] showed that when calculating the parameters of gas emission zones in the roof and floor of the working seam, each of these accounts for different factors: working height only (2), working height and panel width (3), working height and depth of cover (4). Accounting for working height is what all these methods have in common. The methodology outlined in the regulation currently in force [10] takes into account only working height, with the extent of the gas emission zone in the floor being taken as equal to 35 m for any conditions. However, the literature review confirmed the need to take into account working height, depth of cover, and panel width as they cause changes in the zones of gas emission and water drainage. The fact that the regulation currently in force was developed in 1989, when coal was extracted from the Kuznetsk Basin at depths of cover that did not exceed 300 m, can explain why these parameters were not factored in the methodology as their impact on gas emissions in multiple coal seams at such depths is insignificant. However, since 2011, this methodology has been applied to all coal mines in Russia, including very deep mines (for example, depths of cover at mines operating in the Pechora Basin exceed 1,000 m). This means that it should be reviewed and adjusted to the current conditions.

The results of numerical modelling based on the finite element method showed that as the depth of cover increases, both the degree of stress relief and the permeability of underlying seams significantly increase, which must be taken into account when assessing the impact of overmining and predicting methane emissions from underlying coal seams. It was found that the distance of 35 m is not the limit for the extent of the gas emission zone as the effective porosity of the seam lying 50 m below the working seam increases by 34% and 68% at depths of cover of 600 m and 900 m, respectively. At the same time, if thick coal seams are mined using panel widths that do not exceed 200 m, the extent of the gas emission zone may not reach 300 m.

The study proved that in order to accurately predict methane emissions from adjacent coal seams, it is necessary to factor in such parameters as working height, depth of cover, and panel width. It is also very important to take into account the physical and mechanical properties of the interburden and the seam. Further research will be done into the impact of panel width on methane emissions from multiple seams to longwall goafs in order to improve methane emission control when mining multiple coal seams.

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