

## Article

# Research on Gas Control Technology of “U+ Omni-Directional Roof to Large-Diameter High-Level Drilling Hole” at the End Mining Face of Multi-Source Goaf

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**Abstract:** Aiming at the gas over-run problem in the upper corner of the “U-type ventilation” end-mining working face in the multi-source goaf of the #15 coal seam in the Phoenix Mountain Mine, site survey and numerical simulation methods were adopted, which showed that the maximum caving zone height of the #15 coal seam is 14.87 m, and the maximum height of the fissure zone is 51.63 m. On this basis, the gas control scheme of the “U+ omni-directional large-diameter high-level borehole along roof strike” in the end-mining working face was formulated. After adopting this scheme, the extracted gas concentration of each borehole will reach 5–20%, the gas extraction flow rate will reach 1 m<sup>3</sup>/min–2.5 m<sup>3</sup>/min, the gas concentration at the upper corner of the working face will be controlled below 0.54%, and the gas concentration in the return airway will be controlled below 0.35%, achieving the expected effect of gas control.

**Keywords:** multi-source goaf; U-type ventilation; omni-directional large-diameter high-level borehole; gas control; effect evaluation



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## 1. Introduction

The problem of gas control has always been one of the important factors that seriously restrict the safe and efficient production of coal mines [1]. In particular, some mines with multi-seam coal mining are greatly affected by gas gushing from adjacent coal seams or goafs at the stope face [2].

Aiming at the problem of gas control in the mining process of the working face, Han Chengqiang [3] proposed a method combining the carbon isotope method and layered measurement and obtained the proportion of gas in each coal seam during the process of gas drainage from the coal seam, which provides a basis for the calculation of the residual gas content of the coal seam. Aiming at the problem of gas control in the U-type ventilation working face of high-gas mines, Gao Hong et al. [4–6] proposed a gas drainage technique combining a high-level suction roadway and a bottom-level suction roadway, which reduced the gas gushing to the working face. Li Jianwei, Gu Wangxin, et al. [7,8] studied the distribution rules of plastic zones around boreholes with different apertures, which provided a basis for the selection of borehole diameters for gas drainage. Thanh et al. [9–14] used different models to predict the CO<sub>2</sub> trapping index of deep saline aquifers and found that the developed models obtained excellent predictive performance. Wang Yilei et al. [15,16] determined the design parameters of high-level drilling in Tangkou Coal Mine in accordance with the theory of the vertical “tri-zone” and “O” ring and achieved significant results. Gao Yukun et al. [17] solved the problem of gas control in the upper corners of the Pingshan Coal Mine by adopting high-level borehole drainage measures, and they optimized the layout of the boreholes by adopting numerical simulation methods. Aiming at the problem of gas control in irregular working faces, Jiao Zhenhua et al. [18] studied the

law of gas migration in the goaf and adopted comprehensive gas control measures for the sealing of gas-gushing channels, upper-corner drainage and high-level borehole drainage in the goaf. On the basis of analyzing the source of gas emissions in the working face and its influencing factors, Gao Liang et al. [19] formulated gas control measures in a goaf in a directional roof with a long drilling segmental fissure, joint roadway intubation and large-diameter coal pillar drilling bridging the goaf, which achieved good results. Xu Xingfu, Zou Yinxian, et al. [20–23] used numerical simulation methods to simulate and analyze different high-level borehole parameters and optimized the layout of high-level boreholes. Based on the development law of the overlying rock fissures, Hu Jinlin et al. [24] used theoretical analysis, numerical simulation and other methods to study the fissure evolution law in the overburden strata of the working face with the mining process and provided a basis for the selection of high-level drilling layers. Guo Xinhong, Shi Kun, et al. [25,26] used the carbon isotope method to obtain the proportion of gas emissions in each coal seam and determined the optimal layout position of the high-level borehole. Li Quanxin, Tao Yunqi, et al. [27,28] proposed a drainage mode for the large-area gas drainage of medium-hard coal seams, regional gas drainage for broken and soft coal seams and mining pressure relief gas for “replacing the roadway with boreholes”. The accurate coverage of the whole area was realized, and continuous sampling was carried out throughout the period so as to extract as much as possible. Zhang Haoquan [29] adopted numerical simulation methods to study the near-field gas drainage area in the goaf of Shoushan No. 1 Coal Mine and proposed near-field gas drainage technology in the goaf based on a low-level roof and long boreholes, which effectively controlled the gas concentration in the upper corner.

The Phoenix Mountain Coal Mine in the Jincheng Mining Area adopts a “U”-type ventilation method, and the gas content in some areas is relatively high, especially in the adjacent seam, where a large amount of gas gushes out to the goaf, which seriously affects the safe production of the coal mine. This research analyzed the gas source of the working face and the heights of the “three zones” of the overburden of the working face, and on this basis, it conducted a “U+ omni-directional large-diameter high-level borehole along Roof strike” gas extraction test in the goaf, which effectively solved the problem of gas over-run in this area.

## 2. Project Overview

Located 5 km north of Jincheng City, the Phoenix Mountain Coal Mine belongs to Shanxi Jincheng Anthracite Coal Mining Group Co., Ltd. The main coal-bearing strata in the minefield are the Shanxi Formation and Taiyuan Formation, with a total thickness of 147.48 m. There are 14 coal seams, with a total thickness of 14.25 m. The minable coal seams are No. 3, No. 9 and No. 15 coal seams. As of 2017, No. 3 and No. 9 coal seams have been mined out, and the mined coal seam is No. 15, with a production capacity of 3.0 Mt/a.

The XV1306 working face is located in the three-level 151-panel area, the coal seam to be mined is #15, and the elevation of the working face is 524.0–598.1 m. In terms of the specific position of the working face in the mining area, the relationship with adjacent working faces, the mining of adjacent working faces, etc., the north of this working face is the XV1305 working face (mined), the south is the XV1307 working face (excavated), the west is the mine boundary, and the east is the track lane, belt lane and return airway of the 151 panels (all have been excavated). The average thickness of the overlying #3 coal seam on the working face is 6.1 m, from which all coal has been extracted. The overlying #9 coal is the goaf, and the area was damaged by a small coal mine of the 92,308, 92,310, and 91,324 working faces. The thickness of the coal seam in the working face is 1.90–3.10 m, with an average thickness of 2.55 m. The method of one-time full-height mining was adopted, and the thickness of the coal is 2.0–3.0 m. The coal seam dip angle of the working face is 0°–14°, with an average of 4°.

The gas content of the No. 15 coal seam is relatively large, while the average distance between the No. 15 coal seam and the upper part of the No. 9 coal seam is 35 m. In addition to the gas gushing out of this coal seam, the amount of gas gushing out of the adjacent

No. 3 coal seam and No. 9 coal seam is also relatively large during the mining process. Therefore, influenced by multi-source goafs in the No. 3 coal seam and No. 9 coal seam, the problem of gas control in the upper corner of the U-type ventilation coal mining face is particularly important.

