New insights into the permeability-increasing area of overlying coal seams disturbed by the mining of coal

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\textbf{A B S T R A C T}

Many researchers have concluded that the permeability evolution of coal and rock is closely related to the stress change path. However, in the protective coal seam mining practices, the stress change path of the overlying coal seams is ignored, per the related technical criterion and regulations, the traditional permeability-increasing area in the overlying protected coal seam is generally delimited smaller than the mined-out area of the protective coal seam, which wastes a large quantity of coal resources. This study investigates the actual permeability-increasing area of the overlying protected coal seam through theories analysis, FLAC\textsuperscript{3D} numerical simulation and field test. The permeability distribution of the overlying protected coal seam near the mined-out boundary in the strike direction (MBSD) is quantitatively divided into four zones, which are the original permeability zone, permeability decrease zone, permeability insufficient increase zone, and permeability sufficient increase zone. It is suggested that the actual permeability-increasing area is larger than the mined-out area of the protected coal seam. According the permeability distribution of the protected coal seam, optimized cross-measure boreholes were designs for gas drainage. The field tests showed that the outburst risk of the protected coal seam inside the MBSD was eliminated two months after the protective coal seam mining. The theories analysis, numerical simulation and field tests showed that the actual permeability-increasing area is larger than the traditional permeability-increasing area, the protected area in the protected coal seam can be enlarged by the optimized cross-measure boreholes gas drainage.

\textbf{1. Introduction}

Coal is a type of precious nonrenewable fossil fuel which provides important energy resources for the development of the economy. Gas is a self-generated and self-reservoir gas generated in the coalfication process and accumulated in coal seams (Bustin and Clarkson, 1998; Jin et al., 2016; Tao et al., 2007). With the increase of the mining depth, coal seams come into the stage of low permeability and high gas content, and coal and gas outbursts become one of the most serious disasters in mining activities (Guo et al., 2014; Karacan et al., 2011). How to eliminate the outburst risk under the premise of fully exploiting coal resources has gradually developed into an urgent problem.

Coal seams are reservoir rocks containing a large amount of cracks, which is the main flow path for gas. In the process of gas drainage, the permeability of coal is recognized the decisive parameter (Chen et al., 2016; Liu et al., 2015). Many theoretical research and engineering practices have shown that mining protective seams combined with extracting the pressure-relief gas is the most effective technology to eliminate the outburst risk during mining a highly outburst-prone coal seam group (Cheng et al., 2015; Lama and Bodziony, 1998; Ping et al., 2014; Zhou et al., 2015). Due to the redistribution of in situ stress, the permeability of overlying coal seams will changes after mining the protective seam (Kratzsch, 1983; Liu, 1995; Qian et al., 1994; Wang et al., 2017).

The permeability evolution of coal and rock is closely related to the stress change path and damage (Fortin et al., 2005; Wang et al., 2013). After the mining of protective coal seam, the overlying coal seams first experience vertical stress loading process (Zhang et al., 2016). Wang et al. (2013) study the continuous evolution of permeability to water and gas of coal samples under an loading process which prescribed confining stress and increasing deviatoric stress driven to failure. During loading, the permeability first decreases and then suddenly increases by 3-4 orders of magnitude earlier than the switch in the volumetric strain from compaction to dilation. In the whole loading...
process, the permeability evolution is divided into three stages (Han et al., 2016). The first stage is mainly correspond to the linear elastic deformation process, in which the permeability decreases with the increase of stress. But in the second stage, the permeability starts to increase at the beginning of plastic shearing. In the third stage, the permeability will slightly decreases after the peak stress. Chen et al. (2013) conducted X-ray CT scanning and permeability experiments to studied the damage and permeability development of coal during an unloading process. The results shows that the damage cracks appear and permeability increases under the unloading process of fixed deviatoric stress and decreasing confining stress.

