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A Novel Method for Selecting Protective Seam against Coal and Gas Outburst: A Case Study of Wangjiazhai Coal Mine in China

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Abstract: Protective seam mining is a major and critical regional measure to prevent coal and gas outbursts (CGO) in coal mines. In this study, a novel method for selecting protective seam against coal and gas outburst was studied on the basis of gas geology and rock strata control theories and principles for protective seam mining and relevant regulations, which is that theories of gas geology were used to assess the outburst risk inherent in different seams of this mine, and then make preliminary selection of protective seams, and the technical feasibility of the proposed selection method was then analyzed using the theories and principles for protective seam mining and relevant regulations. The case application study results show that the extraction of the upper protective seam (UPS) caused significant decreases in the predicative indicators of outburst risk in the outburst-prone seam and thereby prevented CGO, and the novel method can provide a theoretical basis for selecting protective seam against CGO.

Keywords: coal and gas outburst; protective seam; novel selection method; low permeability; effectiveness in preventing outbursts

1. Introduction

Protective seam mining is a major regional measure [1,2] for preventing CGO in coal mines. For a seam group that is prone to CGO, the seams that carry no or low risk of CGO are normally first extracted to prevent outburst-prone seams from bursting out during mining. The seams that are extracted earlier are referred to as protective seams, and the other seams that are subjected to no or less outburst risk due to the protection from the protective seams are called protected seams. If there are multiple candidates in a seam group, comparative analysis and comprehensive selection can be performed in accordance with the requirements for safety, technical feasibility, and economic rationality.

The former Soviet Union was one of the first countries to extract protective seams. Later, countries such as France, Germany, and Poland began using protective seam mining to prevent CGO. In 1958, this technique was introduced into the Chinese cities of Beipiao and Chongqing as an experimental approach for preventing CGO. By now, protective seam mining has been practiced in about 26% of Chinese mines that have outburst-prone seams [1,2]. Wang et al. [3] investigated the gas emission from a mining face in a short-distance upper protective seam (UPS) and performed parameter optimization for gas extraction. Hu et al. [4] provided an optimized design for pressure relief gas drainage from a pitching oblique face in a steeply-dipping UPS. Shen et al. [5] discussed the mechanism by which short-distance lower protective seam mining prevents rockburst and the technique involved. Gao et al. [6] investigated the rock and coal damage and gas permeability during protective seam mining. Tu et al. [7] examined the effectiveness of far-distance lower protective seam mining in relieving pressure in overlying coal and rock. Shi et al. [8,9] studied the deformation characteristics of far-distance rock and coal caused by the protective seam mining. A study by Tao [10] focused on a gas control technique that involves UPS mining with a pillarless gob-side entry. Xiong et al. [11] explored the pattern of overlying rock movement during far-distance protective seam mining. Gan, Li [12] conducted a research into the technique of gas control by pillarless mining with a gob-side entry. Zhang et al. [13] studied a similar technique that involves protective seam mining with a pillarless gob-side entry formed by advanced roof caving. Wang et al. [14] discussed the technique of short-distance UPS extraction for the purpose of gas control. Jin Kai et al. [15] discussed the remote lower protective seam mining for coal mine gas control. Sun et al. [16] discussed a protective seam with nearly whole rock mining technology. Liu and Cheng [17] discussed long distance lower protective seam mining. Xiong et al. [18] discussed a field investigation of protective seam longwall overmining. Jiang et al. [19] discussed the technology of mining protective coal seam. Li et al. [20] discussed the evolution of permeability and gas composition during remote protective longwall mining. Liu et al. [21] discussed ultrathin protective seam. Chen et al. [22] discussed the permeability distribution characteristics of protected coal seams. Li [23] discussed the hydraulic mining of thin sub-layer as protective coal seam. Li [24] discussed the mining of thin sub-layer as self-protective coal seam. Other relevant studies have looked at the characteristics of rock deformation during protective seam mining and provided methods to avoid gas-related mine accidents. Currently, all of the above studies of protective seam selection are mainly based on approaches such as strata control theory, previous experience, and engineering analogy. However, coal mine design often contains defects, as it is impossible to theoretically determine the outburst risk in each seam of a seam group in advance [25,26]. The differences of this study from others are that the outburst risk in each seam of a seam group are determined using gas geology theory in advance; it then uses strata control theory, previous experience and engineering analogy to determine protective seam selection. The novel method is applied to select medium-distance, low-permeability upper protective seams (UPS) in the Shuicheng mining area, and the case study results were analyzed to determine the effectiveness of the novel method.

2. A Novel Method for Selecting Protective Seam against Coal and Gas Outburst

The novel method for selecting protective seam against CGO is mainly based on the theory of gas geology, strata control theory and relevant laws and regulations. The novel method is as follows:

(1) In target mine, the coal measures strata are divided into sequences based on sequence stratigraphic principles, and theories of gas geology and surrounding mine condition or gas content in geological exploration were used to assess the outburst risk inherent in different seams of this mine, and then make preliminary selection of protective seams.

If the target mine assessed as coal and gas outburst mine, then coal measure strata are divided into several parts using sequence stratigraphy. Sequence stratigraphy deals with genetically related and repeated sedimentary strata that are bounded by erosion surfaces or unconformities rather than by depositional surfaces and deposited within a certain chronostratigraphic framework. A sequence, the basic unit of sequence stratigraphy, refers to a succession of genetically related, isochronous sedimentary units bounded by unconformities or their correlative conformities, with each unit made up of relatively conformable beds. Normally, a sequence consists of three systems tracts. In a type I sequence, the three systems tracts include a lowstand systems tract (LST), a transgressive systems tract (TST), and a highstand systems tract (HST); and, in a type II sequence, they are a shelf margin systems tract (SMST), a transgressive systems tract (TST), and a highstand systems tract (HST) [25–30].

