





Research Article

Determination and Application of Reasonable Levels for Highly Directional Long Boreholes in Deep Outburst Coal Seams

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In order to solve the problem that the gas in the upper corner is easy to exceed the limit in the mining process of the deep outburst coal seam. Based on the theory of “O-ring” and the distribution of stratigraphy in the field, the development law of mining fissures in the overlying rock layer during the workface retrieval was studied by combining theoretical calculation and FLAC3D numerical modeling. The research results show that the range of fissure development zone in 2913 working face is 14.2 to 33 m from the coal seam roof, and the high drilling arrangement can be in the stable rock layer of the roof. For siltstone-fine sandstone interaction stratum, measures such as opening branches to adjust the layer and lowering the casing to protect the hole wall can be taken to ensure the stability of the borehole and the smooth flow of gas extraction channels. Field application shows that the high directional long borehole has the advantages of long extension distance and wide coverage, the average value of extraction mix is 34.3 m³/min, and the average value of extraction pure is 0.4 mm³/min, which helps to prevent the gas overlimit in the upper corner during the workface recovery. The high directional long borehole has obvious economic and safety benefits over the traditional high hole and has important promotion value in coal mine gas management.

1. Introduction

Coal occupies the main position in the energy consumption structure of China. With the national economic development of the demand for coal production increasing year by year, many coal mines in China reach a depth of more than 1000 m and enter the ranks of deep mining [1–3]. In the process of deep mining, the geological conditions are more complex, the ground stress increases, the original gas endowment content increases, and the possibility of coal and gas protrusion accidents further increases [4, 5]. The occurrence of coal and gas protrusion accidents not only tends to cause significant casualties and economic losses but also produces bad negative social and international effects [6–8]. Therefore, taking effective measures to prevent and control the occurrence of coal and gas protrusion acci-

dents has become the focus of research for many coal scientists and technicians [9–11].

In recent years, many researchers have conducted a lot of research on gas extraction technology. Li et al. [12] numerically simulated the effect of different extraction parameters on directional drilling and showed through field tests that directional drilling is better than conventional drilling in operation. Qin et al., Shi et al., and Xu et al. [13–15] used the directional long borehole technique for deep coal seam gas extraction and achieved good results. Cheng et al. [16] considered that the low efficiency of tunneling in coal mines is the main cause of mining disorders and proposed the working mode of “long digging and long exploration” for this reason. Duan et al. [17] determined the best drilling structure of the near-horizontal high directional long hole by analyzing the evolution process of the fracture in the

mining area with the working face and achieved good results. Yan et al. [18] proposed the optimization method and drilling method of directional long borehole arrangement in the surrounding rock based on the law of coalbed methane transport during the directional long borehole arrangement. Duan et al. [19] analyzed the effect of locating directional drilling on the effectiveness of gas extraction from different layers and obtained the optimal location for different distance and height zones. According to the “O-ring” theory, Hou et al. [20] compared and analyzed the gas extraction data and effects of directional long-distance drilling with different drilling heights and came up with the best height of directional drilling. Chen [21] combined the construction of high directional long boreholes by a directional drilling rig and conventional extraction boreholes in complex rock formations to propose a high directional long borehole three-dimensional extraction technique applied to deep coal seam gas extraction. Zhang et al. [22] proposed the design of a reasonable layer and the best drilling arrangement method for the long directional drilling in the perimeter rock with gas-bearing reservoir distribution by simulating the influence range of the top and bottom plate mining. Zhao et al. [23] used Fluent numerical simulation software to simulate the layout of each extraction method of cooperative extraction, analyzed the corner gas concentration of the working face under each layout condition, and determined the optimal layout of the layers. D'Angelo et al. [24] solve the directional rig guidance problem using the Pareto frontier approximation and use a multiobjective evolutionary search approach to solve the optimization. Most of the scientific and technical staff mainly focus on the field drilling construction process and the effect of gas extraction, but not enough research on the theoretical analysis of high directional long holes.

In order to further improve the application of high directional long drilling technology in the coal seam envelope, solve the problem that the gas in the upper corner is easy to exceed the limit during the mining of deep prominent coal seam. Based on the above research, this paper takes the corner gas extraction on the 2913 working face of the 2# coal seam of Dong Pang mine as an example, and based on the “O-ring” theory and the field stratum distribution, the height range of the fissure zone is obtained through theoretical calculation and numerical modeling. Then, the reasonable level of high directional long-hole drilling is determined by the actual situation of field application. Finally, the advantages of the high directional long drill hole extraction technology compared with the traditional extraction technology are explained in terms of economic and safety benefits. The research results have important promotion value in coal mine gas management.

