SLOTTING EFFECT ON PRESSURE RELIEF DURING GAS DRAINAGE OF LOW PERMEABILITY COAL

by

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As the increase of the mining depth in China, the underground temperature, in situ stress and CH_4 gas pressure also increase. Such factors have great influences on the gas drainage engineering. In this paper, the discontinuous deformation analysis is used to model the stress relief effect of drilling and slot. The effects of slot width, height, and ground pressure was analyzed. The rheology property of the coal mass under different temperature and gas pressure are also studied. the results of this paper can be used as a reference for gas drainage engineering in coal mine.

Key words: *gas drainage, pressure, discontinuous deformation analysis, temperature*

Introduction

China is a country of huge coal consumption, and coal is still the dominant energy in long term [1]. China has abundant coal seams with high gas content. Coal and gas outburst and gas explosion have brought great threat to the safety of life and property. However, as a kind of non-renewable clean energy, the coalbed gas has large reserves and its content increases significantly with the increase of mining depth [2]. In China, the proven gas reserves are equivalent to the natural gas reserves, but the amount of coalbed methane (CBM) discharged in coal mining is very high, and the utilization rate of gas is only 31% [3]. Therefore, the realization of efficient gas extraction can not only improve the safety level of coal mines, but also meet the energy demand of China's economic development, and has a very important significance for reducing greenhouse gas emissions.

The permeability of coal seam is the key factor of gas drainage. Thus, a number of studies has been carried out. Based on experiments, Gray [4] proposed a permeability model including the coupling effect of geomechanical effect and coal seam adsorption expansion/contraction. Palme [5] proposed a simple permeability model, which considers the effects of pore pressure and coal expansion/contraction on fracture porosity. Chen [6] considered the influence of mixed gas on gas transport and establishes a new permeability model. Karacan [7] found that permeability varies with the depth of the coal seam.

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Meanwhile, the permeability enhanced technologies such as borehole gas extraction, hydraulic fracturing, mine ventilation gas dilution, protective coal seam mining, have been developed. The coal seams in China are characterized by low permeability, and gas drilling and extraction usually require a lot of extraction boreholes, thus the capture of the gas is a time-consuming process. The high pressure water jet slotting technology has been comprehensively studied and successfully applied in many mining scientific applications [3]. Borehole drainage is one of the important methods of gas drainage, but the deep environment of coal seam is complex, and borehole is prone to serious deformation. The deformation and failure of coal and rock mass is a process from continuous deformation discontinuous deformation. In this paper, the large deformation constitutive equation of coal and rock is added into the code of discontinuous deformation analysis (DDA) to carry out the numerical calculation of coal seam bore-slot pressure relief, the displacement and stress field of the coal mass around the borehole and the slots are analyzed.

Numerical study of pressure relief effect of slotted drilling of coal mass

Shi *et al.* [9] proposed and established the DDA based on the principle of minimum potential energy. Unlike the finite element method, DDA discretizes the research object into a system consisting of blocks and joints. Each block is not a rigid body. Its shape can also be any shape, and it allows deformation and displacement. As the geometric parameters and physical parameters of each block are known, the displacement, deformation and stress can be calculated and analyzed via the system of linear equation.

Model establishment

The ANSYS was used to establish a rectangular model with a length of 10 m and a width of 5 m, and triangular elements were used. Drilling (borehole) was conducted at the center of the model with a radius of 0.2 m, as shown in fig. 1. The ground stress of the coal seam is 7 MPa. The coal seam temperature is assumed as 40 °C and the gas pressure is assumed as 1 MPa. The other parameters are listed in tab. 1. To study the evolution of the stress of surrounding coal mass after drilling, three horizontal monitoring lines H_1, H_2, and H_3 were determined, which are 0.2 m, 0.4 m and 0.8 m away from the drilling center, respectively.