Identification of significant surfaces (e.g., sequence boundaries, transgressive surface, and maximum flooding surfaces) and correct sequence stratigraphic division are the keys to sequence stratigraphy.

Sequence stratigraphic evolution not only controls the coal seam thickness and its variations, lithology of roof and floor strata, seam spacing, and other relevant parameters, but also determines the outburst risk variations between coal seams in the vertical direction. The regional depositional system and sequence stratigraphy of a coal-bearing formation determine seam thickness, lithology of roof and floor strata, conditions of seams and other relevant parameters. Seams closer to the maximum flooding surface in a transgressive (marine or lacustrine) systems tract tend to contain greater amounts of gas (except for those lying between limestone strata) and are thus more prone to outbursts. This can explain the differences in level of outburst risk between seams in a seam group. The reason why rich gas most likely exists in the maximum flooding surface is that coal seam formation is best and the roof and floor permeability (the rock contains more mud) is minimum at the moment.

(2) Protective seams are selected and obtained based on the actual mine conditions.

(3) Technical feasibility of protective seam selection are analyzed based on the theory of strata control theory and relevant laws and regulations, and Protective seams are finally obtained.

3. A Case Study

3.1. Overview of the Shuicheng Mining Area

Guizhou Shuicheng Mining (Group) Co. LTD., Liupanshui, China, (hereinafter "the Shuicheng mining area") is a large integrated enterprise engaged in coal mining, electricity generation, production of coal chemicals, etc. Local coal-bearing rocks are distributed in the Upper Permian Longtan Formation (the Xuanwei Formation). Workable and locally workable seams include seams $1^{\#}$, $4^{\#}$, $7^{\#}$, $8^{\#}$, $11^{\#}$, $12^{\#}$, $13^{\#}$, $14\text{-}1^{\#}$, $14\text{-}2^{\#}$, $17^{\#}$, and $28^{\#}$. The Shuicheng mining area has seven producing mines in total. From northwest to southeast, this area can be divided into three tectonic units: the Ertang syncline (the Shengyuan and Dawan coal mines are coal and gas outburst mines), the Dahebian syncline (the Naluozhai, Wangjiazhai and Dahebian coal mines are coal and gas outburst mines, and Hongqi coal mine is gassy mine), and the Xiaohebian syncline (the Laoyingshan coal mine is coal and gas outburst mine). Figure 1 and Table 1 shows the Shuicheng mining area mines.

Due to the complex distribution of gas in the study area, gas-related accidents are frequent and difficult to prevent. Though the main producing mines are equipped with sound gas drainage systems, CGO accidents still happen occasionally in these mines. By 2009, a large number of CGO have occurred in this area's producing mines. In particular, seam $11^{\#}$ has suffered more and stronger outbursts than other seams.

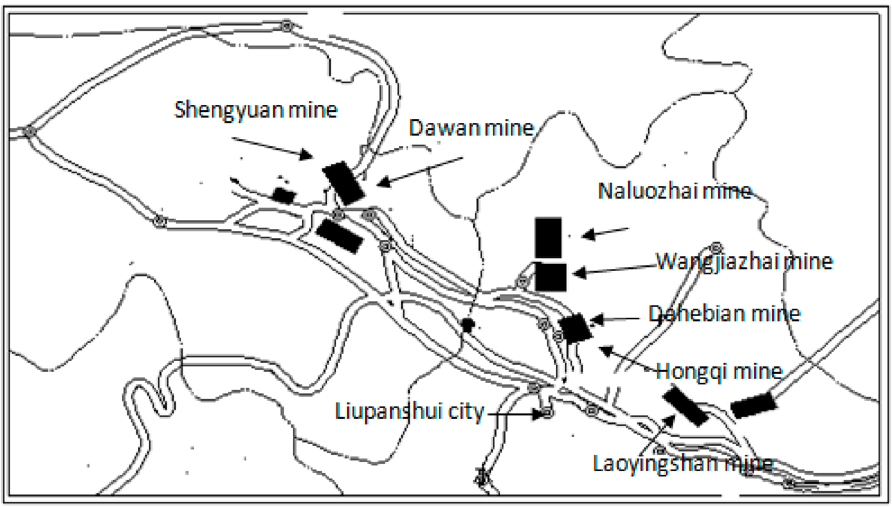

Figure 1. Shuicheng mining area mines.

Table 1. Shuicheng mining area mines.

Mine Name	Production Time	Mine Area (km^2)	Design Production Capacity (Mt/a)	Main Coal Seam
Shengyuan	1975.12	12.65	90	4, 9, 11
Dawan	1997.12	19.69	90	2, 4, 11
Hongqi	1971.01	1.44	10	1, 7, 11, 13, 34
Dahebian	1970.06	9.02	60	1, 7, 11, 13
Wangjiazhai	1970.07	19.89	150	1, 7, 8, 11
Naluozhai	1988.12	25.20	90	1, 7, 11, 13
Laoyingshan	1972.06	7.50	90	8, 11, 13, 26

In the Shuicheng mining area, the protective and protected seams are separated by 6–10 m thick sandy mudstone, 25–35 m argillaceous siltstone, and a 1.2 m coalbed. These interburden rocks are typically characterized by low load-bearing capacity and low permeability. Moreover, as mudstone tends to swell in the presence of water, fractures can hardly develop in this rock, which increases the difficulty of pressure relief and gas drainage for the protected seams. Systematic and in-depth research is needed into protective seam mining in this area, given that there is no experience available on mining under such conditions. Therefore, it is very urgent to study protective seam mining to prevent CGO.

