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INFLUENCE OF FACE ADVANCE RATE ON GEOMECHANICAL AND GAS-DYNAMIC PROCESSES IN LONGWALLS IN GASSY MINES

The article highlights currentness of studies into the influence of mine production rate on geomechanical and gas-dynamic processes in longwalls. It is shown that, despite the quick pace improvement in mining technique, there is essential backwardness of methodical and regulatory framework used to determine basic parameters of geomechanical and gas dynamic phenomena. The normative documents currently in force in Russia in calculating main roof caving steps in longwalls and the earlier research data on influence of longwall face advance rate on rock pressure phenomena in are analyzed. The research findings on undulating nature of change in methane content in high-production longwalls, which is related with movement processes in undermined rock mass, are examined. The field studies carried out in Zapolyarnaya Mine, Vorkutaugol reveal disagreement between the actual and calculated steps of main roof caving and recommend on improvement of the current calculation procedure. In Kotinskaya Mine, SUEK-Kuzbass, investigations of methane emission in longwalls determine the periodic nature of methane release maximums along a longwall panel. As the main causes of wide variation range of roof caving span (25–40 m), the authors show variable lithilogical composition and strength characteristics of roof rocks along longwall panels, significant range of output per face and the presence geological discontinuities. The future directions for research aimed to enhance safety and efficiency of high-production mining in series of gas-bearing coal seams are defined.

Key words: *underground mining, gas-bearing coal seams, longwall face advance, longwall panel, main roof, methane emission*
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Introduction

Wide use of modern, reliable and high-performance longwall machines in Russia in the recent decade has resulted in a jump in face output and advance rate [1]. New records in performance of underground coal mining in favorable ground conditions are reached every year. For example, in 2016 Yalevsky Mine and Talda-Zapadnaya Mine 1 of SUEK-Kuzbass coal mining company for the first time in Russia reached longwall face output more than 1 Mt in separate months of the year. In July 2017, Yalevsky Mine set up a new record in production of 1.56 Mt of coal per month in longwall 400 m long in thick coal seam 50. At the present time, high-production mining in series of gas-bearing coal seams, especially in difficult geological conditions, is accompanied with frequent unpredictable dynamic and gas-dynamic events and features low stability. Prevention of gas emission is the key objective in modern mines that develop closely spaced gas-bearing coal seams [2]. The jump in production output of coal mines greatly affects geomechanical [3–6] and geodynamic [7–9] behavior of host rock mass. The change in the geomechanical behavior is confirmed by the disagreement between the calculated and actual values of the initial and subsequent roof caving steps. Essential nonuniformity of gas emission in longwalls and periodic nature of gas emission maximums emphasized by some researchers also prove alteration of gas-dynamic conditions, which, in turn, increases insecurity of gas-bearing coal mining [7–11]. Furthermore, almost all largest accidents in gas-bearing coal mines in Russia in the past 10 years are associated with methane explosions. The present article authors believe that the high rate of mine accidents, injuries and fatalities exists due to obsolescence of practical guidance and regulatory framework. Major instructions, recommendations and regulations, which are currently in use in prediction of geomechanical and aero/gas-dynamic phenomena, or in substantiation of methods for ground control and gas emission monitoring in mines, are developed in the 1970s–80s [12–14]. In these documents, all calculations are valid for longwalls with a length to 250 m and output to 4 thousand tones per day per face. In the meanwhile at present in Russia, longwalls reach the length of 400 m at the output up to 55 thousand tones per day. Thus, the study of influence exerted by the increased rates of longwall advance on the geomechanical and aero/gas-dynamic behavior of rock mass under high-production extraction of mineral reserves in gas-bearing coal mines is an urgent problem to be solved to ensure safe and efficient high-rate gas-bearing coal mining.

The aim of this study was the analyze influence of longwall face advance rate on geomechanical and gad-dynamic processes in longwalls with a view to improving safety and economic efficiency of in a series of gas-bearing coal seams.

Research method

The integrated research method included analysis of literature data and international experience of high-production coal seam cutting, actual-to-date procedures of determining geomechanical behavior and aero/gas-dynamics of rocks as well as mine information on top coal caving steps, face output and methane emission in longwalls.