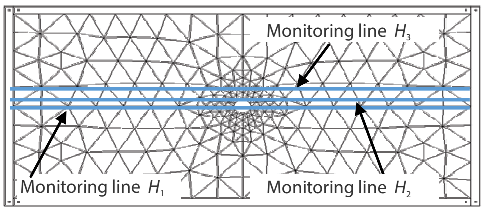

Figure 1. Coal seam calculation model

Table 1. The table of model initial value parameter

Initial stress	Coal parameters		Joint parameters	
Ground stress	Elastic modulus	Poisson's ratio	Friction angle	Cohesion
7 MPa	2 GPa	0.25	35°	3 MPa

Numerical simulation of drilling

It can be seen from figs. 2 and 3 that stress concentration occurs in the surrounding coal mass during simple drilling, and the closer to the borehole, the higher the stress. When the mining depth is deepened and the ground stress is increased, the concentrated stress will decrease the permeability seriously. Thus the *bottle effect*, which will seriously affect the gas drainage efficiency, will come out. It can be seen from fig. 4 that the coal mass around the borehole is deformed greatly, and if the local stress is large, the borehole may be deformed seriously or collapsed. If the drilling radius is simply increased, although the gas permeation area can be increased, the stress concentration around the borehole will not be solved, and the *bottle effect* can not be avoided.

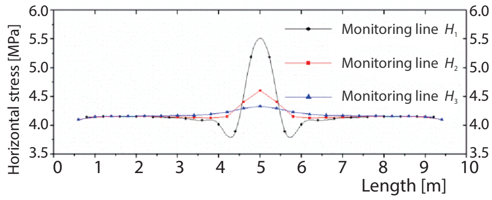

Figure 2. Distribution of horizontal stress

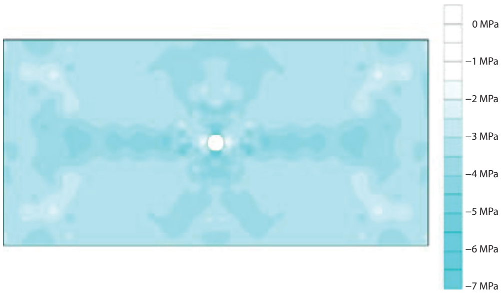

Figure 3. Contour of the horizontal stress

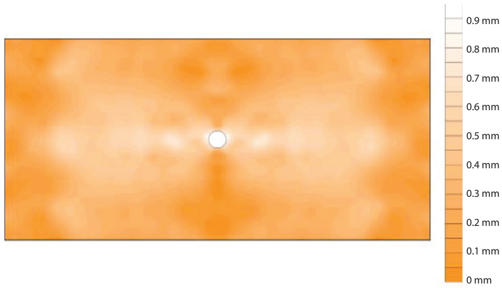

Figure 4. Contour of the horizontal displacement

Therefore, in order to solve the stress concentration caused by drilling, high pressure water jets are often used to eliminate the *bottle effect*. A high pressure jet is used on the inner wall of the borehole to cut a slot of a certain width and depth to achieve the pressure relief of the coal surrounding the borehole. At the same time, because the slot provides space for the horizontal displacement of the coal around the borehole, the pressure of the surrounding coal mass is released. Hence, the borehole is more stable.

Drilling-slotting effect on surrounding coal

Similar to fig. 1, a 50 mm × 950 mm slot is cut out around the borehole. It can be seen from figs. 5-7 that the horizontal pressure of coal mass around the borehole decreases significantly after the slotting. The horizontal stress distribution of the coal mass on the monitoring line is *funnel-shape*, and the closer it is to the center of the borehole, the larger the influence range is.

