CBM drainage engineering challenges and the technology of mining protective coal seam in the Dalong Mine, Tiefa Basin, China

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1. Introduction

In past decades, coal, a non-renewable energy supply, has played a leading role in sustaining China’s energy needs (Eliasson and Lee, 2003; Andrews-Speed et al., 2003; Burgherr and Hirschberg, 2007). Coal is predicted to continue to play an important role in the fossil energy structure of China for many years. The depth of coal mining in China has increased at a rate of 30–50 m/year (Li et al., 2014). Coal bed methane (CBM) has garnered significant worldwide interest as a low-carbon energy source, as is evident by the increasing number of studies and investments related to CBM exploitation (Qu et al., 2010; Wu et al., 2010; Morad, 2012; Karacan, 2013). However, methane is a major threat to coal mine safety (Dai and Ren, 2007; Guo et al., 2014). As the coal seam mining depth has increased, so has the coal seam gas pressure and ground stress. The result has been large numbers of gas outbursts, which have caused personnel and property losses (Xue et al., 2011; Zhou et al., 2014). Gas outbursts and explosions account for a significant share of the casualties associated with coal mining in China (Wang et al., 2014).

The methane drainage conditions in China are poor. The majority of the coal was formed over a long geologic period, and the stratum experienced cycles of repeated uplift and decline, which destroyed the natural fractures in coals (Cheng and Yu, 2007; Cheng et al., 2011). To effectively drain gas and control outbursts, regional gas control methods have been stressed. Primarily, protective

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ABSTRACT

As mining depths increase, new challenges, such as gas drainage, gas outbursts and rock bursts induced by mining extraction, have emerged, particularly in gassy, multiple-seam coal mines. The primary reason for this phenomenon is that increased depths lead to higher stresses, higher gas pressures and lower permeabilities in coal seams. Stress and pressure relief require temporal and spatial pre-drainage protection. However, the pursuit of increased coal production, along with economic interests, has resulted in a lack of time and space for CBM pre-drainage engineering. To solve these challenges, protective seam mining is the best way to reduce stress, increase coal permeability and increase CBM extraction efficiency. The stress relief of the rock mass below the protective seam generated five zones and three belts, providing the time and space for CBM pre-drainage engineering. Based on simulations of the outburst risk and mining economics using LaModel, the gassy No. 12 coal seam was selected as the first-mined protective seam. The floor rock roadway and cross boreholes were designed to drain mining-induced stress-relief gas from the protected seam. Therefore, they should be constructed before the protective seam mining begins. The time and space allocation pattern of CBM drainage can be summarized as follows: CBM drainage before coal seam mining using long bedding boreholes, stress-relief gas drainage during mining using floor roadway crossing boreholes and CBM extraction after mining using the roof roadway. Finally, field applications indicate that the remnant gas pressure and content of the protected seam significantly decreased after mining the protective seam. The permeability coefficient increased 1465-fold. The simultaneous extraction of CBM and coal was realized. The gas drainage rate increased from 45% to 70%, and the CBM utilization rate improved from 23% to 90%. These CBM drainage practices could provide insight and guidelines for other coal mines under similar conditions.

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seams and pre-draining gas have been used to reduce the risk of outbursts. Mining the protective seams should be a priority if conditions permit (State Administration of Coal Mine Safety of China 2009). Although the methane drainage conditions in China are poor, researchers have developed several drainage methods (Yu et al., 2004; Cheng et al., 2003; Liu et al., 2009a, 2009b; Cheng et al., 2011; Liu et al., 2014).

Numerical simulations and physical experiments have been used to investigate the movement and gas pressure relief of protected coal seams during mining at two protective seams (Liu et al., 2011). The Fast Lagrangian Analysis of Continua (FLAC3D) software was used to build a model to study the stress variation, which occurred when mining the protective seam. The three-dimensional figures show that the stress varies within 10 m of the mining face (Yang et al., 2011). For a coal mine with multiple-seams, this stress relief and the effect of expansion deformation could be superimposed by the mining of multiple protective seams. During the mining of high-gas coal seams, the strata movement of the protective and protected seam drainage gas can be utilized to simultaneously extract coal and gas (Qian et al., 2003). However, few studies have investigated the effects of the exploitation of protective seams in gassy multiple-seam coal mines. An analysis of the temporal and spatial distributions of different gas drainage methods, as well as the gas volume before, during and after mining activities in the upper protective seam, can yield significant results. In addition, an effective method must be developed for identifying the appropriate first-mined protective coal seam when multiple seams are present.

In this article, we experimentally investigate the coal and CBM occurrence characteristics of gassy multiple seams in the Dalong Mine. The selection of the first excavated protective seam and development of gas drainage measures were based on numerical investigation. In addition, the gas drainage volumes before, during and after the mining of the protective seam, gas drainage effect assessment and gas utilization were studied.

2. Geological backgrounds

The Tiefa coalfield is a continental deposit of concealed coal basins generated in the Mesozoic Early Cretaceous. It is located in Tieling City, Liaoning province, northeast China. The base of the Tiefa coalfield is a presinian system metamorphic series, on which Cretaceous and Quaternary strata are deposited. The coalfield is 29.5 km long and 14.7 km wide, with a total area of 513.3 km² and identified reserves of 22 × 108 t. The plan of the Tiefa coal basin is shown in Fig. 1.