However, traditionally, in the protective coal seam mining practices, the stress change path of overlying coal seams is ignored. The permeability-increasing area which is also known as the protected area of overlying coal seam is only delimited according to final critical stress, which is the starting stress of the outburst in the coal mine (Hu et al., 2009; Kong et al., 2014; Yang et al., 2011; Yuan et al., 2009). This method simply focuses on the final stress in overlying protected coal seams after mining the protective seam, ignoring the stress change path and permeability evolution process of overlying protected coal seams near the mined-out boundary. Thus, the permeability-increasing area delimited by this method is less than the actual increasing area. Based on this method, the Chinese State Administration of Work Safety enacted the “Technical criterion of protective coal seam exploitation” and “Provisions of the prevention of coal and gas outburst” in 2009 to guide the actual protective coal seam mining. In the technical criterion and provisions, if a protective coal seam working face has been exploited for more than three months and is relatively pressure relieved, the protected area of the protected coal seam in the strike direction can be delimited as the pressure-relief angle $\delta = 56^\circ \sim 60^\circ$ at the mining starting line or mining stopping line, as shown in Fig. 1. That means, the traditional permeability-increasing area of the overlying coal seam is relatively small than the mined-out area. Ignoring the stress change path and permeability evolution process, the area outside the traditional pressure-relief line is delimited as permeability-decreasing area.

With the increase of the mining depth, the coal resources increasingly become scarce, but due to the traditional permeability-increasing area is relatively conservative, the overlying protected coal seam out of the permeability-increasing area cannot be exploited. Moreover, the layout of the working face in overlying protected coal seams is more and more difficult, which wastes a large quantity of coal resources. So, it is necessary to study the actual permeability-increasing area in the overlying coal seam due to the mining of the protective coal seam. Next, a reasonable protected area in the overlying coal seam can be clearly delimited, which contribute to achieve a more rational utilization of the coal resources.

In order to study the actual permeability-increasing area of overlying coal seams disturbed by the mining of coal, this paper takes the protective coal seam mining practice in the Xinzhuangzi coal mine of the Huainan mining group as a typical case. It is well known that the relationship between permeability and volumetric strain is close in the whole stress-strain and permeability-strain curves of the coal body. Based on these theories analysis basis, the stress change path, plastic damage and volumetric strain evolution of the overlying protected coal seam were investigated by the FLAC$^{3D}$ numerical simulation and then the permeability evolution of the overlying protected coal seam was discussed. Finally, the permeability-increasing area of the coal seam was delimited. In addition, the correctness of the permeability distribution was verified by the field test.

2. Method

2.1. Permeability model of coal

Coal and rock is a kind of special geological material formed after a long and complex diagenetic process, which contains a large amount of original damage cracks (Park and Bobet, 2009; Wei et al., 2016), as shown in Fig. 2. The cracks directly determine the mechanical damage and permeability properties of the coal and rocks.

The structure of coal can be simplified into a cube model (Golf-Racht, 1982), according to the widely used cube law (Cui and Bustin, 2005; Gray, 1987; Liu et al., 2010; Lu et al., 2016), the permeability model of coal can be expressed as:

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3$$

Where $k$ is the coal permeability, $k_0$ is the initial coal permeability, $\phi$ is the fracture porosity, and $\phi_0$ is the initial fracture porosity.

The bulk volume of the coal body includes the fracture volume and the matrix volume (Lu et al., 2016), the fracture porosity is defined as the ratio of the fracture volume to the bulk volume of the coal body.

$$\frac{\phi}{V_f} = \frac{V_f}{V}$$

Where $V_f$ is the fracture volume, $V$ is the bulk volume of the coal body.

The volumetric strain is made up of fracture strain and matrix strain, if we ignoring the matrix strain, the fracture porosity can be described as:

$$\phi = \phi_0 + \varepsilon_v$$

Where $\varepsilon_v$ is the volumetric strain of the coal body.

From Eqs. (1) and (3), permeability model is obtained.

$$\frac{k}{k_0} = \left(1 + \frac{\varepsilon_v}{\phi_0}\right)^3$$

As shown in Eq. (4), the permeability $k$ is positively related to the change of the volumetric strain $\varepsilon_v$, the volumetric strain can visually reflect the change of the permeability.

