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Research on damage distribution and permeability distribution of coal seam with slotted borehole

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Abstract: In order to study the effect of high pressure water jet cutting technology on the permeability of single coal seam, we use the damage variable to describe the fracture distribution of coal seam, develop the 3-D finite element program based on the damage theory, and then analyze the damage distribution of coal seam after drilling and slotting. Using MTS815 rock mechanics testing system and the permeability test system, we conduct the permeability test and get the relationship between permeability and damage. Based on the damage distribution of coal seam after drilling and slotting and the permeability change law, we analyze the permeability distribution of coal seam after drilling and slotting. The results show that: after slotting high damage appears in the coal seam around the slot, which is advantageous for gas flow and expands the effect range of the drill. The slot width has little effect on the permeability of coal seam while the slot height has the obvious effect on permeability of coal seam. It is necessary to expand the slot height for increasing the effect range of the drill.

Keywords: Damage, drilling and slotting, fracture, gas extraction, permeability.

1 Introduction

Coal is the main energy source in China and the coal production of China exceeds the one third of world output in 2014. The proportions of production and consumption of primary energy in China are about 76% and 69%. With the increase of the mining depth and the development of coal mining, the number of coal mines which have the risk of gas outburst is increasing. Gas disaster and other dynamic disasters

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threaten the efficient production in highly gassy mine for a long time. Therefore, it is important to carry out effective prevention and control of coal and gas disaster [Xie, Gao, and Zhou (2013)]. In China, most of the coal seams have experienced tectonic movement many times, so the coal seam structure is destroyed, the coal is soft and the permeability of coal seam is low. It is difficult to implement gas drainage in this kind of coal seams. Increasing the permeability of coal seam is the most economical and effective method for the gas drainage [Feng and Jiang (2015); Liu, Deng, and Lei (2015)].

At present, the high pressure water jet cutting technology has been widely used to increase the permeability of the coal seam, providing an effective technical approach to the gas control in single low permeability coal seam. Lin et al. investigated the theory of pressure relief and permeability increase and analyzed the characteristics of the double power slotting process and the effects of coal pressure relief and permeability increase [Lin, Zhang, and Shen (2012)]. Gao et al. discussed the effect of increasing borehole diameter on coal seam permeability and proposed a new method for drilling large diameter cross-measure boreholes by using the water-jet technique [Gao, Lin, and Yang (2015)]. Liu et al. drilled ultrathin protective seam with thickness of 0.3–0.5 m using spiral drilling machine in the field, and systematically studied the changes of roof and floor displacement and coal seam permeability during the drilling process, together with the flow and drainage rules of stress-relief gas of the No. 21 coal seam [Liu, Liu, and Cheng (2014)]. Zou et al. established a modified coal-methane co-exploitation model and proposed a combination of drilling–slotting-separation–sealing to enhance coal permeability and CBM recovery [Zou, Lin, and Zheng (2015)].

In view of the fact that fracture is the main channel of gas seepage and migration, it has the important significance to study the damage field distribution and the permeability distribution of coal after drilling and slotting coal seam. At the same time, fracture is the direct factor that affects the permeability of coal seam and damage can be used effectively to describe the fracture distribution [Shen and Wang (2014); Zhao, Xie, and Meng (2014)]. Firstly, we use the damage variable defined by strain, and develop the 3-D finite element program based on the damage theory. Based on the element program, we analyze the damage distribution of coal seam after drilling and slotting. Secondly, using MTS815 rock mechanics testing system and the permeability test system, we conduct the permeability test and get the relationship between permeability and damage. At last, based on the damage distribution of coal seam after drilling and slotting and the permeability change law, we analyze the permeability distribution of coal seam after drilling and slotting in order to provide theoretical support for coal seam drilling and cutting technology.

2 Damage Constitutive Equation

The damaged variable can be defined by strains. For the uniaxial stress state, the damaged variable can be expressed as [Qian and Zhou (1989)]:

$$D = \begin{cases} 0 & 0 < \varepsilon \le \varepsilon_f \\ \frac{\varepsilon_u(\varepsilon-\varepsilon_f)}{\varepsilon(\varepsilon_u-\varepsilon_f)} & \varepsilon_f < \varepsilon < \varepsilon_u \end{cases} \tag{1}$$

where D is the damaged variable; ε_f is the strain threshold value of damage evolution; ε_u is the ultimate strain.

