Geomechanics and Engineering, *Vol. 8, No. 4 (2015) 495-510*
DOI: http://dx.doi.org/10.12989/gae.2015.8.4.495

Numerical simulation of pressure relief in hard coal seam by water jet cutting

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(*Received May 04, 2014, Revised December 04, 2014, Accepted December 21, 2014*)

Abstract. The applications of water jet cutting (WJC) in coal mine have progressed slowly. In this paper, we analyzed the possibility and reasonableness of WJC application to pressure relief in hard coal seam, simulated the distributive characteristics of stress and energy fields suffered by hard coal roadway wallrock and the internal relationships of the fields to the instability due to WJC (including horizontal radial slot and vertical annular slot) on roadway wallrock. The results showed that: (1) WJC can unload hard coal seam effectively by inducing stress release and energy dissipation in coal mass near its slots; its annular slots also can block or weaken stress and energy transfer in coal mass; (2) the two slots may cause “the beam structure” and “the small pillar skeleton”, and “the layered energy reservoir structure”, respectively, which lead to the increase in stress concentration and energy accumulation in coal element mass near the slots; (3) the reasonable design and optimization of slots’ positions and their combination not only can significantly reduce the scope of stress concentration and energy accumulation, but also destroy coal mass structure on a larger scale to force stress to transfer deeper coal mass.

Keywords: water jet cutting; pressure relief; energy dissipation; hard coal seam; numerical simulation

1. Introduction

Water jet cutting (WJC) technology has been investigated theoretically and practically by many scholars. A high pressure water jet directed to hard materials such as coal, rock, and the like can destroy their original states and structures, or controllably break rocks (Farmer and Attewell 1965, Daniel 1976, Vjay *et al.* 1984, Fenn 1989, Momber and Kovacevic 1997, Kang *et al.* 2012). For the underground soft coal seams subjected to great stress, WJC can destroy them locally and greatly relieve pressures. Moreover, applications of water media could not only avoid producing static sparks, but also prohibit or precipitate coal dust. Thus, WJC technology has been widely used in the prevention of coal and gas outburst. Scholars have conducted some theoretical and

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

experimental researches on the effects of WJC on underground working faces. Lin *et al*. (2011) found through numerical simulations that the cut depth with a high pressure abrasive jet cutter is up to 700 to 800 mm in coal seam; Chang (2006) found that WJC of 70 MPa can cut out a kerf of 1.7 m wide and 50 mm deep coal-like materials; Li *et al*. (2009) studied the relationship between the notch depth and the jet pressure and found that when water jet pressure reaches about 20 times as the compressive strength of the test samples, the depth tends to be constant with the jet pressure. Liu (2007), Nie *et al*. (2008) and Lu *et al*. (2011) used WJC technology for gas extraction, outburst relief, etc. in soft coal seams.

Previous studies have mainly focused on the effects of WJC on soft coal for the prevention of coal and gas outburst. However, there are number of hard coal seams existing in underground, which may store large amounts of elastic energy. Meanwhile, they have good capability to transfer stress and energy. So it's necessary to study how to destroy the structure of hard coal mass subjected to great stress, how to avoid further accumulation of a large quantity of elastic energy (Ortlepp and Stacey 1994, Zembaty 2004, Driad-Lebeau *et al*. 2005), and how to weaken the capacity of energy and stress transfer (Hajiabdolmajid and Kaiser 2003, Nie *et al*. 2007, Orlecka-Sikora *et al*. 2012).

In this paper, we first theoretically analyzed WJC pressure relief in hard coal seams, then numerically simulated the distributions of stress and energy fields in roadway wallrock after WJC through ABAQUS software. The research is of significance for exploring the principle of pressure relief using WJC in hard coal seams.

2. Analysis of WJC pressure relief

2.1 Analyses of stress and energy of coal element

A small element is chosen in hard coal mass, assuming it satisfies the duality of scale. On the one hand, its size is small enough macroscopically so that it can be seen as a material point of continuum damage mechanics and its macroscopic stress-strain field can be regarded as homogeneous. On the other, its size is large enough mesoscopically so that it contains sufficient information of mesoscopic structure and reflects the statistical average properties of materials (Zweben and Rosen 1970, Martínez-Martínez *et al*. 2008). These ensure that it still obey the basic laws of theory of elasticity − Hooke's law, for the purpose of ensuring the strictness of mathematical derivation.