### 3. Field Detection of Fissure's Developing Height

#### 3.1. Time Selection and Principle Analysis of Probe Hole

In order to study the developing height of the fissure zone in the XV1306 working face, the YTJ20 borehole peering instrument was used. By detecting the position of the fissure in the borehole and marking its position, a basis was provided for determining the developing position and height of the fissure zone.

The TJ20 rock stratum detection recorder (Figure 1) was developed by Xuzhou Zhongkuang Huatai Technology Development Co., Ltd. (Xuzhou, China), which is convenient and practical. Before detection, firstly, holes are drilled into the coal wall or rock stratum, and a micro-camera is put in the hole to realize real-time monitoring. The image is transmitted to the display of the recorder through a cable. When there are damaged areas, fissure zones, separation areas or shear fracture zones in the surrounding rock, they can be seen intuitively, and the positions of abnormal areas can be recorded.



**Figure 1.** YTJ20 rock stratum detection recorder.

In this exploration, the No. 1 drill hole in the No. 8 drilling field of the XV1306 stope face and the No. 5 drill hole in the eighth roof strike drilling field were selected. The drilling construction parameters are shown in Table 1. When the distance from the stope face is 29 m, during pre-mining detection, the fissure zone has not yet fully developed. When the distance from the stope face is 15 m, the fissure zone is affected by mining, and fissures have begun to develop. This period is used as post-mining data.

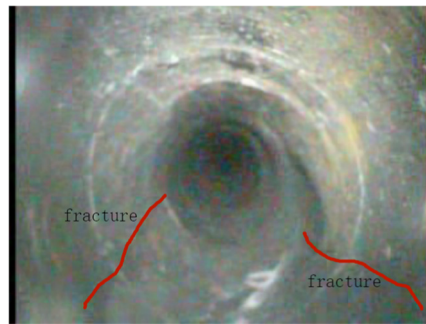
**Table 1.** Construction parameters of probe hole.

| Hole Number | Hole Depth (m) | Angle with Roadway (°) | Angle of Inclination (°) |
|-------------|----------------|------------------------|--------------------------|
| 1           | 55             | 4                      | 35                       |
| 5           | 65             | 11                     | 45                       |

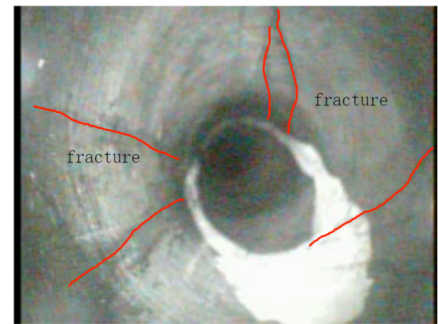
Finally, the image before mining and the image after mining were compared and analyzed, and the developing height of the fissure zone was determined through field measurements, which provided a basis for the design of the high-level boreholes.

#### 3.2. Processing and Analysis of Detection Images

Through the borehole peeping instrument, the pre-mining and post-mining rock stratum of the No. 1 drill hole in the No. 8 drill field of the XV1306 working face and the No. 5 hole along the eighth roof strike drill field were peeked at, and the following abnormal pictures were detected and analyzed (Figures 2–5).



Longitudinal crack at 14.37 m of measuring hole



Longitudinal crack at 21.37 m of measuring hole



Transverse crack at 19.66 m of measuring hole

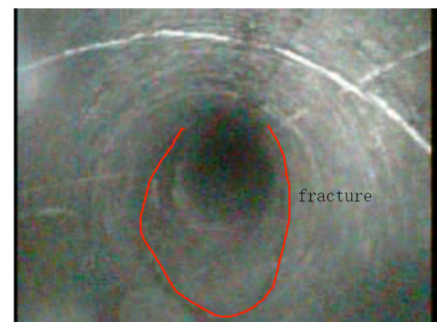


Longitudinal crack at 22.68 m of measuring hole

**Figure 2.** Peeping results of strata before mining in No. 1 hole 29 m away from the working face.

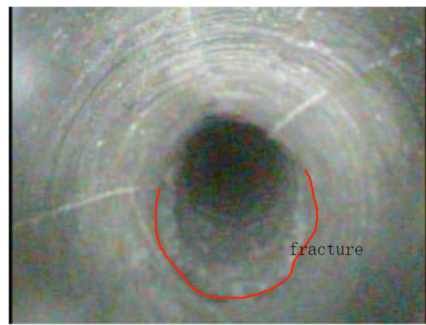


Longitudinal crack at 34.58 m of measuring hole

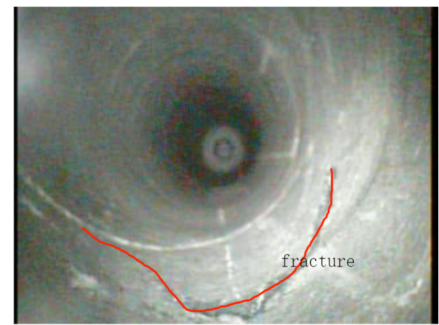


Transverse crack at 36.43 m of measuring hole

**Figure 3.** Cont.



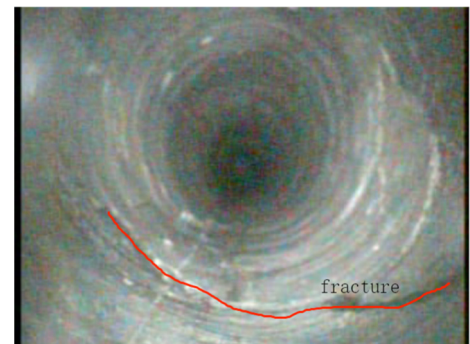
Transverse crack at 39.55 m of measuring hole



Transverse fissure at 46.43 m of measuring hole

**Figure 3.** Peeping results of strata after mining in No. 1 hole 15 m away from the working face.

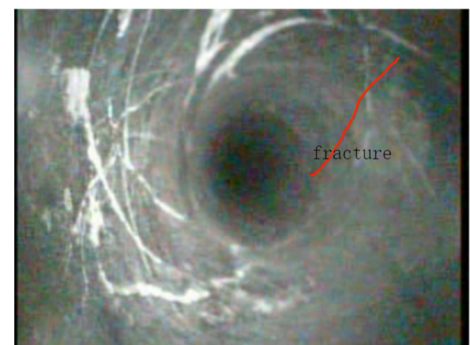
Transverse crack at 14.86 m of the measuring hole



Transverse crack at 18.35 m of measuring hole



Longitudinal crack at 19.08 m of measuring hole

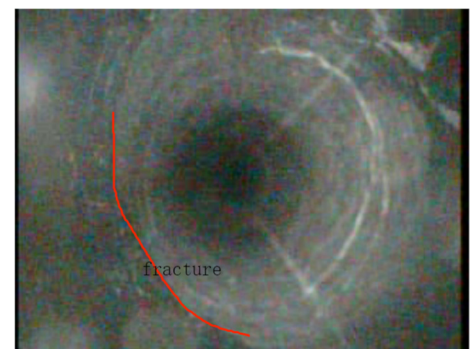


Longitudinal crack at 15.83 m of measuring hole

**Figure 4.** Peeping results of strata before mining in No. 5 hole 29 m away from the working face.



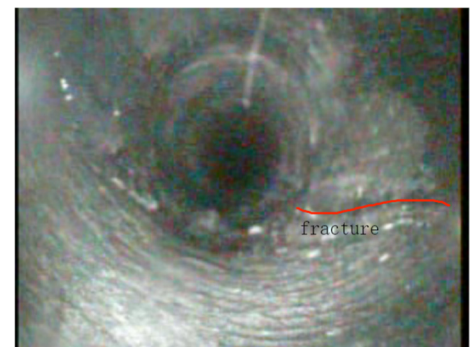
Longitudinal crack at 35.54 m of measuring hole