For the three-dimensional stress conditions, the three principal strains are ε_1, ε_2 and ε_3 respectively. So the equivalent total strain can be expressed as $\varepsilon=\sqrt{\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2}$. The equivalent tensile strain can be expressed as $\varepsilon_t=\sqrt{\sum_i \varepsilon_i^2}(\varepsilon_i>0)$, and the equivalent compressive strain can be expressed as $\varepsilon_c=\sqrt{\sum_j \varepsilon_j^2}(\varepsilon_j<0)$. The total damage of coal can be expressed as

$$D = \alpha_t D_t + \alpha_c D_c \tag{2}$$

where the corresponding weight coefficients are $\alpha_t=(\frac{\varepsilon_t}{\varepsilon})^2$ and $\alpha_c=(\frac{\varepsilon_c}{\varepsilon})^2$.

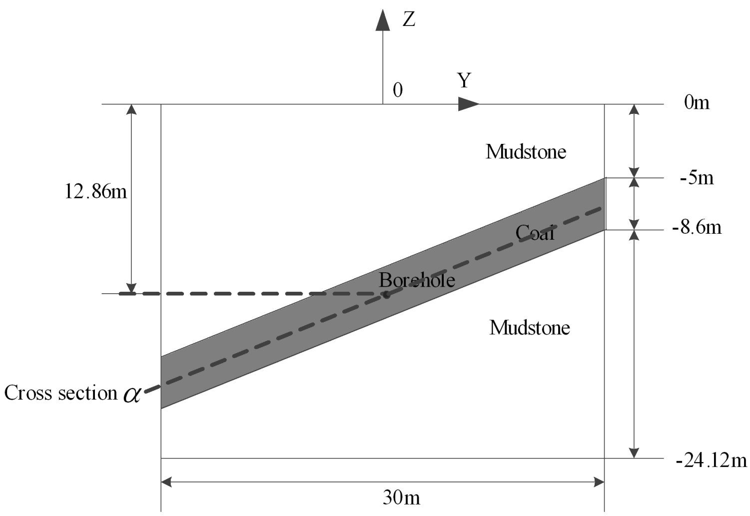
3 Damage distribution of coal seam with slotted borehole

3.1 Calculation model

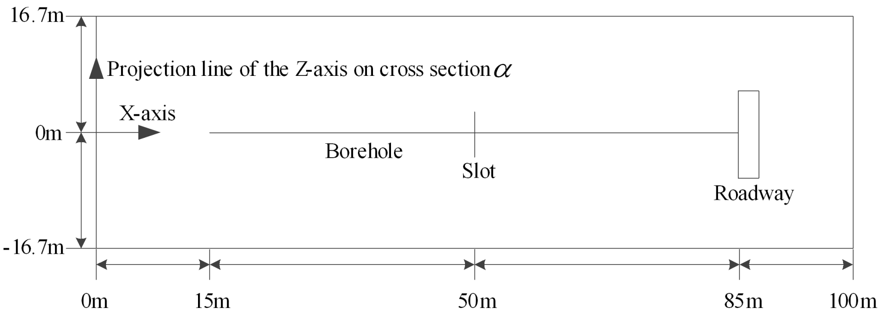
The buried depth of a coal mine is 580 $\sim$ 705m. The strike length is 877m and the dip length is 190m. According to the geological conditions, the 3D model is established. The dip length is 100m, the strike length is 30m, and the vertical length is 24.12m. The thickness of coal seam is 3.6m and the dip of coal seam is 22°. The initial stress of upper boundary is loaded by the overlying strata. Fig. 1 is the side views of the model, Table 1 is the mechanical parameters of rock.

Table 1: Physical and mechanical parameters of rock.

