A new method for layout layer optimization of long horizontal borehole for gas extraction in overlying strata: a case study in Guanshan coalmine, China

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A new method for layout layer optimization of long horizontal borehole for gas extraction in overlying strata: a case study in Guhanshan coalmine, China

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Abstract: The large emission of pressure-relief gas in coal mining will cause atmospheric greenhouse effect. Arranging long horizontal borehole (LHB) to extract the gas is an effective solution. However, the determination of LHB layout layer in strata has a decisive effect on efficient gas extraction. A "zone-block" theoretical method for determining the LHB layout layer, in present study, was proposed by combining physical simulation test, theoretical analysis and engineering application. Three processes of the method were presented. Firstly, stable fractured subzone (SFSZ) was the optimum zone of the LHB layout based on the analysis of mining-induced fractures distribution and the borehole stability, and spatial location boundaries of the SFSZ in overlying strata were defined. Secondly, the SFSZ was divided into nine-grid blocks, the LHB layout suitability rate of each block were determined according to borehole stability rate, fracture permeability rate and gas accumulation rate. Finally, the LHB drilling could be conducted sequentially according to the layout suitability rate of each block in SFSZ. Field application results show that: the maximum and average amount of pure gas extracted through single borehole arranged in block I can reach up to 5.52 and 2.43 m³/min, respectively; and the pure amount in the entire extraction stage of the borehole is 2.53 and 6.69 times of boreholes arranged in blocks II and III, respectively. The proposed method can effectively determine the LHB layout layer in strata, so as to improve the gas extraction efficiency and ensure safe and green mining.

Keywords: "Zone-block" theoretical method; Long horizontal borehole; Layout layer optimization; Pressure-relief gas extraction; Safe and green mining
Declarations

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material

The data studied in this paper are transparent and can be shared.

Code availability

Not applicable.

Author Contributions

Wenbing Guo and Mingjie Guo provided the idea of establishing long horizontal borehole layout method in overlying strata and drafted its initial concept, Mingjie Guo wrote the initial version of the manuscript. Ruifu Yuan reviewed the initial manuscript and revised it. Yi Tan, Erhu Bai, Gaobo Zhao, and Zhibao Ma set up the test bed. Gaobo Zhao, Guofu Li, and Erhu Bai conducted the analyses. Wenbing Guo and Mingjie Guo edited the manuscript. All authors reviewed and finalized the manuscript.

Ethics approval

Not applicable.

Consent to participate

All the authors participated in the study of the paper and agreed to sign.

Consent for publication

All the authors agree to publish the paper in Environmental Earth Sciences.
A new method for layout layer optimization of long horizontal borehole for gas extraction in overlying strata: a case study in Guhanshan coalmine, China

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Abstract

The large emission of pressure-relief gas in coal mining will cause atmospheric greenhouse effect. Arranging long horizontal borehole (LHB) to extract the gas is an effective solution. However, the determination of LHB layout layer in strata has a decisive effect on efficient gas extraction. A "zone-block" theoretical method for determining the LHB layout layer, in present study, was proposed by combining physical simulation test, theoretical analysis and engineering application. Three processes of the method were presented. Firstly, stable fractured subzone (SFSZ) was the optimum zone of the LHB layout based on the analysis of mining-induced fractures distribution and borehole stability, and spatial location boundaries of the SFSZ in overlying strata were defined. Secondly, the SFSZ was divided into nine-grid blocks, the LHB layout suitability rate of each block were determined according to borehole stability rate, fracture permeability rate and gas accumulation rate. Finally, the LHB drilling could be conducted sequentially according to the layout suitability rate of each block in SFSZ. Field application results show that: the maximum and average amount of pure gas extracted through single borehole arranged in block I can reach up to 5.52 and 2.43 m$^3$·min$^{-1}$, respectively; and the pure amount in the entire extraction stage of the borehole is 2.53 and 6.69 times of boreholes arranged in blocks II and III, respectively. The proposed method can effectively determine the LHB layout layer in strata, so as to improve the gas extraction efficiency and ensure safe and green mining.

Keywords “Zone-block” theoretical method; Long horizontal borehole; Layout layer optimization; Pressure-relief gas extraction; Safe and green mining

Bullet points:

(1) SFSZ was the optimum zone of LHB layout, and SFSZ boundaries in overburden were defined.

(2) The LHB layout suitability rate of each subdivided block in SFSZ was determined.

(3) A "zone-block" method to determine layout layer of LHB in overlying strata was proposed.
1 Introduction

Coal mining induces the failure of overlying strata and the evolution of fracture channels, which is further accompanied by the emission, flow, and convergence of pressure-relief gas (Cheng et al. 2021). However, accumulation of a large amount of pressure-relief gas in goaf is a serious safety hazard for safe mining (Zhou and Wang 2018). On the other hand, the gas is an important industrial raw material and a new type of clean energy resource, and its free emission causes waste of resources and atmospheric greenhouse effect (Liu et al. 2017). Therefore, effective extraction of the pressure-relief gas is of great practical significance to realize safe and green mining.

The uneven distribution of fracture channels in overlying strata of a goaf leads to different degrees of gas flow and convergence. In general, the overlying strata are often divided into the caved zone, fractured zone and bending zone in the vertical direction according to the distribution of fracture channels (Peng and Chiang 1984). Based on this, many scholars have carried out extensive research on the gas migration in the fracture channels so as to effectively extract pressure-relief gas in goaf. Qian et al. (1996 and 1998) put forward a key stratum theory, and studied the O-shape circle distribution characteristics of fracture channels. They further pointed out that the O-shape circle was the gas flow channel and storage space. Karacan and Goodman (2011) conducted a probabilistic modeling study to estimate the size of the gas emission zone. Yuan et al. (2011) and Guo et al. (2012) determined the efficient gas extraction range, and proposed the annular fracture ring theory of overlying strata and the double circle theory in order to evaluate the evolution of mining-induced fractures. Qu et al. (2015) proposed a three-zone conceptual model comprising a fractured gas-interflow zone, a de-stressed gas-desorption zone, and a confined gas-adsorption zone in overlying strata of a longwall panel, accounting for the coupled behavior of strata deformation and gas flow. Li et al. (2018) and Zhao et al. (2020b) proposed the elliptic–paraboloid zone as an addition to mining-induced fracture theory and developed a simplified model of mining-induced fractures with a round-rectangle trapezoidal zone. Furthermore, Feng et al. (2018) determined the gas enrichment area of fractured zone, and further calculated the gas storage space area under different advancing distance of working face.

