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Research Article

Construction and Application of Mathematical Model of Stable Fracture Development Zone of Roof

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The fractured zone in the overlying strata of a coal mine goaf is vital for effective gas drainage. The development height of the fractured zone is lied on the “saddle type” theory and calculated by empirical formula, while the horizontal range is dependent on the caving theory of the “O” circle. However, the height of the fracture zone obtained using the above method is usually too large, and only the horizontal boundary of the fracture zone is defined. Besides, the fracture development degree in different regions is not described. To accurately determine the stable development area of the fractured zone and locate the gas migration channel as well as gas enrichment horizon, in this paper, a geometric and mathematical model for gas extraction in the fractured zone is established based on common high-level drilling. Then, a method of investigating the parameters of the directional high-level drilling in the roof is proposed, and a solving means is provided. Taking Wanfeng Coal Mine as an engineering background, the reasonable parameters of the common high-level drilling were investigated, and the effect was verified using the directional high-level drilling in the roof of an adjacent working face. The results show that the stable extraction volumes of the two directional drilling holes is 1~1.8 m^3/min and 0.6~1 m^3/min, respectively, which exceeds the optimal extraction volumes of the ordinary drilling holes. The new method of determining the stable development area of the fractured zone is significant for improving the gas drainage effect of the high-level drill holes in the roof.

1. Introduction

Mine gas disaster is one of the most significant disasters in coal mines. With the increase of mine production intensity and mining depth, the amount of mine gas gushing out increases, and gas disaster seriously threatens and restricts the safe production of mines [1].

During the coal seam mining, the gas in the coal seam and the adjacent layer at the working face is greatly gushed due to the influence of the mining activity. Among them, a part of the gas is discharged to the return airway, and the other part is accumulated in the goaf and roof cracks [2]. With the advancement of the working face, the gas in the goaf and roof cracks gathers near the upper corner under the dual action of negative pressure of ventilation and roof displacement and then enters the return air flow, causing the gas concentration in the upper corner, leading return air flow to exceed the limit, and bringing hidden dangers to the safety of mine production [3]. As an effective control method, the high-level drilling hole in the roof to extract gas in the fractured zone has been widely used in many mines [4–9]. The applicable conditions for gas drainage in the fracture zone are as follows: the gas, in the upper corner of the working face with low gas content and high output, exceeds the category permitted during mining, the insufficient predrainage of the low permeability coal seam leads to the failure of solving the gas emission effectively for the air distribution of the working face, and the gas in the adjacent layers flows into the mining space during coal seam group mining, resulting in the gas overrun of the working face during production. The fracture zone is both the gas migration channel and enrichment area; when a single coal seam is mined, the proportion of gas drainage in the fracture zone can reach 20~35%, while the coal seam group mined, the proportion is generally more than 60%, up to 80%. In this paper, the area with the most developed fractures in the vertical and horizontal directions defined the fracture stable development area. Precisely confirming the stable development zone of fractures in terms of vertical height and lateral dislocation has important guiding significance for gas drainage in fractured zones.

Coal mining forms vertical fractures and horizontal delaminated fractures in the overlying rock layer of the mining area. As the working face advances, the overlying rock of the mining area fully collapses, and the fissures of its central roof rock are compacted, while the support of the coal wall around the mining area makes the off-layer fissures of the upper and lower rock layers can still be retained to a certain extent, forming the coal wall support area, off-layer area, and recompacted area from the boundary of the mining area to the middle of the mining area laterally, and the coal wall support area and off-layer area at the boundary of the mining area form a closed ring mining fissure development area, called mining fissure “O” ring (referred to as “O” ring) [10]. The “O” ring is fixed on one side of the open cut hole in the mining area, while on one side of the working face, it moves forward with the working face advancement, and its moving speed is equivalent to the working face advancement speed, so the “O” ring always exists after the full collapse of the roof plate in the mining area.

Research shows that the “O” ring is not only the main channel for gas transportation, but also an important place for gas accumulation [11]. Under the joint action of gas and air density difference and air leakage in the mining area, the gas accumulated inside it will enter the mining area or tunnel through the confining wall or coal column fissure, which will increase the ventilation burden and unsafe factors in the mine. Therefore, in addition to minimizing the air leakage from the working face, we should also provide a channel for gas circulation in the mining area. The roof high directional long drill hole is the drainage channel to continuously create negative pressure in the fissure zone of the working face and divert the gas in the mining area under the influence of pressure gradient.

In the process of recovery face advancement, the trajectory of high directional drilling should always be within the range of the fracture zone of the mining area, using the vertical fracture formed by the mining pressure and the horizontal off-layer fracture to extract gas from the mining area and the mining influence area. The high-level directional drilling has significant features such as controllable drilling trajectory, high drilling encounter rate of effective extraction layer, and large drilling depth. During the workface recovery process, the drill hole and the mining fissure are kept open, and the free gas is continuously extracted from the fissure zone of the mining area until the coal mining face crosses the area covered by the high directional drill hole [12, 13].

Scholars have conducted various researches on the topic of gas drainage in fractured zones. Previous studies have divided the distribution of fracture zones in the vertical and horizontal directions. It is believed that the deformation of overlying strata, such as caving, dislocation, and layer separation, lags behind the working face around which a mining zone will be formed. The dynamic pressure field and its influence range generate three zones in the vertical direction, namely the caving zone, the fissure zone, and the bending subsidence zone, and three zones in the horizontal direction, respectively; the coal wall support influence zone, separation zone, and recompaction zone [14–17]. The research on the growth characteristics of the fracture zone has initiated the following two theories, among which the “saddle shape” theory is suitable for evaluating the maximum development range of the fracture zone after the mining is stable [18, 19]. The “O” ring theory holds that the fracture boundaries favorable for the drainage of gas after pressure relief during mining share a common orientation towards the mined-out area along the strike and dip [20, 21]. At present, the height of the fracture zone is generally deprived from the empirical formula [22–25], and the calculation result is the maximum of the roof fracture development, which is generally higher than the actual one. Since the fracture extension in the upper part of the fracture zone is not obvious, the effect of gas drainage in this area is not obvious. At the same time, the method does not consider the influence of different lateral dislocations of the working face on the fracture augmentation. According to different drilling techniques, high-level drilling on the roof can be classified into straight holes constructed by ordinary rotary drilling rigs and directional curved drilling constructed by directional ones [26–33]. Under the ordinary drilling process conditions, the drilling hole is obliquely penetrated to the designed horizon, then withdrawn, and connected to the drainage. With the different distances from the working face to the drilling hole, the drilling holes which can be analyzed accordingly are located at different horizontal offsets and vertical horizons. The gas drainage effect of different drilling parameters is obtained, while reasonable drilling parameters are gained. Directional drilling can achieve the continuous and stable investigation of gas drainage effects to corresponding vertical horizon and lateral dislocation [34–41], because of the advantages of stable gas drainage effect and long effective drilling distance. In a word, depending on the occurrence of coal seams, the drilling parameters with the best extraction effect in the fracture zone are obtained through investigation, and the key to ensure efficient extraction by directional drilling is to establish a reliable mathematical model and determine the stable fracture development area accurately.