Theory

One of the main characteristics of geomehanical behavior of enclosing rock mass in longwall is top coal caving step. There are the initial step (when face is advanced from the longwall equipment installation site) and subsequent steps of top coal caving. The initial step exceeds the subsequent steps 3–4 times as a rule. During the period before the initial top coal caving, abutment pressure gradually grows in coal edges and pillars in longwall. During the initial top coal caving, all critical elements in rock mass, roof and longwall face supports experience the highest loads. Adequate determination of caving increment enables efficient ground control and longwall safety. The subsequent top coal caving steps in a series of gas-bearing coal seams condition loading cycle on power support and squeezing of face coal, and also have a considerable effect on gas emission rate in the longwall face [8].

Top coal caving parameters are determined based on regulatory documents specific for each coal basin. For example, in the Pechora Coal Basin, the recommendations [14] developed in 1991 and reissued without almost inalterably in 2001 are used. According to the regulations [14], the steps of the initial and subsequent top coal caving, l_i and l_s, are given by:

$$l_i = (3-4)C\sqrt{\sigma_t T}\text{, m} \quad (1)$$

$$l_s = C\sqrt{\sigma_t T}\text{, m} \quad (2)$$

where C is a coefficient assumed as 0.4 for easily caving main roof, 0.7 for moderate-hard roof and 0.9 for hard and very hard roofs; T is the active roof thickness assumed as 5 coal seam thicknesses and even 10 coal seam thicknesses in case of hard roof; σ_t is the weighted mean value of rock mass extension strength, kg/cm^2.

In the Kuznetsk Coal Basin, the Temporal guidelines on calculation of the initial and subsequent top coal caving steps in in-strike longwall mining in Kuzbass (developed by VostNII in 1973) [13], alongside the strength characteristics of host rock mass, accounts for the longwall face advance rate, longwall length and dip angle of coal seams.

According to [13], the initial $r^{mr}{}_i$ and subsequent $r^{mr}{}_s$ steps of main roof caving are given by:

$$r_i^{mr} = 36(1+\sin\alpha)\frac{F_{mr}\sqrt{V}}{\sqrt{Д}} + 10.5\sqrt{V}(1+\sin\alpha)e^{-0.7\frac{h_{mr}}{F_{mr}}}, \quad (3)$$

$$r_s^{mr} = 10.5\sqrt{V}(1+\sin\alpha)e^{-0.7\frac{h_{mr}}{F_{mr}}}, \quad (4)$$

where α is the dip angle of coal seam, deg; F_{mr} is the factor of hardness of the main roof; V is the average rate of the longwall face advance, m/s; $Д$ is the longwall length, m; h_{mr} is the height of dynamic lamination zone in the main roof, m.

The undulating change in methane content of high-production longwall faces is connected with the processes

Table 1. Basic conclusions on rock pressure phenomena under different longwall face advance rates (according to [19])

Researcher	Basic conclusions
Perm Research Institute	When longwall face advance rate is changed from 0.5 to 2 m/day, roof sagging is decreased up to 30%
Skochinsky Institute of Mining	Advance rate increase influences caving increment to a certain limit. This limit is no more than 1.5 m/day for hard roof. Dynamic events are possible as the overhand is longer and bending strength of rocks is lower
A. K. Kovrizhin	The face advance rate increased to 3.0–4.5 m/day improved roof condition. Stoppage of face advance during high-rate longwalling affects roof condition
V. T. Davidyants	Longwall face advance rate of 10–12 m/day reduces roof sagging by 10 % as compared with the face advance rate of 3–4 m/day. No positive effect should be expected under further increase in the rate of face advance
A. M. Ilshtein	An increase in the face advance rate to 5–10 m/day has no effect on the decrease in the roof rock displacement magnitudes. Additional displacements in roof rocks during subsequent caving are independent face advance rate
D. T. Spelding	During high-rate longwall advance, the roof overhand can be rather large. Higher load on roof support, higher bending stresses in rock mass
K. I. Ivanov	Under hard roof conditions, an increase in the longwall face advance rate cannot influence positively subsequent roof caving
N. M. Sadykov	Roof rocks can accumulate much potential energy that violently liberates in hard roof fracturing
N. M. Dudkin	As main roof caving increment is enlarged, longwall face advance rate should increased to certain critical limits beyond which the main roof caving coordinates occurs in nonhazardous zone
V. P. Belov	In stronger roof rocks, effect of the face advance rate on roof rock displacements gets weaker
A. P. Bobylev V. I. Kulikov V. I. Naumenko	Frequency and value of dynamic displacements in roof rocks decrease as longwalling face advance velocity is raised. The most favorable face advance rate is round 24 m/day
Yu. N. Kuznetsov	When longwall face advance rate ranges from 12 to 27 m/day, sagging of main roof is localized in gob
S. I. Kalinin	Higher rate of longwall face advance favors geotechnical situation in the face area