2. Theoretical Foundation

2.1. O-Ring Theory. Coal mining causes the redistribution of the stress field in the overlying rock layer, resulting in deformation and destruction of the overlying strata and the formation of mining fissures in the overlying rock. When the roof strata of goaf are fully collapsed, the overlying rock

layer of the mining area will form a bubble zone, a fissure zone, and a bending and sinking zone. With the advancement of the mining working face, the middle of the rock body in the mining hollow area is gradually compacted, and the mining fissures are gradually closed. Due to the support of the surrounding coal wall, there is a fissure development area in the lower part of the key layer of the overburden around the mining area, which is called the O-ring [25–27]. It moves forward at the same speed as the working face advances, and after the working face advances, a compaction zone is formed in the middle of the back of the extraction zone, and a fissure zone is still formed around the compaction zone. Due to the unloading and desorption of coal seams and adjacent layers, gas is transported along the gas-conducting crack belt in the way of “diffusion-percolation” and gathered in the O-ring of the roof of the mining area, and the O-ring becomes the main place where gas is gathered [28].

2.2. The Three Zones of the Mining Area Are Divided. The coal and rock layers on the top and bottom of the mining area move, deform, and break, and the coal and rock layers on the top naturally fall down, and the coal and rock layers on the bottom undergo drumming, which makes the ground stress shift outward and forms a stress reduction zone in a certain range. According to the theory of the “masonry beam” model, as the working face advances, the mining pressure field formed around the working face can be divided into bending subsidence belt, crack belt, and collapse zone according to its fracture development degree. Three zones are divided in the horizontal direction, which are the coal wall support influence zone, off-seam zone, and recompaction zone along with the depth of the mining area, as shown in Figure 1. According to the damage characteristics of the rock fall and the accumulation state, the collapse zone can be divided into natural accumulation zone, load impact zone, and recompaction zone along the direction of the depth of the mining area [29–31].

2.2.1. Collapse Zone. The collapse zone is a rock zone where the overlying rock is destroyed and collapses into the mining area and is located in the lower part of the overlying rock of the mining area. The main formation mechanism is that the overlying rock seam gradually loses balance after the coal seam is mined and gradually collapses from the bottom to the top until the falling rock blocks fill the mining space. The broken rock blocks in the collapse zone are irregularly piled up with a large loosening coefficient, and the large gap between the blocks is strongly connected, which is extremely conducive to the flow of gas.

2.2.2. Crack Belt. The crack belt is a zone of rock formation that is bent and deformed with fractures and fractures above the fall zone but still maintains its original rock shape. The main formation mechanism is that after the emergence of the lower rock layer (direct top), the main key layer and subkey layer play a controlling role in the movement and deformation of the upper rock layer. The subcritical layer (old top) moves asynchronously under the load of the

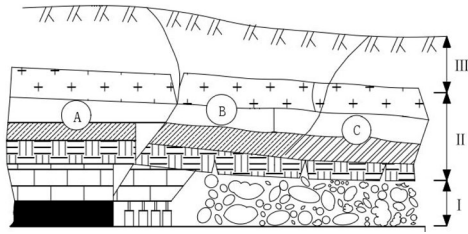


FIGURE 1: Distribution of the “vertical three zones” and “horizontal three zones” after overburden movement damage.

overlying rock due to the different lithology of the rock layer, forming a cis-layer tension fissure. During subsidence, the tensile stress forces the rock to produce longitudinal penetration fractures. The crack belt height gradually expands upward with the expansion of the mining area and reaches a maximum when the mining area expands to a certain extent and then remains constant.

2.2.3. Bending Subsidence Belt. The bending subsidence belt is the overall bending and sinking of the upper rock body under the double action of its own gravity and the support force of the lower rock body, which is located above the fissure zone. The movement of each rock layer in the bending subsidence belt has continuity and regularity and is gently bending and sinking, maintaining better integrity, and there are generally fewer fissures, making it difficult to form a fissure network.