2.2. The relationship between permeability and volumetric strain

Many theoretical and experimental studies show that the essence of the stress-strain and permeability-strain curves in a coal body is the evolution process of cracks emerging and developing. As shown in Fig. 3, the stress-strain curves of the coal body is divided into five stages, and the permeability-strain curves are divided into three stages (Chen et al., 2016; Feng et al., 2017; Han et al., 2016; Martin, 1994; Teng et al., 2016; Viete and Ranjith, 2006).

The stress-strain curves in stages II and III mainly correspond to the linear elastic deformation. With the increase of the axial stress $\sigma$, the initial cracks first close and then initiate, and finally the new stable microcracks grow, and the volumetric strain is compacted continuously. When the axial stress $\sigma$ reaches the damage expansion stress $\sigma_{d,\phi}$, the volumetric strain reaches the transition of the compaction to dilatancy. Meanwhile, the nonlinear plastic deformation stage IV starts. In stage IV, large numbers of the original cracks and new cracks develop rapidly, the coal body is unstable and cracking, and finally the coal body
is fractured, and the fracture ratio increases by 3–4 orders of magnitude compared with its initial value (Xue et al., 2016). After the onset of the post-peak is the residual state stage V, in which the crack propagation is more obvious, and macrocracks emerge in large quantities.

The permeability evolution is characterized by three stages. In this first stage, corresponding to the linear elastic deformation process, the permeability decreases with the volumetric strain compaction when the axial stress increases. In the second stage, corresponding to the nonlinear plastic deformation stage, after the volumetric strain transition of compaction to dilatancy, the permeability suddenly and largely increases approximately linear, finally reaching 3–4 orders of magnitude higher than that of the intact coal (Wang et al., 2013). In the last stage, after the onset of the post-peak, the coal body volumetric strain is overall dilatancy, and the permeability still slightly increases and then reaches a plateau.

Underground mining operations usually induce the fracture and damage of the surrounding coal and rock (Abubakary et al., 2015; Yasitli and Unver, 2005), and the stress-strain and permeability-strain curves reflect the damage and permeability evolution process of the protected coal in the mining of a protective coal seam. We can find that the volumetric strain transition of the compaction to dilatancy is also the permeability transition of the decrease to a large increase. The relation between the volumetric strain and permeability is close. The volumetric strain evolution of the overly protected coal seam can be investigated by the FLAC3D numerical simulation. Through analysis of the volumetric strain in the process of the stress-strain and permeability-strain curves, we can get the permeability evolution.

2.3. Geological background

The Xinzhuangzi coal mine, located in the western Huainan coal field in the Anhui province of China, covers an area of 17.8 km², in which the mine field is 5.6 km long in strike and 3.75 km tilted wide on average. This coal mine is an outburst-prone coal mine, whose main working coal seams are the C13, B11b, B10, B8, B7a, B6, B4, A3 and A1 coal seams, and each of them has a coal and gas outburst danger. The location and geologic column of the Xingzhuangzi coal mine are shown in Fig. 4.

The B11b coal seam is 4.3 m thick on average, the gas pressure is 2.9 MPa, and the gas content is 13.5 m³/t. Due to the high outburst risk, it is difficult to mine the coal safely. The B10 coal seam, which lies 35 m below the B11b coal seam, is a thin and simple structured coal seam; the average thickness of the B10 coal seam is 1.5 m, the gas pressure is 1.8 MPa, and the gas content 11 m³/t. The coal and gas outburst risk in the B10 coal seam is lower than the B11b coal seam, so the B10 coal seam is chosen as a protective seam to exploit in priority, which provides pressure relief protection for the B11b coal seam. The basic parameters of the two coal seams are given in Table 1.
2.4. Situation of the protective coal seam mining

The 62 mining area is the first mining area of the B10 coal seam, which has a simple geological structure. The key protective mining working face is the 62210 working face. After mining the 62210 working face, the overlying 62211 working face in the B11b coal seam would be protected. The 62210 working face is 1230 m in strike, 195 m in tendency, 1.8 m in mining height, varies in elevation from −660 m to −770 m, and the average dip angle is 24°.