Table 2. Main roof caving data in Zapolyarnaya Mine, Vorkutaugol

Longwall	Longwall length, m	Seam	Face advance rate, m/day	Main roof caving step, m			
				Calculation		Actual	
				l_i	l_s	l_i	l_s
624-yu	222	Troinoi	5	50–67	16–17	No data	20
314-s	201	Troinoi	–	56–75	13–19	75	20
113-yu	250	Chetvernoi	–	25–33	8	40	8
724-yu	190	Troinoi	–	51–68	16–18	70	20
614-s	255	Troinoi	–	55–73	18	No data	No data
714-s	150	Troinoi	6	72–95	20–23	No data	No data
834-yu	255	Troinoi	5.7	45–60	13–14	57	55
414-s	195	Troinoi	–	51–68	20	70	20
514-s	222	Troinoi	4.8	48–64	16	60	15
514-s	297	Chetvernoi	4.8	51–68	17	70 (toward 100)	15–20
614-s	285	Chetvernoi	4.6	57–76	19	70 (toward 100)	20
714-s	296	Chetvernoi	4.7	64–85	21	116	No data

of undermined strata movement in some research works [15, 16]. Other works [17] say that main roof caving influences gas emission rate as longwall face is advanced: gas emission values reach maximum as longwall face arrives at the roof caving point and change gas conditions in the longwall. However, the article authors think that by the moment of longwall arrival at the caving point, gas emission is only maximum from the coal seam under cutting, due to formation of a large main roof overhand, which imposes load on coal sidewalls, as well as owing to an increase of stresses in the abutment pressure zone and expansion of zones of limiting state and squeezing. Considering that in gas balance of extended longwalls and longwall panels (in mining a series of gas-bearing coal seams), gas emission from the seam under cutting makes round 10–15% of the total gas emission in the longwall face, the influence of the main roof caving seems insignificant and merely to a certain degree explains nonuniformity of gas emission in the longwall face from the seam under cutting (the other conditions being equal). In other works [18], it is stated that the increment of host rock strata caving is one of the main factors to determine the zone of high-rate gas emission. Thus, hard rocks in the over- or undermined strata contribute to an extension of high-rate gas emission zone and, vice versa, easily caving rocks reduce the size of such zone [18].

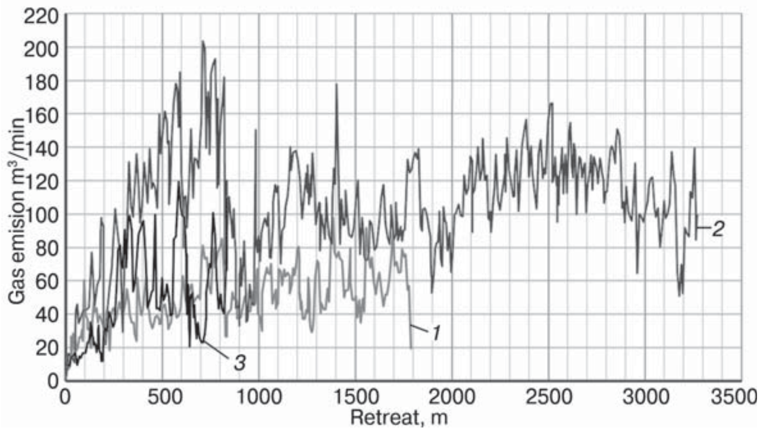

Fig. 1. Gas emission versus length of longwall panels:
***1* — longwall panel 5208; *2* — longwall panel 5209; *3* — longwall panel 5210**

Research results

It seems very interesting to analyze literature data on influence of the longwall face advance rate on rock pressure discussed by Korshunov in his dissertation [19]. It follows from the discussion that researchers come to extremely contradictory conclusions (**Table 1**): some scientists state that roof rock displacements are independent of the longwall advance rate, the other researchers inform on the longwall advance rate at which the roof rock condition is improved but present positively different values such as 1.5, 3, 10 and 12 m. Furthermore, these researches were implemented in the time when underground coal mining was characterized by low rates of face advance, as a rule, 5–7 m/day, while currently high-production longwall mining in favorable ground conditions features face advance rates of 10–15 m/day (some times up to 30 m/day).