2.3. Extraction Mechanisms. Determining the source and flow pattern of gas in the extraction zone is the key to the design of directional length drill holes. The transport of gas in the extraction area is closely related to the state of deposit and mining conditions, and its components mainly include coal gushing gas, adjacent layer gas, and surrounding rock gas. Through the analysis of the coal seam gas distribution law and flow theory, after the influence of coal seam mining, the rock seam will destroy the pressure equilibrium relationship of the rock near the coal seam, so that the rock seam will sink and expand and deform, thus generating off-seam fissures and vertical fracture fissures, and the free gas in the adjacent rock seam and the surrounding rock will flow to the fallout zone of the mining area through the generated fissures. The gas in the mining area can be communicated to the collapse zone through the O-ring, using the leakage wind flow in the mining area to make part of the gas flow to the upper corner of the coal mining face, and part of the gas flow to the rift zone using the buoyancy of the atmosphere [32, 33].

The use of a large diameter high directional long borehole to control gas in mining areas is based on the calculation method of the height of the “three belts” in the mining area before the coal seam is retrieved. On the basis of meeting the applicable conditions for the construction of a large diameter high directional borehole, the height of the crack belt of the mining coal seam is given with the actual measured height of the crack belt in each mine, and the appropriate rock layer within the crack belt is selected

for the construction of horizontal long directional holes as the main hole to ensure that the main hole channel is not destroyed during the coal seam recovery. Then, use the measurement-while-drilling technology to conduct directional drilling pilot holes, and withdraw the drill pipe after reaching the final hole position. Finally, the reaming tool is lowered to ream the entire hole to increase the diameter of the borehole, so that the unloaded gas in the mining area can be extracted through the main hole during the coal seam recovery. By using directional drilling technology to precisely control the trajectory of the drill hole, the high-level directional long drill hole is arranged within the “O-ring” of the mining fissure near the return airway, so that the drill hole is fully and effectively extended within the “O-ring.” High directional long drill hole can exist in the “O-ring” for a long time, so it can effectively extract gas in the fissure zone for a long time, reduce the gas concentration in the upper corner and return wind tunnel, and avoid the gas over-limit in the upper corner and return wind tunnel [34–36].

3. Determination of the Location of High Drilling Holes

3.1. Engineering Background. The gas disaster in the Dong Pang coal mine mainly occurs in the main mining no. 2 coal seam, which is characterized by high gas content, high gas pressure, poor permeability, and complex pore structure of the coal body. The actual measured gas parameters of coal seam no. 2 are the maximum gas content is $6.46 \text{ m}^3/\text{t}$, the coal seam gas pressure is 1.15 MPa , the minimum value of coal solidity coefficient is 0.26 , the coal body damage type is III, and the coal seam permeability coefficient is $0.045\text{--}0.046 \text{ m}^2/\text{MPa}\cdot\text{d}$, which is difficult to extract coal seam. According to the mine’s mining plan, the construction volume of the extraction borehole in the Dong Pang mine in the past 5 years is shown in Figure 2. As can be seen from Figure 1, Dong Pang mine will invest huge manpower and material resources in gas extraction in the past 5 years. However, the low extraction efficiency of ordinary drill holes and the large amount of drilling work make it difficult to meet the needs of mine safety production. Therefore, we choose a high directional long borehole for gas extraction, which has the advantages of large drilling depth, precise and controllable trajectory, and increased drilling diameter to improve the extraction rate.

It is planned to carry out high directional long drilling construction in 2913 working face of Dong Pang mine. From the actual measurement data of 2913 working faces, it is known that the structure of 2913 working faces is more complex and mixed, mainly manifested as fracture structure. The main roof is limestone, medium-thick layered, hard, 4.14 m thick, and light gray. The immediate roof is siltstone, with a thickness of 7.9 m , dark gray in color, silt-like structure, and contains argillaceous, plant, and fossil fragments. The direct bottom is fine sandstone with a thickness of 2.8 m , gray in color, vein-like bedding in the interior, and argillaceous in part. The old bottom is carbonaceous mudstone with a thickness of 1.32 m , dark gray, and high carbon