3.2. UPS Selection Using the Novel Mehtod

3.2.1. Sequence Stratigraphic Analysis of the Coal-Bearing Formation in Wangjiazhai Coal Mine

Wangjiazhai coal mine is coal and gas outburst mine, and the main mining seams are 1$^{\#}$, 7$^{\#}$, 8$^{\#}$ and 11$^{\#}$, and their gas contents are, respectively, 10.45 m^3/t, 9.12 m^3/t, 9.68 m^3/t, and 15.56 m^3/t. In this study, the coal-bearing formation, i.e., the Longtan Formation, in the study area was divided into two sequences based on sequence stratigraphic principles: sequence I and sequence II. Sequence I consists of the strata from the top of the basalt formation to the top of seam 11$^{\#}$, and sequence II spans from the top of seam 11$^{\#}$ to the top of seam 1$^{\#}$. Composed primarily of a transgressive systems tract, the two sequences are deemed retrogradational sequences formed in an environment with rapid sea level rise. After the eruption of the Emeishan basalt and the following period of non-deposition, the sea level rose rapidly and thereby the accommodation space expanded. As a result of significant seal level change over this period, a set of coal seams, including seams C101a through 11$^{\#}$ and seams 10$^{\#}$ through 1$^{\#}$, were deposited in the study area. Due to the continued marine transgression, the seam thickness tended to increase. Seams 11$^{\#}$ and 1$^{\#}$ were deemed to be the maximum flooding surfaces in sequences I and II, respectively.

3.2.2. Theoretical Selection of Protective Seams in Wangjiazhai Coal Mine

Based on the sequence stratigraphic analysis above, it was predicted that, of all seams in the study area, seam 11$^{\#}$ was most prone to CGO, followed by seam 1$^{\#}$, while seams 7$^{\#}$ and 8$^{\#}$ had the least tendency to burst out. In a seam group, coal seams that are at relatively low risk of CGO can be selected as protective seams for those more prone to outburst, in line with the *Regulations on Preventing Coal and Gas Outbursts*.

3.3. Theoretical Selection of Protective Seam Based on the Actual Mine Conditions

Since its construction began, this mine has experienced more than 20 CGO events in seams 11$^{\#}$, 12$^{\#}$, 13$^{\#}$, 14$_{\text{-}1}$$^{\#}$, and 14$_{\text{-}2}$$^{\#}$, especially in seam 11$^{\#}$. The seams that are at no or relatively low risk of CGO can act as protective seams. Based on the actual mine conditions and the theoretical analysis above, seam 7$^{\#}$ was selected as the protective seam for seam 11$^{\#}$.

3.4. Technical Feasibility of Protective Seam Selection

3.4.1. Residual Gas Pressure

After a protected seam is fully relieved of stress, the gas trapped in it is discharged and the gas pressure tends to stabilize at the lowest level, called the residual gas pressure, after a decline. If the protected seam is located within the big fracture zone created by protective seam mining, the value of residual gas pressure has no connection with the original gas pressure and it depends solely on vertical distance between the protected and protective seams, denoted as h. If the protected seam lies within the zone of elasto-plastic deformation induced by protective seam extraction (in this case, coal seam vertical distance $h \geq 60$ m, or relative coal seam vertical distance $h/m \geq 60$–85, coal seam thickness m = 0.7–1 m), the value of residual gas pressure depends not only on h, but also on the original gas pressure and drainage conditions. The study found that the Wangjiazhai coal mine meets the conditions in the former case.

3.4.2. Relative Seam Spacing

With an average thickness of 1.73 m in this coal face, seam $7^{\#}$ is 34.94 m on average from the underlying seam $11^{\#}$. The average vertical distance between them measures 36.07 m in this coal face, suggesting that seam $7^{\#}$ is a medium-distance UPS. The relative seam spacing, i.e., the ratio of average seam spacing to the mining height in the protective seam, was calculated to be 20.85, significantly lower than the internationally accepted threshold (the threshold valve is 75) [1,2]. Therefore, seam $7^{\#}$ is able to effectively protect seam $11^{\#}$ in theory from the point of view of coal mining.

3.4.3. Effective Vertical Distance between Seams

Theoretical Effective Vertical Distance

The effective vertical distance between seams $7^{\#}$ and $11^{\#}$ in the Wangjiazhai coal mine is 36.07 m, which is smaller than the theoretical value of 50 m [1] and thus within the effective vertical distance range.

Calculation of Maximum Effective Vertical Distance

The maximum effective vertical distance between the protected and protective seams in the studied mine can be calculated using the following equation:

$$S_{up} = S_{up}'\beta_1\beta_2 \ [1,2]$$

where S_{up} is maximum effective vertical distance (m). S_{up}' is the theoretical maximum effective vertical distance (m). It is related to the length of coal face, a, and mining depth, H. If a > 0.3 H, its value must satisfy a = 0.3 H and $a \leq 250$ [1,2]. β_1 is the coefficient of influence of protective seam mining. Let M and M_0 denote the protective seam's mining height and the minimum effective mining height for extracting protective seams, respectively. If $M \leq M_0$, $\beta_1 = M/M_0$; otherwise, $\beta_1 = 1$ [1,2]. β_2 is the content coefficient of hard rocks (sandstone and limestone) between the protected and protective seams. Let η denote the percentage of hard rocks in the interburden between the seams. If $\eta \geq 50\%$, $\beta_2 = 1 - (0.4 \times \eta/100)$; otherwise, $\beta_2 = 1$ [1,2]. The depth of mining in the Wangjiazhai coal mine is about 600 m, and the coal face is 150 m long. The mining height in seam $7^{\#}$ is 1.73 m.