The size and shape of the small element acted by an external force are changed. As shown in Fig. 1, the stress of any one of the three dimensional stress states, s_1, s_2, and s_3, can be decomposed into two parts, one is the average stress applied upon the three directions σ_{avg} (Xie 1998)

$$\sigma_1' = \sigma_2' = \sigma_3' = \sigma_{avg} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{1}$$

The other is the stresses borne respectively by the three directions, $\bar{\sigma}_1 = \sigma_1 - \sigma_{avg}, \bar{\sigma}_2 = \sigma_2 - \sigma_{avg}$, and $\bar{\sigma}_3 = \sigma_3 - \sigma_{avg}$, where $\bar{\sigma}_1, \bar{\sigma}_2$, and $\bar{\sigma}_3$ are called the stress deviators of the given states of stresses σ_1, σ_2, and σ_3. The corresponding average stress $\bar{\sigma}_{avg}$ is

$$\bar{\sigma}_{avg} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3 - 3\sigma_{avg}) = 0 \tag{2}$$

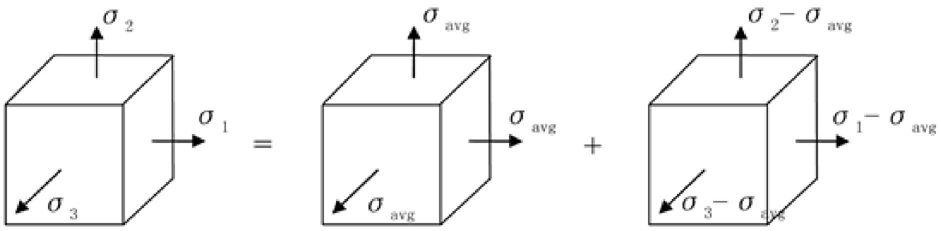


Fig. 1 Stress relationship of coal mass element in the three dimensional stress state

In the action of the average stress σ_{avg}, the shape of the small element is invariant, only its volume changes. Thus its strain energy density (here only the changes in the volume can cause the changes in the strain energy density) can be expressed as

$$\upsilon_V = \frac{1-2\mu}{6E}(\sigma_1 + \sigma_2 + \sigma_3)^2 \tag{3}$$

In the actions of stress deviators σ_1, σ_2, and σ_3, because the corresponding average stress σ_{avg} is zero, the volume of the small element is invariant, only its shape changes, then its strain energy density (here only the deformable energy density) can be expressed as

$$\upsilon_d = \frac{1+\mu}{6E}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \tag{4}$$

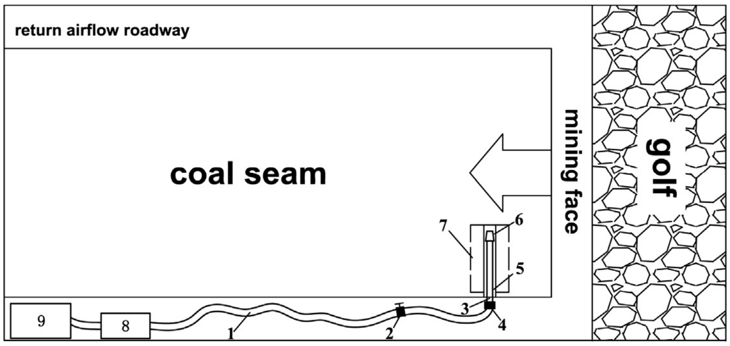
The strain energy density υ equals the deformed energy density υ_d plus the volume-changed energy density υ_V, that is

$$\upsilon = \upsilon_d + \upsilon_V = \frac{1+\mu}{6E}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] + \frac{1-2\mu}{6E}(\sigma_1 + \sigma_2 + \sigma_3)^2 \tag{5}$$

It is clear from Eq. (5) that the energy stored in the coal mass element is closely related to the three dimensional states of stresses. Meanwhile, in accordance with the least energy principle (Zhao *et al*. 2003), the energy stored in the condition of one dimensional stress or two dimensional stresses is smaller than the energy in the condition of three dimensional stresses. Therefore, for the purpose of pressure relief, it is possible for us to use water jet to cut kerfs in the coal mass to change its stress state and to induce its internal energy to be dissipated or released.