The Dalong Coal Mine is located in the Midwest of the Tiefa Basin. The coal strata base is a presinian system metamorphic series, cretaceous system and quaternary strata; the generalized stratigraphy sketch (generated by core data) of the Dalong Mine is shown in Fig. 2. The coal-bearing stratum is primarily the Lower Cretaceous Fuxin group, with 20 coal seams. The Fuxin group is divided into two segments: the Nos. 1-10 coal seams reside in the upper coal-bearing segment, and the Nos. 11-20 coal seams reside in the lower segment. The Nos. 4, 7, 12, 13, 14, 15-1, and 16-1 coal seams are the main minable seams in the Dalong Mine. Currently, the Nos. 4 and 7 coal seams have been basically excavated. The Nos. 12, 13, 14, 15-1 and 16-1 coal seams of the lower coal-bearing segment, which is a short-distance gassy multiple-seam. The No. 12 seam is a gassy coal seam, while the Nos. 13, 14, 15-1 and 16-1 seams are gas-outburst coal seams.

At the coalification stage, the lignite coal rank of Tiefa (Ro = 0.45%) changed to long flame coal (Ro = 0.60%), and the amount of gas generated increased from 68 m³/t to 168 m³/t. Magma (dolerite) intrusion activities in Tertiary system caused secondary hydrocarbon generation, increasing the gas generation volume to 200 m³/t. A sketch of the gas accumulation evolution in the Tiefa coal basin is shown in Fig. 3. The Dalong and Daxing Mines are located at the bottom of the Tiefa Basin. They have the advantage of CBM resources, but the disadvantage of serious coal and gas outbursts.

3. CBM drainage engineering challenges

3.1. Coal sample and geochemical analyses

Samples were taken from the Dalong Mine to study the geochemical characteristics of the coal. Five coal samples were obtained from coal faces or via borehole from the Nos. 12, 13, 14, 15-1 and 16-1 coal seams (Table 1).

The volatile matter, moisture and ash analysis results are listed in Table 1. As the depth increased from 624.3 m to 664.8 m, the Dalong coal VM (daf basis) changed from 40.13% to 44.73%, and the ash content (dry basis) increased from 7.34% to 10.97%. Although the coal samples have high moisture values of 7.38%–8.86% (Table 1), the methane desorption quantity gradually decreased as the amount of injected water increased (Chen et al., 2013). The Dalong coal has a high natural moisture content. However, moisture inhibits the desorption of gas from the coal matrix, which has led to CBM drainage difficulties in the Dalong Mine. The Rₜ values (as measured by oil immersion) of the coal samples are listed in Table 2. The Dalong coal has Rₜ values ranging from 0.57% to 0.65%. Samples DL#12-16 can be identified as medium rank bituminous A, belonging to the lowest metamorphic grade of bituminous coals.

3.2. Gas adsorption/desorption properties of coal

The relationship between gas pressure and adsorption volume fits the Langmuir model (Langmuir, 1918). Adsorption-pores (pore size < 100 nm) have a significant influence on gas adsorption and diffusion in coal seams (Cai et al., 2013).

To obtain the methane adsorption isotherm, crushed coal samples (50 g, particle sizes of 0.2–0.25 mm) were placed in a water bath and subjected to methane pressures of up to ~5 MPa at a constant temperature of 30 °C. Fig. 4 shows the adsorption isotherm of the Dalong coal samples. The Langmuir parameters, a and b (Zhao et al., 2014), can be measured as 34.9 mL/g and 0.71 MPa⁻¹ for sample DL#12, 29.5 mL/g and 0.97 MPa⁻¹ for DL#13, 40.3 mL/g and 0.67 MPa⁻¹ for DL#14, 33.2 mL/g and 0.89 MPa⁻¹ for DL#15, 29.3 mL/g and 0.91 MPa⁻¹ for DL#16, respectively. The data shows that the Dalong coal has a high methane adsorption capacity.

The majority of the coal seam gas remains in the coal matrixes and cracks in the physical adsorption state. When the pressure of the coal reservoir drops below the critical desorption pressure, the methane begins to desorb. This phenomenon typically occurs after mining activities and coal seam stress relief. Therefore, experimental studies regarding the rules of coal bed gas desorption are of great significance to coal mine safety and gas extraction.

The main steps of the initial gas desorption experiments are as follows. First, the coal is broken into samples and sieved to particle sizes of 1–3 mm, which were then used for desorption experiments. The gas desorption experiments were carried out in a 30 °C water bath. Coal samples were on dry ash free (daf) basis, and the equilibrium pressure was set to 5 MPa, 4 MPa, 3 MPa, 2 MPa and 1 MPa.

The relationships between the desorption time and desorption gas volume of each coal seam under different pressures is shown in Fig. 5.