Strata name	Thickness (m)	Young's modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Internal friction (°)	Tensile strength (MPa)	Specific gravity (N/m^3)
Roof	5	5.04	0.22	1.68	32	3.02	22,710
Coal	3.6	4.92	0.27	2.67	44	2.57	12,950
Floor	3.4	5.04	0.22	1.68	32	3.02	22,710



(a) Strike profile

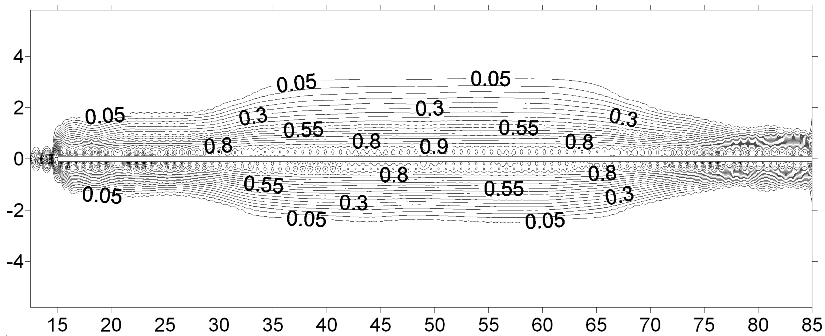


(b) Cross section α

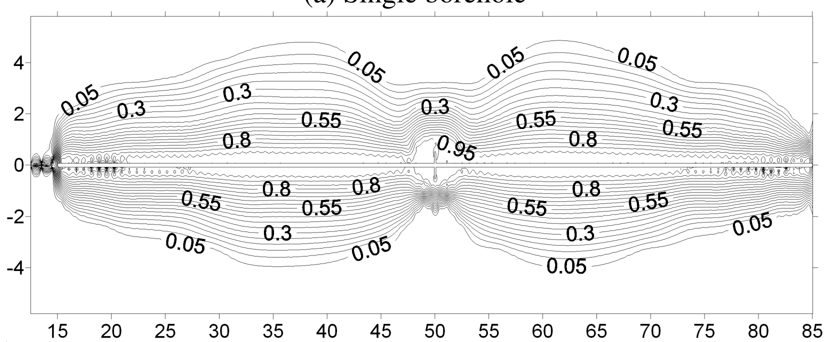
Figure 1: Sectional views of coal seam.

3.2 Damaged distribution of coal seam after drilling and slotting

In order to investigate the influence of the single slot on coal seam, the models of coal seam with slot and coal seam without slot are calculated. The borehole is situated in the center of coal seam (x=50m); the diameter of the borehole is 75 mm; the width of the slot is 50 mm and the height of the slot is 1000mm. The middle surface of the coal seam along the dip direction is chosen as the cross section α.



(a) Single borehole



(b) Slotted borehole

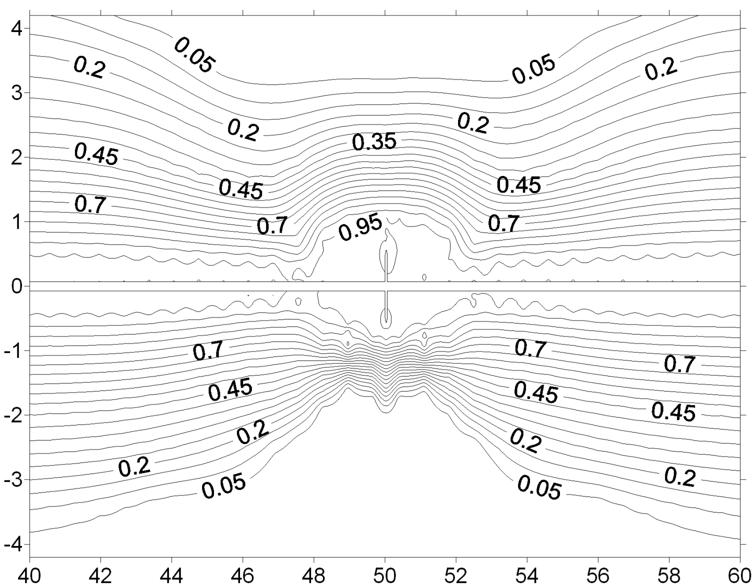
Figure 2: Damage distribution of coal seam of sectional view α (coordinate axis unit: m)

Fig.2 shows the damage distribution of coal seams with single borehole and slotted borehole in the cross section α. It is noted that the coordinate of the point in Fig. 2 is same as that in Fig. 1(b). It can be seen from Fig.2 that the damage value of coal seam around the slotted borehole is high compared with the coal seam without slot. Because of the existence of slot, the stress concentration around the borehole is released and the damage of the area around the slot is high, which results in that a large number of cracks emerge and the channel of gas flow is formed. Compared with the single borehole, the damage of coal around the slot in the range of 2 m is obviously high while damage of the coal far away from the slot is small. Therefore the slot has little effect on the coal far away from the slot. Due to the limited effect of single slot, the multi-slots technology can be adopted in practical engineering.