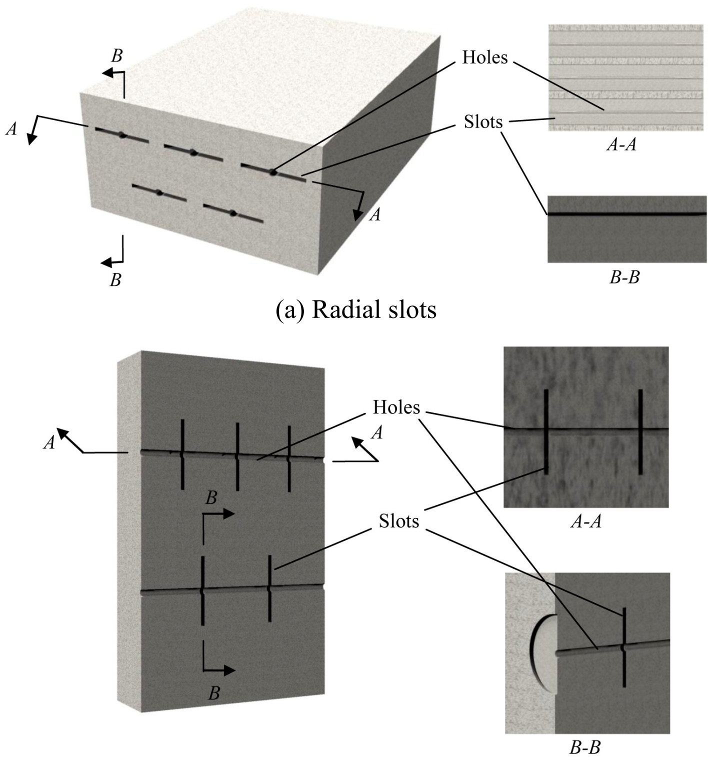
2.2 Pressure relief by water jet (*WJ*)

In the bilateral coal mass of the roadway outside the advance supports of working face, the roadway excavation causes stress redistribution. Thus, from the roadway sides deeper into the coal mass in order form the pressure relief zone, the stress concentration zone, and the original stress zone (Qian and Shi 2003). At the same time, the part of coal mass still has to suffer a certain mining disturbance. In fact, a large amount of elastic energy accumulated in the coal mass of the stress concentration area (in general 5~12 m away from the roadway side) is the direct energy source for roadway collapse and other dynamic disasters.



(1) High-pressure pipe; (2) High-pressure valve; (3) Guiding device; (4) Fixed device; (5) Hole; (6) High-pressure sprinkler; (7) Slot; (8) High-pressure pump; (9) Water tank

Fig. 2 Schematic of WJC pressure relief for coal seam



(a) Radial slots

(b) Circular slots

Fig. 3 WJC pressure relief methods

Pressure relief from the coal mass of this area through WJC can be implemented by the coal seam WJ pressure relief system, whose main equipments include the high-pressure pumping station, high pressure piping and high-pressure nozzle, and auxiliary equipments include the water storage tank, high pressure valves, fixture and guiding devices, etc. Schematic of the coal seam WJ pressure relief system is shown in Fig. 2.

In order to release pressure from coal seam, the currently adopted method in coal mines is to cut the horizontal radial slots and the vertical circular slots in the coal mass of the stress concentration zone of roadway walls (Wu 2009), as shown in Fig. 3.

The impact of the water jet on coal mass can cut a kerf of a certain width and depth in coal/rock mass, turning the primary three-directions force state of the kerf's surrounding coal mass to the two-directions one, thereby resulting in changes in the energy storage states of small coal elements in the vicinity of the kerf, simultaneously providing a free space of elastic recovery for coal mass, and thus releasing the excess energy stored previously in the three dimensional state of stress.

It can be seen from Fig. 3(a) that the important roles of the radial slotting are: (1) the impact of the water jet directly breaks the nearby coal mass, thereby releasing its pressure and dissipating its excess energy; (2) the cutting kerf provides a great space for coal to deform and further induce the deeper compressed coal mass to rebound, unload, and dissipate energy. In addition, due to the capacity to transfer stress and energy of hard coal, the annular slots (See Fig. 3(b)) can also combine the vertical slots, so that inside coal mass forms a strong - weak - strong structure (Wang *et al*. 2009). This structure could not only release some stress, more importantly, it could effectively shield or weaken coal mass elastic energy or stress propagation.

3. Establishment of WJC numerical simulation model

ABAQUS is one of the very important finite element numerical simulation software in the field of geotechnical engineering and has been widely used in a variety of complex issues of geometric and material nonlinearities. The software contains rich element and material libraries and is applied to simulate the force and deformation behaviors of various materials (Wang and Chen 2006).

As the rock failure process is non-linear, purely elastic and plastic models are difficult to satisfy actual geological conditions. However, the hyperbolic D-P (Drucker-Prager) model of ABAQUS can be used to better simulate the brittle materials with triaxial tension and compression data (Wang and Chen 2006). In this paper, we apply the D-P model to simulate the deformation and failure of coal/rock mass in the conditions of surrounding rock pressure.

Through the analysis of triaxial experimental data of coal/rock materials, we calibrated the model parameters, as shown in Table 1.