Based on the understanding of the “three horizontal zones” and “three vertical zones” of rock mass movement [42], this paper illustrates the occurrence characteristics of gas in the fracture zone and the extraction law of high-level drilling in the roof. The geometric and mathematical model of gas drainage in fractured zone with common high-level boreholes is established, and the investigation and calculation method on the parameters of arrangement about roof high-level boreholes is proposed. The author conducted a field inspection of ordinary high-level drilling in Wanfeng Mine where the reasonable drilling parameters were obtained and verified them during the extraction of directional high-level drilling on the adjacent working face roof. This method has good guiding significance for determining the stable development area of fracture accurately, which can provide ideal gas drainage horizons precisely and ensure the gas drainage effect of high-level drilling holes in the roof.

2. Research Methodology

2.1. Developmental Characteristics of Fracture. The fracture space characterized by " three vertical zones" which is formed by the mining stress field is not only a gas migration channel, but also a gas storage. The middle and lower parts of the fracture zone are gas flow channels, and the middle and upper parts are reservoirs. The extraction principle of the high-level drilling is to arrange the drilling in the gas storage in the fracture zone. It uses the negative drainage pressure to extract the pressure-relieving gas there and reduces the gas concentration in the upper corner and the return air flow. The horizontal stagger and vertical horizon of the high-level drilling are the most important factors affecting the pumping effect, and the gas drainage boreholes should be arranged in "gas storage" instead of "gas migration channel."

When the overlying roof of the coal seam deforms under the action of the mine pressure, the break, collapse, and dislocation process of the rock stratum is relatively rapid, which leads to the development of the roof crack also being a relatively discontinuous process; that is to say, the drilling takes effect suddenly, and once the fracture is formed, its recompaction or closure is a continuous process; in other words, the drilling failure is a gradual process, and it can be reflected in the curve of the change between the extraction quantity and the advancing distance of the working face; that is, the curve shows "steep rise and slow fall." Based on the theory of masonry beams, according to the " three horizontal zones" of the rock mass movement law affected by mining, the overlying strata along the advancing direction of the working face will locate the coal wall support-affected zone, the separation zone, and the recompaction zone, respectively. The fracture zone is also divided into three sections: the fracture generation section, the fracture development section, and the fracture compaction section, as shown in Figure 1.

(1) Fracture generation section: a certain distance behind the working face, generally in the initial stage of fracture generation, with the movement of the overburden cracks begin to produce, fracture is relatively undeveloped

(2) Fracture development section: located behind the fracture generation section, and the fracture is well developed in this area

(3) Fracture compaction section: lies behind the fracture development section, and the fractures in this section begin to be compacted and closed gradually

2.2. Gas Drainage Law of Roof High Drilling. The gas gushing during the mining comes from the coal wall of the working face, the coal that has been mined, the coal left in the goaf, the adjacent coal seam, and the surrounding rock and finally enters the return air trough, the caving, and the fracture zone. Part of the gas in the fracture zone deprives from the floating gas released from the coal leftover in the goaf, and the other part stems from the gas out-gushing, caused by mining and pressure relief [14, 15] of the adjacent layers and surrounding rocks. Before the roof is pressed, part of the gushing gas enters the caving and the fissure zone with the leakage air, and during the roof pressing, the gas in the caving zone and the fissure zone is squeezed into the return air trough, and a dynamic balance relationship is maintained among the three.

The ordinary high-level drilling whose profile is a straight line in space is carried out by rotary drilling machine, cutting diagonally from the roadway, or drilling field to the target position. With the advance of the working face, the vertical distance between the drilling hole and the working face decreases gradually, the distance to the working face diminishes gradually until the working face pushes through the drilling, and the directional high-level drilling hole can be drilled stably at the fixed horizontal offset and the vertical layer after it penetrates obliquely to the target position. The relative positional relationship between the two types of boreholes and the advancing period of the working face is different, resulting in different variation laws of gas drainage with the advancing of the working face. The gas extraction rate of ordinary high-level boreholes increases, reaches the peak, and decreases gradually until the boreholes fail completely. Compared with the advancing distance of the working face, the change of the gas extraction rate is generally a parabola, from low to high, and then decreases gradually. The directional high-level drilling is basically stable and only changes greatly in the initial climbing stage of the drilling, and the change curve of the gas extraction scalar and the advancing distance of the working face are generally trapezoidal, as shown in Figure 2.

2.3. Establishment of the Geometric Model. The angle is formed by the line, which links the actual effective point of drilling with the working face, and the horizontal plane is defined as the lag effective angle. During the normal advancement of the working face, the lag effective angle, when the drilling is valid, can be considered as constant. Based on this, a model is conceived to investigate and analyze the key parameters of the high-drilling hole in the roof. The model assumes that the advancing speed of the working face is constant, the coal seam is stable, and the effective horizon is the same at different transverse stagger distances. The service period of drilling is divided into three stages: effective, optimal, and invalid, and the purpose of the model is to obtain the dip angle, which is composed of the line connecting the working face and the drilling action point, when the high-level borehole is in effect (the best or failed), and then to get the height "h" and the lateral offset "w " of the effective horizon, as well as the parameters such as the offset "l_0" between the borehole and the roof of the coal seam when the borehole is in action, it can direct the design of high-level borehole.