Transverse crack at 28.95 m of measuring hole



Longitudinal crack at 27.15 m of measuring hole



Longitudinal crack at 38.85 m of measuring hole

**Figure 5.** Peeping results of strata after mining in No. 5 hole 15 m away from the working face.

By collecting and analyzing the fissure positions of the pre-mining and post-mining boreholes, the stratum where the fissures are located can be calculated according to the elevation angle and depth of the boreholes. Usually affected by mining, the fissure zone will form a fracture surface and fracture space at a layer of a certain height. After the actual measurement, it is concluded that the height of the fissure surface in the caving zone of the #15 coal seam is 8.24~13.49 m, and the height of the fissure surface in the fissure zone is 19.19~27.46 m (see Table 2).

**Table 2.** Fracture height calculation table.

| Hole Number | Depth of Borehole Fracture Location (m) | Angle of Inclination (°) | Height of Fracture (m) | Notes         |
|-------------|-----------------------------------------|--------------------------|------------------------|---------------|
| 1           | 14.37                                   | 35                       | 8.24                   | Before mining |
| 1           | 21.37                                   | 35                       | 12.25                  | Before mining |
| 1           | 19.66                                   | 35                       | 11.27                  | Before mining |
| 1           | 22.68                                   | 35                       | 13.00                  | Before mining |
| 5           | 14.86                                   | 45                       | 10.50                  | Before mining |
| 5           | 18.35                                   | 45                       | 12.97                  | Before mining |
| 5           | 19.08                                   | 45                       | 13.49                  | Before mining |
| 5           | 15.83                                   | 45                       | 11.19                  | Before mining |
| 1           | 34.58                                   | 35                       | 19.83                  | After mining  |
| 1           | 36.43                                   | 35                       | 20.89                  | After mining  |
| 1           | 39.55                                   | 35                       | 22.67                  | After mining  |
| 1           | 46.43                                   | 35                       | 26.62                  | After mining  |
| 5           | 35.54                                   | 45                       | 25.12                  | After mining  |
| 5           | 28.95                                   | 45                       | 20.46                  | After mining  |
| 5           | 27.15                                   | 45                       | 19.19                  | After mining  |
| 5           | 38.85                                   | 45                       | 27.46                  | After mining  |

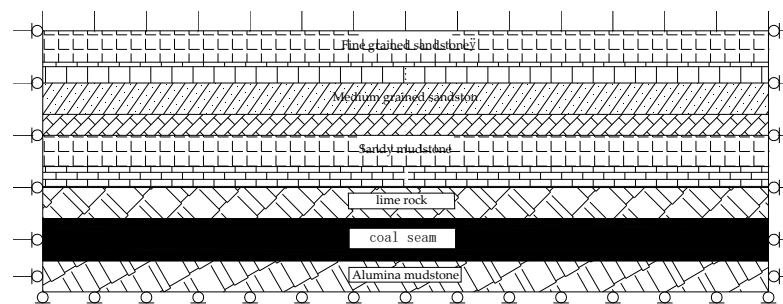
#### 4. Numerical Simulation of Fissure's Developing Height in Mining Overburden

##### 4.1. Numerical Calculation Model and Boundary Conditions

##### 4.1.1. Model Establishment

The numerical simulation was performed using Flac<sup>3D</sup> software, which is simulation calculation software developed by ITASCA Company in the United States, and the generalized finite difference method was used to simulate the nonlinear continuum mechanical behavior.

The numerical calculation model takes the geological conditions of the #15 coal seam of the Phoenix Mountain Mine as the prototype of the model and establishes a numerical simulation mechanical model according to the distribution and lithology of the rock stratum (Figure 6).

**Figure 6.** Mechanical model of numerical simulation.

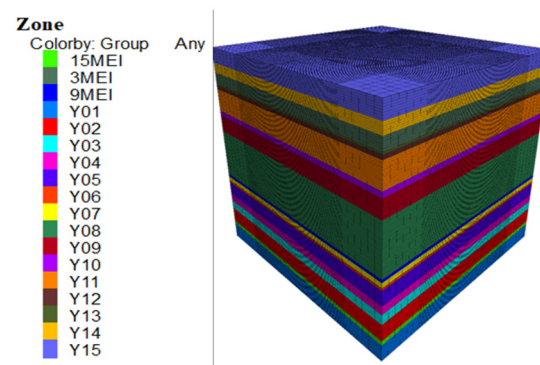
In the actual mine, the #3 and #9 coal seams on the #15 coal seam have been mined. Considering the compaction of the goaf and the conduction of forces in the model during the simulation, according to experience, the cohesive force strength and tensile strength of the lithology of the #3 and #9 coal seams are taken as 1/10 of the original lithology strength.

The mechanical property parameters of each rock stratum in the calculation model are shown in Table 3.

According to the actual conditions and the needs of this calculation, the geometric dimensions of the established model are 160 m × 120 m × 120 m in length × width × height, and the established numerical calculation model is shown in Figure 7.

**Table 3.** Rock mechanical parameter table.

| Serial Number | Rock Character           | Density (Kg/m <sup>3</sup> ) | Elastic Modulus (GPa) | Cohesion (MPa) | Tensile Strength (MPa) | Internal Friction angle (°) | Poisson's Ratio |
|---------------|--------------------------|------------------------------|-----------------------|----------------|------------------------|-----------------------------|-----------------|
| 1             | Coal                     | 1400                         | 2.7                   | 1.6            | 0.8                    | 28                          | 0.35            |
| 2             | Fine-grained sandstone   | 2626                         | 9.9                   | 2.6            | 3.0                    | 43.6                        | 0.23            |
| 3             | Medium-grained sandstone | 2644                         | 6.5                   | 2.4            | 2.7                    | 42.3                        | 0.24            |
| 4             | Sandy mudstone           | 2649                         | 5.4                   | 2.1            | 0.1                    | 38.8                        | 0.11            |
| 5             | Lime rock                | 2625                         | 52.5                  | 2.8            | 6.0                    | 77.5                        | 0.21            |
| 6             | Alumina mudstone         | 2646                         | 6.0                   | 2.3            | 1.4                    | 40.6                        | 0.18            |

**Figure 7.** Numerical calculation model.

#### 4.1.2. Model Boundary and Load Conditions

The calculation model boundary conditions are as follows:

1. The boundaries of the four sides of the model are fixed; that is, the horizontal displacement is zero, and horizontal stress is applied.
2. The bottom boundary of the model is fixed; that is, the horizontal displacement and vertical displacement are both zero.
3. The top of the model is a free boundary, and vertical stress is applied. The load conditions of the model were determined: the #15 coal seam is about 370 m away from the surface, and the upper boundary of the model is used as the equivalent stress by applying the gravity of the overlying strata. In the model, the #15 coal seam is 100 m away from the upper part of the model, and the upper boundary of the model is about 270 m away from the surface.

$$\begin{cases} P = \gamma H \\ P' = \lambda H \end{cases} \quad (1)$$

In the formula,  $P$  is principal stress, MPa;  $P'$  is horizontal stress, MPa;  $\gamma$  is bulk density, KN/m<sup>3</sup>;  $H$  is vertical depth, m; and  $\lambda$  is the coefficient of lateral pressure.