The model is a hexahedral eight-node linearly reduced integral element with the following boundary conditions: (1) Its upper is subjected to a 10 MPa vertical stress; (2) Its sides is subjected to 0.5 MPa supporting resistance, and (3) its other surfaces are subjected to the displacement constraints. During the simulation, 10 MPa of initial stress is first applied in the model to simulate the weight of the overburden stratum. After the model calculation equilibrium, the slots of corresponding sizes are cut in the coal seam. In order to in-detail study the changes in the large-scale stress and energy fields to which the slotted coal mass is subjected, the slotting process

Table 1 Assignment of model parameters

Model parameters	Elastic modulus (GPa)	Poisson's ratio μ	Friction angle (°)	Cohesive force (MPa)
Parameter value	3.9	0.25	38	2.68

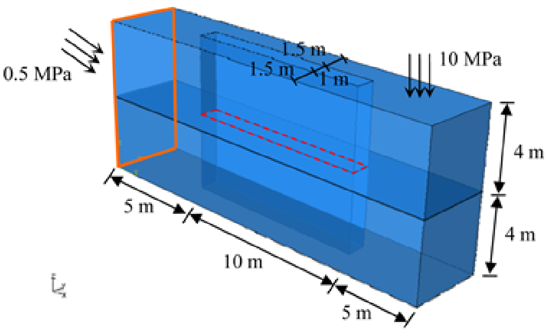
is ignored for all the kerfs, that is, assuming that all the slots are formed once.

Because there are interactions among neighboring slots and boreholes, which cause the impacting scope of each borehole to change. Thus in this paper, for the radial and annular slots, a slotting group of single slot and three other slots with the same size are simulated.

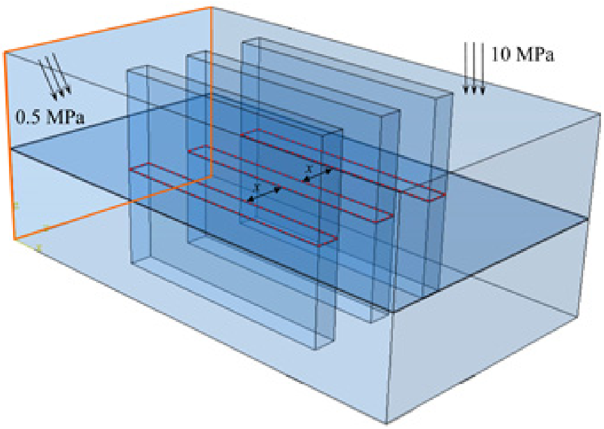
3.1 Radial slots

As shown in Fig. 4(a), the size of single horizontal radial slot is 20 × 4 × 8 m^3 in length × width × height; the design size of the slot is 10 × 1 × 0.04 m^3 in length × width × height. The slot is located in the middle of the model, that is, the two ends of the slot are 5 m and 15 m away from the roadway side, respectively; the other sides are 1.5 m far away from the model boundaries, respectively, the plane on which the slot is positioned is 4 m away from the upper and lower surfaces of the model, respectively.

Considering that at the extraction site it is necessary to cut a slot at some distance along the roadway strike and the adjacent slots would impact each other, we simultaneously simulate the group of slots consisting of three slots with the same size cut on the same horizontal plane. The slot spacing is determined by simulating the horizontal impacting distance of a single slot. The schematic diagram of the slot group is shown in Fig. 4(b).

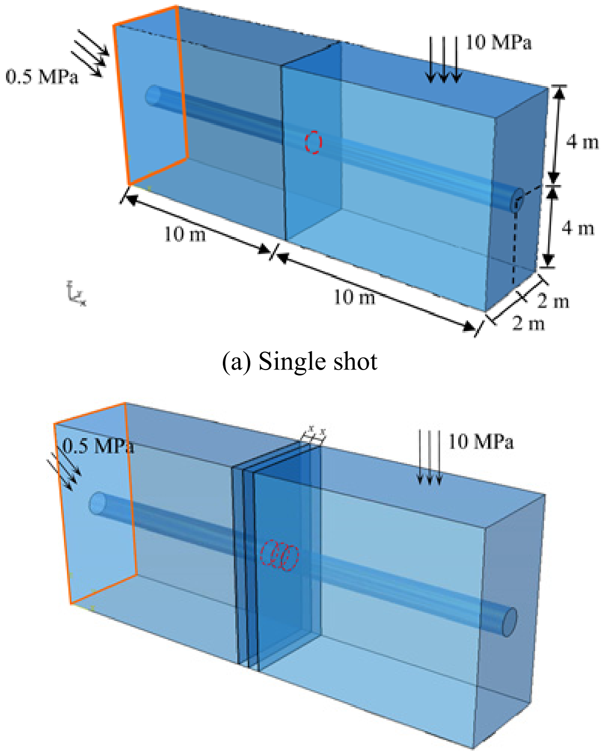


(a) Single slot



(b) A group of three slots

Fig. 4 Radial slotting model



(a) Single shot

(b) A group of three slots

Fig. 5 Annular slot model

3.2 Annular slots

The annular slot model is shown in Fig. 5. In Fig. 5(a), the model size of single annular slot is $20 \times 4 \times 8$ m^3 in length × width × height, the slot is designed to be a circular slot with radius of 0.5 m and located in the middle of the model, that is, 10 m away from the roadway side. Its ends are 2 m and 4 m from the front and rear of the mode and the lower boundaries, as well as the upper and lower boundaries, respectively. Similar to the radial slots, we also simultaneously simulate the group of slots consisting of three vertical slots, as shown in Fig. 5(b).