Based on the execution of the borehole in the high-level drilling field, a geometric model is set up as follows: the borehole is projected to the vertical plane where the return air passage is located. The relative position between the actual point

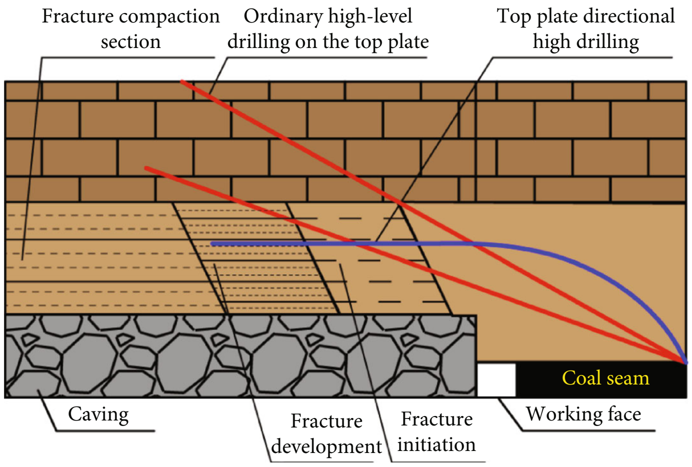


Figure 1: Schematic diagram of the development and evolution law of high-level borehole extraction and fracture zone in the roof.

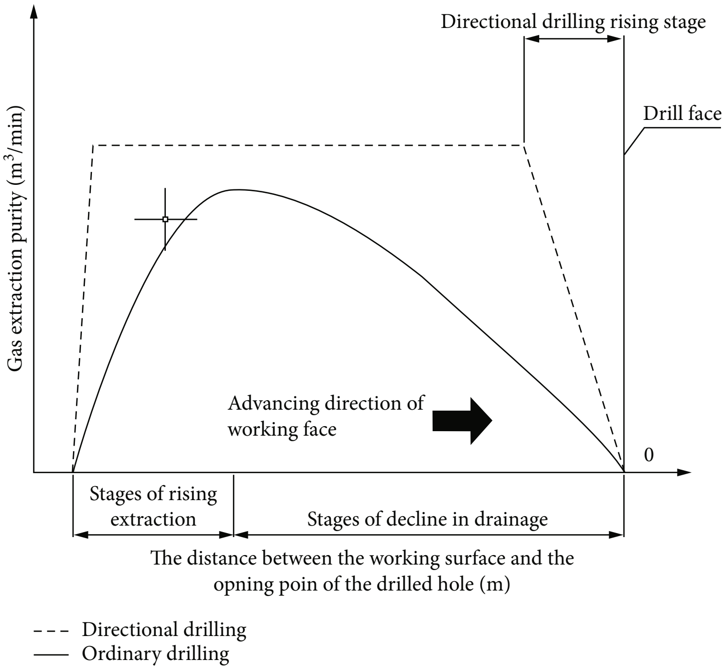
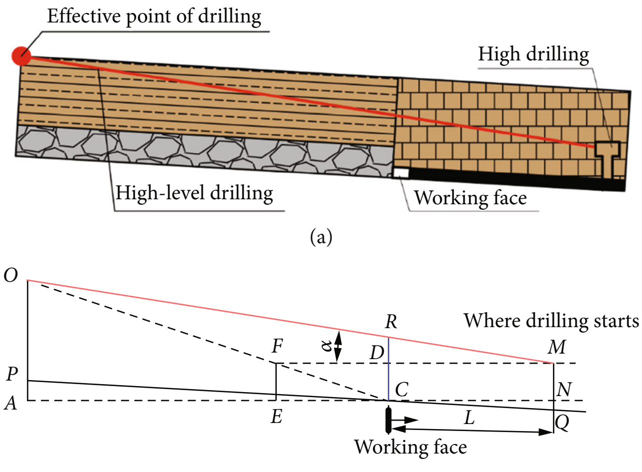


Figure 2: The relationship between the extraction volume of the high-level drilling in the roof and the advancing distance of the working face.

of the borehole and the advance of the working face is shown in Figure 3(a), and its geometric model is illustrated in Figure 3(b). A few symbols and definitions necessary must be made as follow: the end point of the drilling is just at the upper boundary layer of the effective gas drainage in the fracture zone, "MO" is the drilling channel, point "*O*" is the projection of the plumb plane where the return air is located when the drilling is actually effective, point "*C*" is where *t* the working face is located, "β"is the inclination angle of the line connecting the drilling effective point and the working face (lag effective angle), "α" is the drilling inclination angle, "PQ" is the roof of the coal seam, "MQ" is the height between the drilling point and the roof of the coal seam, the coal seam is along the working face, the inclination angle of the advancing direction is "δ_1," and the inclination angle along the inclination direction of the working face is "δ_2".

With the advance of the working face, the fissures go through three stages: sudden generation, gradual development, and piecemeal compaction. Therefore, the design principles for the high-level drilling should be followed.

(1) The opening height shall be kept at a high level, the inclination angle of the borehole as gentle as possible, the height difference between the opening point



(a)

(b)

FIGURE 3: Schematic diagram of common high-level drilling in the roof.

and the final hole point shortened, and the effective extraction section length of the borehole in the fracture zone increased

(2) Along the working face trend, the high-efficiency extraction layer is distributed in a strip shape that is gradually raised, as well as the high-level borehole layout layer

(3) The horizontal offset of drilling holes should not exceed one-third of the inclined length of the working face at the farthest. The final horizon of ordinary high-level drilling holes should be slightly higher than the investigated and be arranged distinctly

2.4. Establishment of Mathematical Model. Known conditions: dip angle "α," borehole azimuth angle "γ," dip angle "δ_1"of coal seam along advancing direction of working face, dip angle "δ_2"along working face direction, the height "Δh "(MQ) from the location of borehole opening to coal seam roof, and the distance "L"(CQ) from the face position to the opening point along the roadway direction when the drill hole is actually in effect.

Solution: the inclination angle "β" composed of the line connecting the drilling effective point and the working face, the vertical distance "l_0" (OP) from the roof when the drilling is effective, and the lag distance "CP" from the lateral offset "w" to the working face along the roadway. The process of solving and analyzing the model is as follows:

$$\mathrm{CD} = \mathrm{MN} = \mathrm{MQ} - \mathrm{NQ} = \Delta h - L \sin \delta_2, \tag{1}$$

$$\mathrm{FD} = \frac{\mathrm{CD}}{\tan \beta} = \frac{\Delta h - L \sin \delta_2}{\tan \beta}, \tag{2}$$

$$\mathrm{FM} = \mathrm{FD} + \mathrm{DM} = \frac{\Delta h - L \sin \delta_2}{\tan \beta} + L \cos \delta_2, \tag{3}$$

$$\mathrm{FC} = \frac{\mathrm{CD}}{\sin \beta} = \frac{\Delta h - L \sin \delta_2}{\sin \beta}, \tag{4}$$

$$\mathrm{define} m = \mathrm{FD} = \frac{\Delta h - L \sin \delta_2}{\tan \beta}, \tag{5}$$