Moreover, the stability of borehole also significantly influences the efficient gas extraction. For the stability of horizontal borehole, Liang et al. (2016) used the method of support vector machine (SVM) to establish the diagnostic model for horizontal borehole wall sloughing in the process of drilling construction. Jia et al. (2017) used the particle flow code (PFC2D) to analyze horizontal borehole failure mechanism during drilling in the shale of well-developed weak planes. Lan and Moore (2017) conducted numerical simulation study on the two failure mechanisms including shear failure and tension fracture of horizontal borehole during drilling. Zhao et al. (2020a) studied the three-dimensional deformation characteristics of horizontal borehole under steady vertical load, by using a gas drainage borehole stability dynamic monitoring device. However, a quantitative description of the heterogeneity of fracture structures is difficult because of the complexity and
irregularities of fracture structures in overlying strata affected by mining. Therefore, the stability of long horizontal borehole (LHB) in overlying strata affected by mining has rarely been investigated till date.

As a result, the results of aforementioned studies provide a theoretical basis for arranging high-level boreholes, high drainage roadway, and surface vertical boreholes to extract pressure-relief gas in goaf (Pan and Wood 2015; Sun et al. 2017). However, it has become a trend that adopting LHB extraction method replaces the three methods to extract the pressure-relief gas, because it has the advantages of cost effectiveness, long extraction time, and high construction efficiency (Xie et al. 2012; Johnny et al. 2017). However, owing to the horizontal arrangement of the LHB and small diameter (about 100 mm) and extraction radius, the requirements of overburden layer for the layout of the LHB are more stringent. The following three parameters are involved: First is the stability of the layout layer, which ensures the prevention of the occurrence of collapse and plugging of the LHB. The second is the permeability of the layout layer, which ensures the continuous inflow of gas into the LHB. The third is gas accumulation of the layout layer, which ensures that the gas extracted by the LHB has a high concentration value.

Thus, the optimization of layout layer of the LHB in overlying strata is the key to efficient gas extraction. However, currently, the layout layer of the LHB is mostly based on engineering experience and physical or numerical simulation results (Ruban et al. 2012; Wang et al. 2018). Theoretical analysis and determination of the layout layer of the LHB based on the above-mentioned three parameters have rarely been studied.

Therefore, the main objective of this study was to propose a “zone-block” theoretical method to determine the layout spatial location of the LHB for gas extraction. First, based on the O-shape circle theory, physical simulation test and theoretical analysis were conducted to analyze and define the optimum zone of the LHB layout in overlying strata. Second, based on blocks division of the zone, the LHB layout suitability rate of each block were determined according to the above-mentioned three parameters. Then, the “zone-block” theoretical method was proposed. The proposed method was employed for a field test of the Jiaozuo Guanshan coal mine in Henan Province, China.

2 Geological settings

Guhanshan coal mine is located in the north of Henan Province, China. The coal mine is a highly gassy mine, with a gas content of approximately 16.62 m³·t⁻¹ and a pressure of 0.2–2.42 MPa. The No. 16031 working face of the coal mine with coal seam no. 2 in Jiaozuo coalfield was used as representative site of the study, and the longwall and slice mining technology was adopted for investigating the working face. Moreover, a caving method was used to manage the roof. The working face showed a coal seam with a strike length, an inclined length, an average buried depth, and a mining thickness of 600, 155, 650, and 3 m, respectively. The gently inclined coal seam with an average inclination of 12° was utilized. The geological column and lithology parameters of the partial strata of the working face are shown in Fig. 1.
3 Methods

Noteworthy, the goaf becomes inaccessible after its closure, which renders it challenging to conduct additional measurements and further in situ study (Karacan 2015). Therefore, ground physical model simulations (Feng et al. 2018) have been widely applied in mining engineering research. A physical model of a rock mass was constructed at a specified scale using materials with mechanical properties similar to those of underground rock masses in order to simulate the actual mining with similar boundary conditions. In this study, based on the geological and mining conditions of working face 16031, a physical simulation test was conducted to simulate the distribution characteristics of the fracture channels of gas migration in overlying strata and the stability of the LHB in different strata layers, so as to determine the layout spatial location of the LHB for gas extraction.

3.1 Laboratory bench

The experiment was performed using a two-dimensional (2D) plane simulation test bench from State and Local Joint Engineering Laboratory for Gas Extraction and Ground Control of Deep Mines in Henan Polytechnic University. It contains the following three parts: a main device, a hydraulic loading system, and a monitoring system (Fig. 2).
3.2 Establishment of the experimental table

For physical simulation, gypsum, light calcium carbonate, and cement were selected as cementing agents, and sand was used as the skeleton in the model. Similar materials were mixed in varying proportions to simulate different rock strata with different strength (Fumagalli 1973). Furthermore, each rock stratum was separated from the others by uniformly spreading the mica powder on their surfaces, so as to ensure the accuracy of rock stratum failure and fracture development. The LHB was made of special semicircular wood strips. During the construction of the model, five strips were laid along the entire length of the model. After the model baffle was dismantled, the wood strips were removed to form the LHB. The boreholes were, respectively, 3, 15, 25, 35, and 45 m away from coal seam. Based on the currently used similarity criterion, the similarity constants in line with the actual situation of the working face were calculated and listed in Table 1.

| Model size (mm × mm × mm) | Similarity constant | Geometry | Poisson’s ratio | Weight | Strength | Time |
|----------------------------|---------------------|---------|----------------|--------|----------|------|
| 2500 × 200 × 1300          | 50                  | 1.0     | 1.73           | 86.5   |          | 7    |

The test was simulated for No. 10 to 20 of the strata (Fig. 1), and 0.18 MPa of self-weight stress of overlying strata was applied on the top of the model. Based on the distribution of the prototype coal strata and as-obtained similarity constant, the required mechanical properties of the coal strata and the proportion of similar materials in the model were calculated. Table 2 lists the amount of layered similar materials used in the model.
Table 2 The amount of layered similar materials used in the model

| Geological column No. | Layer                  | Thickness (cm) | Sand (kg)  | Calcium carbonate (kg) | Cement (kg) | Gypsum (kg) |
|-----------------------|------------------------|----------------|------------|------------------------|-------------|-------------|
| 10                    | Mudstone               | 17.8           | 111.25     | 6.68                   | 15.58       |             |
| 11                    | Medium grain sandstone | 11.4           | 64.13      | 10.69                  | 10.69       |             |
| 12                    | Sandy mudstone         | 13.8           | 90.56      | 3.88                   | 9.06        |             |
| 13                    | Mudstone               | 9.0            | 54.00      | 4.05                   | 9.45        |             |
| 14                    | Siltstone              | 9.6            | 60.00      | 7.00                   | 5.00        |             |
| 15                    | Mudstone               | 3.4            | 20.40      | 1.53                   | 3.57        |             |
| 16                    | Sandy mudstone         | 12.4           | 81.38      | 3.49                   | 8.14        |             |
| 17                    | Fine grain sandstone   | 15.2           | 91.20      | 11.40                  | 11.40       |             |
| 18                    | Sandy mudstone         | 9.4            | 61.69      | 2.64                   | 6.17        |             |
| 19                    | Coal seam              | 6.0            | 37.50      | 5.25                   | 2.25        |             |
| 20                    | Mudstone               | 2.0            | 12.00      | 0.90                   | 2.10        |             |

Notably, the model consists of 9 rows and 25 columns of measuring points, distance between the measuring points is 10 cm, and the outermost column is 5 cm away from the boundary of the model shelf. A row of measuring points was arranged at 1 cm above each borehole, and then another row was arranged at 10 cm above it. For the convenience of observation and analysis, the surface of the model was painted white and the borehole was colored.