The mining of the 62210 working face makes part of the overlying B11b coal seam become pressure relieved and permeability increased. Next, by being combined with gas drainage measures, the regional outburst-prone danger in the B11b coal seam will be eliminated. However, according to the “Technical criterion of protective coal seam exploitation” and “Provisions of the prevention of coal and gas outburst”, the protected area in the B11b coal seam should be less than the mining areas of the 62210 working face, including in the strike and trend.

Because the small coal pillar mining technology is adapted for mining the 62210 working face and the adjacent working faces in a row, the working face in the protected coal seam could get protected in tendency. However, large parts of the B11b coal seam are unprotected in the strike direction, even though the traditional pressure-relief boundary is delimited as the maximum relief angle of 60°, as shown in Fig. 5.

If we lay out the protected coal seam working face per the relevant

<table>
<thead>
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<th>Parameters</th>
<th>Protective coal seam (B10)</th>
<th>Protected coal seam (B11b)</th>
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</thead>
<tbody>
<tr>
<td>thickness</td>
<td>1.5 m</td>
<td>4.3 m</td>
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<tr>
<td>dip angle</td>
<td>24°</td>
<td>24°</td>
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<tr>
<td>original gas pressure</td>
<td>1.8 MPa</td>
<td>2.9 MPa</td>
</tr>
<tr>
<td>original gas content</td>
<td>11 m³/t</td>
<td>13.5 m³/t</td>
</tr>
</tbody>
</table>

Table 1
Basic parameters of the coal seams.

Fig. 4. Location and geologic column of the Xingzhuangzi coal mine.

Fig. 5. Unprotected area of the B11b coal seam.
regulations, the overlying 62211 working face of the B11b coal seam would be shorter by 20 m than the 62210 working face on both sides in the strike direction. Thus, approximately 11076 t of coal cannot be extracted, which is a large waste of coal resources, and not only reduces the benefit of the protected coal seam but also makes the layout of the working face in the protected coal seam become increasingly difficult.

Therefore, it is meaningful to study the permeability evolution characteristics of a protected coal seam near the MBSD. It is useful to expand the protected area and to decorate the working face equally with the protective coal seam working face in the strike direction by adopting targeted gas drainage measures.

2.5. Numerical simulation

Based on the geological conditions of the Xinzhuangzi coal mine, we adopted the FLAC3D software for numerical simulation analysis. The relevant mechanical parameters and the thickness of the strata are shown in Table 2, which were determined based on the typical values cited from the geological prospecting report of the Xingzhuangzi Coal Mine. As shown in Fig. 6, the numerical calculation model is 450 m wide in X-direction, 600 m long in Y-direction, and 360 m high in Z-direction; the dip angle of coal and rock seams is 24°. The length of the working face in the protective coal seam is 300 m, extending from 150 m to 450 m in the Y-direction, the width is 170 m, and mining height is 2 m. To simulate the load of the 530 m overburden, a compressive stress of 15 MPa was imposed on the top of the model. The area around and at the bottom of the model were rolling fixed boundaries. The Mohr-Coulomb failure criterion is used to evaluate the failure of the coal and rocks caused by the coal seam excavation, and the post-failure strength of the coal and rocks is described using the strain-softening constitutive model.

The model contains 1009875 zones and 1053219 grids after building. During the mining of the protective coal seam, we selected the A-A’ cut face in the center of the working face, with X = 225 m serving as the monitoring surface, which is shown in Fig. 7.

3. Results and analyses

3.1. Evolution of the three-dimensional stress in the protected coal seam near the MBSD

After the coal seam mining, the original stress state will be broken due to the formation of the mined-out area, which subsequently forms a new stress state. In the process of the working face mining, the break and balance of the stress state is an ongoing recycle. The evolution of the vertical stress (Z-axis stress), the horizontal stress (X-axis stress, Y-axis stress) in the overlying protected coal seam are shown in Fig. 8, Fig. 9 and Fig. 10.