Under different equilibrium pressures, the methane desorption volume of coal seam No. 14 is the largest (Fig. 5c), while the gas...
The desorption quantity of coal seam No. 12 is the smallest (Fig. 5a). At the same equilibrium pressure, the gas desorption quantities from large to small are No. 14 coal seam > No. 15-1 coal seam > No. 13 coal seam > No. 16-1 coal seam > No. 12 coal seam (Fig. 5). The major similarity between these desorption curves was that the methane desorption quantity increased quickly from 0 to 20 min. The gas desorption amounts then increased slowly from 20 to 120 min. This suggests that the best time for gas extraction is during the period of early pressure relief, within 0–20 min. During the early period, the gas desorption volume and gas concentration are stable at relatively large values. In addition, significant attention should be given to low concentration gas extraction in the latter period of gas desorption and to properly sealing the drilling hole, thereby improving the gas extraction rate.

By comparing Figs. 4 and 5, we found that the adsorption and desorption volumes of the five coal seams (samples) showed consistency, suggesting that the adsorption and desorption processes of coal samples from the Dalong Mine are reversible. However, coal samples analyzed via the desorption test were on daf basis, and moisture had been removed. In fact, the high natural moisture content of the coal in the field will make gas desorption more difficult.

### 3.3. Gas pressure

The measured maximum gas pressures of the Nos. 12, 13, 14, 15-1 and 16-1 coal seams are presented in Table 1. The No. 13 coal seam has the highest pressure, 4.10 MPa, while the No. 16-1 coal seam has the lowest pressure at 2.00 MPa (Table 1). The pressures of the Nos. 12, 13, 14, 15-1 and 16-1 coal seams exceed 0.74 MPa, which is the critical value for evaluating coal and gas outburst risks (Jiang et al., 2011). Fig. 6 shows the relationship between the pressure and buried depth. The linear regression of gas pressure and depth can be expressed by Equation (1)

$$ P = 0.0255 \times H - 13.4046 $$

where $P$ is the gas pressure (MPa) and $H$ is the buried depth (m).

The gas gradient of the Dalong coal seams is 0.0255 MPa/m, which is larger than the normal hydrostatic pressure gradient of 0.01 MPa/m. This may be caused by the trapping effect of the intrusive igneous sill intrusion in the Tertiary system, which prevents gas flow through the fault or other fractures to the surrounding rock or outcrop.

### 3.4. CBM drainage engineering challenges

As mining depths increase, new challenges have emerged, such as gas drainage and gas outbursts, which are induced by mining extraction. These challenges have primarily occurred in gassy, multiple-seam coal mines. The primary reason for this phenomenon is that, as coal seam depth increases, stress and gas pressures increase, while permeability decreases. Stress and pressure relief require temporal and spatial pre-drainage protection. However, increased coal production and associated economic interests have resulted in a lack of necessary time and space for CBM pre-drainage engineering.

CBM drainage engineering challenges in the Dalong Mine are as follows. First, the Dalong coal has low permeability, with an average value of $1.1 \times 10^{-4}$ mD, which was tested according to the standard MT 223-90. This is the largest challenge for gas extraction engineering. In addition, the Dalong coal has a high gas adsorption ability, gas pressure and natural moisture content. The moisture can inhibit gas desorption from the coal matrix. In addition, the influence of the dolerite igneous intrusion (Fig. 2) caused the...
formation of secondary coal seam hydrocarbons, and the trapping effects of the sill igneous made gas drainage from the Nos. 12, 13, 14, 15-1 and 16-1 coal seams difficult.

The Dalong coal seams belong to the short-distance outburst coal seam group. Since 1987, 10 gas outburst accidents have occurred in the vicinity of the igneous intrusion zone in the Daxing Mine, which is adjacent to the Dalong Mine (Fig. 1). The thermal evolution effects of an igneous dike increase the adsorption capacity of the heat affected coals as well as the gas diffusivity and storage capacities (Saghafi et al., 2008).

After shallow excavation of the Nos. 4, 5 and 7 coal seams in the Dalong Mine (Fig. 2), a large goaf area was formed. This is not conducive to gas pre-drainage via surface well drilling at depth in the coal seam portion of the formation. This presents a new engineering challenge related to CBM drainage at the Nos. 12, 13, 14 and 15 coal seams, which are located in the lower coal-bearing segment.

Reducing geostress is the best way to increase coal seam permeability and CBM extraction efficiency, and can potentially solve the CBM drainage challenges in the Dalong Mine. The in situ rock stress measurements below and above a mining coal seam are very important for mining technology and coal mine safety. However, they are restricted by the field observation conditions, making it difficult to measure the rock mass stress during coal seam mining. Numerical simulations could predict the in-situ stress and rock stress changes in coal and rock around the stope. Therefore, we attempt to solve the problem using numerical simulations.

The mining movements of a certain coal seam will cause stress relief in adjacent coal seams. The number of cracks in and permeability of the adjacent coal seams will increase. Applying the appropriate protective seam mining technologies and extracting stress-relief gas from adjacent coal seams can solve the problems facing the Dalong Mine.