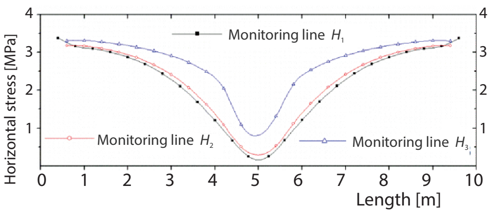

Figure 5. Distribution of horizontal stress after slotted

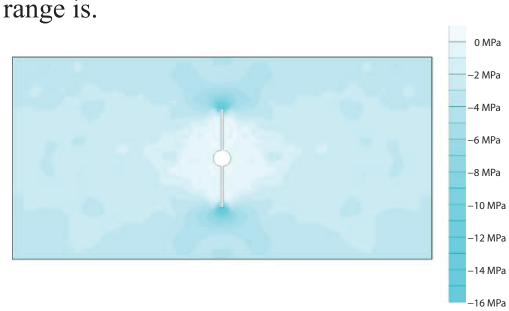

Figure 6. Contour of the horizontal stress

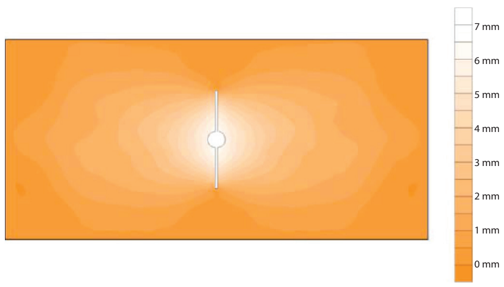

Figure 7. Contour of the horizontal displacement

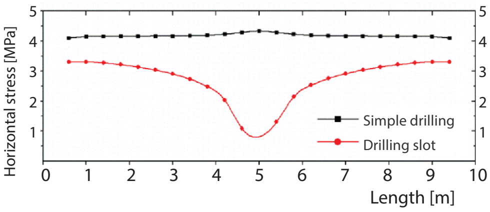

Figure 8. Comparison of stress before and after slotted seam (monitoring line H_3)

Figure 8 shows the stress distribution of coal mass on each monitoring line. It is found that the horizontal stress of the coal mass decreases slightly after the slotting. For example, in the case of drilling, stress concentration starts to occur about 2 m away from the borehole center, while after the slotting, the influence range of the drilling is extended significantly, and the pressure relief effect is obvious at 3 m away from the borehole. For the drilling case, the maximum stress on monitoring lines H_1, H_2, and H_3 is 5.18 MPa, 4.6 MPa, and 4.3 MPa, respectively. After slotting, the stress of the points where the maximum stress occurs reduced to 0.24 MPa, 0.50 MPa, and 1.09 MPa, respectively. It can be seen that the slotting has a great effect on pressure relief of the coal mass. As can be seen from fig. 8, the horizontal displacement of the coal mass around the borehole and the slot is relatively large, and the horizontal displacement of the coal mass above and below the slot is relatively small, the whole contour of the horizontal displacement is *butterfly-shape*.

Influence of slot width and height on pressure relief effect

It can be seen from the simulation analysis of borehole and slot that the slot has a significant impact on the stress of the coal mass around the borehole, and provides horizontal displacement space for the coal mass. The slot also effectively alleviates the stress concentration phenomenon of the coal mass around the borehole, and plays a role in the pressure relief of the coal seam. While, the geometry parameters of the slot such as width and height may have an important impact on the pressure relief effect of coal seam. Therefore, this section will discuss the influence of slot width and height on the pressure relief effect of coal mass.

Effect of slot width on pressure relief effect

The slot width are selected as 30 mm, 50 mm, 80 mm, and 100 mm, respectively. The model parameters such as slot position and drilling radius are the same to those used in Section *Drilling-slatting effect of suronding coal*. The stress changes of coal body on the line were compared under different slot (seam) widths, and the influence of slot width on the pressure relief effect of coal seam was analyzed.

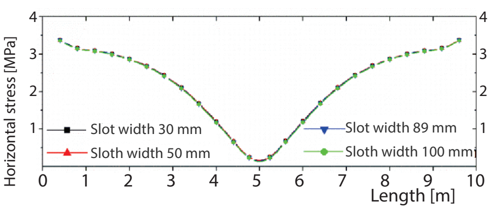

Figure 9. Horizontal stress distribution of coal seam with different slot width (monitoring line H_3)

It can be seen from fig. 9 that the pressure relief degree under different slot widths is basically the same. The displacement of the coal mass on both sides of the slot is also basically the same. The relative displacement of the coal on both sides of the slot on the monitoring lines H_1 and H_2 are about 12.4 mm, and the monitoring line H_3 is about 9.5 mm, which is much smaller than the minimum slot width of 30 mm. The coal mass on both sides of the slot are not in contact, thus the horizontal stress of the coal body can be fully released. Therefore, the stress of the coal mass on the monitoring line under different widths does not change much. However, the deep coal mass is subjected to large ground stress. If the width of the slot is consistent with the gas extraction in the middle and shallow parts, the slot may be completely closed, and the horizontal stress of the coal around the hole may not be fully released. The deformation is serious or even collapsed, which seriously affects the gas drainage efficiency. Therefore, in practical engineering, due to the mining depth and the characteristics of the coal seam, the slot with a large width is used as much as possible to ensure the effect of pressure relief and permeation.