According to the table, [1,2], $S_{up}' = 55$ m and $M_0 = 0.43$ m. Since $M > M_0$, $\beta_1 = 1$ [1,2].

The average vertical distance between seams $7^{\#}$ and $11^{\#}$ is 36.07 m. As mudstone, shale and marl make up the major part of the interburden while the percentage of hard rocks is less than 50%, $\beta_2 = 1$ [1,2].

The maximum effective vertical distance from the UPS to the protected seam was calculated to be 55 m, greater than actual vertical distance. It follows that mining seam $7^{\#}$ can provide effective protection to seam $11^{\#}$.

3.5. Numerical Simulation and Analysis of UPS Selection

3.5.1. Numerical Modeling

The tested face was the X40702 coal face in the protective seam. The maingate and tailgate of this face are at elevations of +1465 m and +1505 m, respectively. The maximum and minimum heights of the face above the surface are 571 m and 460 m, respectively. It is 771 m long along the strike of the seam and 128 m wide on average. The dip angle of the protective seam ranges from 12° to 16°, and averages at 14°. Its thickness is between 1.75 and 1.05 m, with an average of 1.73 m in this coal face, and bulk density is 1.5 t/m^3. This seam exhibits a complex structure. The immediate roof above consists of argillaceous siltsone, or off-white fine-grained sandstone where it bifurcates. The floor rock is 0.2–0.3 m thick off-white clay, succeeded by off-white fine-grained sandstone. The vertical distance between seams 7$^\#$ and 11$^\#$ is 36.07 m in this coal face. The interburden is composed of clay, seam 8$^\#$ and argillaceous siltsone.

The basic conditions and physical and mechanical parameters of the coal and rocks were derived from the stratigraphic column of the study area as well as the results of physical and mechanical tests on the coal and rocks. The parameters obtained are presented in Table 2. A three-dimensional (3D) numerical model of the Wangjiazhai coal mine, a representative coal mine in the Shuicheng mining area, was created using the software FLAC3D. Figure 2 shows the model.

As the coal seams in the Wangjiazhai coal mine dip 12 to 16°, a dip angle of 14° was assigned to the seams in the model. The modeled region includes the strata from the immediate floor of seam 11$^\#$ through the surface. The entire model is divided into 10 layers and has dimensions of 770 m × 390 m × 515 m (L × W × H). The dimensions of the coal block where the X40702 coal face is located are 560 m × 130 m × 1.73 m (L × W × H).

Based on the actual conditions of the Wangjiazhai coal mine, the model was determined to be 770 m long (along the strike of the seams), 390 m wide (along the dip direction of the seams) and 515 m deep. It has 9438 elements and 10,948 grid points (Figure 2).

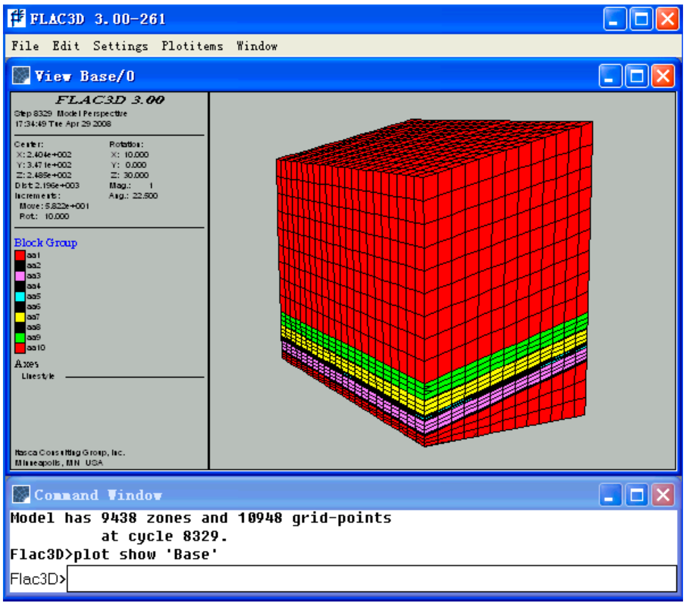

Figure 2. 3D numerical model.

Table 2. Physical and chemical parameters of coal and rocks.

No.	Rock Type	Bulk Density (Kg/m^3)	Thickness (m)	Elastic Modulus (Mpa)	Poisson's Ratio, μ	Compressive Strength (MPa)	Tensile Strength (MPa)	Cohesive Force (MPa)	Shear Strength (MPa)	Dilation Angle, γ	Friction Angle, φ
1	Shale	2000	390	13,500	0.29	42	0.9	11	17	14	42
2	Grey shale	2012	33.5	14,090	0.26	48	1.1	12	16	12	36
3	Seam 1#	1540	1.59	1000	0.36	8	0.032	3	3.5	13	26
4	Argillaceous siltstone	2140	29.1	13,000	0.25	45	0.97	15	1.8	13	34
5	Seam 7#	1540	1.73	1000	0.36	8	0.032	3	3.5	13	26
6	Mudstone and siltstone	2004	8.2	10,090	0.2	10	0.1	10	0.1	13	20
7	Seam 8#	1540	1.34	1000	0.36	8	0.032	3	3.5	13	26
8	Argillaceous siltstone	2100	25.4	12,090	0.24	48.3	1.01	12	16	12	36
9	Seam 11#	1540	4.6	1000	0.36	8	0.032	3	3.5	13	26
10	Siltstone	2408	19	16,530	0.15	90	1.628	18	21	16	42

3.5.2. Analysis of Numerical Results

The results of the numerical simulation were analyzed. Suppose that the rock stress declined 10% after seam 7# was mined. The stress relief angles were then determined. Along the strike of the protected seam, the stress relief angle was 68° on both the left and right sides. The stress relief zone exhibited a distinct symmetrical pattern. Along the dip direction of the seam, the stress relief angle was 87° at the lower end and 79° at the upper end. Figures 3–6 depict the simulated distribution of stress induced by mining seam 7# as a protective seam for seam 11#.