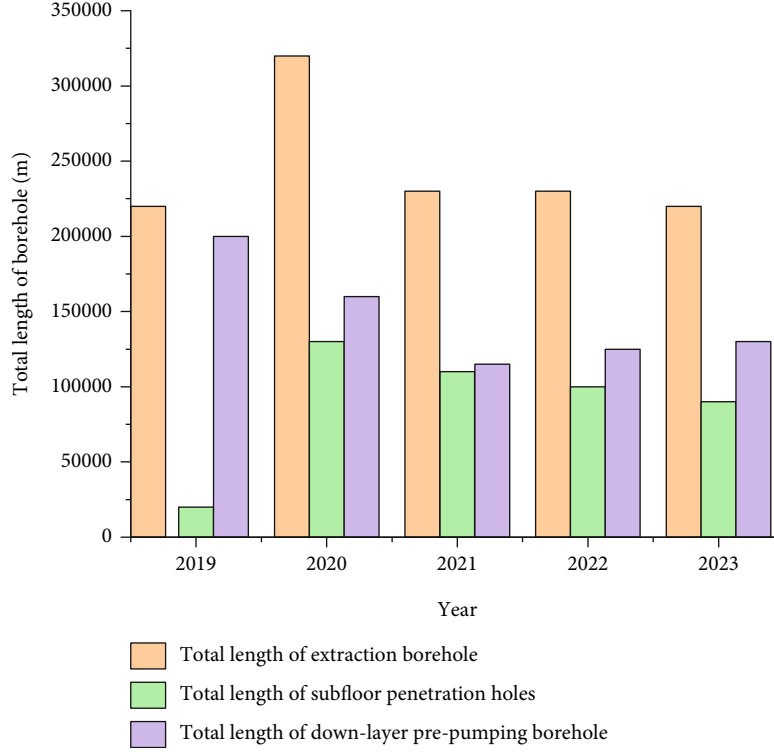


FIGURE 2: Planned drilling volume in the next five years.

content, and a layer of bauxite mudstone developed at the top with a thickness of 0.01-0.1 m.

3.2. Theoretical Calculation. The coal seam mining process will affect the overlying rocks, and the overlying rocks appear obvious O-ring feature in the direction. From the top to the bottom of the seam, there is a bending subsidence belt, crack belt, and collapse zone in order. The division of the height of the “three zones” in the empty mining area is related to the basic parameters such as the thickness of the recovery surface, the mining method, and the lithology of the overlying rock layer. The formula for calculating the height of the three zones in the mining area is shown in Table 1.

According to the engineering profile of 2913 working faces of Dong Pang mine, the main roof of the #2 coal seam of Dong Pang mine is siltstone, and the lithology of the seam is medium-hard rock. The basic roof is limestone, and the lithology of the seam is hard rock. Referring to Table 1, the medium-hard lithology was selected as the calculation formula by comprehensive consideration. Therefore, the high borehole height H_z should satisfy the following condition: $H_m < H_z < H_l$. The thickness of 2# coal seam in 2913 working face of Dong Pang mine is 4.0 to 4.9 m, and the average thickness is 4.3 m. From this, the height of the three zones in the extraction area can be calculated, and the calculation process is as follows.

3.2.1. Height of Collapse Zone. The height of the fall zone is determined by the rock fragmentation and coal mining height, which is about 3 to 5 times the height of coal mining.

The formula is calculated using the medium-hard overburden lithology as follows.

$$H_m = \frac{100\sum M}{6.2\sum M + 19.0} \pm 2.2 \quad (1)$$

$$= \frac{100 \times 4.3}{6.2 \times 4.3 + 10.0} \pm 2.5 = 11.7 \pm 2.5,$$

where H_m is the height of the collapse zone, m; $\sum M$ is the average thickness of coal seam, m.

The thickness of 2# coal seam in 2913 working face of Dong Pang mine is 4.0 ~ 4.9 m, and the average thickness is 4.3 m. According to the calculation of the full height of primary mining, the height of the collapse zone is taken from 9.2 ~ 14.2 m according to the formula.

3.2.2. Height of Crack Belt. The formula is calculated using the medium-hard overburden lithology as follows.

$$H_l = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6 = \frac{100 \times 4.3}{1.6 \times 4.3 + 3.6} \pm 5.6 = 41 \pm 5.6, \quad (2)$$

where H_l is the height of the crack belt, m; $\sum M$ is the average thickness of coal seam, m.

The thickness of the coal seam mined at the working face is calculated according to 4.3 m, and the height of the crack belt is in the range of 35.4 to 46.6 m.

TABLE 2: Physical and mechanical parameters of rock formations.