$$\mathrm{define} L' = \mathrm{FM} = \mathrm{FD} + \mathrm{DM} = m + L \cos \delta_2, \tag{6}$$

$$\angle \mathrm{MOF} = \beta - \alpha, \tag{7}$$

$$\mathrm{OF} = \frac{FM \sin \alpha}{\sin (\beta - \alpha)} = \frac{\mathrm{L}' \sin \alpha}{\sin (\beta - \alpha)}, \tag{8}$$

$$\mathrm{OC} = \mathrm{OF} + \mathrm{FC} = \frac{L' \sin \alpha}{\sin (\beta - \alpha)} + \frac{m}{\cos \beta}, \tag{9}$$

$$\mathrm{OA} = OC \sin \beta = \frac{L' \sin \alpha \sin \beta}{\sin (\beta - \alpha)} + m \tan \beta, \tag{10}$$

$$\mathrm{AC} = OC \cos \beta = \frac{L' \sin \alpha \cos \beta}{\sin (\beta - \alpha)} + m, \tag{11}$$

$$\mathrm{PC} = \frac{\mathrm{AC}}{\cos \delta_2} = \frac{L' \sin \alpha \cos \beta}{\sin (\beta - \alpha) \cos \delta_2} + \frac{m}{\cos \delta_2}, \tag{12}$$

$$\mathrm{PA} = \mathrm{AC} \tan \delta_2 = \left[\frac{L' \sin \alpha \cos \beta}{\sin (\beta - \alpha)} + m \right] \tan \delta_2, \tag{13}$$

$$\mathrm{define} \mathrm{PQ} = 1_0, \tag{14}$$

$$1_0 = \mathrm{PC} + \mathrm{CQ} = \frac{L' \sin \alpha \cos \beta}{\sin (\beta - \alpha) \cos \delta_2} + \frac{m}{\cos \delta_2} + L, \tag{15}$$

$$\mathrm{OP} = \frac{1_0 \cos \delta_2 \tan \delta_2}{\cos \gamma} - 1_0 \sin \delta_2 - 1_0 \cos \delta_2 \tan \gamma \tan \delta_1 + \Delta h. \tag{16}$$

2.5. Solution of Mathematical Model. The solution condition of the simultaneous equations is that the vertical distance l_0 (OP) between the drilling hole and the coal seam roof is the same when the two ordinary high-level drilling holes are valid. That is, $l_{01} = l_{02}$; the inclination angle "β" composed of the line, which connects the actual effective point of the drilling hole and the working face, is obtained by iterative method, and then the same parameter "l_0," different parameters "PC," and lateral offset "w" of the two drilling holes are obtained as well. After the initial solution results are received, verify whether the lateral offset and vertical distance of different drilling holes and the projected length along the roadway, when the drilling is effective, are within the range estimated according to the empirical formula, as well as the service range of the high-level drilling. When the solution results meet the above conditions, the lateral offset of the two boreholes should be further analyzed. When the difference is large, the design of the high-level drilling in the next drilling site can be guided according to the solution results until the lateral offset is within the reasonable range set.

In order to speed up the investigation progress and obtain reasonable results, two rows of boreholes, which possess the same azimuth, are constructed at the same location. It is better to parallel the advancing direction of the working face, and the positions of boreholes, characterized by an alternating upward and downward, are all higher than the maximum effective horizon, then the pumping effect of the upper and lower drill holes with different transverse stagger distance is investigated, and the lag effective angle of the roof drill hole is obtained according to the above formula, and finally the effective horizon of different internal dislocation distance is available.

In engineering practice, it is difficult to meet the abovementioned ideal investigation conditions. Generally, high-position boreholes are arranged radially in the direction of advancing toward the working face in the drilling site. The approximate formation can be obtained by solving according to the method; through the comprehensive investigation and calculation of several boreholes, the reasonable arrangement of boreholes with different transverse stagger distance is analyzed. The flow chart of inspection and calculation of the common high-level borehole layout parameters of the roof is shown in Figure 4.

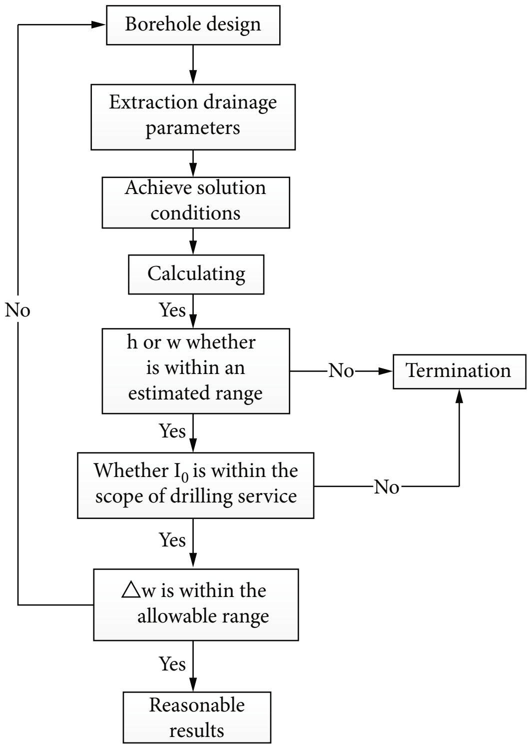


Figure 4: The flow chart of inspection and calculation.

3. Engineering Applications

The engineering investigation was carried out in Wanfeng Coal mine. After the construction of ordinary high drilling hole, the parameters of gas extraction were detected during the advance of working face. The preliminary results were calculated according to the effective advance steps of different hole and compared with the high directional drilling hole.

3.1. Working Face Overview. No. 1 coal is mined in the 1115 working face of Wanfeng Mine, with a strike length of about 1461 m, a dip length of 167 m, and an average thickness of the coal seam of 1.5 m. The dip angle is 3° to 10°, and the average dip angle is 6°. The direct top of the coal seam is sandy mudstone with an average thickness of 4 m, and the direct bottom is sandy mudstone and siltstone with an average thickness of 7.5 m. The old roof of the coal seam is siltstone or fine sandstone with a dense and thick-bedded lithology, as well as a relatively stable structure. The working face adopts "U" shape ventilation; the air distribution is 1000~1200 m^3/min. The fully mechanized mining method is selected to falling coal; meanwhile, all the height is mined at one time, and the roof is managed by the caving method.

3.2. Drilling Design. According to the empirical formula for calculating the height of the fractured zone provided by "Coal-mining Under Three Circumstances" theory

$$H_l = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6, \tag{17}$$

where the variable H_l presents the height of the fracture zone along the normal direction of the coal seam. The variable $\sum M$ denotes the cumulative mining thickness of the coal seam.