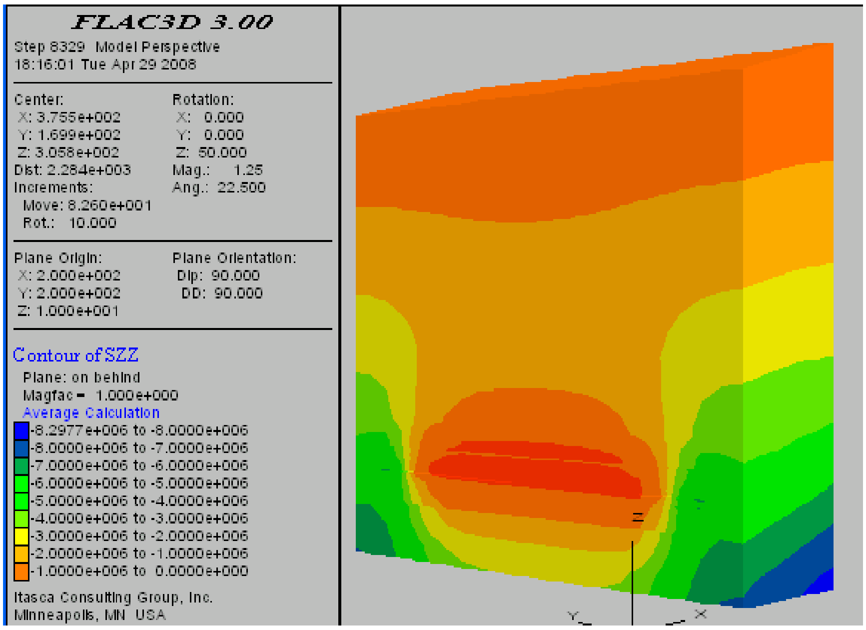

Figure 3. Contour plot of stress in the section along the strike.

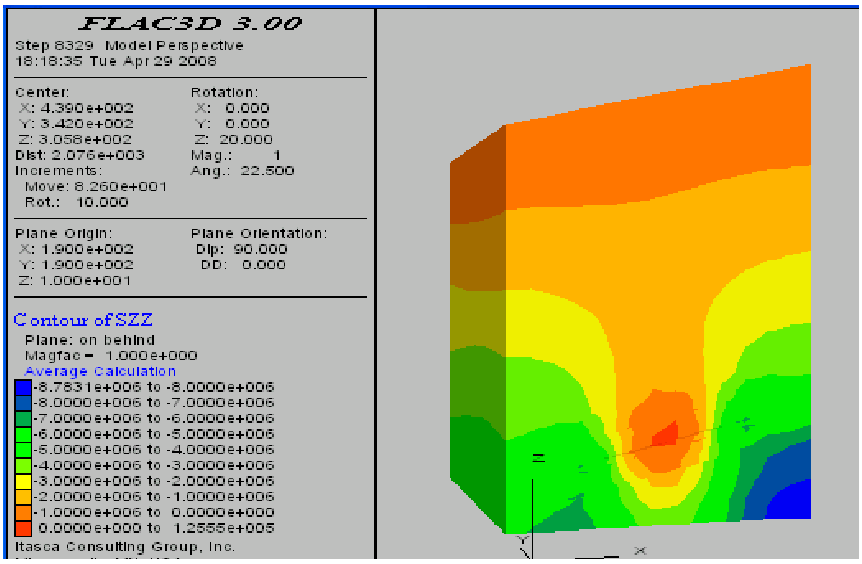

Figure 4. Contour plot of stress in the section along the dip direction.

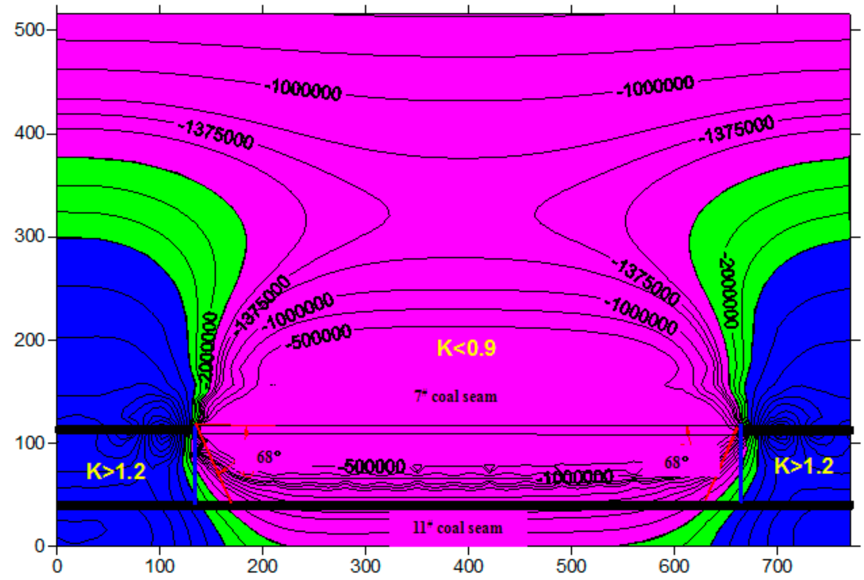

Figure 5. Stress distribution along the strike.