$\gamma$  is taken as 25, and  $H$  is taken as 270. Referring to the data of the Phoenix Mountain Mine, the ground stress of the mine is dominated by tectonic stress, and its coefficient of lateral pressure  $\lambda$  is taken as 1.12.

According to Formula (1), the equivalent stress load applied on the upper part of the model is 6.75 MPa, and a load of 7.56 MPa is applied in the horizontal direction. The initial balance diagram of the model is shown in Figure 8.

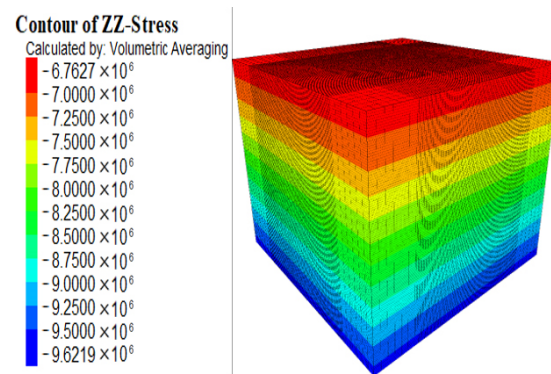


**Figure 8.** Initial equilibrium diagram of model.

#### 4.2. Numerical Simulation Scheme

The numerical simulation calculation mainly analyzed the various changing characteristics of the surrounding rock mass in the goaf under the existing mining conditions of the working face. The calculation mainly included:

1. The stress distribution characteristics of the surrounding rock in the goaf;
2. The distribution characteristics of the plastic zone of the surrounding rock in the goaf.

The stratum attitude of the Phoenix Mountain Mine is nearly horizontal. According to the mining data of the Phoenix Mountain Mine, when its XV1306 working face is mined, the first weighting step distance is about 30 m, and the periodic weighting step distance is 11–24 m. Simulations were run to monitor the changes in the surrounding rock of the working face when the working face advances 50 m, 60 m, 80 m and 100 m; that is, the stress situation and damage characteristics of the surrounding rock mass of the #15 coal seam working face during the first and periodic weighting of the working face were calculated using simulation theory.

#### 4.3. Analysis of Numerical Simulation Results

When the whole caving method is adopted, the caving zone, fracture zone and bending subsidence zone will generally appear in the roof strata of the goaf from the bottom to the top. The formation and development of these three zones not only directly affect the evolution of the stress field around the mining face but also directly affect the evolution of the stress field. It is of great significance to accurately determine the heights of the collapse zone and fracture zone for the arrangement of strata in the high-level borehole. The strata in the caving zone are deposited in the goaf in a loose state after caving, while the strata in the fissure zone are still in a stress state. The height of the fracture zone can be determined by analyzing the stress state of the rock stratum using numerical simulations, and the height of the collapse zone can be determined by analyzing the change in the plastic zone.

3. The stress distribution characteristics of the surrounding rock in the goaf with different advances of the working face. The distribution of the stress field in the stope is also continuously changing, while the stope goes through the process from the first weighting to periodic weighting. Figure 9 shows the vertical principal stress profiles of the central part of the goaf with different advance distances.

As shown in the figure, when the working face advances 50 m, the release height of the principal stress of the roof is about 28.00 m (Figure 9a); when the working face advances 60 m, the release height of the principal stress of the roof is about 33.45 m (Figure 9b); when the working face advances 80 m, the release height of the principal stress of the roof is about 44.80 m (Figure 9c); and when the working face advances 100 m, the release height of the principal stress of the roof is about 51.63 m (Figure 9d). It can be seen in Figure 9 that with the advancement of the working face, after the stope is fully mined, the maximum height of the pressure release on the roof in the goaf is about 51.63 m; that is, the height of the loose circle of the roof-surrounding rock is about 51.63 m.

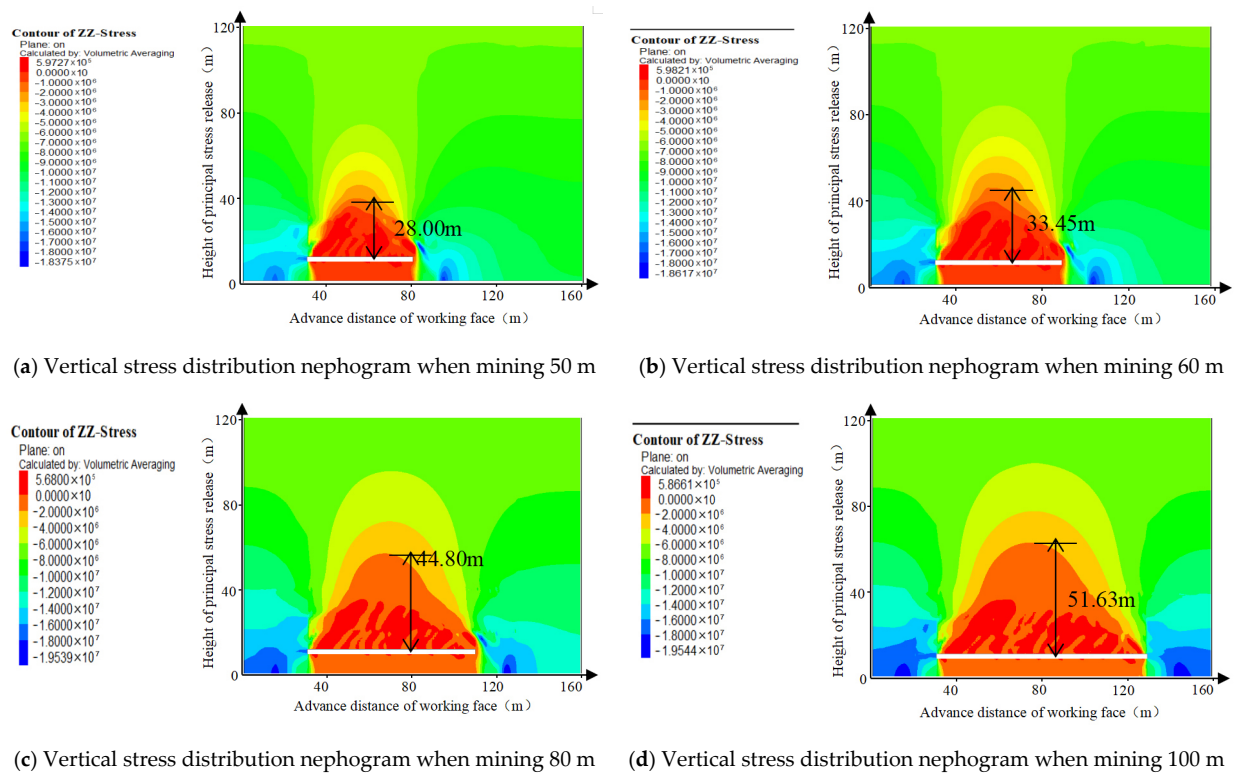


**Figure 9.** Distribution nephogram of vertical principal stress in goaf.

- The distribution characteristics of the plastic zone of the surrounding rock in the goaf with different advance distances. Figure 10 shows the distribution nephogram of the plastic zone of the surrounding rock in the goaf with different advance distances.