The roof of No. 1 coal seam is medium-hard, and the maximum height of the water-conducting fracture zone is calculated by 30.6 m. The production practice shows that the gas drainage effect is extremely weak when the height of the high-level drilling in the working face exceeds 17 m. Therefore, the results, depriving from the calculation of the empirical formula, clearly exceeded the tolerable level. In order to ensure the safe mining and to meet the needs of this investigation, there are already 12 conventional drilling holes in the No. 7 drilling site of the No. 1115 working face; 3 additional inspection holes, numbered as No. 5, No. 10, and No. 15, are put into effect, and the design parameters are shown in Table 1.

3.3. Determination of the Stable Development Zone of Fracture. With the advancement of the working face, the variation curves of the extraction parameters of the three inspection holes are shown in Figures 4–6. When the working face is 54 meters away from the hole point, the concentration of No. 5 increases

Table 1: Construction parameters of ordinary high-level drilling.

Bore number	Axial horizontal angle with the tunnel (°)	Obliquity (°)	Opening height (m)	Hole depth (m)
5#	22	8	3	92
10#	25	11	3	72
15#	36	15	3	57

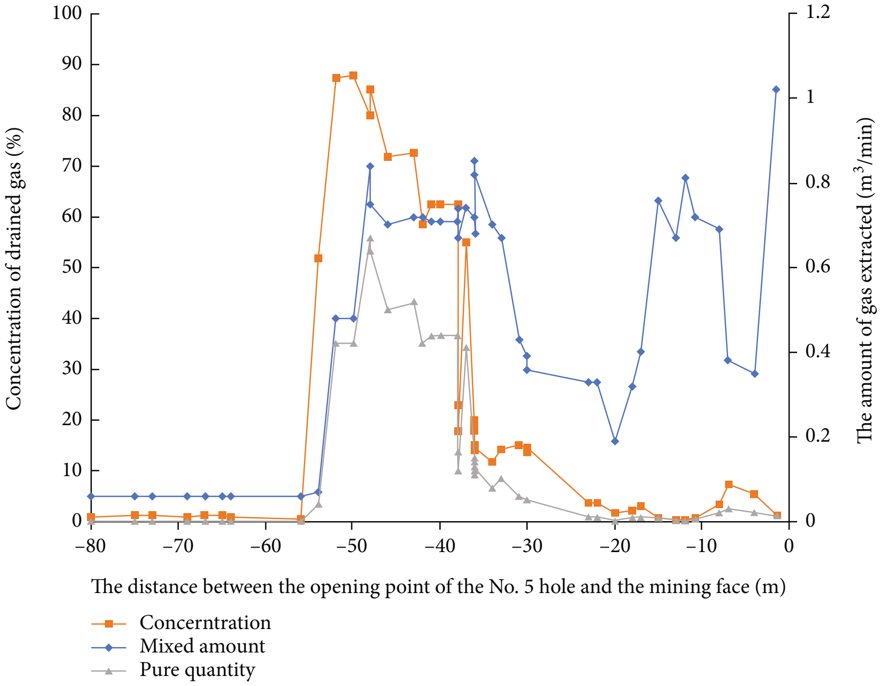


Figure 5: The relationship between the extraction parameters of the No. 5 hole and the advancing step distance.

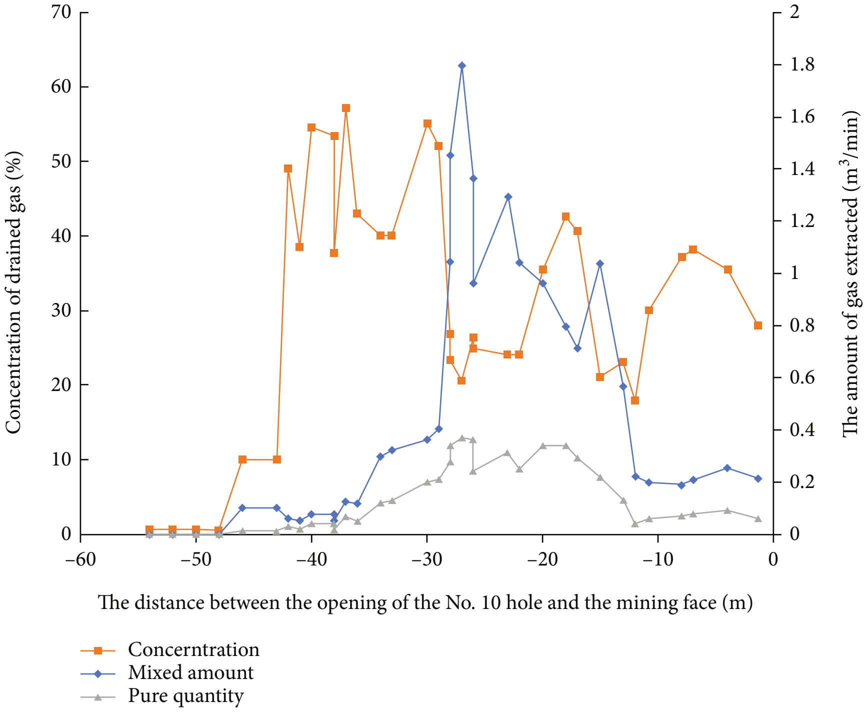


Figure 6: The relationship between the extraction parameters of the No. 10 hole and the advancing step distance.

Table 2: Calculation results of ordinary high-level drilling.

Solution drilling	Lag effective angle (°)	w_1 (m)	w_2 (m)	H (m)
5#, 10#	32.20	28.26	23.10	15.53
5#, 15#	33.46	27.82	21.56	15.34

Table 3: 1201 drilling hole design and actual layout parameters of directional drilling field with return air downhole.