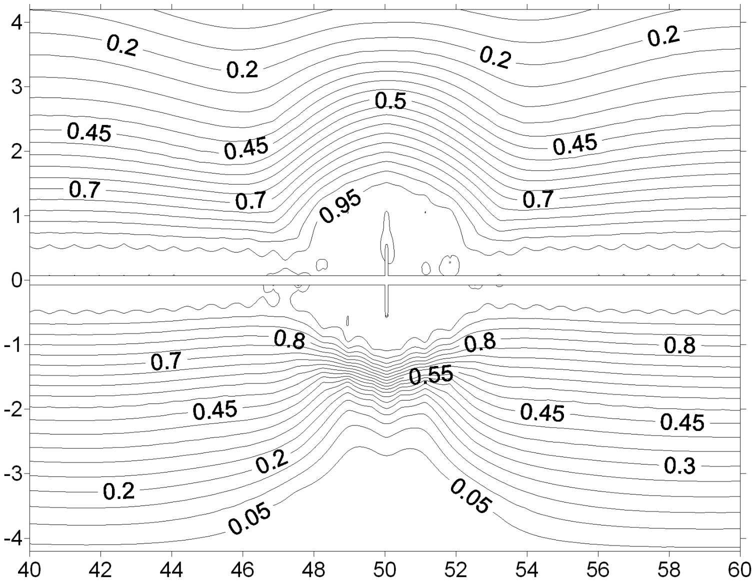
3.3 Influence of the slot width on damage distribution

In order to investigate the influence of the slot width, the slot widths are chosen as 50mm, 80mm and 100mm. The diameter of the borehole is 75 mm and the height of the slot is 1000mm.

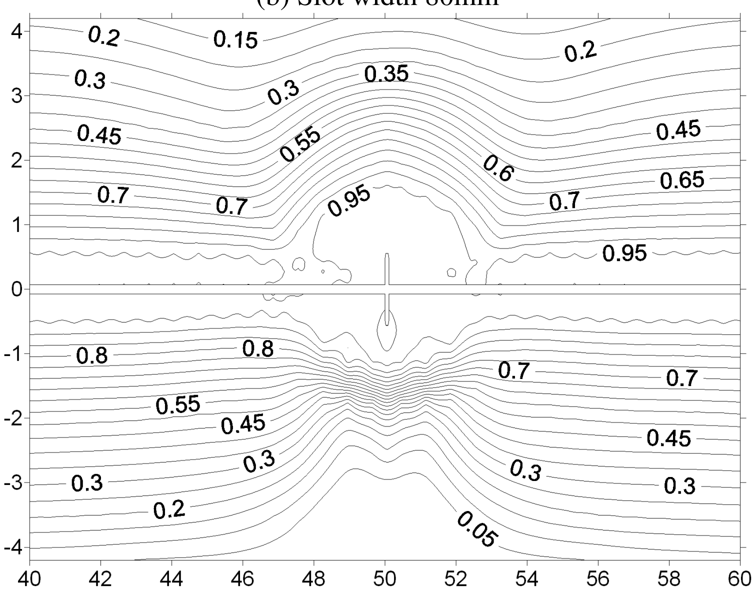
Fig. 3 shows the damage distribution of coal seam around the slot in the range of 10 m. Because slot has a significant influence on coal around the slot while the effect is small for the coal far away from the slot, we mainly analyze the damage distribution of coal seam around the slot. With the increase of the slot width, the area that damage is higher than 0.95 does not expand obviously. The existence of slot releases the horizontal stress, while the change of slot width does not change the horizontal stress obviously. Therefore the method of increasing slot width to increase the influence of slot is not desirable. But in the practical engineering, due to the high in-situ stress, the coal creep, etc., the coal around the slot may move slowly and get in touch with each other, impeding the stress release. Therefore, the slot width should maintain a certain value to avoid the close of slot.