Aiming to assess accuracy of determining the main roof caving step, the calculations by the procedure from [14] were compared with the actual data from Zapolyarnaya Mine of Vorkutaugol company. The comparative analysis (**Table 2**) allowed concluding that the actual data exceeded the calculation results, as a rule.

In terms of Kotinskaya Mine, SUEK-Kuzbass, gas emission was assessed during high-production longwalling in

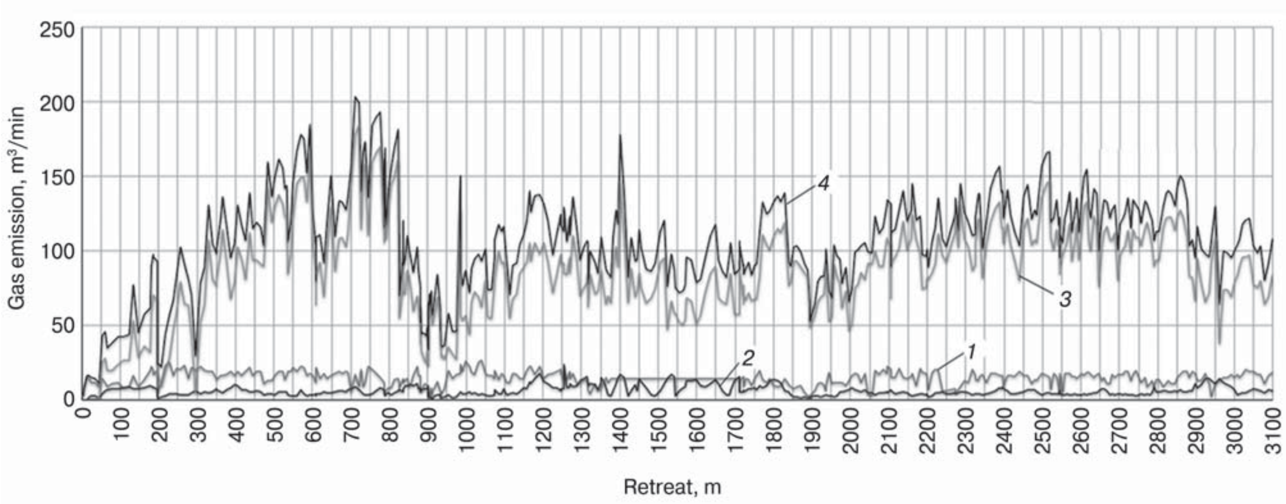

Fig. 2. Gas emission per separate sources along longwall panel 5209:
***1* — ventilation; *2* — underground goaf drainge; *3* — surface goaf drainage; *4* — cumulative**

seam 52 having average thickness of 4.3 m. Gas emission relationship with the length was plotted for longwall panels 5208, 5209 and 5210 (**Fig. 1**). Evidently, high-production longwall mining at the output to 20000 t/day (face advance rate to 18 m/day) features considerable nonuniformity of gas emission and noticeable periods when total gas emission reaches peak values.

For the detailed analysis of gas emission dynamics, gas emission in longwall panel 5209 was plotted with regard to each gas source and with determined periods of peak total methane emission (**Fig. 2**).

The accomplished analysis shows that disagreement between the calculated and actual data of main roof caving increment in Zapolyarnaya Mine, Vorkutaugol is caused by a few drawbacks of the procedure [14], namely:

1. No accounting is made for technological factors (longwall length, face advance rate) which have a considerable influence on the roof caving step. By preliminary estimate, for the face advance rate to 5 m/day in longwalls 200–300 m long, the disagreement between the actual roof caving increment and calculated values from the empirical formulas can reach 20%.

2. No account is made for strength and deformation characteristics of rock mass and their changes in the zones of stress relief and high rock pressure. Strength testing data fail to reflect real strength of fractured rock mass (especially bending strength). For this reason, it is necessary to perform additional research and to introduce a structural weakness coefficient to pass from the properties of test specimens to the properties of real fractured rock mass, which is important for estimating effect of undermining.

3. No sufficient justification of the parameter of active roof thickness assumed as 5 seam thicknesses for easily caving, medium-hard and hard roofs and as 10 seam thicknesses for very hard roofs while many researches have found that this parameter has a wide range of change depending of specific geological and geotechnical conditions.