Lithologic	Apparent density/kg-m ³	Cohesion/MPa	Bulk modulus/GPa	Shear modulus/GPa	Internal friction angle/°	Tensile strength/MPa
Coal seam	1470	2.4	1.45	0.74	18	1.43
Medium sandstone	2432	6.8	4.89	2.13	35	2.7
Silty sandstone	2421	4.8	3.69	3.24	38	2.00
Mudstone	2422	4.8	3.69	3.24	38	2.00
Fine sandstone	2454	4.3	2.32	1.82	29	1.53

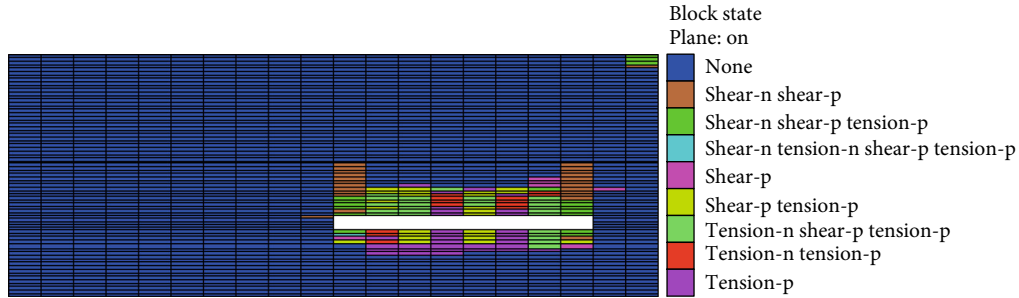


FIGURE 4: Model unit failure state when mining 80 m.

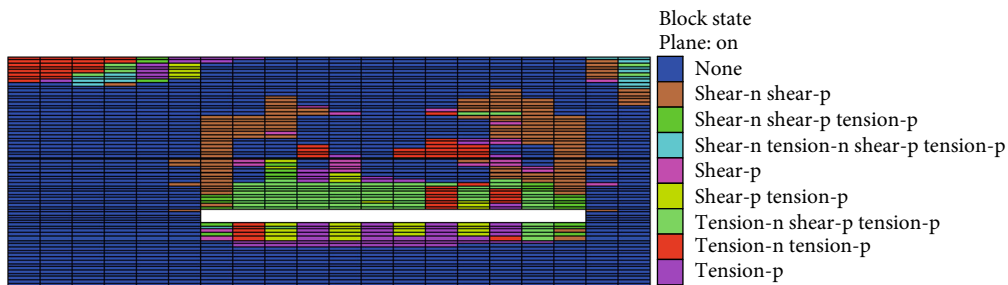


FIGURE 5: Model unit failure state when mining 120 m.

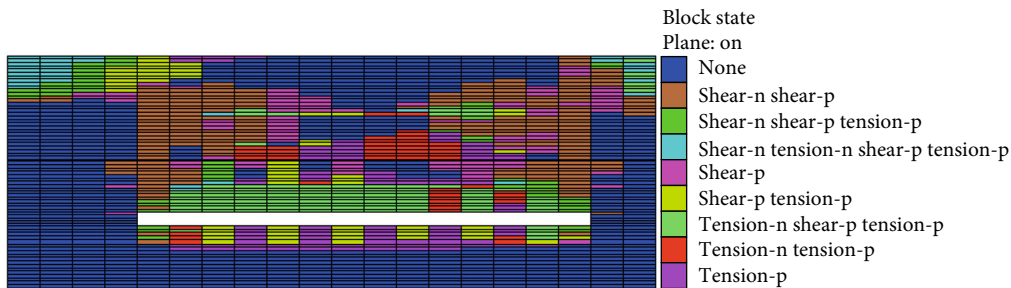


FIGURE 6: Model unit failure state when mining 140 m.

is 28 m at this time. Figure 6 shows the tensile yield area of the overburden rock in the mining area when the working face advances 140 m. It can be seen from the figure that after the calculation is smooth, the maximum height of the tensile yield area is about 33 m above the extraction area, and the area above 33 m is the elastic undamaged area; thus, it can be judged that the maximum height of the fissure zone is 33 m at this time, and the height of the fissure zone is basi-

cally unchanged at this time, which means that the full extraction has been reached.