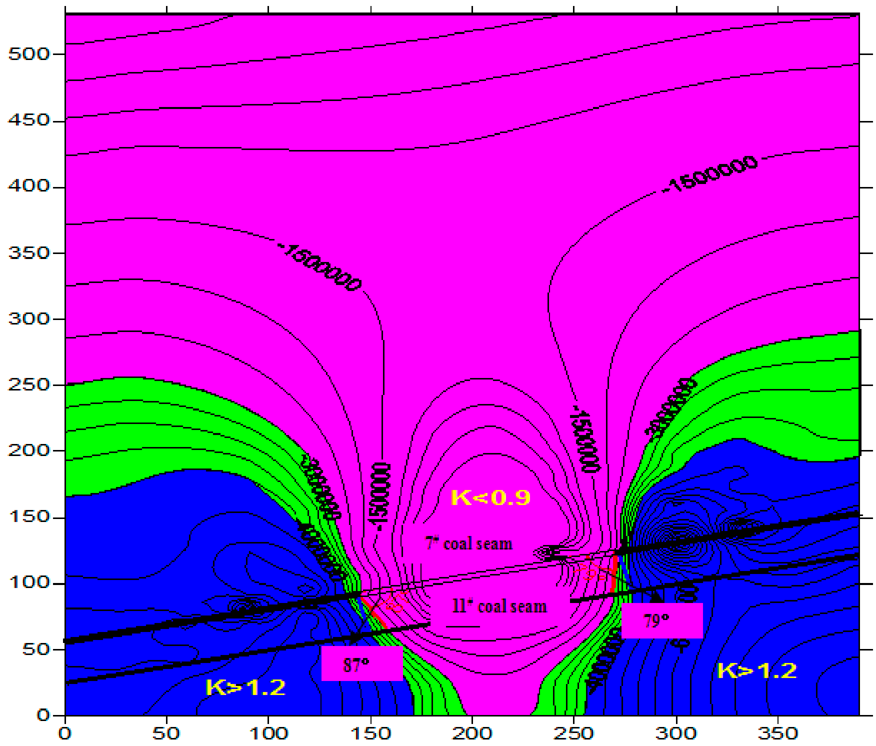

Figure 6. Stress distribution along the dip direction.

3.6. Practical Application of UPS Mining in the Studied Mine

3.6.1. Subjects of Investigation

First, the basic gas parameters of seam 11# in the Wangjiazhai coal mine were measured. These parameters include seam's gas pressure and content, permeability coefficient, initial rate of gas diffusion, firmness coefficient of the coal, borehole gas flow and its attenuation coefficient, etc.

UPS mining was carried out in the Wangjiazhai coal mine, in order to determine the effectiveness of the protective seam, the scope of protection it provided, and proper horizontal distance between the protective seam's face and the protected seam's face behind. The gas pressure in seam $11^{\#}$, borehole gas flow, permeability coefficient, volumetric expansion and its variation during mining were obtained.

3.6.2. Investigation Scheme

An investigation scheme was designed based on the layout of existing roadways in the Wangjiazhai coal mine, the mining plan, and actual safety requirements. It is detailed as follows:

(1) A dedicated investigation roadway was driven in the mine. The observation points for investigating the scope of protection were located around the open-off cut of the face in the protected seam, in order to make the investigation efficient and provide basis for designing the layouts of coal faces in the protective and protected seams as soon as possible. Moreover, these locations can ensure safety and reliable results. As there was no gas drainage roadway in the floor below the protective seam, a 120 m long roadway dedicated to investigation was driven in the floor strata under seam $11^{\#}$. The minimum distance from the investigation roadway to seam $11^{\#}$ was about 16 m. The investigation roadway had an arc-shaped section, whose area was 8.01 m^2. Steel net reinforced shotcrete was used to support the investigation roadway (steel framework was erected to support a few fractured regions). The wall rocks include clay and coal, they were fractured under rock stress. The investigation found that the roadway floor could easily heave and the wall was prone to deformation.
(2) To measure the initial values of basic gas parameters of seam $11^{\#}$, two pressure measurement boreholes were drilled at two positions in the investigation roadway that were unaffected by mining. The coal samples from seam $11^{\#}$ were tested in the laboratory for the coal's porosity, gas adsorption constant, parameters of proximate analysis, firmness coefficient (f), and initial rate of gas diffusion (ΔP). Then, the protected seam's initial gas content and permeability coefficient, denudation coefficient of borehole gas flow, and other parameters were calculated from the field measurements combined with the test results.
(3) Two arrays of boreholes were drilled from the investigation roadway's wall into the protected seam along its strike, one array for measuring gas pressure and the other for measuring deformation and gas flow. Another two arrays of boreholes were drilled into the seam along its dip for the same purpose. Variations in gas pressure, relative volumetric expansion, gas flow and permeability of the protected seam were investigated, in order to determine the effectiveness of UPS mining and the scope of protection, i.e., the stress relief zone, along the strike and dip of the seam.
(4) Two coal samples were cut from seam $11^{\#}$ exposed by the investigation roadway. The two samples then went through a series of laboratory tests for their parameters of proximate analysis, adsorption constant, porosity, initial rate of gas diffusion ΔP, relationship between gas pressure and gas desorption index K_1 (the K_1-P curve), firmness coefficient f, and other parameters affecting the seam's outburst risk.
(5) During tunneling and mining at the X41104 coal face (Figure 7) in the protected seam, the predictive indicators of outburst at this face and relevant strata behavior parameters were observed in order to reveal their patterns of variation along the strike and dip. The main indicators and parameters examined included the amount of drill cuttings S, gas desorption index of drill cuttings k_1, and gas emission, and their measurements were then used to analyze and validate the stress relief angle along the strike during UPS mining.