Influence of slot height on pressure relief effect

The width of the slot is fixed at 50 mm, and the height is selected from 500 mm, 950 mm, and 1350 mm. The stress distribution of the coal body on the monitoring line is compared under different slot heights, and the influence of the slot height on the pressure relief effect is analyzed.

It can be seen from fig. 10 that the horizontal stress of the coal mass on the monitoring line decreases with the increase of the slot height. When the slot height is 950 mm or 1350 mm, the minimum stress is almost 0, which indicates that when the slot height reaches a certain height, the hole is drilled. The surrounding coal has been fully depressurized. The monitoring line H_3 is 800 mm away from the borehole and exceeds the minimum height of 550 mm. It is obvious that when the height is 550 mm, the stress on the coal body mass the monitoring line H_3 is concentrated seriously and the pressure is not well released. When the height is 950 mm or 1350 mm, the stress distribution is *funnel type*, and the higher the height, the larger the *funnel*, which means that the slot height has a great influence on the influence range of the borehole. The higher the height, the larger the influence range, and the better the pressure relief effect.

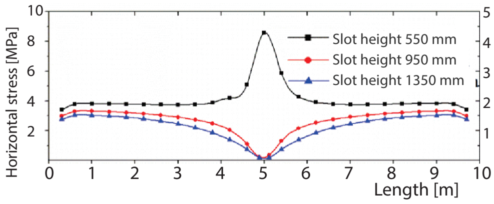

Figure 10. Horizontal stress distribution of coal seam with different slot height (monitoring line H_3)

Rheology numerical analysis of the pressure relief effect of borehole and slot

Rheology calculation process and calculation model

In this section, the coal rock creep model is added to the DDA, and the borehole-slot model of the coal seam is simulated.

The improved calculation program increases the creep time based on the original static calculation time. The original static calculation time can satisfy the requirement of calculation convergence, and the creep time discretizes the target time into several time segments.

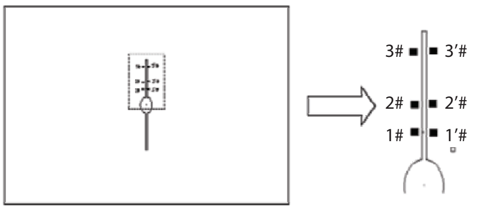

Figure 11. Monitoring point diagram

This section takes the borehole-slot calculation model as an example to investigate the displacement and stress variation of the surrounding coal body over time after drilling-cutting. Assume that the model is subjected to a ground stress of 7 MPa and that the horizontal direction is equal to the vertical direction. Considering the coal seam temperature and the gas pressure, it is assumed that the coal seam temperature is 40 °C and the gas pressure is 1 MPa. Calculated by the Burgers model, the model calculation parameters are shown in tab. 2, where represents the cohesion force, represents the friction angle, which is the joint parameter, and the rest represents the block parameters.

Table 2. Mechanical parameters of coal blocks and joints

Parameter	E_0 [GPa]	μ	E_1 [GPa]	η_1 [GPa·d]	η_2 [GPa·d]	ρ [kgm^{-3}]	C_J[MPa]	φ_J [°]
Value	5	0.3	6	7	18.87	2700	5	10

Calculation results and analysis

This simulation is mainly to investigate the deformation of the slot under the action of ground stress with time. The two sides of the slot are the research objects, and three pairs of calculation points ($1^\#$, $1'^\#$), ($2^\#$, $2'^\#$), ($3^\#$, $3'^\#$) is the monitoring target, which is 0.4 m, 0.6 m, and 1 m away from the center of the hole. As shown in fig. 12, the displacement of the slot with time can be obtained from the displacement of the research point.