As a result of studies carried out for Kotinskaya Mine, SUEK-Kuzbass, it is found that total absolute methane emission in a longwall panel is variable along its length and features noticeable frequency of maximum values which exceed average data by 30–40% and sometimes by more than 2 times. The studies reveal that maximum gas emission is behind the main roof caving, and the delay size is conditioned by the distance to the undermined closely spaced seams as the main source of gas emission to the gob. Such dependence of gas emission is also observed in foreign mines in coal seams with high gas content [20].

The wide range of change in frequency of increased gas emission (20–45 m) is explained, in this article authors' opinion, by instability of longwall face operation (considerable variation in face output and advance rate), variability of strength characteristics and lithology of roof rocks in seam 52 within the longwall panel limits, as well as by the presence of geological discontinuities that drastically change permeability of rocks and govern the rate of gas emission from closely spaced coal seam to gob area.

Fig. 3 shows the plots for the increment in roof caving in different strength roof rocks in a longwall 300 m long, at the seam dip angle of 5º, according to the calculations from the formula (4) [13]. As is seen in the figure, the change in the longwall face advance rate from 2 to 25 m/day results in the main roof caving increment 4.5–5.5 times. The highest step in the roof caving is observed when the rate of face advance is changed from 1 to 5 m/day—2 times.

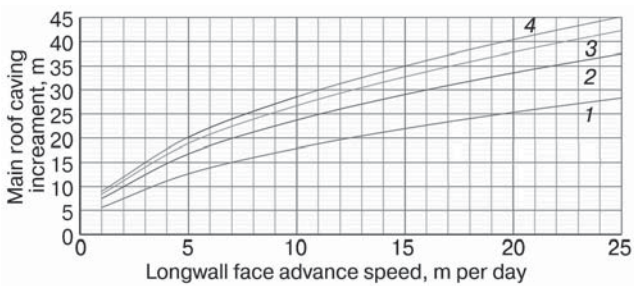

Fig. 3. Influence of longwall face advance rate on the main roof caving increment:
***1* — intact rock strength 30 MPa; *2* — intact rock strength 50 MPa; *3* — intact rock strength 70 MPa; *4* — intact rock strength 90 MPa**

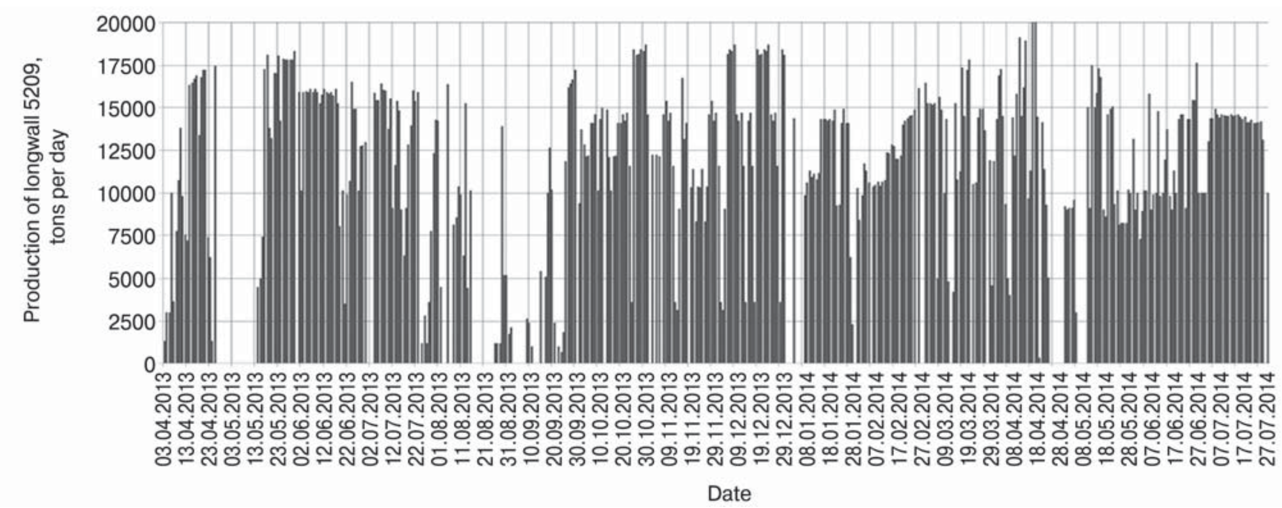

Fig. 4. History of production output in longwall panel 5209

Moreover, even at the constant rate of face advance in longwall panel 5209 (round 12 m/day), the variation in lithological composition with an increase in rock strength from 50 to 90 MPa causes the increment in the roof caving step from 27 to 32 m. At the same time, the analysis of the data on output per longwall face 5209 (**Fig. 4**) points at the unstable operation of the longwall and at considerable fluctuation of its production output, which is governed, among other things, by gas emission nonuniformity conditioned by the long spans of the main roof caving.