(a) Slot width 50mm



(b) Slot width 80mm

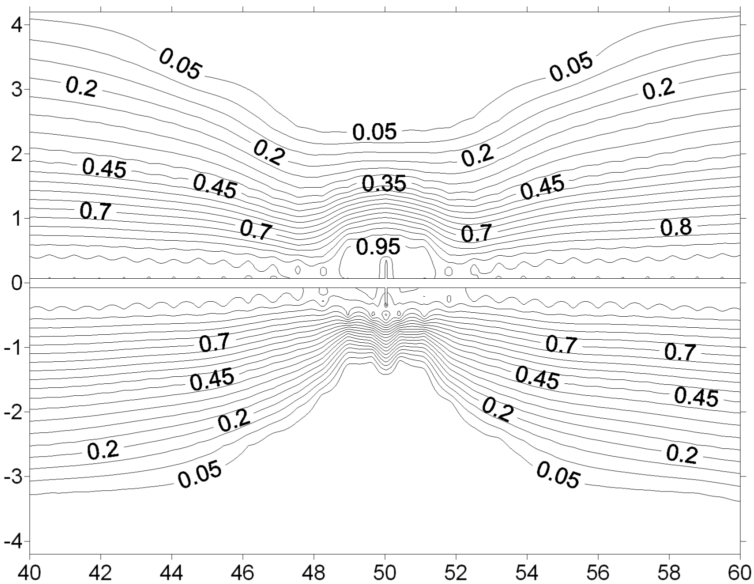


(c) Slot width 100mm

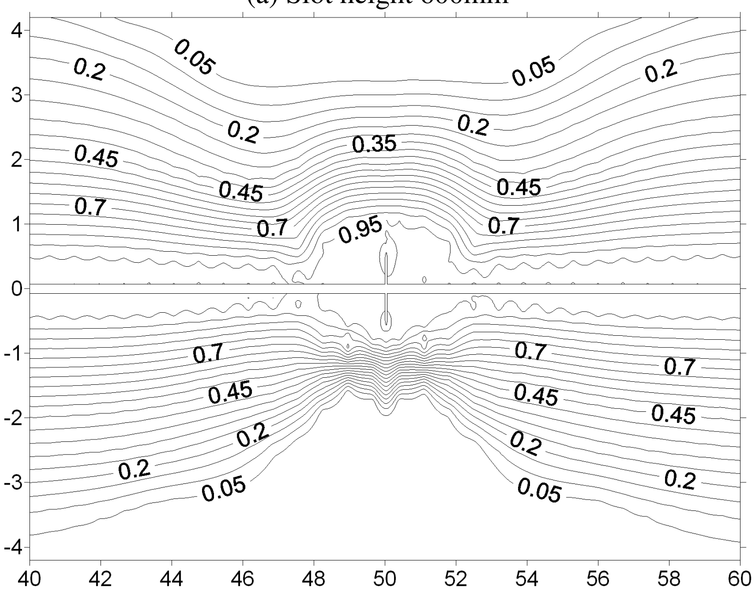
Figure 3: Damage distribution of coal seam of sectional view α under different slot widths (coordinate axis unit: m).

3.4 Influence of the slot height on damage distribution

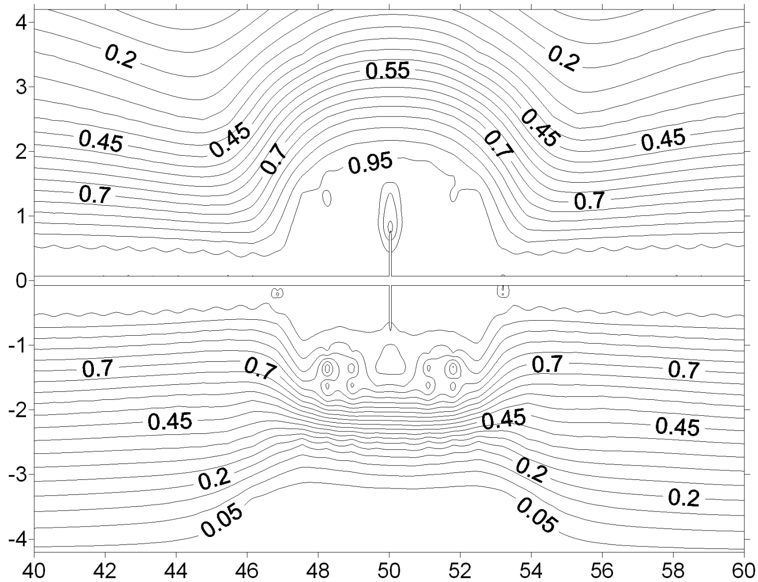
In order to investigate the influence of the slot height, the slot heights are chosen as 600mm, 1000mm and 1500mm.