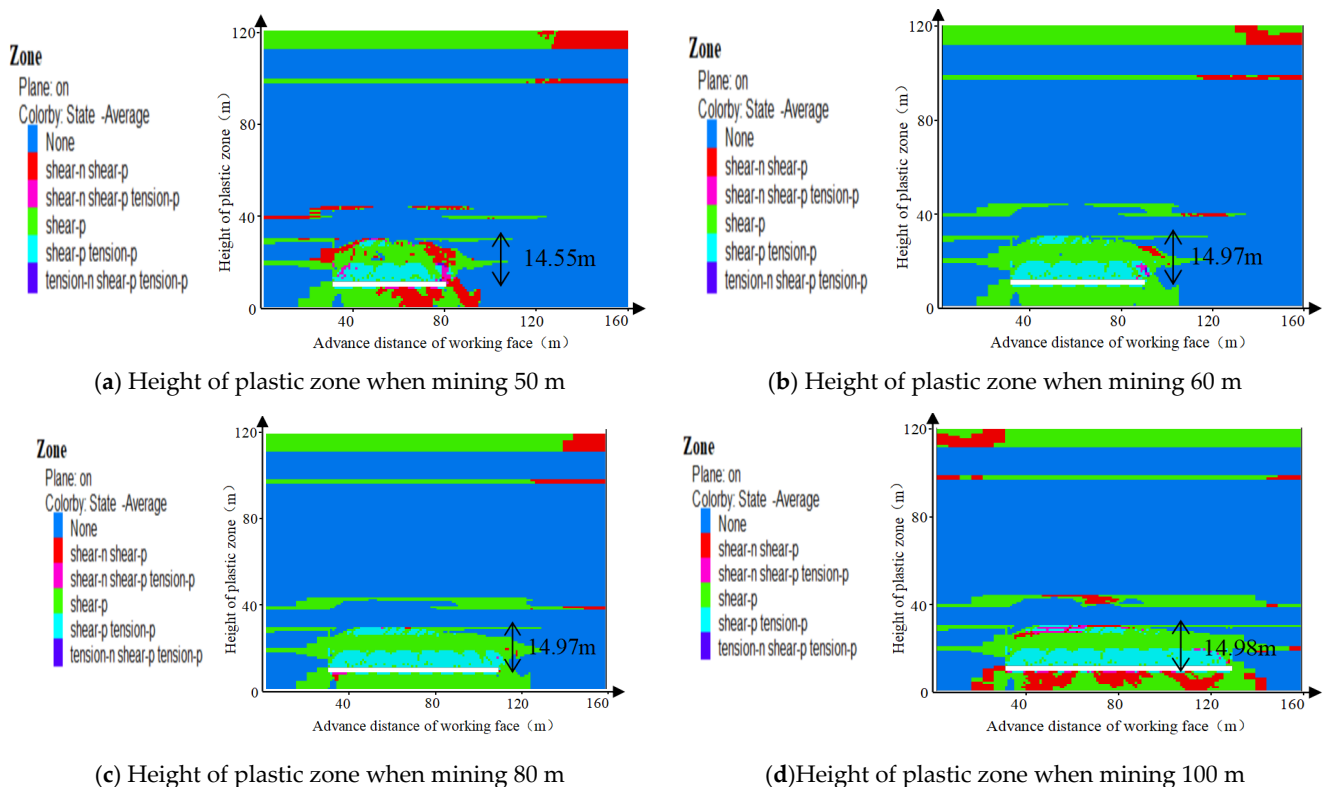


**Figure 10.** Distribution characteristics of the plastic zone of the surrounding rock in the goaf.

As shown in the figure, when the working face advances 50 m, the height of the plastic zone of the roof-surrounding rock is about 14.55 m (Figure 10a); when the working face advances 60 m, the height of the plastic zone of the roof-surrounding rock is about 14.97 m (Figure 10b); when the working face advances 80 m, the height of the plastic zone of the roof-surrounding rock is about 14.97 m (Figure 10c); and when the working face advances 100 m, the height of the plastic zone of the roof-surrounding rock is about 14.98 m (Figure 10d). It can be seen in Figure 10 that with the advancement of the working face, the crushing height of the surrounding rock of the roof is about 14.87 m; that is, the height of the roof-caving zone is about 14.87 m.

### 5. Reasonable Arrangement of Parameters of Omni-directional Roof High-Level Boreholes

Affected by the roof caving of the coal seam, the high-level boreholes constructed in the low-level drilling field all have a certain effective drainage range. With the advancement of the stope face, some boreholes will lose their drainage function. Affected by the drilling angle and the roof-caving shape of the goaf, blind drainage areas are easy to find in drainage boreholes between low-level drilling fields [30,31]. Under such conditions, an omni-directional high-level borehole can be constructed, which can reduce drilling field construction on the one hand and effectively solve the problem of blind drainage areas on the other hand.

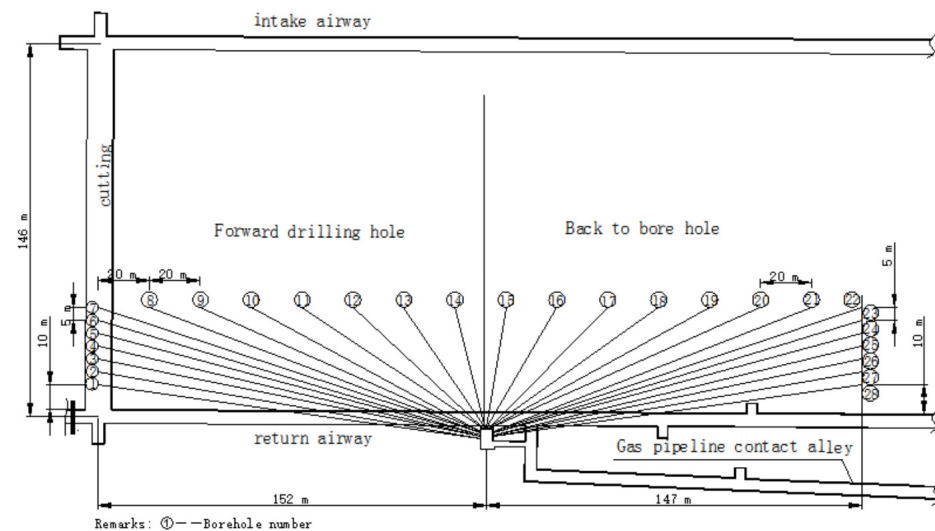
The high-level drilling field is arranged at a position 5–8 m above the roadway roof. An omni-directional drainage borehole is a 180° borehole constructed in a high-level drilling field. The drilling covers a large area and has a wide radiation range. According to the lithology of the roof of the #15 coal seam and the occurrence of the coal seam, the location with the better drilling effect was designed. Combined with the weighting step distance of the old roof of the #15 coal seam roof, the caving fissure zone is determined to be 5 to 8 times the mining height, and in terms of the characteristics of gas occurrence in the goaf, the zone 10–30 m away from the upper corner is the O-shaped gas enrichment zone, and the position of the final borehole is finally determined. The design of a high-level drilling field includes the high-level suction roadway and all boreholes in the drilling field. The omni-directional drainage borehole can drain the gas in the adjacent seam and the goaf at the same time, and the high-level borehole constructed in the opposite direction can advance the recovery position of the working face, drain the gas in the goaf of the upper adjacent seam and control the gas in the goaf of the adjacent seam in advance to reduce the impact on the gas gushing out of the mining seam.