4. Gas drainage method and technology of mining protective seam

4.1. Gas drainage method and drainage criteria in coal mine

4.1.1. Comprehensive gas drainage method

The latest comprehensive gas drainage method classification is shown in Fig. 7. Gas drainage methods can be temporally categorized as gas drainage before, during and after mining. Meanwhile, gas extraction can be spatially classified as gas extraction from mining seams, adjacent seams, the working face and the goaf (Wang et al., 2013).

4.1.2. Gas drainage criteria for evaluating gas extraction project

According to the coal mine gas extraction regulations (State Administration of Coal Mine Safety of China (2011)), gas drainage boreholes should be uniformly set in the effective range. Areas with boreholes with similar spacing and drainage times can be divided into an evaluation unit. When evaluating the gas drainage effects, the remnant gas content or gas pressure should be calculated based on extraction measurement parameters (borehole spacing, extraction time, extraction negative pressure, gas density, gas drainage volume and other factors). The gas content and gas pressure should be measured according to GB/T23250 and AQ/T1047, respectively.

For coal seams with outburst risks, the evaluation area can be treated as having no outburst risks when the remnant gas pressure and gas content are all below their limits, and no outburst dynamic phenomenon exists during borehole drilling. The expected critical value can be chosen according to the gas content and pressure measured at the shallowest depth of the first outburst. If there is no record of this occurrence, it is preferable to values of 0.74 MPa (for pressure) and 8.00 m³/t (for gas content) as the critical values.

4.2. Technology of mining protective seam

4.2.1. Technique principle of mining protective seam

Mining the protective seam is considered to be the most
The overburden depth of the initial outburst site of Dalong coal mine is 450 m. Chosen as protected seam, and excavated. Seams with low gas content and small outburst risk should be effective way to achieve regional gas control. It eliminates outburst dangers over short-distances and for multiple-seams in coal mines. Seams with low gas content and small outburst risk should be chosen as protected seam, and excavated first. The stress-relief gas of the upper and lower adjacent seams can be drained via the unloading effect of protective seam mining. Meanwhile, it can regionally eliminate the outburst danger of adjacent seams. The seams adjacent to the protective seam, both above and below, are known as protected seams. The protective seam at the bottom of the protected seam is called the lower protective seam, and the protective seam at the top of the protected seam is called the upper protective seam. A comparison of the stress and displacement (five zones and three belts) of the rock mass below the protective seam, and in a multiple-seam context, is shown in Fig. 8. The stress-relief zones and belts will provide the time and space for CBM pre-drainage engineering.

When mining the protective seam, stope events, movement and deformation occur, thereby redistributing the stress field. In a certain range of the roof and floor of the goaf, the ground stress reduces and stress relief appears. Coal seams above and below the protective seam experience swelling deformation, resulting in a thousand fold increase in permeability, which enhances gas desorption and flow. The stress-relief gas of the protected seam forms the gas flow conditions of “Desorption-Diffusion-Seepage” (Cheng et al., 2009). This is the theoretical basis of protective seam mining.

Extracting protective seams is an effective and economical way to improve the gas drainage rate and prevent outbursts. It increases the seam permeability and reduces the seam pressure. Borehole drilling and gas extraction engineering in protected seams should be done in advance. Thus, the stress-relief gas in the protected seams could be effectively drained when mining the protective seam.

### 4.2.2. Regulations of choosing the protective coal seam

When mining coal seams in gassy, multiple-seam outburst coal mines, an outburst-free coal seam within the effectively protected vertical distance, and with a thickness greater than 0.5 m, should be mined first, as the protective seam. While more than one coal seam can be treated as a protective seam, we should analyze each scenario and choose the best option. If all coal seams have a potential outburst risk, the seam with the lowest outburst risk should be mined first. During the mining of the protective seam, gas in the protected seam should be extracted (State Administration of Coal Mine Safety of China 2009).

It is preferable to choose the upper coal seam as the protective seam. If mining the lower protective seam is necessary, the mining conditions of the protected seam should not be altered. The maximum distance between the upper protective seam and protected seam is 60 m (coal seam dip \( < 8^\circ \)). The stress-relief gas extraction effect indexes of the protected coal seam are shown in Table 3.

The characteristics of coal seams in the Dalong Mine are as follows. As the average interlayer spacing of the No. 12 and No. 13 coal seams is 11.17 m, the No. 12 coal seam will be destroyed when mining the No. 13 coal seam. The average interlayer spacing of the Nos. 14 and 15-1 coal seams is 34.87 m. The depth of the No. 16-1 coal seam (664.8 m) is greatest. As buried depth increases, so do gas pressure and stress. The outburst danger of the No. 16-1 coal seam is the largest (Fig. 6). So the Nos. 13 and 16-1 coal seams are not suitable to be the protective coal seam. We analyze the Nos. 12, 14 and 15-1 coal seams as prospective protective layers by observing and analyzing the effects of changes in stress and pressure relief on the protected seams.

### 4.3. Simulation model and case simulation results

A boundary element model (BEM) program, LaModel (Heasley, 1998), was employed to analyze the seam pressure. LaModel uses the displacement-discontinuity (DD) variation of the BEM and has been widely used in underground coal mines in the U.S. (Mark et al., 2007; Heasley, 1998, 2008; Zhang et al., 2014; Zhang and Heasley, 2007).