As shown in the stress contour, the evolution of the vertical stress and horizontal stress is similar. After mining the protective coal seam, the stress concentration phenomenon appears in the protected coal seam behind the starting line and in front of the working face. The stress relief of the protected coal seam will emerge behind the protective coal seam working face and reaches the maximum relief degree in the center of the mined-out area. In the process of the protective coal

<table>
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<th>Lithology</th>
<th>Density/Kg.m&lt;sup&gt;−3&lt;/sup&gt;</th>
<th>Bulk modulus/GPa</th>
<th>Shear modulus/GPa</th>
<th>Cohesion/MPa</th>
<th>Friction angle/°</th>
<th>Tensile strength/MPa</th>
<th>Thickness/m</th>
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<td>30</td>
<td>2.2</td>
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Table 2
Thickness and mechanics parameters of the strata.
Seam working face advancing, the overlying protected coal seam, in front of the protective coal seam working face, has experienced the stress concentration and relief in turns.

After the data extraction of the numerical simulation results in the process of the working face mining, the three-dimensional stress of the overlying protected coal seam, in front of the protective coal seam working face, is shown in Fig. 11.

Approximately 200 m ahead the working face, the three-dimensional stress concentration phenomenon appears in the overlying protected coal seam. After the stress concentration peak, the stress began to decline rapidly. The vertical stress (Z-axis stress) concentration degree is much higher than the horizontal stress (X-axis stress, Y-axis stress). The vertical stress peak value increases with the working face mining, which is 27.6 MPa when the working face is mined to 150 m, and...
31.1 MPa when the working face is mined to 210 m. After 210 m, the stress peak value remains at a stable level and finally reaches 31.4 MPa. The three-dimensional stress peak and distance to the working face are listed in Table 3.

The average distance of the vertical stress peak in the overlying protected coal seam to the protective coal seam working face is 13.3 m, and the horizontal stress peak to the working face are 10.6 m and 8.6 m, respectively. The vertical stress concentration factor is 1.7, which is larger than the horizontal stress (X-axis stress, Y-axis stress) concentration factors of 1.3 and 1.4. It indicates that, in the process of the working face mining, the vertical stress in the protected coal seam reaches its peak earlier than the horizontal stress, and the increase in the concentration degree of the vertical stress is larger than in the horizontal stress.

According to the above analysis, in the process of the protective coal seam working face mining, the overlying protected coal seam in front of the working face experienced four stress states, which respectively are the initial stress, the slow increase, the marked increase, and the marked decrease. As shown in Fig. 12, after the peak, the stress in the protected coal seam decreases markedly.

![Fig. 10. Evolution of the horizontal stress (Y-axis stress) in the process of the working face mining.](image1)

![Fig. 11. Three-dimensional stress of the overlying protected coal seam.](image2)

### Table 3

<table>
<thead>
<tr>
<th>Advancing distance/m</th>
<th>Z-axis vertical stress peak</th>
<th>X-axis horizontal stress peak</th>
<th>Y-axis horizontal stress peak</th>
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<td></td>
<td>Distance to working face/m</td>
<td>Value/MPa</td>
<td>Stress concentration factor</td>
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<td>----------------------</td>
<td>----------------------------</td>
<td>-----------</td>
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<tr>
<td>150</td>
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<tr>
<td>Average</td>
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<td>30.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>

3.2. Stress change path of the overlying protected coal seam near the MBSD

To analyze the stress change path in the different positions of the protected coal seam, in the FLAC\textsuperscript{3D} numerical simulation, we set several monitoring zones in the protected coal seam near the stopping line, as shown in Fig. 13.

In Fig. 13, the location of the #1 zone is calculated by the maximum press relief angle of 60° according to the “Technical criterion of protective coal seam exploitation” and “Provisions of the prevention of coal and gas outburst”. In the process of the working face advance, the stress evolution of the monitoring zones is shown in Fig. 14.