4. Results and analysis

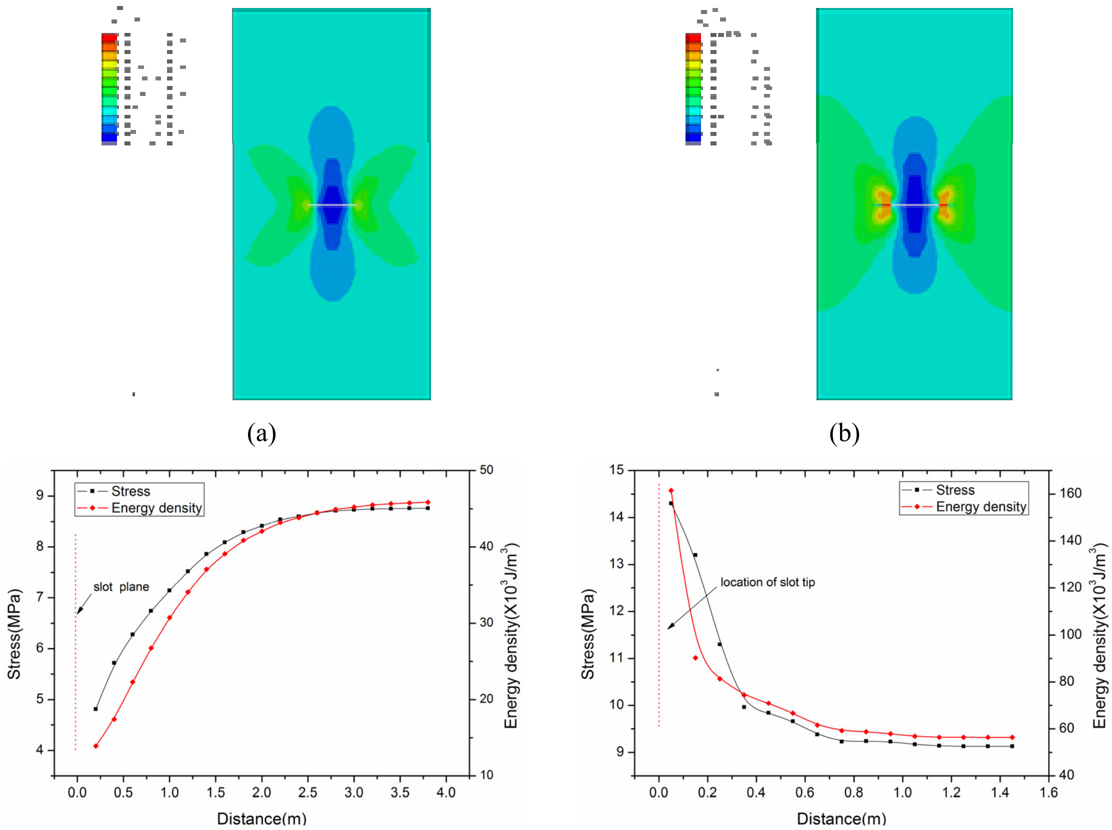
4.1 Radial slots

4.1.1 Single slot

Fig. 6 shows the distributions of stress and energy density in the vicinity of the single horizontal slot. It can be seen that in the horizontal direction, at the tips of the slot, the concentration and energy accumulations occur at small scales of stress. The phenomena don't reach the borders of both sides of the model, i.e., smaller than 1.5 m, while the energy density is greater than 1.5 m. In the vertical direction, stress release and energy dissipation are significant.

From Fig. 6 it is also obvious that the minima of stress and energy density are 4.18 MPa and 13.19 J/m^3 near the slot walls, respectively. The stress drops by 52.3% compared with its original value, while the energy density decreases to 71.2%. Stress and energy density values gradually increase with the distance from the slot increasing, while beyond 3 m above the slot, their values remain almost unchanged.