Hole number	Designed internal staggered distance to return air trough (m)	Designed distance to 1# coal roof (m)	Hole depth (m)	Projection length of borehole (m)
1#	40	15	255	246.72
2#	20~25	14	267.6	257.04

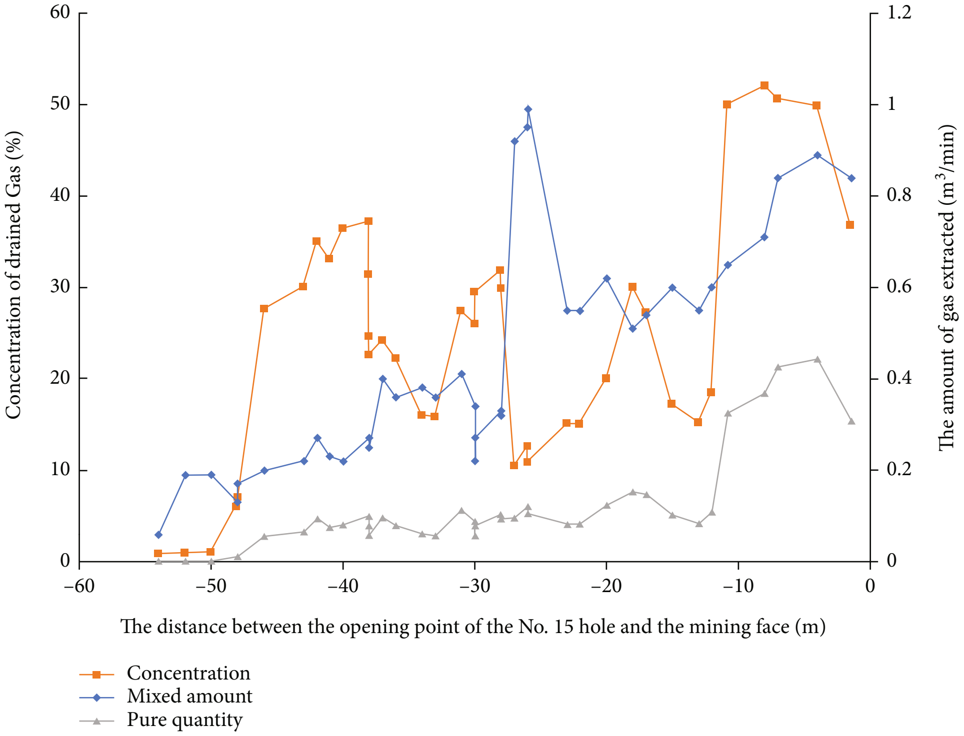


Figure 7: The relationship between the extraction parameters and the advancing step distance of No. 15 hole.

to 86%, and the mixing amount is 0.06 m^3/min, which did not increase immediately but boomed to 0.8 m^3/min as it was delayed for 6 meters. When 42 meters away from the opening point for No. 10 borehole, its concentration changes from 10% to 50%, and the mixing amount remains at 0.1 m^3/min, while the lag is 12 meters, which suddenly increases to 1.8 m^3/min. The concentration summit of borehole No. 15 is 46 meters away from the working face, with a maximum of 40%, but the mixing amount augments from 0.3 m^3/min to 1m^3/min after a lag of 16 meters suddenly. The three boreholes show common characteristics. The pumping concentration of the high-level boreholes in the roof increases sharply at the beginning, generally by more than 5-10 times. After a certain lag distance, the volume fluctuates sharply, resulting in an apparent climbing in the net pumping volume. This is because with the gentle growth of fractures, the passage of gas flow gradually increased, and the pressure-relief gas in goaf and adjacent strata is drained into the borehole in the role of negative pressure. However, attributing to the incomplete development of the fractures, the mixing gas quantity is low, and the gas concentration boomed obviously at the early stage under the condition of tight sealing, and then the quantity is increased successively. In Wanfeng Mine, the effective single-hole drainage purity is generally 0.2~1 m^3/min. The area, where the extraction purity is more than 0.2 m^3/min, is defined as the effective extraction area, in which No. 5, No. 10, and No. 15 drill holes are 52 m, 30 m, and 11 m far away from the hole point, respectively.

With the advancing of the working face, the pure quantity and the mixed quantity of extraction continuously jump up and generally remain stable in a certain distance after

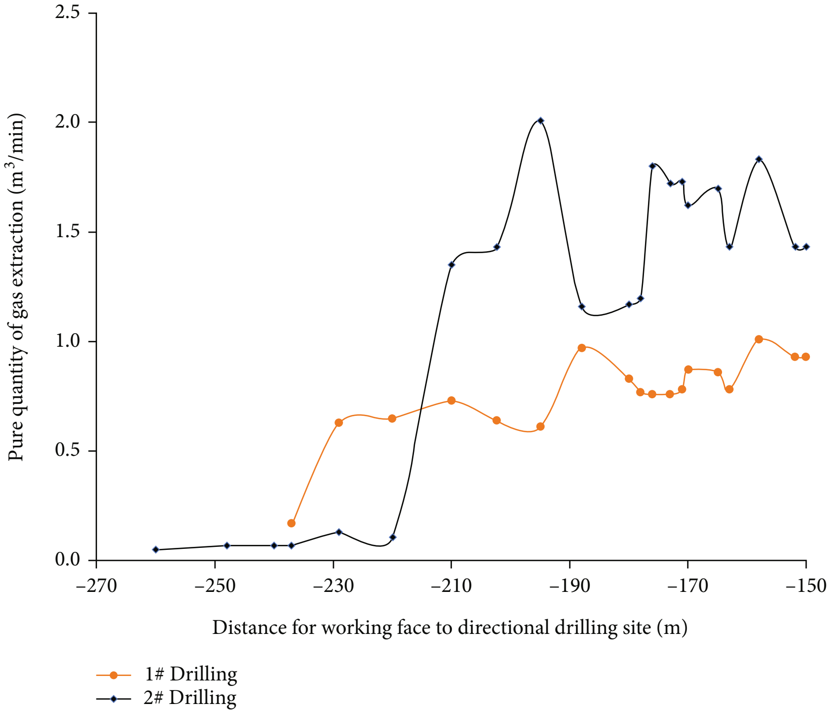


FIGURE 8: The relationship between the extraction parameters of the directional high-level drilling and the advancing step distance.

reaching the peak. Gradually the end of the drilling hole enters the compaction section of fracture; however, the front section of the borehole moves towards the caving zone slowly until entering completely, so the mixing pumping-production continues to be stable or slightly decreased. With the further reduction of the effective horizon, the concentration becomes lower and lower, resulting in the gradual diminishment of the pumping-production purity. The former analysis gets verified.

The calculation results of drilling holes Nos.5, 10, and 15 are shown in Table 2. The fluctuating value of the transverse offset is only 5 m, so it can be considered as a reasonable range. The investigation conclusion is that, during normal mining of No. 1 coal in Wanfeng Mine, the area of 25 m in dip and 15 m in vertical height is a stable fracture zone. It should be noted that the mathematical model established in this paper is universal, but its parameters are not fixed. When using the model under different mines and coal seam occurrences, the model must be solved by specific conditions based on the working face parameters of the target coal seam, and the design parameters of the borehole must be determined according to the solution results.