The Phoenix Mountain Mine mainly comprises a high-level drilling field constructed next to the return airway of the XV1306 working face. The high-level drainage boreholes constructed in the drilling field are arranged in a fan shape. There are a total of 28 boreholes with a depth of 48–160 m and a diameter of 94 mm. The spacing of the drilling holes is 0.5 m, the spacing between the left and right sides of the drilling field is 5–10 m, and the spacing of the drilling field's final boreholes is 10–20 m. The specific parameters are shown in Table 4.

The omni-directional high-level drainage borehole layout of the XV1306 working face is shown in Figure 11.

**Table 4.** XV1306 working face high-level drilling field drainage borehole layout parameters.

| Hole No. | Hole Depth (m) | Angle with XXV 1212 Lane (°) | Elevation Angle (°) | Height Difference between Terminal Hole and Roof (m) | Hole No. | Hole Depth (m) | Angle with XXV 1212 Lane (°) | Elevation Angle (°) | Height Difference between Terminal Hole and Roof of Drilling Site (m) |
|----------|----------------|------------------------------|---------------------|------------------------------------------------------|----------|----------------|------------------------------|---------------------|-----------------------------------------------------------------------|
| 1        | 156.5          | 7.8                          | 0.3                 | 15.5                                                 | 15       | 48.3           | 81                           | 6.5                 | 13.5                                                                  |
| 2        | 157.2          | 9.5                          | 0.2                 | 16                                                   | 16       | 55.1           | 59.8                         | 7.8                 | 14                                                                    |
| 3        | 158            | 11.1                         | 0.4                 | 16.5                                                 | 17       | 67.4           | 45.3                         | 8.7                 | 14.5                                                                  |
| 4        | 159            | 12.8                         | 0.3                 | 17                                                   | 18       | 82.5           | 35.3                         | 8.3                 | 15                                                                    |
| 5        | 160.1          | 14.4                         | 0.6                 | 17.5                                                 | 19       | 99.4           | 28.8                         | 8.6                 | 15.5                                                                  |
| 6        | 161            | 16                           | 0.4                 | 18                                                   | 20       | 117.1          | 24.1                         | 8.3                 | 16                                                                    |
| 7        | 162.7          | 17.6                         | 0.7                 | 18.5                                                 | 21       | 135.6          | 21.2                         | 8.4                 | 16.5                                                                  |
| 8        | 138.9          | 20.7                         | 0.4                 | 18.5                                                 | 22       | 154.6          | 18.5                         | 8.1                 | 16.5                                                                  |
| 9        | 120.2          | 23.8                         | 0.5                 | 18                                                   | 23       | 153.2          | 16.9                         | 8.2                 | 16                                                                    |
| 10       | 102.1          | 28.3                         | 0.4                 | 17.5                                                 | 24       | 151.8          | 15.1                         | 8                   | 15.5                                                                  |
| 11       | 85.5           | 33.7                         | 1.2                 | 17                                                   | 25       | 150.7          | 13.5                         | 8.1                 | 15                                                                    |
| 12       | 70             | 42.8                         | 1.8                 | 16.5                                                 | 26       | 149.6          | 11.6                         | 7.9                 | 14.5                                                                  |
| 13       | 57.1           | 56.1                         | 2.1                 | 14                                                   | 27       | 148.7          | 10                           | 8.1                 | 14                                                                    |
| 14       | 49             | 76                           | 3.6                 | 13.5                                                 | 28       | 147.9          | 8.1                          | 7.8                 | 13.5                                                                  |

**Figure 11.** Omni-directional high-level drainage borehole layout.

The high-level boreholes are constructed by ordinary drilling; the drilling rig model is ZDY-3200S, the drill pipe length is 1.5 m, with a diameter of 73 mm, and the drill bit specification is 94 mm. The “Two Sealing and One Grouting” sealing method with pressure is adopted. After the hole is sealed, the borehole is connected to the drainage system, and the drainage parameters are promptly inspected according to regulations. The investigation data on the gas drainage parameters shall be added to the on-site management layout in a timely manner, and according to the investigation results of the drainage parameters, invalid boreholes shall be promptly removed to optimize the gas drainage system.

## 6. Analysis of Gas Drainage Effect of High-Level Boreholes in the Final Mining Face and the Influence of Air Distribution Volume on High-Level Boreholes

### 1. Analysis of the effect of gas drainage from head-on high-level boreholes

From the time-varying curves of the flow rate and the concentration of some high-level boreholes in the No. 8 drilling field of the XV1306 working face, it can be seen that the gas flow rate in the boreholes is mostly between 1 and 2.5 m<sup>3</sup>/min, and the average gas flow

rate in the boreholes is about  $1.5 \text{ m}^3/\text{min}$ . Most of the extracted gas has a concentration between 5% and 20%, and the maximum reaches 23%. The scalar quantity of drilling single-hole drainage reaches between  $0.05 \text{ m}^3/\text{min}$  and  $0.5 \text{ m}^3/\text{min}$ , with an average of  $0.15 \text{ m}^3/\text{min}$ , achieving a good gas extraction effect.

Affected by the mining stress, the coal seam roof produces a large number of fissures, and a large amount of gas gradually flows into the mining face through the fissures. When the roof is subjected to pressure for the first time, with the caving of the roof, a large amount of gas flows into the goaf and gradually stabilizes in the later period. The gas flow increases gradually with the proximity of periodic pressure in the later period.

The gas flow and concentration curves of some boreholes in the No. 8 drilling field of Lane XV1306 are shown in Figures 12 and 13.