3.3 Simulation test

The simulated actual mining length of the model was 85 m. A coal pillar with a length of 20 m was reserved on both sides of the working face, which could reasonably reduce the boundary effect caused by the model during the test, and the open-off cut of the working face was 5 m. The advanced distance of working face was designated as 2 and 3 m alternately, which could imitate the complete actual mining process in the field. The coal seam was subjected to a uniform load during the physical simulation.

4 Results and discussion

4.1 Layout zone of the LHB

Considering the distribution of fracture channels for gas migration and the stability of the LHB as two controlling factors, the simulation test results were analyzed, so as to determine the optimum zone for the LHB layout for gas extraction.

4.1.1 In the vertical direction

(1) Distribution of fracture channels

The analysis of the distribution characteristics of fracture channels in vertical “three zones” (Fig. 3) indicates the following results.
The caved zone. The height of the zone is 8.5 m from the coal seam roof, and the separation fracture rate can reach up to 313.4 \( \text{mm} \cdot \text{m}^{-1} \). Nonetheless, the development of the fractures is quite unstable and the mutation is very large, which is obvious only on both sides of the zone and near the shear dislocation.

The fractured zone. The height of the zone is 36.4 m from the coal seam roof. Owing to the existence of voussoir beam structure, the separation fracture rate on both sides of the zone can reach up to 129.5 and 86.6 \( \text{mm} \cdot \text{m}^{-1} \), respectively. Moreover, the fractures development is stable, with a width in the range of 25–30 m. In the middle of the zone, the separation fracture rate decreases significantly.

The bending zone. No through-layer fractures are developed in the zone. Furthermore, with the bending and subsidence of the strata, the separation fracture develops, however, the overall separation fracture rate is very small, less than 10 \( \text{mm} \cdot \text{m}^{-1} \).

Therefore, from the perspective of distribution of fracture channels, the caved zone and fractured zone are suitable zones for the LHB layout for gas extraction.

(2) Stability of the LHB

According to the division results of vertical “three zones”, three boreholes, 3 m (red, located in caved zone), 25 m (blue, located in fractured zone), and 45 m (yellow, located in bending zone) away from coal seam roof, were considered for analysis, respectively. The LHB was arranged along the mining advancing direction; therefore, they were affected by the entire stage of mining. Thus, considering a certain width of the side of the open-off cut of model where the strata fracture was serious, the stability of the LHB in each zone was analyzed (Fig. 4).
Fig. 4 Stability of the LHB: (a) In caved zone; (b) In fractured zone; and (c) In bending zone.

Mining causes the movement and deformation of the strata, which could lead to the failure of boreholes arranged in these layers due to tensile and shear action (Lan and Moore 2017). In caved zone, many shear dislocations of the LHB are present, and the borehole is completely destroyed [Fig. 4(a)]. In contrast, in fractured zone, the LHB basically maintains the original layer feature, which is more stable than that of the borehole in caved zone; however, the tensile fracture and tensile-shear failure may occur locally [Fig. 4(b)]. In bending zone, the LHB only shows bending deformation with the stratum, and the borehole stability is the best [Fig. 4(c)]. Consequently, the fractured zone and bending zone are suitable zones for the LHB layout for gas extraction.

In summary, the analysis of the two controlling factors, vertically, indicates that the fractured zone is the suitable zone for the LHB layout for gas extraction.

4.1.2 In the horizontal direction

The fractured zone is suitable for the LHB layout for gas extraction, thus, within the height of this zone, the fracture channels are divided into horizontal “four subzones” according to their morphological characteristics. Each subzone is symmetrically distributed with compaction fractured subzone as the center (Fig. 5).

These subzones are described as follows.

Subzone I. Initial fissure subzone: The strata are slightly affected by mining, and no new fracture channel is generated. The strata basically maintain the original rock state.

Subzone II. Tensile fractured subzone: The strata have experienced the process of “original rock stress – bearing (abutment pressure) – unloading” and the fracture channel is slightly developed; however, the separation fracture rate is less
than 1 mm·m$^{-1}$. Considering the green measuring point with horizontal deformation of about 2 mm·m$^{-1}$ as the boundary point [Fig. 5(a)], the initial boundary of the subzone was obtained by connecting with the mining boundary.

**Subzone III.** Stable fractured subzone (SFSZ): The strata were broken down at a certain angle, and the broken stratum rocks formed voussoir beam structure in the subzone. The analysis of the entire stope space indicates that the broken rocks of the stratum hinge with each other, forming “circular bearing beam” structure. Moreover, the structure consists of a large number of fracture networks, and then forms a circular zone of gas flow and convergence. The separation fractures in this subzone are obviously developed (the separation fracture rate of the upper, middle, and lower strata can reach up to 195.6, 148.2, and 122.1 mm·m$^{-1}$, respectively), and are stable for a long time, with a width of about 25 m. Furthermore, the broken boundary of the strata layers is the outside boundary of the subzone.

**Subzone IV.** Compaction fractured subzone: The fractures get gradually closed with the periodic weighting of the main roof. Importantly, research statistics show that (Qin and Xu 2018) the separation fracture rate of 3‰ can be used as the critical value of fracture closure of the broken stratum layer after bearing. The simulation test results (Fig. 5) also verify this result. Therefore, considering the separation fracture rate of 3‰ as the boundary, it is defined as the inside boundary.

As a result, based on the analysis of the distribution of fracture channels in each subzone, horizontally, the SFSZ was found to be the suitable zone for the LHB layout for gas extraction.