3.4. Engineering Verification. The calculation results are verified by directional high-level drilling in 1201 working face. The drilling parameters are shown in Table 3. The effect of gas drainage is shown in Figure 7.

From a statistical data perspective based on Figure 8, the data of directional high-level hole indicate that when No. 1 and No. 2 boreholes come into effect, they lag behind the working face by 26 m and 18 m, respectively, and the obtained lag effective angles are all about 29°, which is close to the calculated value of 32° by the model, The stable drainage pure quantity of borehole is up to 1~1.8 m^3/min and 0.6~1 m^3/min, respectively, which acquires a good extraction effect and is in good agreement with the mathematical model of the stable fracture development zone and its solution results. The pure amount of extraction is 0.7 m ^{3}/min at the top effect of ordinary boreholes; the average of directional high-level drilling is maintained at 1.4 m ^{3}/min, which has a much longer service cycle than that of ordinary drilling. When directional high-level drilling is arranged in the stable fracture development area to extract gas, its technology is more advanced, and the engineering quantity and economy are more reasonable.

4. Conclusions

The stable development area of the fractured zone is vital to ensure the effective gas drainage. The drill hole service period is divided into three stages: effective stage, optimal stage, and ineffective stage. After the analysis of gas drainage laws of the ordinary and directional high-level boreholes in various stages, it is clarified that the lag effective angle, the lateral dislocation distance, and the lag distance of the effective point along the roadway are the key parameters to determine the stable development area of the fractured zone in the overlying strata.

In stable coal seam area, the geometric model and mathematical model are relatively distinct. Usually, the geometric model of gas drainage from the high-level boreholes is set up based on the ordinary high-level boreholes in the drilling field. With the occurrence of coal seams and boreholes, a mathematical model is established to determine the key parameters of stable fracture development zone, and the parameter investigation and model calculation methods are proposed.

In Wanfeng Mine, the established mathematical model of stable fracture development zone and its solution method are quantitatively implemented by using ordinary high-level boreholes, and the solution results are testified by directional high-level boreholes. There is a clear consistence between these two results, which confirms the reliability of the method. In production practice, the low-cost and easy-to-operate ordinary high-level drilling can be used to obtain the required parameters. Then the directional high-level drilling is guided in the stable crack developing area to ensure the efficient extraction of directional high-level drilling.

The mathematical model established in this paper contains many parameters, and the solution process is complex. In the next, a special calculation software will be compiled based on the mathematical model to realize rapid solution.

Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no competing financial interest.

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References

[1] Y. Xue, J. Liu, X. Liang, S. Wang, and Z. Ma, "Ecological risk assessment of soil and water loss by thermal enhanced methane recovery: numerical study using two-phase flow simulation," *Journal of Cleaner Production*, vol. 334, article 130183, 2022.

[2] Y. Xue, J. Liu, P. G. Ranjith, Z. Zhang, F. Gao, and S. Wang, "Experimental investigation on the nonlinear characteristics of energy evolution and failure characteristics of coal under different gas pressures," *Bulletin of Engineering Geology and the Environment*, vol. 81, no. 1, p. 38, 2022.

[3] D. F. Chen and Y. Lu, "Research and application on comprehensive gas treatment technology in upper corner of working face," *Coal Science and Technology*, vol. 41, no. 10, pp. 57–59, 2013.

[4] X. L. Zhang, Y. P. Cheng, L. Wang, J. W. Mu, and X. Wu, "Optimized design on high level borehole in roof of coal mining face in coal and gas outburst mine," *Coal Science and Technology*, vol. 42, no. 10, pp. 66–70, 2014.

[5] H. Shi, "Gas drainage technology and its application of large diameter and high directional long drilling," *Coal Science and Technology*, vol. 46, no. 10, pp. 190–195, 2018.

[6] H. Li, Y. Liu, W. Wang et al., "The integrated drainage technique of directional high-level borehole of super large diameter on roof replacing roof extraction roadway: a case study of the underground Zhaozhuang Coal Mine," *Energy Reports*, vol. 6, pp. 2651–2666, 2020.

[7] C. L. Zhang, J. Xu, S. J. Peng, Q. Li, F. Yan, and Y. Chen, "Dynamic behavior of gas pressure and optimization of borehole length in stress relaxation zone during coalbed methane production," *Fuel*, vol. 233, pp. 816–824, 2018.

[8] H. J. Duan, S. J. Hao, and Y. Z. Zhao, "Differential gas drainage technology for upper corner of working face by high position directional long borehole," *IOP Conference Series: Earth and Environmental Science*, vol. 687, article 012180, 2021.

[9] H. C. Ding, Z. G. Jiang, and Q. M. Zhu, "Optimized parameters and forecast analysis of high-position hole for goaf gas drainage," *Procedia Engineering*, vol. 45, pp. 305–310, 2012.

[10] W. Qin, J. Xu, and G. Hu, "Optimization of abandoned gob methane drainage through well placement selection," *Journal of Natural Gas Science and Engineering*, vol. 25, pp. 148–158, 2015.

[11] W. Zhao and W. Qin, "Computational fluid dynamics optimization of gas drainage technology in gas-mining areas," *Energy Exploration & Exploitation*, vol. 40, no. 2, pp. 873–886, 2022.

[12] B. Zhang, Y. Liang, H. Sun, K. Wang, Q. Zou, and J. Dai, "Evolution of mining-induced fractured zone height above a mined panel in longwall coal mining," *Arabian Journal of Geosciences*, vol. 15, no. 6, p. 476, 2022.

[13] Z. Wang, B. Liu, Y. Han, Z. Li, Y. Cao, and F. Qi, "Determining the layout parameters of the gas drainage roadway: a study for Sima coalmine China," *Advances in Civil Engineering*, vol. 2021, Article ID 3007807, 8 pages, 2021.

[14] H. Q. Zhang, H. F. Wang, and X. D. Wang, "Study on gas drainage with large diameter high level borehole to replace high level gas drainage gateway," *Coal Science and Technology*, vol. 40, no. 6, pp. 51–53, 2012.

[15] Y. Zhang, X. B. Zhang, C. Y. Li, C. Liu, and Z. Wang, "Methane moving law with long gas extraction holes in goaf," *Procedia Engineering*, vol. 26, pp. 357–365, 2011.