After the slot being cut, the upper coal element loses its support, but it gains a deformation space, causing it to rebound and its internal stress and elastic energy to change. This change is different with the distance between the coal element and the slot changing. The coal element near the slot acted by the overlying load must deform to a bigger extent and the structural element of larger deformation strength recovers elastically, releasing its internal stress and elastic energy at the same time, while the structural element with smaller deformation strength will produce irreversible destruction and failure to dissipate its energy. The amount of the deformed coal element farther away from the slot decreases accordingly; most of its internal structures only show rebound and release its elastic energy accumulated previously. Therefore, the farther the coal element is away from the slot, the smaller the changes in stress and energy density of the coal



(a) (b)

(c) (d)

Fig. 6 (a) Distributions of stress and energy density of coal element around single radial slot; and (b) distributions of stress and energy density, respectively; (c) and (d) are their changes in corresponding vertical and horizontal directions element. When their distance is greater than 3 m, the changes in various parameters are small. Hence, it can be considered that the impacting range of the slot with this size in the vertical direction is 3 m.

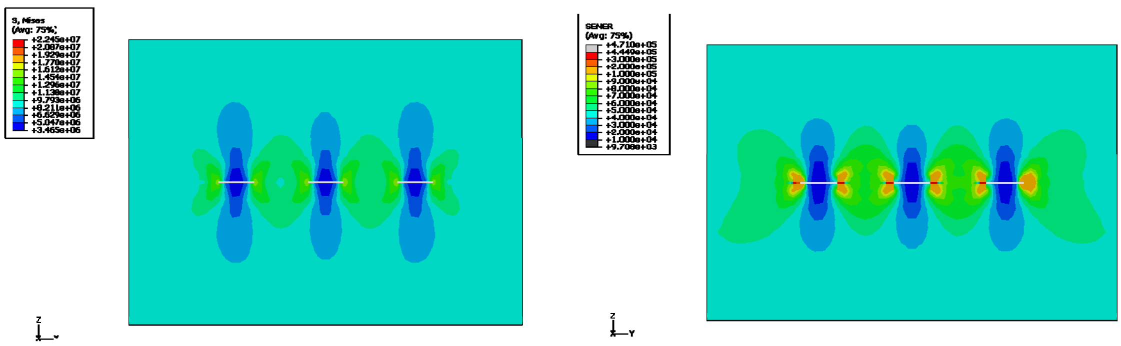
In the horizontal direction, in order to simulate the coal mass subject to rock burst, the coal element with higher strength is chosen. Its upper element after cut forms "beam structure" rather than collapse. The vertical stress above the beam could increase the movement of external force at the beam ends (Yang and Gao 2010), and concentrate stress in the coal mass, thus showing enlargement of the stress concentration and energy density in the analog sink.

4.1.2 Group of slots

From the above simulated results of single horizontal slot, it is known that its horizontal impacting range is about 1.5 m. After several slots being cut, it is possible that the mutual influences among the slots appear. In the following, a slot group consisting of three slots of the same size and different intervals (1.5 m, 2.0 m and 2.5 m) is simulated to study the spatial distributions of internal stress and energy in the coal mass model.

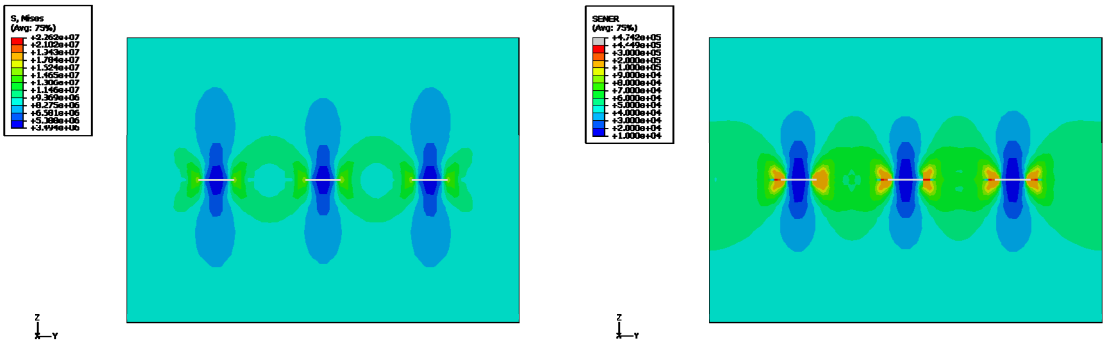
Fig. 7 shows the stress and energy density distributions of coal element around the group of trislots with different spaces. From the stress and energy density data of the coal element located at 0.1 m above the trislots plane, it is found that in the vast majority of region just above the trislots, the effect of pressure relief is evident, and the impact of different slot spacing on the relief effect is weak. At the ends of trislots the increases in stress concentration and energy density are significant. As the interslot distance is smaller, the stress concentration areas formed by two slots produce the constructive superposition effect, making the stress and energy density become larger, such as at the points A and B shown in Figs. 7(a)-(b), the stress and energy density are higher than them in the initial states. While as the interslot spacing increases to some distance, the coal elements between slots are no longer affected by the open cut slots. As shown in Figs. 7(d)-(e), the point C is relatively close to the original state. Therefore, the simulated results are of guidance for on-site determining the interval of WJC cuts.