As can be seen from Figure 7, the maximum amount of subsidence is at 8 m from the observation line, and the layer completely enters the collapse zone with a maximum sinking displacement of about 1.1 m. The maximum subsidence after stabilization at 10 m of the observation line can also reach 0.85 m. It is still in the zone of strong displacement change

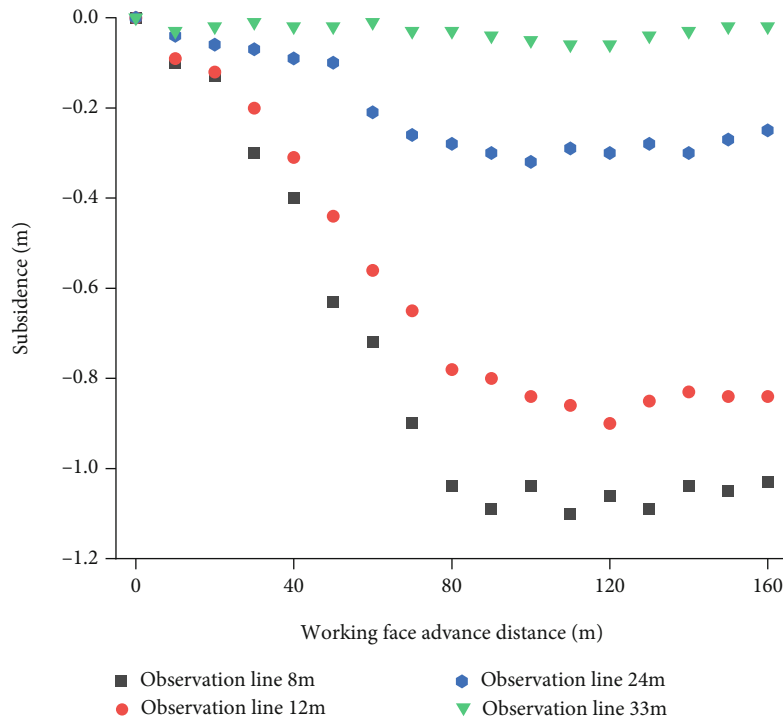


FIGURE 7: Variation curve of sinking volume of each measurement line.

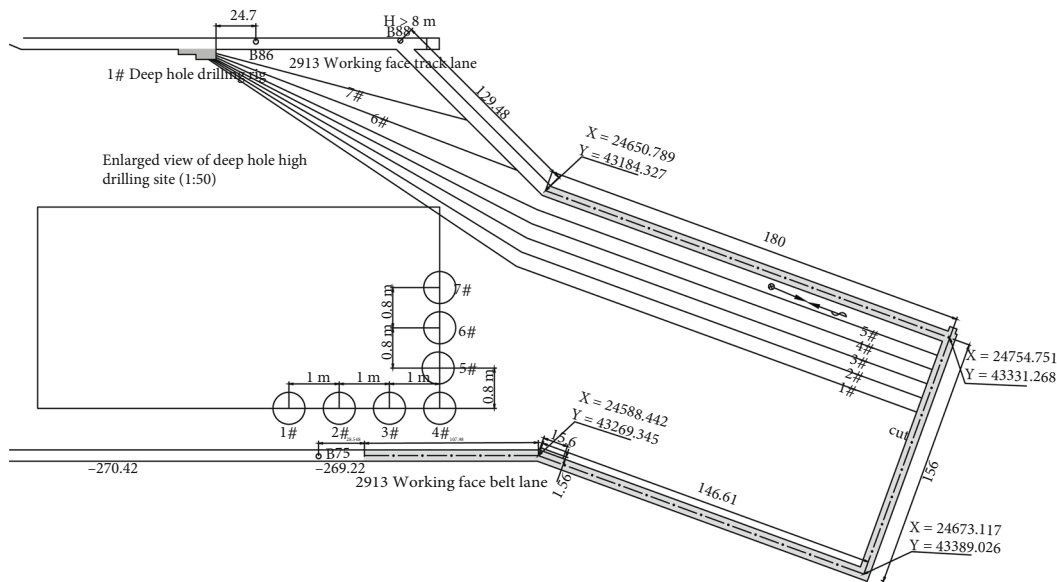


FIGURE 8: 2913 working face high drilling layout.