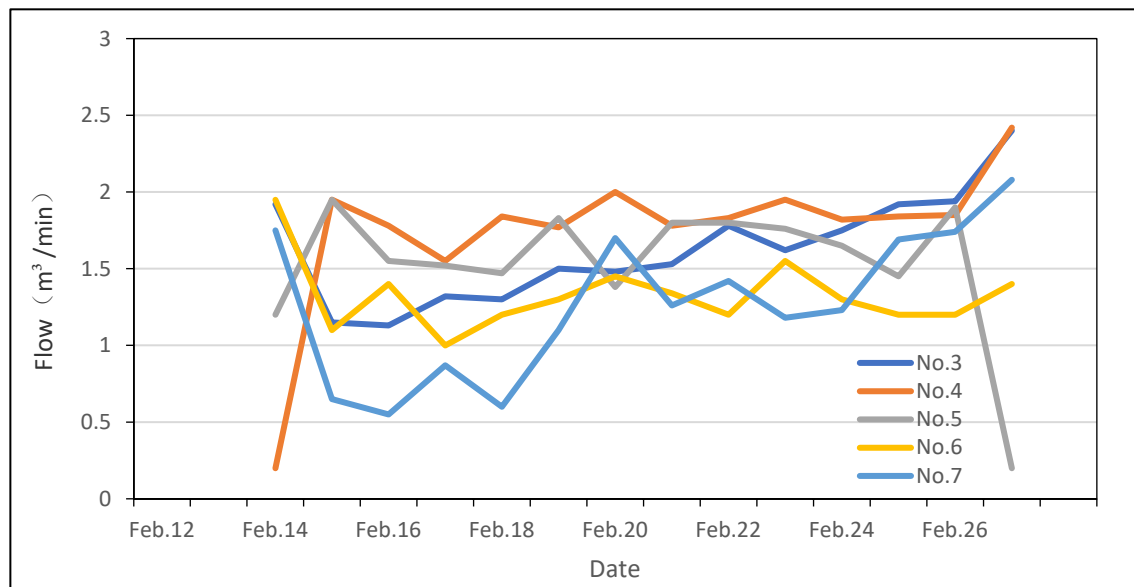


**Figure 12.** Gas flow curve of some boreholes in No. 8 drilling field of Lane XV1306.

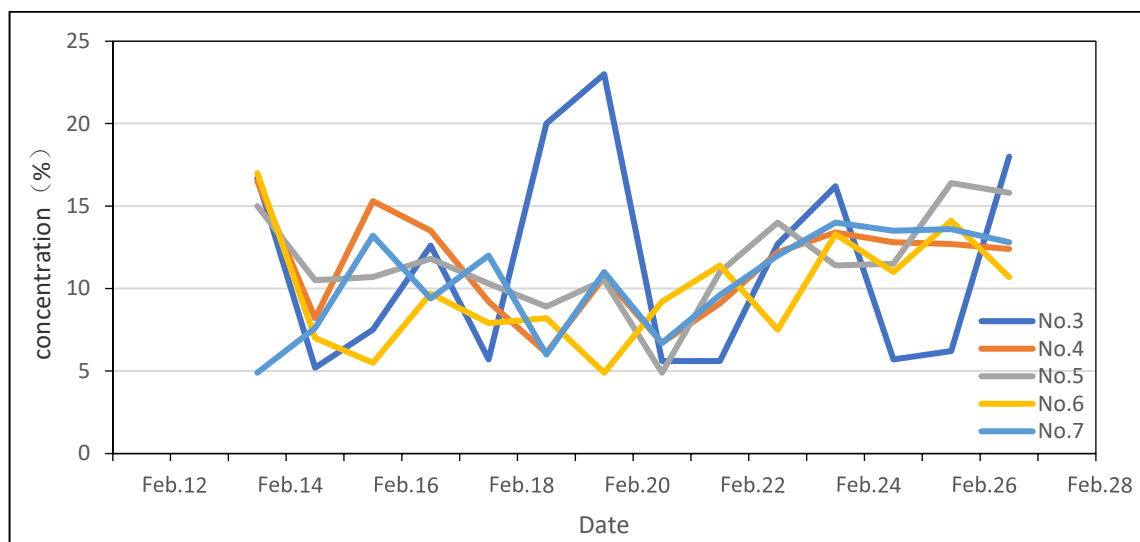


**Figure 13.** Gas concentration curve of some boreholes in No. 8 drilling field of Lane XV1306.

Practice has proved that when the negative drainage pressure increases to a certain level, the flow rate cannot be increased. On the contrary, the flow rate can be increased when the negative pressure is reduced to an appropriate level. The drainage effect is

optimal when the negative pressure is 15–22.4 KPa in the high drilling field of the XV1306 working face.

## 2. Analysis of gas drainage effect of reverse high-level boreholes

Since reverse boreholes are less affected by mining stress, the gas drainage effect is relatively stable during the mining of the working face. From the time-varying curves of the flow and concentration of the No. 8 drilling field of the XV1306 working face facing away from the high position, it can be seen that the gas flow rate in the boreholes is mostly between 0.5 and 0.6 m<sup>3</sup>/min; the gas drainage concentration is mostly between 14 and 20% and up to 25% at most, achieving a relatively good gas extraction effect.

Figures 14 and 15 show the gas flow and gas concentration curves of the reverse boreholes in the No. 8 drilling field of Lane XV1306. After adopting the reverse high-level borehole drainage method, the gas existing in the overlying goaf on the XV1306 working face is controlled in advance. Since it is less affected by the mining of the working face, a stable drainage effect is achieved, and the working face is reduced. The amount of gas gushing from the working face after mining to the reverse drainage position of the borehole reduced the pressure of gas in the goaf of the working face and achieved remarkable results.

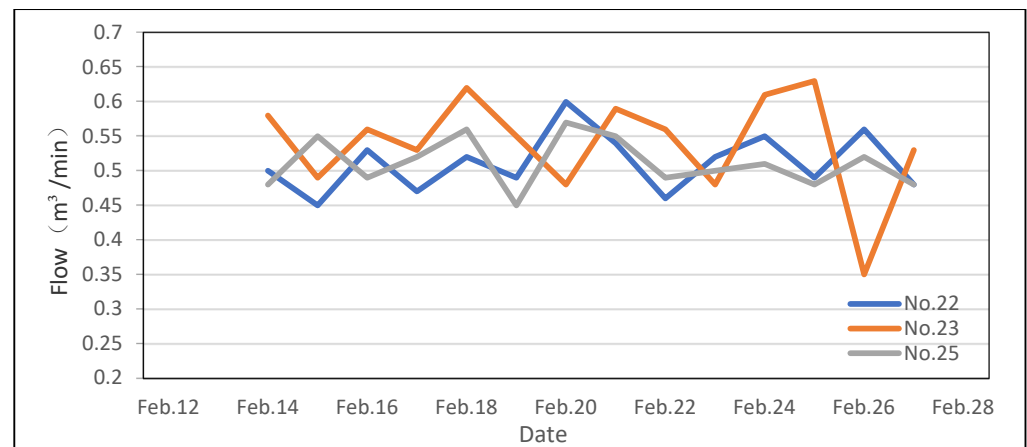


Figure 14. Gas drainage flow curve of some reverse boreholes.