Based on the "beam structure" formed by slots mentioned in Section 4.1.1, the reason for the described phenomenon is that cutting the group of slots makes the intermediate coal elements

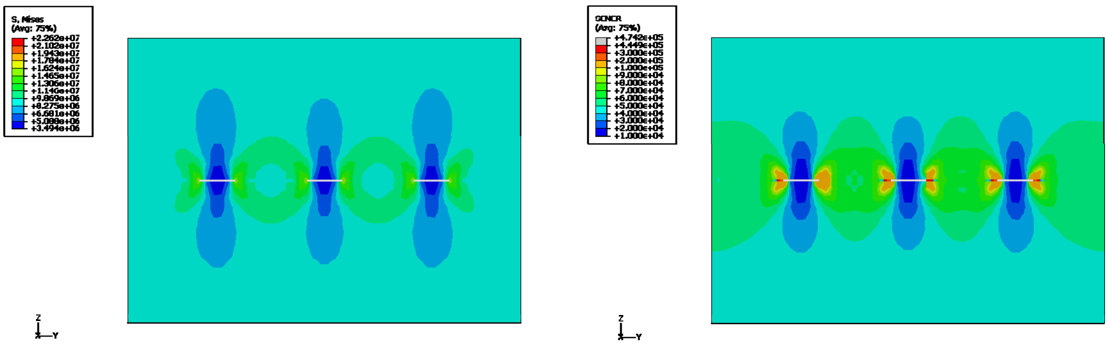


(a) 1.5 m

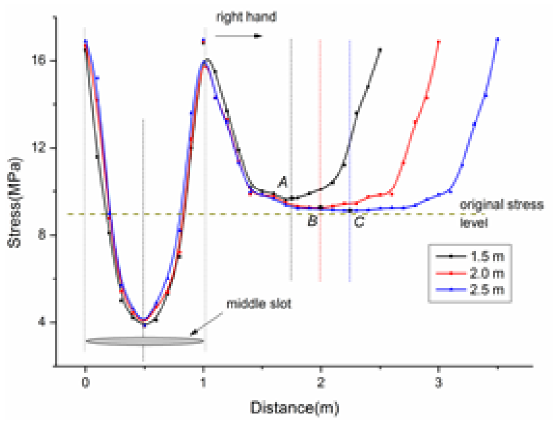
Fig. 7 Stress and energy density distributions of coal element around the group of slots with different spacings: (a), (b) and (c) are the stress and energy density distributions in coal element cut with three slots whose spacings are 1.5 m, 2.0 m, and 2.5 m; (d) and (e) are the stress and energy density distributions in the coal element 0.1 m away from the slot plane



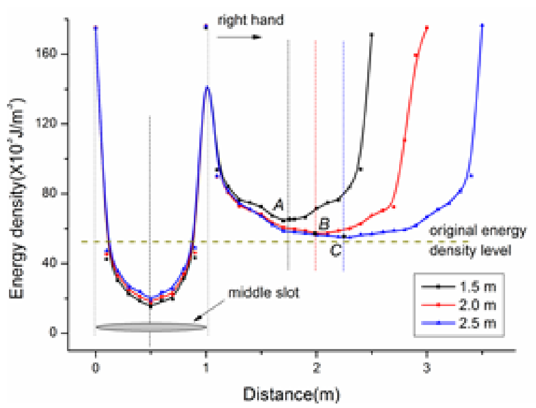
(b) 2.0 m



(c) 2.5 m



(d)



(e)

Fig. 7 Continued

further form “small coal pillar skeleton structure” bearing the overlying load. The existence of these small coal pillars has significant effect on their surrounding stress and energy distributions (Ashok and Shrivastva 2009, Wattimena *et al*. 2013). In practical applications, the width of coal pillars, that is, the spacing between two radial slots, should be reasonably determined (Zhang 2011). Otherwise it is difficult to achieve the good effect of rock burst prevention, or even it is possible to increase the risk of rock burst due to locally concentrated stress.