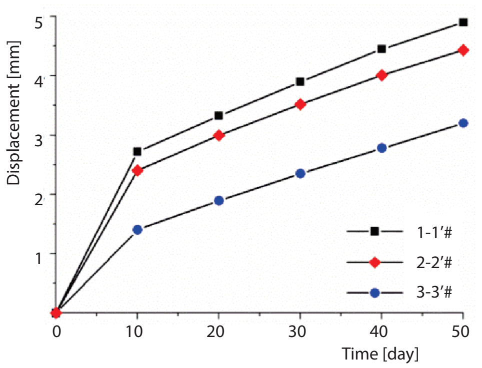

Figure 12. The displacement on both sides of the slot

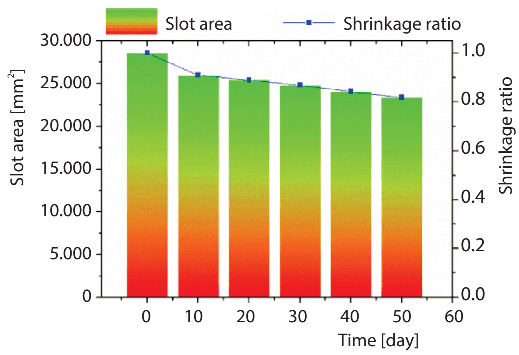

Figure 13. Slot area shrinkage ratio

It can be seen from fig. 12 that the displacement distribution of the monitoring points is basically the same. In the 10 days after the slotting, the slot shrinkage rate is faster. The relative displacement of $1^\#$ and $1'^\#$ points is 0.27 mm per day, the relative displacement of $2^\#$ and $2'^\#$ point is 0.24 mm per day, the relative displacement of $3^\#$ and $3'^\#$ points is 0.14 mm per day. While the relative displacements mentioned above after slotting 40 days to 50 days are 0.045 mm per day, 0.042 mm per day, 0.041 mm per day. Compared with the deformation rate in the first 10 days, the deformation rate decreased obviously, and the deformation rate of each monitoring point is gradually decreased with time. The deformation amount of each monitoring point after 50 days was 4.9 mm, 4.4 mm, and 3.2 mm, respectively. Therefore, the closer to the borehole, the larger the amount of deformation of the slot and the slightly higher deformation rate. According to the deformation of the block around the slot, the slot area and shrinkage ratio can be obtained, as shown in fig. 13. The slot area shrinks faster within the first 10 days after slotting, which is 9.07% smaller than the original size. The shrinkage of the slot area gradually slows down after 10 days. After 30 days, it is 16.3% smaller than the original size.

Conclusion

In this work, the finite deformation geometry field, the coal constitutive equation and the coal creep equation were added to the DDA method and the pressure relief of the surrounding coal mass under the effects of borehole and slotting was studied. By comparing the stress changes of the surrounding coal mass after drilling-slotting and simple drilling, it can be concluded that the concentrated stress generated in the surrounding coal after simple drilling is the main cause of the *bottle effect*. And the slot has a significant effect on the pressure relief of the coal mass the borehole. By comparing the effect of different slit width and height on the pressure relief effect, it is found that the slot width has little effect on the pressure relief effect when the slot is not closed, and the slot height has a certain influence on the pressure relief range. When the local stress is large, the slot is severely deformed or even closed, resulting in poor pressure relief effect. Therefore, when the local stress is large, the width and height of the slit should be appropriately increased. Comparing the creep of different positions of the slot, it is found that the closer to the borehole is, the larger the deformation is, and the faster the deformation rate is. The contraction of the slot area is analyzed, and the slot phase is found within 10 days after the slotting. It was 9.07% smaller than the initial size, and the shrinkage of the slot gradually decreased after 10 days, and decreased by 16.3% at 50 days.

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Nomenclature

C_J – cohesion force of the coal mass joint, [MPa]
E_0 – elastic modulus of the coal mass, [GPa]

Greek symbols

η_1 – first coefficient of the viscosity of the coal mass, [GPa·d]
η_2 – second coefficient of the viscosity of the coal mass, [GPa·d]
μ – Poisson's ratio of the coal mass, [–]
ρ – density of the coal mass, [kgm^{-3}]
φ_J – friction angle of the coal mass joint, [rad]

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