but slightly weakened, which also indicates that the location of the observation line is close to the top of the collapse zone. When the observation line is located at 24 m, the maximum subsidence of the roof is only 0.3 m. This displacement value cannot form the macroscopic phenomenon of large collapse of the roof, but it can also modify the plastic characteristics of the rock formation and form a large number of new fissures, indicating that the level enters the rock crack belt. When the observation line is located at 33 m, the subsidence of the roof is only

0.06 m, and the degree of fracture is not too obvious, so it can be considered that the line has reached the maximum height of the crack belt. Therefore, from the distribution characteristics of the observation line, we can calculate the maximum height of the roof collapse zone is 10 m, and the top range of the crack belt is 24~33 m. Combining with the lithology of the roof and the mining height, it is determined that the best layout of the high level borehole should be located 10~33 m above the roof of the 2# coal seam during mining.

TABLE 3: Table of high drilling parameters.

Hole	Normal distance/m	Opening orientation (°)	Opening inclination (°)	Drilling depth/m	Hole opening position/m
1	15	50	15	110	In front of the drill site, 1.0 m below the top plate
2	15	55	15	140	
3	15	60	18	330	
4	18	62	18	330	In the right gang of the drill site, 1.0 m below the top plate
5	20	64	18	330	
6	22	66	18	330	
7	24	68	18	330	

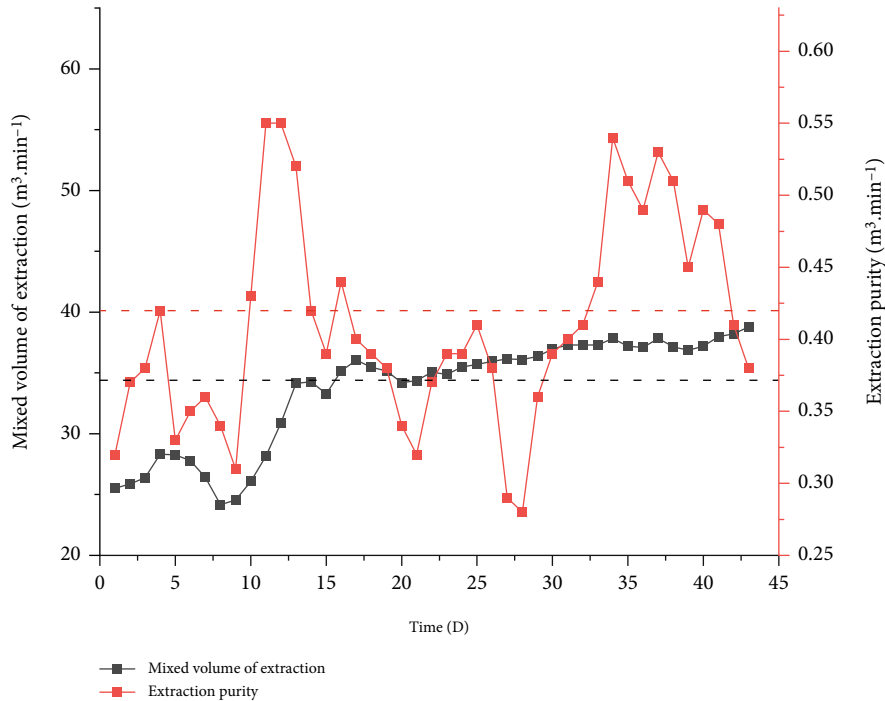


FIGURE 9: Change trend of gas drainage quantity.

The theoretical calculation obtained the fissure zone ranges from 14.2~46.6 m, and the numerical simulation obtained the fissure zone ranges from 10 to 33 m. The final range of the fissure zone can be determined as 14.2 to 33 m by combining the two results. Combining with the rock condition of the top slab of the 2# coal seam, the high-level hole can be arranged in the stable rock layer of the top slab during the construction process.

4. Field Applications

4.1. Analysis of Extraction Effect. Taking the 2913 working face of Dong Pang mine as an example, the reasonable level of high directional long drilling is 14.2 to 33 m after theoretical and numerical analysis. In order to further verify the accuracy of the reasonable layer position, this construction used the ZDY6000LD directional drilling rig to drill 7 high-level holes of 113 mm diameter in the 1# drilling field

of the coal gang in the return airway of 2913 working faces. The layout of each high-level borehole is shown in Figure 8, and the specific parameters are shown in Table 3.