---

**Table 1**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Coal seam no.</th>
<th>Average thickness (m)</th>
<th>Site</th>
<th>Depth (m)</th>
<th>Gas pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL#12</td>
<td>No. 12 coal seam</td>
<td>3.08</td>
<td>coal face 1201</td>
<td>624.3</td>
<td>3.10</td>
</tr>
<tr>
<td>DL#13</td>
<td>No. 13 coal seam</td>
<td>2.74</td>
<td>pathway downhill in seam 13</td>
<td>639.5</td>
<td>4.30</td>
</tr>
<tr>
<td>DL#14</td>
<td>No. 14 coal seam</td>
<td>1.85</td>
<td>belt transport lane in seam 14</td>
<td>646.2</td>
<td>3.30</td>
</tr>
<tr>
<td>DL#15</td>
<td>No. 15-1 coal seam</td>
<td>3.72</td>
<td>gas lane in seam 15-1</td>
<td>653.1</td>
<td>2.10</td>
</tr>
<tr>
<td>DL#16</td>
<td>No. 16-1 coal seam</td>
<td>2.15</td>
<td>gas lane in seam 16-1</td>
<td>664.8</td>
<td>2.00</td>
</tr>
</tbody>
</table>

The overburden depth of the initial outburst site of Dalong coal mine is 450 m.

**Table 2**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Coal seam no.</th>
<th>Proximate analysis (wt.%)</th>
<th>Rₒ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Moist</td>
<td>Ash</td>
</tr>
<tr>
<td>DL#12</td>
<td>12</td>
<td>8.21</td>
<td>7.34</td>
</tr>
<tr>
<td>DL#13</td>
<td>13</td>
<td>8.86</td>
<td>9.85</td>
</tr>
<tr>
<td>DL#14</td>
<td>14</td>
<td>7.93</td>
<td>10.31</td>
</tr>
<tr>
<td>DL#15</td>
<td>15-1</td>
<td>7.38</td>
<td>8.30</td>
</tr>
<tr>
<td>DL#16</td>
<td>16-1</td>
<td>7.54</td>
<td>10.97</td>
</tr>
</tbody>
</table>

Mois: moisture; Ash is on a dry basis; VM: volatile matter, on dry ash free (daf) basis; FC – fixed carbon (daf basis); Rₒ: random vitrinite reflectance.

**Fig. 4.** Methane adsorption isotherm and the fitting Langmuir curves of samples of Dalong coal seams.
In this paper, the Nos.12, 14, and 15-1 coal seams were selected as the protective seams in three numerical models, which compared the seam stress induced by extracting different protective seams.

For the LaModel simulation of the multiple-seam mine, five coal seams (Nos.12, 13, 14, 15-1, and 16-1) were discretized with 2.0 m square elements in five overlapping grids. Each mine grid was 150 by 150 elements (300.0 by 300.0 m). The seam heights of the Nos. 12, 14, and 15-1 seams were set as 3.1 m, 2.1 m, and 3.7 m, respectively. The length of the longwall panel was set as 140.0 m, and its width was 100.0 m. Two barrier pillars, with longitudinal lengths of 80.0 m, were set at two ends of the longwall panel. Symmetric boundary conditions were set at all sides of the models. In this paper, the following assumptions were made: the coal is homogeneous in distribution; the mining procedure has no effect on the final stress distribution; and tectonic stress, temperature stress and the stress induced by gas are not important. The mechanical parameters used for the seams and gobs are listed in Table 4.

Fig. 9 shows the vertical stress redistributions of the seams after the extraction of the protective seam. The results are based on a numerical investigation using the LaModel. Case A analyzes the No. 12 coal seam as the first-excavated, protective seam and the balanced redistribution of the vertical stress of protected seams Nos. 13, 14, 15-1, and 16-1 (Fig. 9a). Case B analyzes the No. 14 coal seam as the first-excavated protective seam (Fig. 9b). Case C analyzes the No. 15-1 coal seam as the first-excavated protective seam (Fig. 9c). The stress rule was applied to evaluate whether an outburst would occur. The potential critical stress value can be estimated according to Equation (2) (Hu et al., 2009; Yang et al., 2013). In this paper, the Nos. 12, 14, and 15-1 coal seams were selected as the protective seams in three numerical models, which compared the seam stress induced by extracting different protective seams.

Fig. 5. Desorption volume of methane under pressures of 1–5 MPa.
where \(\sigma_{ZC}\) is the vertical stress of the coal seam, \(\alpha\) is the coal seam angle, \(\lambda\) is the horizontal stress coefficient, \(\gamma\) is the bulk density and \(H\) is the depth of the first gas outburst.