**4.1.3 The optimum layout zone**

Based on the comprehensive analysis of the two controlling factors, the SFSZ is considered as the optimum zone for the LHB layout for gas extraction in overlying strata. Moreover, according to the law of gas migration, the pressure-relief gas converges to the uphill side of the SFSZ in an annular and upward manner under the action of diffusion, uplift, and permeability. Therefore, for the strike longwall mining face, the LHB should be arranged along the strike on the uphill side of the SFSZ (Fig. 6).
Fig. 6 Regional division and the LHB layout in overlying strata: (a) Schematic illustration of dip section; and (b) Three-dimensional diagram. Note: $B_t$, $B_b$, $B_o$, and $B_i$ are the top, bottom, outside, and inside boundary of the SFSZ, respectively; $\psi_s$ and $\psi_d$ are the critical deformation angle of overlying strata in strike and dip, respectively; and $\beta_s$ and $\beta_d$ are the breaking angle of overlying strata in strike and dip, respectively.

4.2 Defining the boundaries of the layout zone

The boundary of the SFSZ (shown in Fig. 6) is defined as follows: Vertically, the SFSZ boundary is defined as the normal distance from the coal seam roof, which is divided into bottom boundary ($B_b$) and top boundary ($B_t$). Horizontally, the SFSZ boundary is defined as the horizontal distance from the adjacent coal pillar, which is divided into outside boundary ($B_o$) and inside boundary ($B_i$). The SFSZ is annular; therefore, it is necessary to define the outside and inside boundaries in the direction of strike and dip, respectively. The outside and inside boundaries in strike direction are expressed as $B_{os}$ and $B_{is}$, while those in dip direction are expressed as $B_{od}$ and $B_{id}$.

4.2.1 The bottom boundary

According to the characteristics of the SFSZ, when the voussoir beam structure is formed by the broken stratum rocks, the stratum enters the SFSZ, which is the bottom boundary ($B_b$) of the zone. It is affected by several factors including mining height, expansion ratio, and structure sliding rotary instability characteristics. The broken stratum rocks to form voussoir beam structure can be determined by using Eq. (1) (Hou 2003) as follows:

$$h_t > 1.5 \left[ M - \sum_{r=0}^{c} h_r (k_r - 1) + \sum h (k_z - 1) \right]$$

where $h_t$ is the layered thickness of main roof $r$ from bottom to top; $M$ is coal mining height; $k_r$ is the expansion coefficient of main roof $r$ and its load strata, in the range of 1.15–1.33; $\sum h$ is the immediate roof thickness; $k_z$ is the expansion coefficient.
of the immediate roof, in the range of 1.33–1.5; and \( l_r \) is the broken rock length of main roof \( r \).

Under the condition of Eq. (1), the bottom boundary \((B_b)\) can be obtained by using Eq. (2) as follows:

\[
B_b = \sum h + \sum_{r=0}^{r-1} h_r
\]  

(2)

### 4.2.2 The top boundary

In the SFSZ, the broken stratum is transmitted upward with the structure of “circular bearing beam” until the strata are no longer broken under the support of broken rocks, which is the top boundary \((B_t)\) of the SFSZ. Therefore, whether the stratum is broken or not can be used as the criterion to judge the top boundary of the SFSZ.

The breaking of the stratum needs to meet two requirements: first the span of the stratum should be longer than the critical span of its initial breaking; the second is that the maximum bending subsidence value of the stratum should be less than the free space height below it.

Relevant research (Guo et al. 2019) shows that the dip length of longwall mining working face plays a decisive role in the breaking height of strata. Therefore, the relationship between the span of stratum \( i \) \((l_{si})\) and the dip length \((L)\) of the working face is as follows:

\[
l_{si} = L - \left( \sum_{i=1}^{i-1} h_i \cot \beta_{d1} + \sum_{i=1}^{i-1} h_i \cot \beta_{d2} \right)
\]  

(3)

where \( h_i \) is the thickness of stratum \( i \); \( \beta_{d1} \) and \( \beta_{d2} \) represent the breaking angles of strata at the return and intake airway, respectively.

The unbroken stratum \( i \) is simplified as a fixed beam structure, and the uniform load \((q_i)\) is distributed on it, then the critical span of the stratum \( i \) \((l_{simax})\) can be expressed as follows:

\[
l_{simax} = h_i \sqrt{\frac{2R_i}{q_i}}
\]  

(4)

where

\[
q_i = \frac{E_i h_i^3 (\gamma_i h_i + \gamma_{i+1} h_{i+1} + ... + \gamma_n h_n)}{E_i h_i^3 + E_{i+1} h_{i+1}^3 + ... + E_n h_n^3}
\]  

(5)

where \( R_i \) is the ultimate tensile strength of stratum \( i \); \( E_i \) is the elastic modulus of stratum \( i \); and \( \gamma_i \) is the bulk density of stratum \( i \).

Then, the first condition for the breaking of stratum \( i \) is \( l_{si} > l_{simax} \).

During the upward transmission of the voussoir beam structure of the broken stratum, the separation space gradually decreases. When it is transmitted to stratum \( i \), the stratum is supported by broken rocks below. Assuming that the foundation
supporting stratum $i$ conforms to the Winkler foundation assumption, the maximum bending subsidence ($y_i$) of stratum $i$ can be expressed as follows (Qian 1996):

$$y_i = \frac{q_i}{EI_i} \left[ \frac{12\alpha - 1}{24} l_i^4 + \left( \frac{\sqrt{2}}{\omega} + \frac{1}{2} \right) l_i^2 \right]$$

where $I_i$ is the moment of inertia of stratum $i$; $l_i$ is half of the span of stratum $i$, given by $l_i = l_i/2$; $\omega$ is coefficient and can be calculated by using $\omega = (p/E_i)^{1/4}$, where $p$ is elastic foundation coefficient, given by $p = (E_0/d_0)^{1/2}$ and $E_0$ is elastic modulus of foundation, $d_0$ is cushion thickness; and $\alpha$ is coefficient and can be calculated by using the following relationship:

$$\alpha = \left( \sqrt{\omega^2 l_i^2 + 6\omega l_i + 6} \right) / \left( 6\omega l_i \right) \left[ 6\omega l_i (2 + \sqrt{2} \omega l_i) \right].$$

Under the bearing, the expansion coefficient of broken strata eventually tends to the residual crushing expansion coefficient, thus the free space height under stratum $i$ can be expressed as follows:

$$\Delta_i = M \sum_{i=1}^{i-1} h_i (k_{si} - 1)$$

where $k_{si}$ is the residual crushing expansion coefficient of each stratum layer below stratum $i$. Then, the second condition for the breaking of stratum $i$ is $y_i < \Delta_i$.