It should be mentioned that some disagreement between the maximum gas emission period (25–40 m) in actual conditions of Kotinskaya Mine, SUEK-Kuzbass and the calculated main roof caving step (27–32 m) can result from the shortcoming of the procedure [13] developed in 1973 when the rate of longwall face advance was not higher than 4 m/day. In the procedure [13], the largest changes in the caving step are observed in the range to 5 m/day while the further increment in the roof caving step with the higher face advance rate is made more chary: predicted roof caving increment is not so great as in the range of actual face advance rates in the time of the procedure development (1973). Thus, this procedure needs additional commercial-level testing under conditions of high-production longwalling.

Conclusion

Recently in Russia, underground coal mining in favorable geological conditions has reached new level of productivity: output per face exceeds 50 thousand tons per day at the longwall face advance rate of 27 m/day. The available procedures to calculate main roof caving steps [13, 14] and to design mine ventilation [12] were developed in the time when coal production featured low performance by an order of magnitude worse than the current indexes, which necessitates studies into the influence of longwall face advance rate on gas–geomechanical behavior of rock mass in longwall panels. The modern high-performance longwall machines ensure increased output per face owing to enhanced power supply capacity and also much longer extraction panels (in Russia longwalls reach 400 m and longwall panels are to 4.5–5 km long), which results in the growth of undermined area, expansion of its influence zone and, consequently, higher gas emission from undermined coal seams. The review of literature and analysis of influence exerted by longwall face advance rate on geomechanical behavior and gas-dynamic processes in enclosing rock mass have proved the essential dependence of the initial and subsequent main roof caving increment on the longwall face advance rate and roof rock strength. The increase in the face advance rate results in the increment in the main roof caving step which, in its turn, governs expansion of total cave-in and extensive fracturing zones that condition permeability of undermined strata and gas emission from closely spaced seams. The relationship is found between the main roof caving step and the periodic nature and spacing of peak total methane emission in longwall mining of a series of gas-bearing coal seams. For Kotinskaya Mine, SUEK-Kuzbass, the spacing of maximum methane emission values (25–40 m) is determined and the methane emission variability along longwall panel is explained. The key factors to govern the main roof caving step are set as the rate of the longwall face advance, strength properties of roof rocks and the effect of geological discontinuities. The authors show that more reliable methane emission prediction aimed to determine rational gas emission control in longwalls requires that the main roof caving step in variable strength rocks is estimated with regard to rock mass fracturing as the main criterion of difference between the strength characteristics of real rock mass and laboratory test specimens. It is worthy of mentioning that with an increase in the longwall face advance rate and roof rock caving step increment, nonuniformity of total gas emission in longwalls grows: maximum values of gas emission in gob from undermined seams are observed periodically, and their frequency and absolute gas emission value are governed by strength characteristics of undermined rock mass, distance to the closest-spaced gas-bearing seam and by the presence and parameters of geological discontinuities. These aspects should be taken into account in selecting and justifying gas emission control measures in longwalls. In mining a series of coal seams with high gas content, gas drainage and ventilation designs are imposed with the exclusive standards as it is necessary that gas emission control in this case is rated at periodic peak methane releases in longwalls.

The nonuniformity of gas emission from undermined rock mass can be reduced by making a longwall longer, from

250–300 to 400–480 m, by means of decreasing the rate of the longwall face advance (at the same production output), and, consequently, by shorter step of the main roof caving. However, in this case, smoothing of gas emission maximum boundary will be accompanied with an increase of its minimum boundary since the total gas emission grows in this case owing to expansion of undermined area and extension of undermining influence zone. At the same time, the decrease in gas emission nonuniformity allows favorable conditions for gas release control in longwalls.

The further research is connected with the check and improvement of the current procedure for roof caving calculation [13] and with the development of a prediction procedure for gas-dynamic and geomechanical behavior of rocks under longwall mining of a series of gas-bearing coal seams with regard to geological and geotechnical data, and with the substantiation of gas emission control (including deep mines).

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