Based on the coal seam occurrence in the Dalong Mine (\(\alpha=3^\circ\), \(\lambda = 1\), \(\gamma = \rho g = 25,000 \text{ kg/m}^2 \text{ s}^2\) and \(H = 450 \text{ m}\)) (Table 1), \(\sigma_{ZC} \leq 2500 \times 510 = 11.25 \text{ MPa}\). Therefore, when the vertical stress decreases to 11.25 MPa, a coal and gas disaster will not occur. Thus, 11.25 MPa is determined to be the critical stress value of the Dalong Mine. As shown in Fig. 9d, the stress-relief performances of the protected seams are different based on different mining methods. The re-established vertical stresses in the Nos. 15-1 and 16-1 coal seams remain at high levels in Case A, with vertical stress changes of 62.62% and 52.85%, respectively (Table 5). This result is attributed to the distance between the coal seams. However, in Cases A, B and C, the vertical stresses after the release of the protected coal seams are all lower than the critical value, indicating that the Nos. 12, 14 and 15-1 coal seams could be chosen as the first-mined coal seam.

4.4. Selection of the first excavated protective seam

The simulation results suggest that first mining the No. 12 coal seam, the protective seam, generates stress relief in the Nos. 13 and 14 protected coal seams. The stresses of the protected Nos. 15-1 and 16-1 seams change less and have limited stress relief effects. Mining the Nos. 14 and 15-1 coal seams, as prioritized protective layers, produces better stress relief effects (Table 5). Considering that the No. 12 coal seam is a high-gas seam with no outburst danger, while the Nos. 13, 14, 15-1 and 16-1 seams are coal and gas outburst seams, a floor rock roadway would need to be excavated if the No. 14 coal seam was chosen as the first-mined seam. This would involve drilling a grid-style crossing borehole within the No. 14 coal seam. If the No. 12 seam is chosen as the first protective seam, only the drilling of long boreholes in the mining face bedding would be required. Meanwhile, if the floor rock roadway of the Nos. 13 and 14 coal seams is excavated, crossing boreholes would be drilled toward the Nos. 13 and 14 coal seams (Fig. 10).

This method can save considerable manpower, as well as financial and material resources. In conclusion, the No. 12 seam was ultimately selected as the first mined protective seam. Thus, excavation should proceed from top to bottom in the following order: seam Nos. 12, 13, 14, 15-1 and 16-1. This method is called multiple progressive protection and stereoscopic gas extraction technology.

5. Protective seam mining and CBM drainage engineering

5.1. CBM drainage before mining the protective seam

The long bedding borehole was used to extract coal bed methane from coal face 1201, the first-mined coal face of the protective coal seam, before mining the No. 12 seam (Fig. 10). Gas...
drainage should reach the standard residual gas pressure of the mining area (less than 0.74 MPa or a gas content less than 8.0 m³/t). After pre-draining the gas for 180 days, the gas pressure of the No. 12 coal seam decreased from 3.10 MPa to 0.50 MPa, and the gas content of the No. 12 coal seam decreased from 8.50 m³/t to 3.39 m³/t.

5.2. CBM drainage of protected seams during mining protective seam

After mining the protective seam, the gas drainage volume variation of the protected seam exhibited stress relief. The procedure for the 1201 working face of the Dalong Mine can be divided into two stages: insufficient and sufficient pressure relief (Fig. 11).

Before the 60-m stoping of coal face 1201, the pressure relief gas drainage volume of the protected seam was smaller, which was due to the inadequate development of interlaminar fractures. Vast gas in the protected seam prevents timely desorption and emission. Thus, the insufficient pressure relief stage appears (Fig. 11). When coal face 1201 was mined from 60 m to 350 m, the pressure relief gas extraction quantity of the protected seam increased significantly, primarily because the protected coal seam was fully pressure released. The expansion deformation of the protected seams increased, and the inter-laminar fractures developed and connected. The gas seepage channel formed, and the sufficient pressure relief stage began. The gas drainage volume of the floor rock roadway increased to 45.0 m³/min, and the average volume was 26.2 m³/min (Fig. 11).

5.3. CBM drainage after mining protective seam

Xu and Qian (2004) proposed the O-shaped circle theory, laying a foundation for understanding the crack space of goaf edges. This theory suggests that goaf gas in the flow path of the fracture is caused by mining. After mining the coal, the stratum stress around the protective coal seam is concentrated. In addition, the coal and

<table>
<thead>
<tr>
<th>Index</th>
<th>Gas pressure (MPa)</th>
<th>Gas content (m³/t)</th>
<th>Coal seam expansion deformation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical value</td>
<td>&lt;0.74</td>
<td>&lt;8.00</td>
<td>&gt;0.3</td>
</tr>
</tbody>
</table>

Table 3: Critical indexes of gas drainage effect of protected seam.

Table 4: Mechanical parameters used for the coal seams and goafs.

![Fig. 8. Comparison of stress and displacement (five zones and three belts) of the rock mass below the protective seam.](image-url)
rock mass above the goaf are slowly caving into the goaf, resulting in stress unloading and fracture. After excavating the coal from the 1201 coal face, a large goaf area was formed. The goaf gas was drained by the roof rock roadway along the overlying rock fracture, which was caused by mining (Fig. 10). The gas drainage distribution in the roof rock roadway and upper corner, methane concentration in the return airway and relative methane emissions are shown in Fig. 12.