Therefore, the breaking of stratum $i$ needs to meet the following requirements:

$$\begin{align*}
&L - \frac{12\alpha - 1}{24} \left( \sum_{i=1}^{i-1} h_i \cot \beta_{si} + \sum_{i=1}^{i-1} h_i \cot \beta_{si} \right) > h_i \sqrt{\frac{2R_i}{q_i}}, \\
&q_i \frac{12\alpha - 1}{24} l_i^4 + \left( \frac{\sqrt{2}}{\omega} + \frac{1}{2} \right) l_i^2 \left( \frac{l_i}{\omega} \right) \right] < M \sum_{i=1}^{i-1} h_i (k_{si} - 1)
\end{align*}$$

Accordingly, when the strata are finally broken to stratum $i$, the top boundary ($B_i$) of the SFSZ can be determined by using Eq. (9) as follows:

$$B_i = \sum_{i=1}^{i-1} h_i$$

4.2.3 The outside boundary

With the coal mining, the strata can break at a certain angle, and the angle between breaking line and horizontal line is called breaking angle. The breaking angle of horizontal stratum $i$ can be obtained by using Eq. (10) as follows (Xu et al. 2018):

$$\beta_i = 45 - \frac{1}{2} \varphi + \frac{1}{2} \arctan \eta \sqrt{\frac{R_i}{q_i}}$$

where $\varphi$ is the internal friction angle of stratum $i$; $\eta$ is the standard number of breaking span, which is $\sqrt{\omega^2}$ for the first broken and $\sqrt{\omega^2}$ for the periodic broken.
According to the key stratum theory, key stratum of overburden plays a controlling role in the failure of strata, which is synchronous with the load layers above it. Therefore, the key stratum and its load layers can be regarded as a whole, and the combined breaking angle can be approximately replaced by the breaking angle of the key stratum. Therefore, in the strike direction, the strata breaking angle \( \beta_s \) can be obtained by using Eq. (11) as follows:

\[
\beta_s = \arccot \frac{\sum_{j=1}^{m} h_j \cot \beta_j + \sum_{k=1}^{n} h_k \cot \beta_k}{\sum_{j=1}^{m} h_j + \sum_{k=1}^{n} h_k}
\]

where \( m, h_j, and \beta_j \) are the number of immediate roof stratum below the first key stratum, the thickness and the breaking angle of the stratum \( j \), respectively; \( n, h_k, and \beta_k \) are the number of key stratum of overburden within the range from coal seam to the top boundary of the SFSZ, the total thickness and the combined breaking angle of the key stratum \( k \) and its load layers, respectively.

In the inclined direction, the dip angle of strata is set as \( \delta \), according to the characteristics of strata movement and deformation, and the breaking angle of strata should be corrected according to a certain angle. Therefore, the inclined breaking angle of strata \( \beta_d \) can be obtained by using Eq. (12) as follows:

\[
\beta_d = \arccot \frac{\sum_{j=1}^{m} h_j \cot \beta_j + \sum_{k=1}^{n} h_k \cot \beta_k}{\sum_{j=1}^{m} h_j + \sum_{k=1}^{n} h_k} + f \delta
\]

where \( f \) is the coefficient related to lithology, usually 0.3–0.8; \( \delta \) is the dip angle of strata, negative value is taken on the uphill side, and positive value is taken on the downhill side.

Assuming that the breaking of strata is transmitted up to stratum \( i \), the outside boundary \( (B_{os} and B_{od}) \) of the SFSZ can be expressed as follows:

\[
\begin{align*}
B_{os} &= H_i \cot \beta_i \\
B_{od} &= H_i \cot (\beta_d + \delta) \cos \delta + H_i \sin \delta
\end{align*}
\]

where \( H_i \) is the normal distance from coal seam roof to stratum \( i \); and \( \delta \) is the dip angle of strata, positive value is taken on the uphill side, and negative value is taken on the downhill side.

4.2.4 The inside boundary

Based on the characteristics of the voussoir beam structure of broken strata, fractures in bending section of the structure are relatively developed. Extending to the center of the goaf, the structural curve gradually flattens, and correspondingly, fractures between the broken rocks are gradually closed. Therefore, the bending section of the structure is defined as the width of the SFSZ.

The first layer of strata in the SFSZ was taken for analysis. It was assumed that the length of the periodic broken rock is
the same, that is, \( l_1 = l_2 = \ldots = l_n = l \). When the broken rock \( n+1 \) is in the horizontal state, the width of the SFSZ \( (L_a) \) can be expressed as follows:

\[
L_a = n \times l
\]  

(14)

where \( n \) is the number of broken rocks in the bending section of the structure; and \( l \) is the length of the broken rock, given by

\[
l = h \sqrt{\frac{R_f}{3q}}.
\]

Assuming that the rotation angle of the first broken rock of the stratum is \( \theta_1 \), combined with Eq. (1), from the stability analysis of key broken rock “S–R” (Zhang et al. 2020), the rotation angle can be obtained by using Eq. (15) as follows:

\[
\sin \theta_1 = \frac{1}{l} \left[ M - \sum_{r=0}^{n-1} h_r (k_r - 1) + \sum h_r (k_r - 1) \right].
\]  

(15)

According to the displacement law calculated by using the whole structure of voussoir beam, the rotation angle of broken rocks satisfies the following equation:

\[
\theta_2 \approx \frac{1}{4} \theta_1, \quad \theta_3 \approx \left( \frac{1}{4} \right)^2 \theta_1, \ldots, \quad \theta_n \approx \left( \frac{1}{4} \right)^{n-1} \theta_1
\]  

(16)

According to the relevant research (Qin and Xu 2018) and simulation test results, when \( \theta_n \) is about 3‰, fractures are close to closure, and the broken rock \( n+1 \) enters the compaction fractured subzone. Thus, the number of broken rocks in the SFSZ can be obtained by using Eq. (17) as follows:

\[
n = 1 - \frac{\ln 0.003 - \ln \theta_1}{\ln 4}
\]  

(17)

By using Eqs. (14), (15), and (17), the width of the SFSZ \( (L_a) \) can be obtained, and then the inside boundary \( (B_{is} \text{ and } B_{id}) \) of the SFSZ can be expressed as follows:

\[
\begin{align*}
B_{is} & = B_{on} + L_a \\
B_{id} & = B_{od} + L_a
\end{align*}
\]  

(18)

4.3 Layout block of the LHB

The SFSZ is the optimum zone for the LHB layout for gas extraction; nonetheless, how to arrange the boreholes in the zone is still an urgent problem to be solved. As mentioned above, borehole stability rate \( (R_s) \), fracture permeability rate \( (R_p) \), and gas accumulation rate \( (R_a) \) are the three parameters of the LHB layout for stable and efficient gas extraction. Therefore, based on the simulation test, the SFSZ on the side of the model open-off cut was considered for analysis. The strata in the SFSZ are divided into nine-grid blocks (Fig. 7), and the three parameters of each block are analyzed quantitatively.