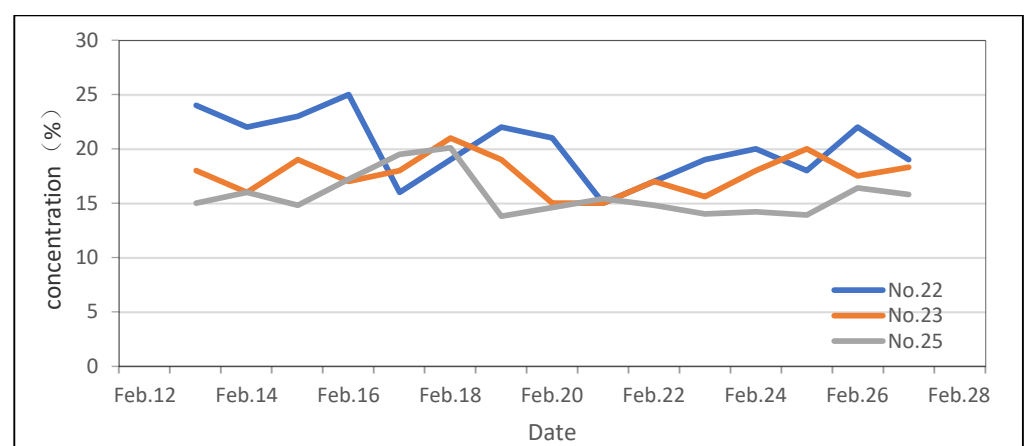


Figure 15. Gas drainage concentration curve of some reverse boreholes.

After adopting omni-directional high-level borehole drainage on the roof, the gas concentration in the upper corner is controlled below 0.54%, the gas concentration in the return airway is controlled below 0.35%, and the gas drainage effect has been significantly improved.

### 3. Site Management of High-Level Drilling Field

Since the high-level drilling site is 5–8 m higher than the roadway roof and is located on the outside of the roadway, the ventilation route of the high-level drilling field is cut off after the recovery progress of the working face pushes past the drilling field, and the gas pipeline connection roadway becomes a blind alley. Therefore, it is necessary to seal the connection roadway of the gas pipeline connected to the high-level drilling field at the mouth of the blind alley and retain the original drainage system to ensure that the omnidirectional high-level borehole on the roof is always in a state of drainage. By monitoring the measuring device on the gas pipeline outside the airtight area, the negative drainage pressure is adjusted to optimize the drainage system.

### 4. Influence of Air Distribution Volume on High-level Boreholes

Combined with the gas emission characteristics of the XV1306 coal mining face of the Phoenix Mountain Mine, the relationship between the air distribution volume of the coal mining face and the scalar volume of the high-level borehole is analyzed and studied.

The air volume of the coal mining face is calculated according to the gas emissions using the following formula:

$$Q_{\text{mining}} = \frac{Q_{CH_4}}{c} K \quad (2)$$

In the formula,  $Q_{\text{mining}}$  is the air volume required by the coal mining face,  $\text{m}^3/\text{min}$ ;  $Q_{CH_4}$  is the Ventilation Air Methane (VAM),  $\text{m}^3/\text{min}$ ;  $c$  is the maximum allowable gas content in the return air flow of the coal mining face, 0.8%; and  $K$  is the ventilation coefficient of the coal mining face and taken as 1.8.

The gas emission volume of the XV1306 working face is composed of two parts: Ventilation Air Methane (VAM) and the gas drainage volume. When the overlying layer on the XV1306 working face is coal pillars, the gas emission rate is  $11.48 \text{ m}^3/\text{min}$ . Calculated according to a daily output of 3769 t/d and an air distribution volume of  $1008 \text{ m}^3/\text{min}$ , the maximum Ventilation Air Methane (VAM) is  $4.48 \text{ m}^3/\text{min}$ . The gas scalar volume extracted is  $7 \text{ m}^3/\text{min}$ .

It can be seen from Table 5 that, taking the average daily output of 3769 t/d as an example, the maximum Ventilation Air Methane (VAM) is  $4.48 \text{ m}^3/\text{min}$ , and the drainage volume is  $7 \text{ m}^3/\text{min}$ . One ZWY105/132 drainage pump can provide a drainage flow of  $80 \text{ m}^3/\text{min}$ , and the corresponding drainage volume is  $3.73 \text{ m}^3/\text{min}$ , which cannot meet the drainage demand of the working face. Therefore, two ZWY105/132 drainage pumps were selected in the later stage; the drainage volume can reach  $160 \text{ m}^3/\text{min}$ , and the corresponding drainage volume is  $7.46 \text{ m}^3/\text{min}$ , which can meet the gas drainage requirements of the working face.

**Table 5.** Relation between daily output, gas content, air distribution volume and high-level borehole drainage volume of XV1306 working face.

| Daily Output (t) | Working Face Emission Quantity ( $\text{m}^3/\text{min}$ ) | Working Face Air Distribution ( $\text{m}^3/\text{min}$ ) | Maximum Gas Discharge in Strong Wind ( $\text{m}^3/\text{min}$ ) | Extraction Quantity ( $\text{m}^3/\text{min}$ ) |
|------------------|------------------------------------------------------------|-----------------------------------------------------------|------------------------------------------------------------------|-------------------------------------------------|
| 2500             | 7.1                                                        | 719                                                       | 3.2                                                              | 3.9                                             |
| 3000             | 8.44                                                       | 818                                                       | 3.64                                                             | 4.8                                             |
| 3500             | 10.27                                                      | 916                                                       | 4.07                                                             | 6.2                                             |
| 3769             | 11.48                                                      | 1008                                                      | 4.48                                                             | 7                                               |
| 4000             | 11.91                                                      | 1015                                                      | 4.51                                                             | 7.4                                             |

Lane XV1214 is the return airway of the XV1306 working face, with a designed net section of  $10.75 \text{ m}^2$ . To ensure that the wind speed does not exceed  $4 \text{ m/s}$ , the air distribution volume should be less than  $2580 \text{ m}^3/\text{min}$ . When the amount of gas gushing out from the working face is large, it is possible to appropriately increase the air distribution

volume of the return airway within the wind speed limit. At the same time, combined with high-level boreholes for gas drainage, the gas concentration in the return airway corner can be effectively controlled to prevent gas over-run.

## 7. Conclusions

1. Through on-site detection and numerical simulation, it is concluded that the caving zone of the #15 coal seam has a maximum height of 14.87 m, and the maximum height of the fissure zone is 59.29 m, which provides a basis for the selection of the high-level borehole position in the working face.
2. According to the calculation results of the heights of the fissure zone and caving zone of the coal seam roof, the gas control scheme of the “U+ omni-directional large-diameter high-level borehole along roof strike” in the final mining face was formulated. After adopting this scheme, the drainage concentration of each borehole will reach 5–20%, with a gas drainage flow rate of 1 mm<sup>3</sup>/min–2.5 m<sup>3</sup>/min, and the average gas drainage volume will reach 0.15 m<sup>3</sup>/min. The maximum gas concentration in the upper corner is 0.54%, and the maximum gas concentration in the return airway is 0.35%, which achieved the expected gas control effect.
3. The reasonable air distribution volume of the 1307 stope face should be less than 2580 m<sup>3</sup>/min. When the amount of gas gushing out from the working face is large, the air distribution volume of the return airway can be appropriately increased within the wind speed limit, combined with high-level boreholes for gas drainage, which can effectively prevent gas over-run in the upper corner.

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