Roof rock roadway drainage goaf gas (Fig. 10) is associated with gas drainage after mining (Cheng et al., 2003; Cheng and Yu, 2007). Before coal face 1201 was mined to 75 m, the quantity of gas drainage was low (~4 m³/min). When the mining reached 75 m, the goaf area increased, and the gas drainage volume increased, reaching a maximum of 27 m³/min. The gas drainage volume then slowed and stabilized at approximately 7 m³/min (Fig. 12a).

When coal face mining (the section before 75 m) began, the roof rock roadway was not connected with the goaf through the fractures, and roof gas drainage was not yet important. In addition, the gas drainage volume of the upper corner of the mining face is larger. When the mining face was mined to ~75 m, the gas drainage volume increased to the maximum of 7.2 m³/min. After the coal face mining reached 75 m, the roof rock roadway became important, and gas drainage in the upper corner quickly reduced. When the coal face reached approximately 220 m, the gas drainage volume increased to 6.8 m³/min, and upper corner gas drainage volume slowly reduced (Fig. 12b).

In the early mining stages of protective seam coal face 1201, due to the lag movement of the coal rock bed, the Nos. 13 and 14 coal

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Table 5
Comparison of the deferent protective coal seam mining method.

<table>
<thead>
<tr>
<th>First extracted protective coal seam</th>
<th>Protected coal seam</th>
<th>Vertical stress before mining (MPa)</th>
<th>Vertical stress after mining (MPa)</th>
<th>Vertical stress changing rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 12</td>
<td>No. 13</td>
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<td>0.93</td>
<td>94.17</td>
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<tr>
<td>No. 14</td>
<td>No. 12</td>
<td>16.89</td>
<td>3.31</td>
<td>80.42</td>
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<tr>
<td></td>
<td>No. 15-1</td>
<td>17.83</td>
<td>6.66</td>
<td>62.62</td>
</tr>
<tr>
<td></td>
<td>No. 16-1</td>
<td>18.45</td>
<td>8.70</td>
<td>52.85</td>
</tr>
<tr>
<td>No. 14</td>
<td>No. 12</td>
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<td>0.80</td>
<td>94.84</td>
</tr>
<tr>
<td></td>
<td>No. 13</td>
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<td>0.63</td>
<td>96.04</td>
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<tr>
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<td>No. 15-1</td>
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<td>86.42</td>
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<tr>
<td></td>
<td>No. 16-1</td>
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<td>75.70</td>
</tr>
<tr>
<td>No. 15-1</td>
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<td>15.57</td>
<td>2.20</td>
<td>85.87</td>
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<tr>
<td></td>
<td>No. 13</td>
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<td>94.19</td>
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<tr>
<td></td>
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<td>97.90</td>
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<tr>
<td></td>
<td>No. 16-1</td>
<td>18.45</td>
<td>1.13</td>
<td>93.85</td>
</tr>
</tbody>
</table>
seams did not release stress. The gas emissions from the protective seam coal face stem mainly from the coal seam wall, and the methane concentration in the return airway is low (0.22–0.29%). After the mining face moved to 25 m, it increased to 0.75%. When the gas drainage drilling borehole in the floor roadway became important, the pressure-released gas of the protected seam, along with fractures flow to the protective seam, decreased. The gas concentration in the return airway of the protective seam coal face was maintained at 0.55% (Fig. 12c).

The relative methane emission (RME) of the 1201 mining face is smaller, and at the initial stoping, the maximum value was 3.90 m³/t. As the roof rock roadway drained goaf gas, the floor rock roadway drained pressure relief gas from protected coal seams Nos. 13 and 14. In the late stoping, the RME was stable at ~1.3 m³/t (Fig. 12d).

6. Gas drainage effect assessment and gas utilization

6.1. Remnant gas pressure and content of protected coal seams

The main investigation indicators of the protective seam mining effect test include remnant gas pressure, remnant gas content, roof and floor displacement (expansion deformation) of the protected coal seam and other proven effective indexes and methods (State Administration of Coal Mine Safety of China 2009). The relative displacement of the roof and floor determination method was used to investigate the protective effect of the protected coal seam after mining a thin portion of the protective seam (Liu et al., 2009a). After mining the protective seam, the captured CBM volume in the Luling coal mine reached 70 million m³/year, while the gas drainage efficiency reached 75% (Zhou et al., 2014).

When the 1201 coal face was mined, the protected layer of the Nos. 13 and 14 coal seams experienced a certain degree of stress.
To analyze the pressure relief of the protected seams Nos. 13 and 14, we measured gas pressure, gas content, relative expansion deformation and permeability coefficients before and after mining the No. 12 seam. The monitoring point and borehole should be located in the protected coal seams. Each coal seam contains six expansion deformation measuring points, 10 gas pressure points and 10 gas flow and concentration measuring points. The spacing between measuring points in the Nos. 13 and 14 coal seams is 30 m. The gas flow rate and concentration are used to calculate permeability coefficients and the CBM drainage volume.

The gas parameters before and after mining the protective coal seam are shown in Table 6.