As shown in Fig. 14, the stress in the #1 zone increases gradually with the working face advance, reaching a maximum value when the working face is mined 270 m, the vertical stress peak is 28.9 MPa, and the horizontal stress peaks in the X-axis and Y-axis are 10.1 MPa and 11.0 MPa, respectively. Next, the vertical stress decreases rapidly, and after the working face is mined to the stopping line, the vertical stress decreases to 5.9 MPa, and the horizontal stress in the X-axis and Y-axis slowly decrease to 7.9 MPa and 9.0 MPa, respectively. Finally, the vertical stress is even less than the horizontal stress, as the vertical stress is fully relieved. The stress evolution of the #2 zone is the same as the #1 zone, in which the vertical stress reaches a maximum of 30.0 MPa when the working face is mined 280 m, drops to 10.5 MPa when it is mined 300 m, and the evolution of the horizontal stress in the whole process is unremarkable.

The vertical stress of the #3 zone rises to the peak point at 30.6 MPa when the working face is mined 288 m, and quickly decreases to 19.4 MPa, which is higher than the initial vertical stress of 17.4 MPa. The stress of the #4 zone increases with the working face advance, and the vertical stress eventually reaches 31.2 MPa.

After analyzing the stress evolution of the different location zones near the stopping line, it can be found that in the process of the working face advance, the vertical stress changes obviously, while the variation of the horizontal stress is not unobvious. Thus, the stress change path can be simplified as the minimum principal stress \( \sigma_1 \) (horizontal stress) invariant, while the maximum principal stress \( \sigma_2 \) (vertical stress) increase and decrease. As shown in Fig. 15, and according to the Mohr-Coulomb failure criterion, while the maximum principal stress \( \sigma_2 \) reaches \( \sigma'_{1m} \), it decreases markedly because of the shear failure occurs in the coal.

3.3. Plastic damage state of the coal and rock overlying the MBSD

In FLAC\textsuperscript{3D}, two types of failure mechanisms are indicated by the plasticity state plot. Which are shear failure and tensile failure, and each type is designated by a different color on the plot. The plot also indicates whether stresses within a zone are currently on the yield surface (i.e., the zone is at active failure now, -n), or the zone has failed earlier in the model run, but now the stresses fall below the yield surface (the zone has failed in the past, -p).

As shown in Fig. 16, the plastic state plot reflects the plastic damage of the coal and rocks overlying the mined-out area. After the coal seam mining and due to the increasing vertical stress, plastic shear failure occurs in the overlying coal and rock in front of the working face, and the plastic damage area in the protected coal seam is larger than the rock. The plastic shear failure in the protected coal seam occurs approximately 30 m in front of the working face. In the middle of the mined out area, tensile failure occurs after the shear failure.

With the working face advancing, the range of the plastic damage in the overlying coal and rocks becomes larger from the bottom to top, and the height of the plastic damage on both sides is higher than in the center. After the working face is mined 300 m, the distribution of the plastic damage failure in the coal and rock overlying the mined-out area presents as “saddle” shape.

4. Discussion

4.1. Permeability evolution in the protected coal seam near the MBSD

According to the results of the numerical simulation, the overlying protected coal seam approximately 30 m in front of the working face has become plastic damage under the vertical stress loading, and by analyzing the change of the volumetric strain we can get the permeability evolution in the protected coal seam near the MBSD.

After the FLAC\textsuperscript{3D} numerical simulation, the evolution of the volumetric strain and vertical stress in different monitoring zones of the protected coal seam near the stopping line is shown in Fig. 17. The negative volumetric strain is compaction and the positive is dilatancy.

As shown in Fig. 17, in the process of the protective coal seam working face mining, different zones of the protected coal seam have experienced the volumetric strain transition of compaction to dilatancy due to the vertical stress increasing. Similar to the whole stress-strain and permeability-strain curves, the coal in the protected coal seam has been largely increased in permeability after the transition of compaction to dilatancy. The volumetric strain of the #1 and #2 zones, respectively 20 m and 10 m inside the mining stopping line, are overall dilatancy after the protective coal seam working face is mined to the stopping line, which indicates the permeability is significantly higher than that of intact coal, possibly by 3–4 orders of magnitude.