(a) Slot height 600mm



(b) Slot height 1000mm



(c) Slot height 1500mm

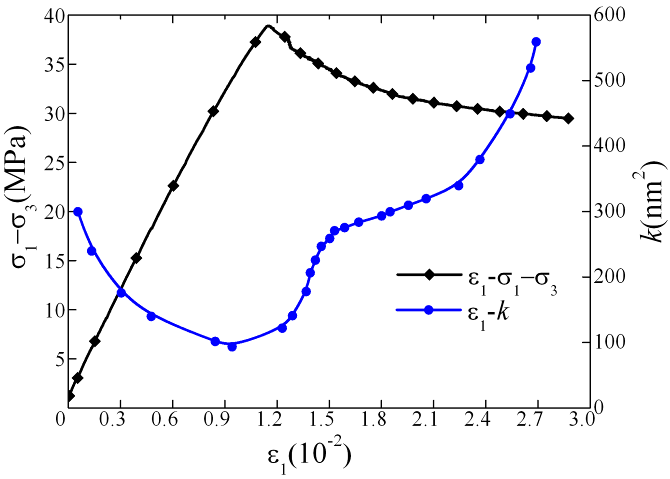
Figure 4: Damage distribution of coal seam of sectional view αunder different slot heights (coordinate axis unit: m).

Fig. 4 shows the damage distribution of coal seam around the slot in the range of 10 m. It can be seen from Fig. 4 that with the increase of the slot height, the area that damage is higher than 0.95 expands obviously. This indicates that a large number of cracks appear in the coal, the pressure relief area expands with the increase of the height, and the permeability of coal also increases. When the slot height increases, the slot area also increases, the pressure relief area expands, and the cracks develop, which are good for the gas extraction. Therefore the slot height affects the coal seam significantly and the slot height should be increased to expand the influence radius of borehole.

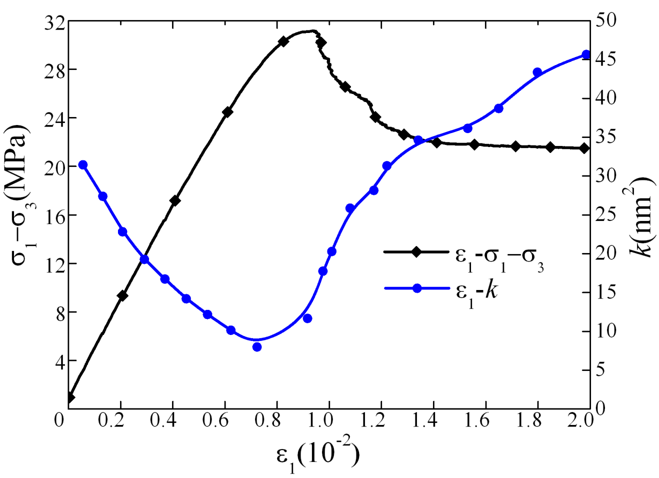
4 Effect of slotted borehole on permeability distribution of coal seam

4.1 Conventional triaxial permeability experiment

The coal mass used in the experiment was chosen from No. 8 Coal Mine of Pingdingshan, Henan Province, China. The laboratory test was conducted on a MTS815 Flex Test GT. The equipment permitted tests including dynamic and static tests, uniaxial and triaxial compression processes, acoustic emission testing, and pore and seepage pressure tests. The coal samples were further processed into cylinders of 50 mm diameter and 100 mm length. The gas was 99.9 % pure methane. The confining pressure was set at 10 MPa. The conventional triaxial compression tests were conducted to measure the permeability in the whole deformation process when pore pressure is 1, 2, 3, and 5 MPa, respectively.