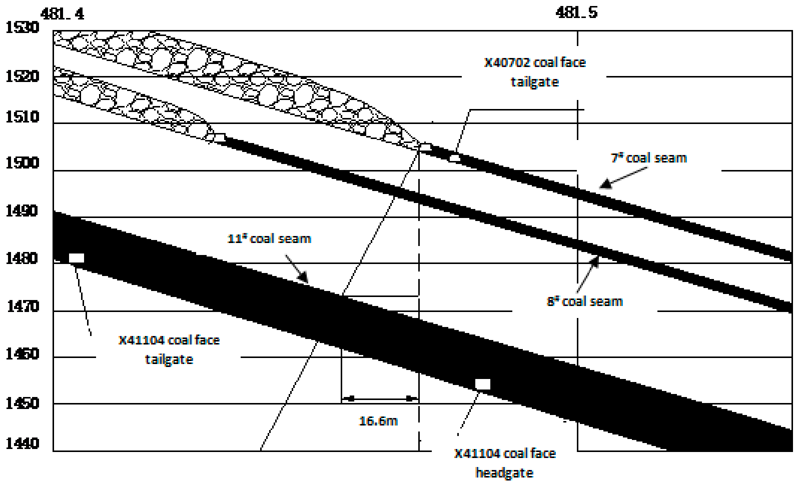

Figure 7. X41104 coal face position.

3.6.3. Results

The UPS mining created an open space in the coal-bearing strata, resulting in stress reduction from the initial level and stress redistribution. In response, the strata moved and deformed towards the gob. In the zone under direct influence of rock movement, the stress further decreased, and the outburst-prone seam was under diagonal compression and heaved. This deformation process created fractures in the seam, thus significantly increasing the seam's permeability. Besides, the stress relief in the protected seam facilitated gas desorption, thereby increasing the seam's gas discharge capacity and lowering its gas pressure. Measurements of gas pressure, borehole gas flow, permeability, and relative volumetric expansion of seam $11^{\#}$ obtained from a representative borehole during UPS mining were plotted in a complex chart, in order to comprehensively analyze the effectiveness of extraction of seam $7^{\#}$ in protecting seam $11^{\#}$.

Effectiveness Analysis

Table 3 and Figure 8 show the variations in the parameters of seam $11^{\#}$ induced by extraction of seam $7^{\#}$. Different stress zones have been measured from filed.

Table 3. Gas parameters of seam $11^{\#}$ during UPS mining.

Parameter	Normal Stress Zone	Stress Concentration Zone	Stress Relief Zone	
			Initial Stress Relief	Significant Stress Relief
Distance from the X40702 face, L (m)	<-40	$-40\sim-20$	$-20\sim+17$	$+17\sim+42$
Gas pressure, P (MPa)	2.7	2.8	2.8~0.95	0.95~0.00
Gas flow, q (m^3/min)	0.070	0.046	0.046~0.54	0.54~0.95
Permeability coefficient, λ (m^2/$MPa^2 \cdot d$)	1.23	0.82	13.5	26.23
Relative volumetric expansion, $\varepsilon \times 10^{-3}$	0	0	0~10.54	13.18

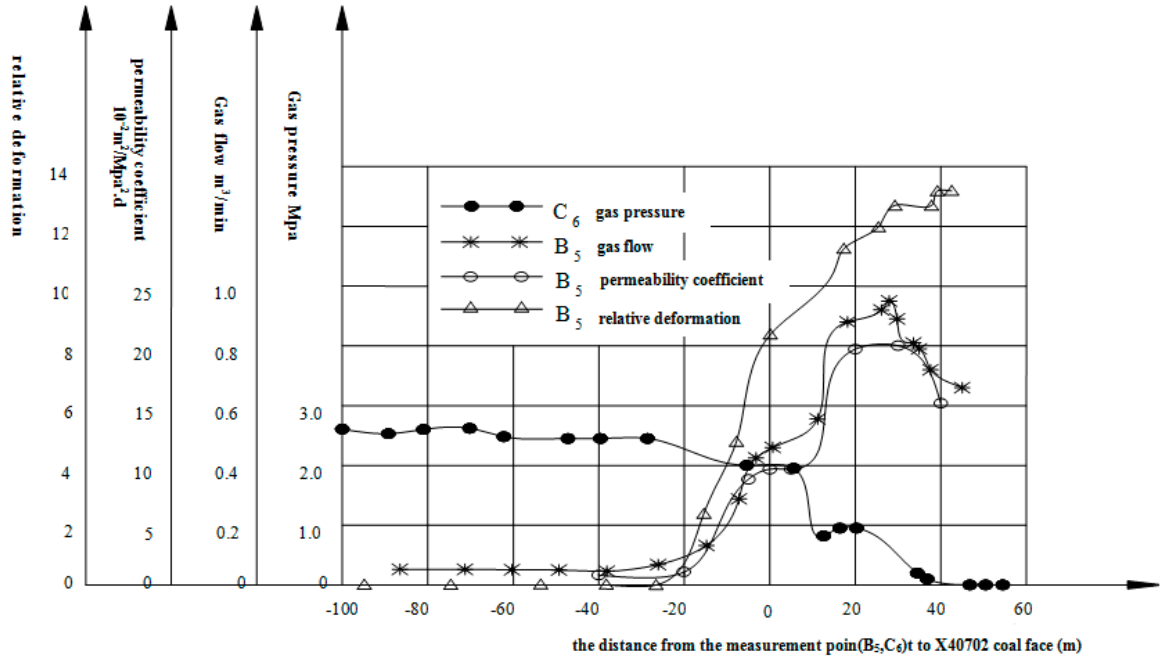

Figure 8. Variations in the gas parameters of seam 11# during UPS mining.