[16] H. Shuang, H. Wang, S. Li, Y. L. D. Du ZX, and W. I. Guo, "High level borehole drainage technique of the overlying strata mining-induced pressure-relief gas," *Journal of Xi'an University of Science and Technology*, vol. 35, no. 6, pp. 682–687, 2015.

[17] Z. F. Wang and B. Li, "A fine detection technology for the best extraction layer in mining fissure zone," *Safety in Coal Mines*, vol. 46, no. 10, pp. 70–72, 2015.

[18] T. T. Li, B. Wu, and B. W. Lei, "Study on the optimization of a gas drainage borehole drainage horizon based on the evolution characteristics of mining fracture," *Energies*, vol. 12, no. 23, p. 4499, 2019.

[19] C. Fan, H. Xu, G. Wang, J. Wang, Z. Liu, and Q. Cheng, "Determination of roof horizontal long drilling hole layout layer by dynamic porosity evolution law of coal and rock," *Powder Technology*, vol. 394, pp. 970–985, 2021.

[20] Z. D. Liu, Y. P. Cheng, J. Y. Jiang, W. Li, and K. Jin, "Interactions between coal seam gas drainage boreholes and the impact of such on borehole patterns," *Journal of Natural Gas Science and Engineering*, vol. 38, pp. 597–607, 2017.

[21] H. Frank, R. Ting, and A. Naj, "Evolution and application of in-seam drilling for gas drainage," *International Journal of Mining Science and Technology*, vol. 23, no. 4, pp. 543–553, 2013.

[22] S. Q. Lu, Y. P. Cheng, J. M. Ma, and Y. Zhang, "Application of in-seam directional drilling technology for gas drainage with benefits to gas outburst control and greenhouse gas reductions

in Daning coal mine, China," *Natural Hazards*, vol. 73, no. 3, pp. 1419–1437, 2014.

[23] G. R. Feng, S. Y. Hu, Z. Li et al., "Distribution of methane enrichment zone in abandoned coal mine and methane drainage by surface vertical boreholes: a case study from China," *Journal of Natural Gas Science and Engineering*, vol. 34, pp. 767–778, 2016.

[24] H. Guo, L. Yuan, B. T. Shen, Q. Qu, and J. Xue, "Mining-induced strata stress changes, fractures and gas flow dynamics in multi-seam longwall mining," *International Journal of Rock Mechanics and Mining Sciences*, vol. 54, pp. 129–139, 2012.

[25] J. G. Zhao, "Construction technology and development tendency of high level directional drilling in seam roof," *Coal Science and Technology*, vol. 45, pp. 137–141, 2017.

[26] W. P. Cai, J. Liu, and D. S. Sun, "Research and application of gas drainage technique with high-located drilling method along roof strike," *Journal of Safety Science and Technology*, vol. 9, pp. 35–38, 2013.

[27] F. H. An, Z. F. Wang, H. M. Yang et al., "Application of directional boreholes for gas drainage of adjacent seams," *International Journal of Rock Mechanics and Mining Sciences*, vol. 90, pp. 35–42, 2016.

[28] T. X. Hao, Z. C. Jin, and F. Li, "Optimization of goaf gas drainage parameters based on numerical simulation studying fracture in overlying strata," *Procedia Engineering*, vol. 43, pp. 269–275, 2012.

[29] S. Guangyao and B. Bharath, "Performance analysis of vertical goaf gas drainage holes using gas indicators in Australian coal mines," *International Journal of Coal Geology*, vol. 216, article 103301, 2019.

[30] M. H. Zhang, S. Y. Wu, and Y. W. Wang, "Research and application of drainage parameters for gas accumulation zone in overlying strata of goaf area," *Safety Science*, vol. 50, no. 4, pp. 778–782, 2012.

[31] D. Zhao, J. Liu, and J. T. Pan, "Study on gas seepage from coal seams in the distance between boreholes for gas extraction," *Journal of Loss Prevention in the Process Industries*, vol. 54, pp. 266–272, 2018.

[32] H. F. Lin, E. H. Yang, B. Q. Xiang et al., "Directional drilling replacing tailgate gas drainage technology in gassy fully-mechanized coal mining face," *Coal Science and Technology*, vol. 48, pp. 136–143, 2020.

[33] G. S. Hao, B. Hao, and K. Shen, "Analysis on differential layout and gas drainage effect of high position directional borehole in roof of goaf," *Coal Science and Technology*, vol. 46, pp. 101–106, 2018.

[34] Z. Y. Qin, L. Yuan, H. Guo, and Q. D. Qu, "Investigation of longwall goaf gas flows and borehole drainage performance by CFD simulation," *International Journal of Coal Geology*, vol. 150, pp. 51–63, 2015.

[35] C. Zhang, J. Xu, S. Peng, Q. Li, and F. Yan, "Experimental study of drainage radius considering borehole interaction based on 3D monitoring of gas pressure in coal," *Fuel*, vol. 239, pp. 955–963, 2018.

[36] Y. Wang, W. Yan, Z. Ren, Z. Yan, Z. Liu, and H. Zhang, "Investigation of large-diameter borehole for enhancing permeability and gas extraction in soft coal seam," *Geofluids*, vol. 2020, Article ID 6618590, 13 pages, 2020.

[37] T. Liu, B. Q. Lin, X. H. Fu, and C. Zhu, "Modeling air leakage around gas extraction boreholes in mining-disturbed coal seams," *Process Safety and Environmental Protection*, vol. 141, pp. 202–214, 2020.

[38] H. F. Wang, Y. P. Cheng, Y. T. Shen, and H. B. Liu, "Gas drainage T echnology of along-S trike roof drills in working face with high production and efficiency," *Journal of Mining & Safety Engineering*, vol. 25, pp. 168–171, 2008.

[39] G. R. Feng, A. Zhang, S. Y. Hu et al., "A methodology for determining the methane flow space in abandoned mine gobs and its application in methane drainage," *Fuel*, vol. 227, pp. 208–217, 2018.

[40] Q. D. Qu, H. Guo, and M. Loney, "Analysis of longwall goaf gas drainage trials with surface directional boreholes," *International Journal of Coal Geology*, vol. 156, pp. 59–73, 2016.

[41] X. Liu, J. Nian, and G. Du, "Technology of roof failure law and high level borehole gas drainage in high gassy fully-mechanized top coal caving mining face," *Coal Science and Technology*, vol. 44, no. 8, pp. 132–136, 2016.

[42] H. C. Ding and J. L. Zhang, "Application of high level borehole goaf gas drainage technology to Zhangji mine," *Coal Engineering*, vol. 12, pp. 53–55, 2011.