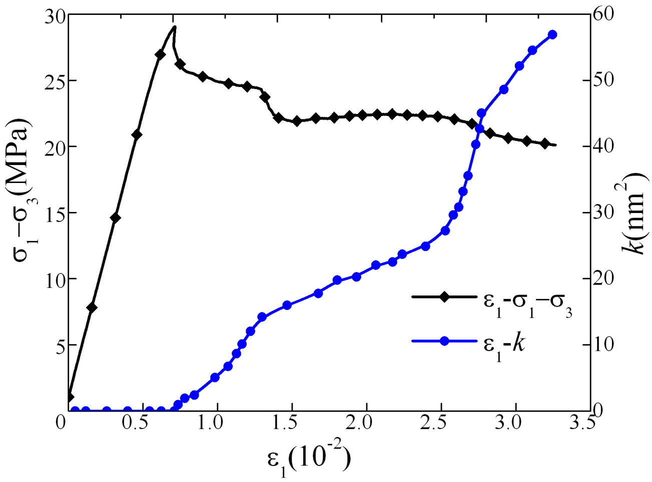


(a) Sample A1 (gas pressure 1MPa)

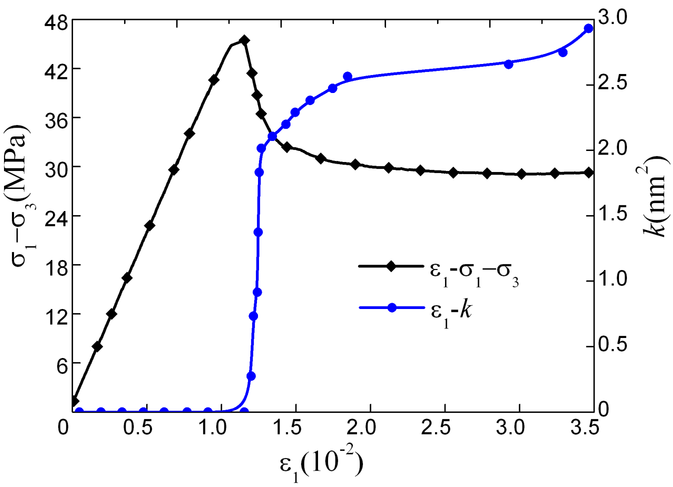


(b) Sample A2 (gas pressure 2MPa)

Fig.5 shows the axial strain-deviatoric stress and axial strain-permeability curves of coal samples. The permeability of coal sample decreases firstly and then increases



(c) Sample A3 (gas pressure 3MPa)



(d) Sample A4 (gas pressure 5MPa)

Figure 5: The axial strain-deviatoric stress and axial strain-permeability curves of coal samples.

during the whole loading process [Murthy, Palani, and Gopinath (2013); Umesh and Ganguli (2014)]. According to Fig.5 and the damage variable defined in the above section, the relationship between permeability and damage can be defined as

$$\begin{cases} k = k_1 + \alpha_1 e^{\beta_1 D} & 0 \le D < 0.7 \\ k = k_2 + \alpha_2 e^{\beta_2 D} & 0.7 \le D \le 1 \end{cases} \tag{3}$$

where k is the permeability; $D$is the damage variable, obtained by Eq. (2); k_1, k_2, α_1, α_2, β_1, and β_2 are the fitting parameters.

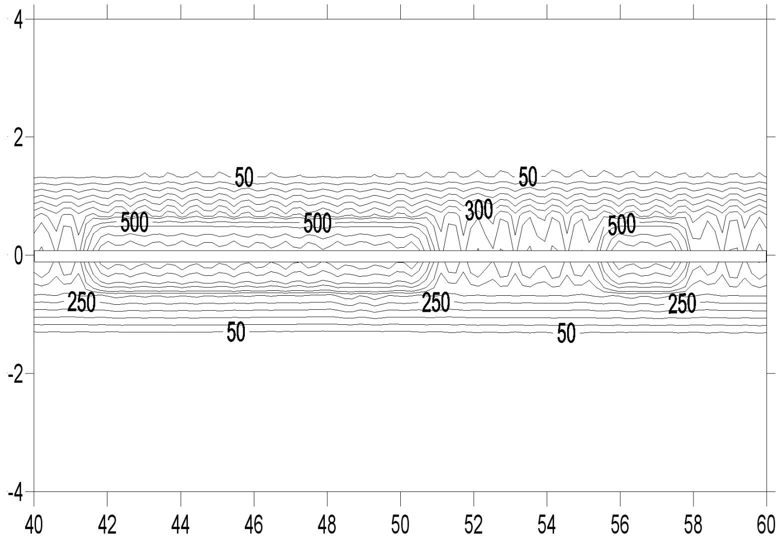
The fitting results obtained by Eq. (3) are shown in Table 2. When damage increases from 0 to 0.7, the internal crack initiation and crack propagation emerge in the coal until the formation of through-cracks, and permeability increases steadily firstly and then increases substantially, showing an exponential increase. When damage is higher than 0.7, the permeability is comparatively large. With the increase of the fracture density, the permeability increases slowly until the connection of cracks and formation of gas flow channel, increasing in an exponential form. In order to simplify the calculation, the fitting parameters of coal sample A3 are used in the following calculation.