Based on the variation patterns of gas parameters, the protected seam can be divided into three zones as follows:

① Normal stress zone

The normal stress zone in seam 11# was the region that was unaffected by mining seam 7#, located more than 40 m in front of the face in the protective seam. The rocks in this zone experienced only in-situ stress and did not move or deform. The seam's gas pressure in this zone was at its initial level (2.7 MPa on average) and its permeability was poor (1.23 $m^2/MPa^2{\cdot}d$ on average). The borehole gas flow was so low (0.07 m^3/min on average) that it could be measured only by a gas meter.

② Stress concentration zone

Horizontally, the stress concentration zone was 20 to 40 m in front of the X40702 coal face in the protective face. In this zone, the stress experienced by seam 11# increased from the initial level and peaked. The gas pressure in seam 11# reached 2.8 MPa, 0.1 MPa higher than the normal level. As fractures were generally closed, the protected seam's permeability decreased to 0.82 $m^2/MPa^2{\cdot}d$ and borehole gas flow decreased to 0.046 m^3/min.

③ Stress relief zone

The stress relief zone was subdivided into two subzones. In the subzone that began 20 m in front of the X40702 face and terminated 17 m behind it, seam 11# started to undergo stress relief. The protected seam's volumetric expansion increased to 10.54×10^{-3} and its permeability increased to 13.5 $m^2/MPa^2{\cdot}d$, 11 times its original permeability coefficient. As a result of gas desorption, the gas pressure declined to 0.95 MPa and the borehole gas flow increased to 0.54 m^3/min. This subzone corresponded to the initial stage of stress relief.

In the subzone 17 to 42 m behind the X40702 face, the volumetric expansion of seam 11# peaked at 13.18×10^{-3}, which is 6‰ higher than the internationally accepted effective value. The protected seam's permeability coefficient increased drastically to 26.23 $m^2/MPa^2{\cdot}d$, about 21 times its original permeability coefficient. As the gas desorption from the seam accelerated rapidly, the borehole gas flow increased to its maximum of 0.95 m^3/min, which is 13.6 times the initial level before stress relief. Meanwhile, the gas pressure in the seam dropped sharply to 0.0 MPa, lower than the threshold of

0.74 MPa [1] specified in *Regulations on Preventing Coal and Gas Outbursts*. This subzone corresponded to the stage of significant stress relief in the protected seam.

As the mining at the X40702 face stopped in advance, parameter variations in the region more than 42 m behind the face were not observed.

Protection Parameters

Along the strike, after the mining at X40702 face stopped, the gas pressure in seam 11# dropped from 0.62 MPa to 0.0 MPa, the borehole gas flow increased from 0.193 m^3/min to 0.61 m^3/min, the permeability coefficient of drill cuttings increased from 4.4874 $m^2/Mpa^2 \cdot d$ to 16.8682 $m^2/Mpa^2 \cdot d$. Based on the results of field investigation and the aforementioned regulations [1], the stress relief angles along the strike on both ends of seam 11# were determined to be 59° for a certain safety factor.

Along the dip direction of the seam, after the mining at X40702 face stopped, the gas pressure in seam 11# dropped from 2.78 MPa to 0.0 MPa, the borehole gas flow increased from 0.063 m^3/min to 0.532 m^3/min, and the permeability coefficient increased from 1.3296 $m^2/Mpa^2 \cdot d$ to 11.9806 $m^2/Mpa^2 \cdot d$. Based on the results of field investigation and the aforementioned regulations, the stress relief angle along the dip direction at both the upper and lower ends of seam 11# were determined to be 75° for a certain safety factor.

The analysis above, together with the results of field investigation, suggests that seam 7# was a reasonable protective seam for seam 11#, which confirms the validity of the selection method proposed in this study.

4. Conclusions

(1) The novel method for selecting protective seam against coal and gas outburst is feasible and reasonable.

(2) Sequence stratigraphic evolution not only controls the coal seam thickness and its variations, lithology of roof and floor strata, seam spacing, and other relevant parameters, but also determines the vertical variability in the level of outburst risk across a seam group. A theoretical analysis based on gas geology indicates that, of all seams in the study area, seam 11# was most prone to CGO, followed by seam 1#, while seams 7# and 8# were least prone to outburst. An investigation of gas occurrence in different seam in the Shuicheng mining area, combined with statistics on previous CGO events, demonstrates that the theoretical results are in line with the actual conditions. Therefore, it is feasible to assess CGO risk in coal seams using the theories of gas geology and the results can provide theoretical basis for protective seam selection.

(3) The numerical simulation and analysis of the Wangjiazhai coal mine (a representative mine in the study area) show that, if mining seam 7# caused a 10% decline in rock stress, the stress relief angle along the strike of seam 11# was 68° on both the left and right sides. The stress relief zone exhibited a distinct symmetrical pattern. Along the dip direction, the stress relief angle was 87° at the lower end and 79° at the upper end.

(4) Based on practical experience in protective seam mining and the results of numerical analysis and field investigation, the stress relief angles induced by mining seam 7# were determined: 59° along the strike and 75° along the dip direction at both the lower and upper ends of seam 11#. Extraction of seam 7# caused significant decreases in the parameters of seam 11# that signify outburst.

(5) The study demonstrates that the theories of gas geology can be used to assess the CGO risk in coal seams of a seam group and the assessment results can provide theoretical basis for protective seam selection. Mining medium-distance, low-permeability UPS can significantly lower the predicative indicators of outburst risk in the protected seam and thereby help achieve the goal of preventing coal and gas outburst. This CGO prevention technique applies to the low-permeability coal-bearing strata in western China which are interpreted as transitional marine to continental deposits.

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