4.3.1 Borehole stability rate
Owing to the small diameter of the LHB and the horizontal layout along the advancing direction of the working face, the simulation test reveals that the smaller tensile fracture and shear dislocation may lead to the borehole failure (collapse and plugging). Therefore, the statistical study of the larger fractures produced due to the tension and dislocation in each block is conducted (Fig. 7).

Fig. 7 Block division of SFSZ and statistics of tensile and dislocation fractures of each block

Fig. 7 illustrates the numerical values of the fractures in each block that may lead to the failure of the LHB. The values are calculated by the reciprocal method, and the as-obtained value provides the relative stability degree of the borehole. The overall borehole stability rate \( R_s \) of the SFSZ is set to 1, and then the \( R_s \) of each block after normalization is listed in Table 4.

4.3.2 Fracture permeability rate

The exponential function was used to fit the separation fracture rate of the measuring points in the SFSZ of the simulation model, and the fitting curves of the upper, middle, and lower strata in the SFSZ were obtained (Fig. 8).
Fig. 8 shows that by integrating the three fitting curves in sections respectively, the integral area of the separation fracture rate of the outer, middle, and inner strata are obtained. Then, the average separation fracture rate of each block is obtained, and the results are listed in Table 3.

### Table 3 Average separation fracture rate of each block

|       | Horizontal Separation fracture rate (mm·m⁻¹) |   |
|-------|--------------------------------------------|---|
|       | Outer                                      | Middle | Inner |
| Upper | 85.47                                      | 34.63  | 10.31 |
| Middle| 106.05                                     | 48.29  | 17.42 |
| Lower | 111.65                                     | 36.54  | 18.06 |

The formation of mining fractures results in a significant increase in permeability. If the broken strata are regarded as porous media, a large number of experimental data show that (Hu and Liu 2008), the equation of permeability (K) and fracture rate of broken strata (φ_p) in fractured zone can be expressed as follows:

\[
K = 0.01605\mu\phi_p^2
\]  

(19)

where \(\mu\) is the dynamic viscosity coefficient of air, at room temperature, \(\mu = 1.834 \times 10^{-5}\) Pa·s.

The permeability of each block can be obtained by substituting the separation fracture rate presented in Table 3 into Eq. (19). The overall fracture permeability rate (R_p) of the SFSZ is set to 1, and then the R_p of each block after normalization is listed in Table 4.

### 4.3.3 Gas accumulation rate

The density of gas is far lower than that of air, and it gradually accumulates upward under the effect of diffusion and uplift. The results of previous related studies (Feng et al. 2018) revealed that when the gas migration fracture channels are obviously developed in fractured zone, the equation between the gas concentration and the height from the bottom of the goaf
can be expressed as follows:

\[ \rho = a \exp(\lambda d) \] (20)

where \( \rho \) is the gas concentration; \( a \) denotes a constant; \( \lambda \) is a coefficient considering the molecular diffusion and pressure diffusion of gas in the fracture channels, which can be taken as 0.019; and \( d \) represents the height from the bottom of the goaf.

The fracture channels are obviously developed in the SFSZ, and then the gas concentration can be calculated by using Eq. (20). If the height between the coal seam and the bottom boundary of the SFSZ is set as \( b \) and the zone height of the SFSZ is set as \( 3c \), the average height of the lower, middle, and upper strata of the SFSZ from the bottom of the goaf can be expressed as \( b+c/2, b+3c/2, \) and \( b+5c/2 \), respectively. By substituting the corresponding values obtained from the simulation test \((b = 11.5 \text{ m}, 3c = 27.9 \text{ m})\), the average gas concentration of the lower, middle, and upper strata in the SFSZ can be expressed as follows:

\[
\begin{align*}
\rho_{\text{lower}} &= a \exp(0.019 \times 16.15) \\
\rho_{\text{middle}} &= a \exp(0.019 \times 25.45) \\
\rho_{\text{upper}} &= a \exp(0.019 \times 34.75)
\end{align*}
\] (21)

Notably, the higher the gas concentration in a specific block, the higher the degree of gas accumulation. Then, according to the calculation results of Eq. (21), the gas concentration was used to represent the degree of gas accumulation, and the overall gas accumulation rate \( (R_a) \) of the SFSZ was set to 1, then the values of \( R_a \) of each block after normalization are listed in Table 4.

| Parameter values | Horizontal | Vertical | Borehole stability rate \((R_s)\) | Fracture permeability rate \((R_p)\) | Gas accumulation rate \((R_a)\) \\
|------------------|------------|----------|-------------------------------|-------------------------------|-------------------------------|
|                  | Outer      | Middle   | Inner            | Outer      | Middle   | Inner            | Outer | Middle   | Inner            |
| Upper            | 4.84%      | 33.85%   | 33.85%           | 19.95%     | 3.27%    | 0.29%           | 13.12%| 13.12%   | 13.12%           |
| Middle           | 2.82%      | 6.77%    | 8.46%            | 30.71%     | 6.37%    | 0.83%           | 11.00%| 11.00%   | 11.00%           |
| Lower            | 2.26%      | 3.76%    | 3.39%            | 34.04%     | 3.65%    | 0.89%           | 9.22% | 9.22%    | 9.22%           |

### 4.3.4 LHB layout suitability rate

The LHB layout suitability rate \( (R_b) \) of each block in the SFSZ was decomposed into the three parameters mentioned above, and then the calculation formula can be expressed as follows:

\[ R_b = R_s \cdot R_p \cdot R_a \] (22)

By substituting the corresponding values listed in Table 4 into Eq. (22), the values of \( R_b \) of each block can be obtained. Similarly, the overall \( R_b \) of the SFSZ is set to 1, and then the \( R_b \) of each block after normalization is obtained as shown in Fig. 9.
4.4 “Zone-block” theoretical method of the LHB layout

Further, based on the analysis and definition of the LHB layout zone and blocks, a “zone-block” theoretical method of the LHB layout was proposed (Fig. 10) in this study. Notably, in engineering practice, the LHB can be arranged according to the process following some specific steps. First, the location range of the SFSZ in overlying strata should be defined by the boundary theoretical formulas. Subsequently, the SFSZ should be divided into blocks, the LHB layout suitability rate of each block in the SFSZ were determined according to the borehole stability rate, the fracture permeability rate and the gas accumulation rate (as shown in Fig. 9, the blocks were marked as No. I–IX). Finally, the LHB drilling could be conducted sequentially according to the layout suitability rate of each block in SFSZ.
5 Engineering application

Furthermore, based on the process of the theoretical method, engineering application was conducted to investigate the effectiveness of the proposed method. In overlying strata of working face 16031 of Guhanshan coal mine, the LHBs are arranged, and the pressure-relief gas in goaf is extracted.