Table 2: Fitting equations between permeability and damage.

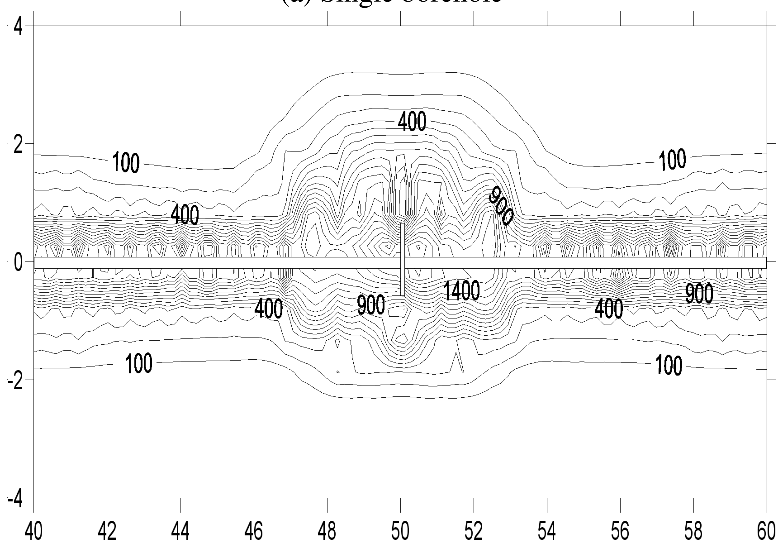
Number	Fitting equation ($D < 0.7$)	Fitting equation ($D \ge 0.7$)
A1	k_1=9.138+0.02886exp(9.276D)	k_2=31.549+6.51$\times 10^{-16}$exp(40.794D)
	R^2=0.97241	R^2=0.94537
A2	k_1=1.28+0.0468exp(4.9D)	k_2=2.297+3.03$\times 10^{-15}$exp(10.33D)
	R^2=0.89345	R^2=0.89245
A3	k_1=0.00514exp(7.67574D)	k_2=1.7529+2.44$\times 10^{-13}$exp(31.39976D)
	R^2=0.99761	R^2=0.950011
A4	k_1=3.42437$\times 10^{-5}$exp(12.16897D)	k_2=0.24436+2.735$\times 10^{-29}$exp(65.355D)
	R^2=0.91374	R^2=0.93372

4.2 Permeability distribution of coal seam with slotted borehole

Combining the damage distribution with the relationship between damage and permeability, the permeability ratio distribution is obtained, as shown in Fig.6. The diameter of borehole is 75mm; the slot width is 50mm and the slot height is 1000mm. It can be seen that the permeability increases significantly around the borehole in a small range after drilling, while the area where permeability increases significantly is large, especially in the range of 3 m around the slot, showing that slot affects the gas extraction and expands the influence of borehole.



(a) Single borehole



(b) Slotted borehole

Figure 6: Permeability ratio distribution of coal seam of sectional view α (coordinate axis unit: m).

5 Conclusions

(1) The 3-D finite element program is developed based on the damage theory and the damage distribution of coal seam after drilling and slotting is obtained. After

slotting the coal seam, fracture appears around slot obviously. It is beneficial for gas flow and expands the influence of single borehole. The slot width had little effect on the damage distribution while the slot height affects the damage distribution obviously.

(2) Using MTS815 rock mechanics testing system and the permeability test system, we conduct the permeability test, and get the relationship between permeability and damage. When damage increases from 0 to 0.7, the internal crack initiation and crack propagation emerge, showing an exponential increase. When damage is higher than 0.7, the permeability increases slowly until the connection of cracks and formation of gas flow channel, increasing in an exponential form.

(3) Based on the damage distribution of coal seam after drilling and slotting and relationship between permeability and damage, we analyze the permeability distribution of coal seam after drilling and slotting. The permeability increases significantly around the borehole in a small range after drilling, while after slotting the area where permeability increases significantly is large, especially in the range of 3 m around the slot, showing that slot affects the gas extraction and expands the influence of borehole.

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