The volumetric strain of the #3 and #4 zones are still not in overall dilatancy after the protective coal seam working face is mined to the stopping line, but still experience the transition from compaction to dilatancy, and the permeability will suddenly and significantly increase approximately linearly.
The volumetric strain contour of the coal and rocks overlying the middle of the mined-out area $X = 225$ is shown in Fig. 18.

As shown in Fig. 18, much of the overlying coal and rocks is dilatancy in vertical, but in the strike, the volumetric strain is compaction outside of the mining starting line and stopping line, inside which is dilatancy. The distribution is nearly symmetric, and far from the mining starting line and stopping line there are no changes in the volumetric strain. After the working face is mined-out, the volumetric strain distribution of the protected coal seam is shown in Fig. 19.

The volumetric strain curve of the protective coal seam is a centrosymmetric distribution, and the evolution process from the outside to the center of the mined-out area boundary in the strike is the same as the whole stress-strain and permeability-strain process (Xue et al., 2012).

As shown in Fig. 19, the coal seam is compaction under the stress concentration from 150 m to 16 m outside the MBSD, in which initial cracks first close and then initiate, and finally, the new stable micro-cracks grow. The permeability there decrease continuously.

In the location 16 m outside the MBSD, the volumetric strain of the coal seam reaches the minimum −0.59% and plastic damage and expansion emerge. In the coal seam inside that location, large cracks develop rapidly, the coal body is unstable cracking, and the permeability suddenly and significantly increases.

Near the MBSD, which is 2 m outside the mining starting line or 8 m inside the mining stopping line. The volumetric strain began to be positive, 0.04% and 0.05% respectively, and in the center of the mined-out area the volumetric strain of the protected coal seam reached the maximum of 2.5% and the coal seam became overall dilatancy and fractured, with large numbers of macro-cracks appearing, and the permeability still significantly increasing and then reaching a plateau.

Based on the above analysis, after the protective coal seam working face mining, the permeability distribution of the overlying protected seam in the strike is quantitatively divided into four zones. As shown in Fig. 20, the zones are the original permeability zone (150 m outside the MBSD), the permeability decrease zone (16 m - 150 m outside the MBSD), the permeability insufficient increase zone (16 m - 0 m outside the MBSD), and the permeability sufficient increase zone (inside the MBSD).

The results show that the actual permeability increase boundary is larger than the traditional pressure-relief boundary, which is 20 m inside the MBSD and delimited as the maximum relief angle of 60°. The zone inside the MBSD is the permeability sufficient increase zone, and
Fig. 16. The strata damage situation of the overlying coal and rocks.

Fig. 17. The volumetric strain and vertical stress in different monitoring zones.
the permeability there is significantly higher than the original permeability. In the permeability sufficient increase zone, the highly efficient and simultaneously safe exploitation of the coal and gas is ensured (Liu et al., 2011; Zhou et al., 2016). Therefore, the outburst-prone danger in the protected coal seam between the MBSD and the traditional pressure-relief boundary can be eliminated by being combined with optimized gas drainage measures.

4.2. Practice of the protective coal seam mining in the Xinzhuangzi coal mine

4.2.1. Gas drainage in the overlying protected coal seam near the MBSD

In the Xingzhuangzi coal mine, after the 62210 working face in the protective coal seam (B10 coal seam) is mined out, to decorate the overlying 62211 working face in the protected coal seam (B11b coal seam) equal to the 62210 working face in the strike, we decorated with optimized gas drainage drilling in the protected coal seam by combining with the permeability distribution.

As shown in Fig. 21, the cross-measure boreholes were constructed at the 62210 high drainage roadway and the 62213 end-located drainage roadway to drain the gas in the B11b coal seam. From the traditional pressure-relief boundary to the permeability insufficient increase zone, we decorated the denser cross-measure boreholes, with a distance of 10 m in the strike direction and 10 m in the dip direction in the coal seam, to drain gas. By contrast, in the permeability sufficient increase zone, relatively sparse cross-measure boreholes with a distance of 20 m in the strike direction and 20 m in the dip direction in the coal seam were decorated inside the traditional pressure-relief boundary to drain gas.