5.1 The Layout of the LHB

5.1.1 Definition of the SFSZ boundaries

According to the above-mentioned mining parameters and lithology parameters of overlying strata (Fig. 1), boundaries of the SFSZ (uphill side) were defined by using the theoretical formulas, and the corresponding results are listed in Table 5.

| Boundary       | Parameter values |
|----------------|------------------|
| Bottom boundary (B_b) | From Eq. (1), main roof (fine grained sandstone) is divided into two layers (3.8 m each layer), forming the structure of voussoir beam. By using Eq. (2): |
|                | \[ B_b = \sum_{i=1}^{n} h_i = 4.7m \] |
| Top boundary   (B_t) | From Eq. (8), the No. 11 stratum (medium grained sandstone) is no longer broken. By using Eq. (9): |
|                | \[ B_t = \sum_{i=1}^{n} h_i = 36.4m \] |
| Outside boundary (B_o) | From Eq. (11), the strata periodic breaking angle, \( \beta_s = 67.7^\circ \). From Eq. (12), the strata (uphill side) initial breaking angle \( f = 0.4, \delta = 12^\circ \), \( \beta_d = 63.7^\circ \). By using Eq. (13): |
|                | \[ B_o = H_i \cot \beta_s = 0.41H_i \]
|                | \[ B_d = H_i \cot (\beta_d + \delta) \cos \delta + H_i \sin \delta = 0.46H_i \] |
| Inside boundary (B_i) | Then, \( L_o = 4 \times 8.56 = 34.24 m \). By using Eq. (18): |
|                | \[ B_i = B_o + L_o = 0.41H_i + 34.24m \]
|                | \[ B_d = B_d + + L_o = 0.46H_i + 34.24m \] |

5.1.2 Block determination and drilling

Next, the defined SFSZ (uphill side) is divided into nine-grid blocks, and five LHBs with a diameter of 96 mm each are drilled along the strike in overlying strata. The LHBs layout parameters and locations are listed in Table 6.

| No. | Distance from coal seam roof and coal pillar (m) | Length (m) | locations |
|-----|-----------------------------------------------|------------|-----------|
| 1#  | 29.5 / 33.0                                   | 291        | Block I in the SFSZ |
| 2#  | 29.5 / 13.5                                   | 336        | Block II in the SFSZ |
| 3#  | 30.0 / 18.5                                   | 252        | Block II in the SFSZ |
| 4#  | 26.0 / 21.0                                   | 264        | Block III in the SFSZ |
| 5#  | 41.0 / 29.0                                   | 228        | Bending zone |

The layout of the LHBs of working face 16031 is shown in Fig. 11.
5.2 Gas extraction

During the mining period of working face 16031, the actual gas emission is 6.98 m$^3$·min$^{-1}$. For the pressure-relief gas extracted through the LHBs, the gas concentration in return airway fluctuates in the range of 0.18~0.46%, and the gas volume fluctuates in the range of 1.71~3.90 m$^3$·min$^{-1}$, thus indicating that gas extraction effect of the LHBs is significant. Fig. 12 presents the extraction data of the LHBs.
Figs. 12(a–d) show the gas extraction data occur when the boreholes 1–4# are 18, 14, 3, and 7 m away from the working face, respectively, and the boreholes enter into tensile fractured subzone. In this subzone, the average values of pure amount of the gas extracted through the boreholes are 0.04, 0.06, 0.53, and 0.24 m$^3$·min$^{-1}$, respectively. When the working face passes 11, 11, 12, and 9 m of the borehole 1–4#’s end, respectively, the gas extraction flow of the boreholes increases rapidly, and the boreholes enter into the SFSZ. In this subzone, the values of maximum pure amount of extracted gas through the boreholes are 5.52, 1.27, 0.63, and 1.05 m$^3$·min$^{-1}$, respectively, and the corresponding average pure amount is about 2.43, 0.61, 0.17, and 0.41 m$^3$·min$^{-1}$, in the entire stage of gas extraction.

Fig. 12(e) shows that the extraction flow of borehole 5# is very small in the entire extraction stage, and the maximum pure amount of gas extraction is 0.04 m$^3$·min$^{-1}$.

5.3 Analysis

According to the proposed method, the boundaries of the SFSZ are defined, and then the blocks are divided. The LHBs extraction data show that:

*The layout zone.* When the LHBs enters tensile fractured subzone, the extraction flow is very small, and after entering the SFSZ, the flow increases rapidly. This verified that the SFSZ is the optimum zone for LHB layout and gas extraction.

*The layout block.* In block I of the SFSZ, the maximum and average values of pure amount of gas extracted through borehole 1# are up to 5.52 and 2.43 m$^3$·min$^{-1}$, respectively, thus the extraction effect is the best. In block II of the SFSZ, the maximum and average values of pure amount of gas extracted via borehole 2# are 1.27 and 0.61 m$^3$·min$^{-1}$, respectively, thus the extraction effect is the second. However, there is possibility of occurrence of collapse and plugging in borehole 3# in this block, and the gas extraction data are abnormal. In block III of the SFSZ, the maximum and average values of pure amount of gas extracted through borehole 4# are 1.05 and 0.41 m$^3$·min$^{-1}$, respectively, thus the extraction effect is the third. Furthermore, through the integral calculation of the pure amount of extraction data of boreholes 1–5# in the entire extraction stage, the gas extraction through borehole in block I is 2.53 and 6.69 times of that in block II and block III, respectively (Fig. 13). It is thus verified that the definition of the three parameters, and then the determination of the LHB layout suitability rate of each block
in the SFSZ are reasonable.

![Graph showing integral area of extraction data of the LHBs]

**Fig. 13** Integral area of extraction data of the LHBs

### 6 Conclusions

1. Within the height of fractured zone, mining-induced fracture channels were divided into horizontal “four subzones”, named as, initial fissure subzone, tensile fractured subzone, SFSZ, and compaction fractured subzone. The distribution of fracture channels and the stability of the LHB were considered as the controlling factors to be analyzed, and the SFSZ was determined as the optimum zone for the LHB layout. Furthermore, the boundary theoretical formulas for defining the location range of SFSZ in overlying strata were deduced.