During the drilling process in the field, the following construction difficulties are easily encountered. First, the stratum is the siltstone and fine sandstone interaction stratum. Although siltstone is not as easy to neck and collapse as mudstone, siltstone (related to mud content) is close to mudstone in drilling construction, and it is easy to drop the block and collapse holes. In addition, the siltstone contains rhodochrosite nodules, which affects drill bit wear. In response to this situation, specific measures were taken to open branches during drilling to find stable sandstone layers as a way to adjust the layer level. Second, there is a fault within the drilling area, which affects the construction. The solution is to put down the casing to protect the hole wall and adjust the left and right displacement of the drilling in the program according to the construction situation on site.

The 2913 working face was pumped, and the trend of the variation of the pumping mix and pure volume was statistically analyzed, as shown in Figure 9. From the trend of the graph, it can be obtained that the maximum value of the mixed volume of extraction is up to $39.4 \text{ m}^3/\text{min}$, and the average value is $34.3 \text{ m}^3/\text{min}$. The maximum value of the extraction purity was $0.55 \text{ m}^3/\text{min}$, and the average value was $0.42 \text{ m}^3/\text{min}$. During the extraction process, the gas extraction situation had slight ups and downs, but because it was only the initial extraction of retrieval, the gas gushing out was relatively small and generally stable, and the extraction effect was relatively good.

4.2. Benefit Analysis

4.2.1. Economic Benefits. Take Dong Pang mine 2913 working face 1# directional drilling field as an example, the average cost per meter of construction of high directional long holes is 700 yuan/m, 1# drilling field total construction effective hole depth of 1900 m, total cost: $700 \text{ yuan/m} \times 1900 \text{ m} = 1.33 \text{ million yuan}$. The directional long drill holes of this construction can replace the common high-level holes of 7 high-level gas drilling sites, the cost of common high-level gas drilling in 2913 working faces is 191.8 yuan/m, and the total construction hole depth of the replaceable high-level gas drilling is 14000 m. Ordinary high hole cost: $191.8 \text{ yuan/m} \times 14000 \text{ m} = 2,685,200 \text{ yuan}$. From the above comparison, it can be seen that the total cost saving of 1# directional drilling field in 2913 working face of Dong Pang mine is 1,355,200 RMB.

4.2.2. Safety Benefits. Dong Pang mine uses high directional long drill holes to increase the final hole coverage, improve the effective length of the drill holes, and increase the extraction rate of the working face. The use of large-diameter, long drill holes provides an advanced technical means for coal mines to solve gas disasters with high construction accuracy, while the construction of high directional long drill holes reduces the number of transfers of drilling rigs, avoids the hidden risks when transferring drilling rigs, and saves construction drilling time.

5. Conclusion

In this paper, the reasonable seam position of the high directional long borehole of Dong Pang mine 2# coal seam was determined and applied comprehensively with the engineering background, and the main conclusions obtained are as follows.

- (1) Based on the “O-ring theory” and combined with the empirical formula of “three zones” in the mining area, the crack belt range of 2913 working face of Dong Pang mine is 14.2 m to 46.6 m. The numerical simulation gets the fissure zone range from 10 m to 33 m, and the combined result can get the crack belt range of 2913 working face of Dong Pang mine from 14.2 to 33 m. The pumping application was carried out on-site at the beginning of the recovery period, the maximum value of the mixed volume of extrac-

tion was up to $39.4 \text{ m}^3/\text{min}$, and the average value was $34.3 \text{ m}^3/\text{min}$. The maximum value of the extraction purity was $0.55 \text{ m}^3/\text{min}$, and the average value was $0.42 \text{ m}^3/\text{min}$

- (2) For the siltstone-fine sandstone interaction stratum, the possibility stratum of falling block collapse phenomenon is easy to happen, and there are faults within the drilling area, which affect the construction and other difficulties. Measures such as opening branches to adjust the stratigraphic position and lowering the casing to protect the hole wall can be taken to ensure the stability of the borehole and the smooth flow of gas extraction channels
- (3) The use of high directional long holes instead of traditional high penetration holes in the 2# coal seam of Dong Pang mine to extract the test working face will save a large amount of drilling work and create obvious economic and safety benefits and has wide popularization and application value

Data Availability

The data used to support the findings of this study have not been made available because the original data relating to the intellectual property rights of the author, all the original data cannot appear in the paper, and the experimental data that cannot appear is related to privacy.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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