4.2.2. Statistics of the gas drainage in the protected coal seam

The gas drainage statistical data of the 62210 high drainage...
roadway and the 62213 end-located drainage roadway among the mining of the 62210 working face is shown in Fig. 22.

The 62210 working face mining started on November 3, 2013 and finished on November 10, 2014. The gas drainage boreholes of this region started construction on August 18, 2013 and was completed on January 16, 2014. The gas drainage was kept on a high level during the 62210 working face mining, with a maximum pure gas flow of 39.2 m$^3$/min and 49.5 m$^3$/min, respectively. Before November 28, 2014, the gas drainage boreholes of the 62210 and the 62213 end-located drainage roadway had extracted 1654.9 × 10$^4$ m$^3$ of gas from the B11b coal seam, and the gas drainage rate of this area was 79.8%, exceeding the critical value of 60%.

4.2.3. Effects of the gas drainage in the protected coal seam near the MBSD

The original gas pressure and content of the B11b coal seam were 2.9 MPa and 13.5 m$^3$/t, respectively. Two months after the 62210 working face mining, the maximum residual gas pressure of the protected coal seam near the mining starting line is 0.06 MPa, which is less than the critical value of 0.74 MPa, as shown in Fig. 23. The area in the protected coal seam, which starts from 20 m outside the 62210 working face mining starting line to the traditional pressure-relief boundary, has experienced the same drainage by the 10 m × 10 m dense cross-layer boreholes. But, due to the difference in the permeability distribution, the residual gas content of the protected coal seam is different in the strike. The residual gas content is 9.77 m$^3$/t 10 m outside the mining starting line, 7.52 m$^3$/t at the mining starting line, and 6.49 m$^3$/t 10 m inside the mining starting line. The residual gas content inside the mining starting line is less than the critical value of 8 m$^3$/t.

Based on the measurement results of the residual gas pressure and residual gas content, the outburst danger of the B11b coal seam inside the MBSD has disappeared after the pressure-relief gas drainage by the dense cross-layer boreholes. The results indicate that the 62211 working face in the B11b coal seam can be decorated equally with the 62210 working face in the strike at the same time, and the permeability distribution in the protected coal seam of our study is verified to be correct.

5. Conclusions

The FLAC$^3$D numerical simulation results showed that in the process of the working face advance, the stress change path of the overlying protected coal seam can be simplified as the minimum principal stress $\sigma_3$ (horizontal stress) invariant, while the maximum principal stress $\sigma_1$ (vertical stress) increases continuously. After the maximum principal stress reaches the peak stress, the stress decreases suddenly due to the coal body fracturing. The plastic shear damage in the overlying protected coal seam occurs approximately 30 m in front of the protective coal seam working face. After the coal body becomes plastic damage, the volumetric strain reaches the transition from compaction to dilatancy, and the permeability will suddenly and considerably improve. The relationship between the volumetric strain and permeability is close. According to the evolution of the volumetric strain in the protected coal seam, the permeability-increasing area of the overlying coal seam in the strike direction is delimited. The permeability distribution of the overlying protected seam near the MBSD is divided into four zones, which are the original permeability zone (150 m outside the MBSD), the permeability decrease zone (16 m - 150 m outside the MBSD), the permeability increase zone (16 m inside the MBSD), and the permeability decrease zone (16 m - 150 m inside the MBSD).
In the Xingzhuanzi coal mine, after the protective coal seam working face is mined out, the actual permeability-increasing area in the strike direction is larger than the traditional permeability-increasing area. The zone inside the MBSD is the permeability significant increase zone, whose permeability is significantly higher than the original permeability. Therefore, the outburst danger inside the MBSD can be eliminated through the gas drainage of the dense cross-layer boreholes. After that, the working face in the overlying protected coal seam can be decorated equally with the protective coal seam working face in the strike.

The permeability distribution of the overlying protected seam also has guiding significance for the coal reservoir exploitation. After the protective coal seam working face mining out, the permeability insufficient increase zone and the permeability sufficient increase zone are the target area for gas drainage, and the optimized cross-measure boreholes should be decorated here.

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