2. By subdividing the SFSZ into nine-grid blocks, the LHB layout suitability rate of each block in the SFSZ were determined according to the borehole stability rate, the fracture permeability rate and the gas accumulation rate. Based on the analysis and definition of the LHB layout zone and blocks, a “zone-block” theoretical method of the LHB layout in overlying strata was proposed.

3. An engineering example with five LHBs was presented for the application of the theoretical method. The results show that: the maximum and average amount of pure gas extracted through single borehole arranged in block I can reach up to 5.52 and 2.43 m³·min⁻¹, respectively; and the pure amount in the entire extraction stage of the borehole is 2.53 and 6.69 times of boreholes arranged in blocks II and III, respectively. The proposed method can effectively determine the LHB layout layer in strata, so as to improve the gas extraction efficiency and ensure safe and green mining.

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References

Cheng ZH, Pan H, Zou QL, Li ZH, Chen L, Cao JL, Zhang K, Cui YG (2021) Gas flow characteristics and optimization of gas drainage borehole layout in protective coal seam mining: a case study from the Shaqu coal mine, Shanxi Province, China. Nat Resour Res 30:1481–1493.

Feng GR, Zhang A, Hu SY, Cheng JW, Miu XY, Hao GC, Han DD, Guan SW, Zhao GZ (2018) A methodology for determining the methane flow space in abandoned mine gobs and its application in methane drainage. Fuel 227:208-217.

Fumagalli E (1973) Statical and geomechanical models. Springer, New York.

Guo H, Yuan L, Shen BT, Qu, QD, Xue JH (2012) Mining-induced strata stress changes, fractures and gas flow dynamics in multi-seam longwall mining. Int J Rock Mech Min 54:129-139.

Guo WB, Zhao GB, Lou GZ, Wang SR (2019) A new method of predicting the height of the fractured water-conducting zone due to high-intensity longwall coal mining in China. Rock Mech Rock Eng 52:2789-2802.

Hou ZJ (2003) The criterion on determining main roof in breaking zone and its application to the shallow seam. J China Coal Soc 28:8-12. (In Chinese)

Hu YH, Liu QS (2008) Experiment study on mechanical properties of granite under repeated loading and unloading. Int J Mod Phys B 22: 1634-1639.

Jia LC, Chen M, Jin Y, Jiang HL (2017) Numerical simulation of failure mechanism of horizontal borehole in transversely isotropic shale gas reservoirs. J Nat Gas Sci Eng 45: 65-74.

Johnny Q, Qu QD, Guo H (2017) CFD simulations for longwall gas drainage design optimization. Int J Min Sci Techno 27: 777-782.

Karacan CÖ (2015) Modeling and analysis of gas capture from sealed sections of abandoned coal mines. Int J Coal Geol 138:30-41.

Karacan CÖ, Goodman GVR (2011) Probabilistic modeling using bivariate normal distributions for identification of flow and displacement intervals in longwall overburden. Int J Rock Mech Min 48:27-41.

Lan HT, Moore ID (2017) Numerical investigation of the circumferential stresses around boreholes during horizontal directional drilling. Int J Geomech 17:04017114.

Li SG, Du XH, Zhao PX, Xiao P, Lin HF, Shuang HQ (2018) Experimental study on crack evolution characteristics of rock-like materials under different strain rates. J Geophys Eng 15:2071-2078.

Liu T, Lin BQ, Yang W, Liu T, Zhai C (2017) An integrated technology for gas control and green mining in deep mines based on ultra-thin seam mining. Environ Earth Sci 76:243.

Liang HB, Huang XQ, Sun YQ, Cheng XZ (2016) A diagnostic model based on support vector machine for the collapse of
horizontal well borehole wall. J Residuals Sci Tech 13:167-175.

Pan ZJ, Wood DA (2015) Coalbed methane (CBM) exploration, reservoir characterisation, production, and modelling: A collection of published research (2009–2015). J Nat Gas Sci Eng 26:1472-1484.

Peng SS, Chiang HS (1984) Longwall mining. Wiley, New York.

Qian MG, Miaox XX, Xu JL (1996) Theoretical study of key stratum in ground control. J China Coal Soc 3:2-7. (In Chinese)

Qian MG, Xu JL (1998) Study on the “O-shape” circle distribution characteristics of mining-induced fractures in the overlaying strata. J China Coal Soc 23:466-469. (In Chinese)

Qin W, Xu JL (2018) Horizontal subzone characteristics and methane seepage properties of the gas flowing fracture zone above the gob. Adv Civ Eng 2018:9071578.

Qu QD, Xu JL, Wu RL, Qin W, Hu GZ (2015) Three-zone characterisation of coupled strata and gas behaviour in multi-seam mining. Int J Rock Mech Min 78:91-98.

Ruban AD, Zaburdyaev VS, Kharchenko AV (2012) Coal bed methane drainage with long directional boreholes. J Min Sci 48:436-439.

Sun HT, Zhao XS, Li RH, Jin HW, Sun DL (2017) Emission reduction technology and application research of surface borehole methane drainage in coal mining-influenced region. Environ Earth Sci 76:336.

Wang G, Fan C, Xu H, Liu XL, Wang R (2018) Determination of long horizontal borehole height in roofs and its application to gas drainage. Energies 11:2647.

Xie SR, Zhao YJ, Zhang SB, Yang HZ, Xiao DC, Tian CY (2012) Mechanism and experiment of substituting high drainage roadway with directional long drilling group to extract pressure-relief gas. J Cent South Univ 19:2591-2597.

Xu B, Jiang JQ, Dai J, Zheng PQ (2018) Mechanical derivation and experimental simulation of breaking angle of key strata in overlying strata. J China Coal Soc 43:599-606. (In Chinese)

Yuan L (2011) Theories and techniques of coal bed methane control in China. J Rock Mech Geotech Eng 3:343-351.

Zhang CW, Jin ZX, Song XM, Feng GR, Li Z, Gao R, Zhu DF, Li C (2020) Failure mechanism and fracture aperture characteristics of hard thick main roof based on voussoir beam structure in longwall coal mining. Energy Sci Eng 8:2.

Zhao HB, Li JY, Liu YH, Wang YK, Wang T, Cheng H (2020a) Experimental and measured research on three-dimensional deformation law of gas drainage borehole in coal seam. Int J Min Sci Techno 30:397-403.

Zhao PX, Zhuo RS, Li SG, Shu CM, Bin LW, Jia YY, Shi Y, Suo L (2020b) Analysis of advancing speed effect in gas safety extraction channels and pressure-relief gas extraction. Fuel 265:116825.

Zhou AT, Wang K (2018) A new gas extraction technique for high-gas multi-seam mining: a case study in Yangquan Coalfield, China. Environ Earth Sci 77:150.