After mining the No. 12 protective coal seam, the gas pressure and content of the Nos. 13 and 14 protected coal seams significantly decreased. The gas pressure of the No. 13 coal seam decreased from 4.10 MPa to 0.40 MPa, and that of the No. 14 coal seam decreased from 3.30 MPa to 0.55 MPa. The gas content of the No. 13 coal seam decreased from 9.50 m³/t to 3.09 m³/t, while that of the No. 14 coal seam decreased from 7.80 m³/t to 2.68 m³/t. The permeability coefficients of the Nos. 13 and 14 coal seams increased 1465 and 687 times, respectively (Table 6).

6.2. Deformation expansion of protected coal seams

An empirical value of 0.3‰ of the protected coal seams expansion deformation was used to evaluate whether a significant protective effect occurred (Yu et al., 2004). This stress-relief and expansion deformation effect could be superimposed by mining multiple protective seams. The roof and floor displacement of the protected seams was measured as more than 20‰ in the Wulan Mine of China (Liu et al., 2011). The distribution regularities of expansion deformation are shown in Fig. 13.

The maximum roof and floor displacement of the Nos. 13 and 14 coal seams were 0.62‰ and 0.36‰, respectively, both exceeding 0.3‰. Therefore, mining the No. 12 seam as the first protective seam generated pressure relief in the Nos. 13 and 14 protected seams. Gas drainage measures before, during and after mining ensured the safe and efficient mining of coal face 1201.

After mining the No. 12 seam and extracting the No. 13 seam, the Nos. 14, 15-1 and 16-1 coal seams were subsequently extracted to generate secondary pressure relief and increase expansion deformation and permeability. Similarly, mining the No. 14 seam will generate tertiary pressure relief in the Nos. 15-1 and 16-1 protected seams. According to different pressure release areas of the protected seam, the optimal placement of the crossing borehole in the floor roadway and the effect of pressure relief gas extraction were improved.

6.3. Gas utilization in Dalong Mine

The quantities of methane drainage due to borehole drilling engineering were calculated as 120,001 m³ in 2011, 137,980 m³ in 2012 and 140,670 m³ in 2013, respectively. Methane drainage and utilization in the Dalong Mine is shown in Fig. 14.

From 2007 to 2013, a total of 84.5 million m³ CBM was exploited, while a total of 48.39 million m³ CBM was utilized in the Dalong Mine. The mine gas extraction rate increased from 45% in 2007 to 70% in 2013. This is mainly due to the floor roadway drilling
crossing borehole and pre-drainage gas technology used over the past three years. The gas utilization rate improved from 23% to 90% (Fig. 14). This is because the mine established a CBM extraction system both above-ground and underground. The majority of the extracted CBM was incorporated into the urban pipeline and used for fuel gas by residents in the cities of Diaobingshan and Faku. The field study suggests that mining the protective seams in multiple coal seams of the Dalong Mine can not only prevent pressure relief gas flow to the protective mining face and ensure the safety of the mining face during stoping but also drain considerable CBM from the protected seams. Thus, a simultaneous extraction of coal and gas is achieved. Eventually, the CBM drainage and utilization rate can increase annually in the Dalong Mine, and coal mine safety conditions can continuously improve.

7. Conclusions

1) Deep outburst multiple-seam mining has led to difficulties related to safety and CBM drainage in the Dalong Mine. The samples had high moisture values, ranging from 7.38% to 8.86%. The moisture inhibits the desorption of gas from the coal matrix. An adsorption test (Langmuir parameter \( a = 40.3 \text{ mL/g} \)) showed that the coal has a high adsorption capacity. However, the coal has low permeability, with an average value of \( 1.1 \times 10^{-4} \text{ mD} \). CBM drainage in the Dalong Mine is very difficult.

2) Reducing geostress is the best way to increase coal seam permeability and CBM extraction efficiency. Applying protective seam mining technology can solve the CBM drainage challenges in the Dalong Mine. The rock mass stress-relief below the protective seam generated prove zones and three belts under multiple-seam conditions. It can provide the temporal and spatial context for the CBM pre-drainage engineering of protected seams.

3) Based on numerical simulations using LaModel, the coal seam outburst risk degree and an extraction economic analysis, the No. 12 coal seam is chosen as the first-exploited protective seam. Desorption tests suggest that the best time for gas extraction is during the early pressure relief period of 0–20 min. The floor rock roadway and cross boreholes were designed to drain stress-relief gas from the protected seam. Therefore, they should be constructed before protective seam mining.

4) Field applications indicate that the remnant gas pressure and content in the protected seams significantly decreased after mining the protective seam. The permeability coefficients of the Nos. 13 and 14 seams increased 1465-fold and 687-fold, respectively. The gas extraction rate increased from 45% to 70%, which improved the coal mine safety conditions. The quantitative case studies and CBM drainage practice provide an example for other coal mines under similar conditions.

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References


Nomenclature

\( P \): the gas pressure [MPa]
\( H \): the buried depth [m]
\( R_a \): random vitrinite reflectance
\( CBM \): coalbed methane
\( RME \): relative methane emission [m^3/t]
\( \sigma_{sc} \): The critical stress relief value [MPa]