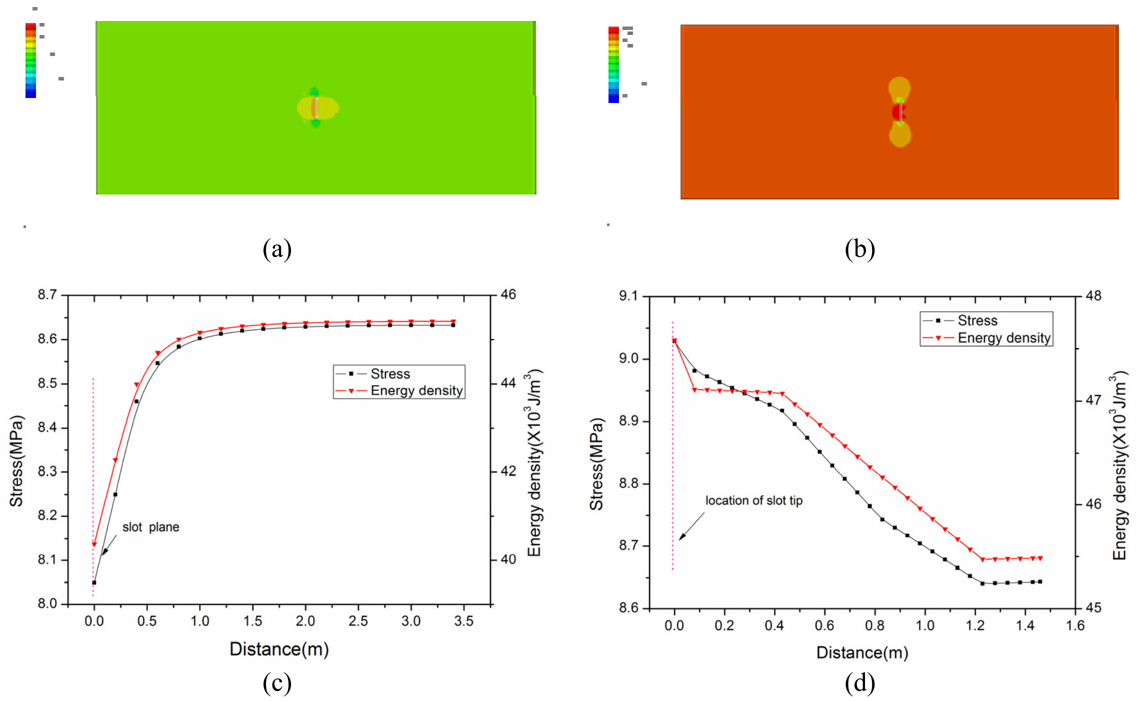


Fig. 8 (a) Stress and energy density distribution in coal elements around single annular slot; and (b) the stress and energy density distributions, respectively; (c) and (d) are their relevant changes in the directions of vertical and horizontal directions, respectively

4.2 Annular slots

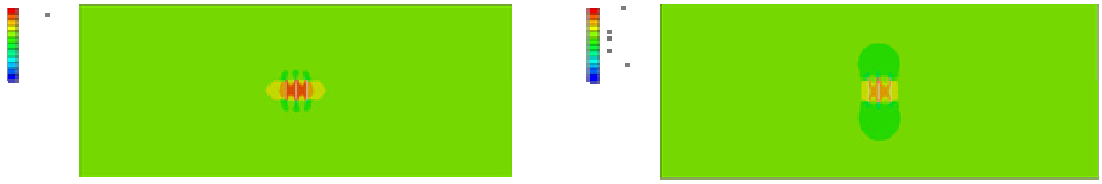
4.2.1 Single annular slot

Fig. 8 shows the stress and energy density distributions of coal mass in the vertical direction right above the open cut vertical annular slot and in the axial direction of the slot's center of circle. From Fig. 8 we know that although the circular slot is only 0.04 m wide and has very small horizontal projection, a pressure release zone of about 1 m still appears over the slot, where the stress lowers by 0.5 MPa, and the change in the energy density is also relatively weak. In the horizontal direction, a stress concentration and energy accumulation region forms within the range of 1.2 m from the slot.

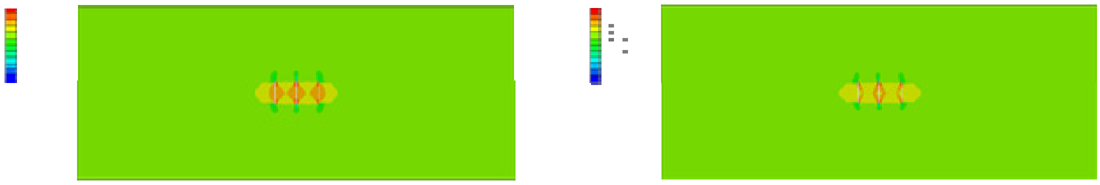
Through analysis it is found that because the projection of the circular slot on the horizontal plane is very small, it can only provide very limited stress release and movement space for the coal mass above the slot. Therefore, its impact in the vertical direction is also very limited. In the horizontal direction, because the slot is parallel to the direction of the maximum principal stress, the coal element can move only laterally under external load. But because the strength of the coal element is bigger, the overlying load is not sufficient to enable it to blend and damage, thus causing the above phenomenon.

4.2.2 Group of slots

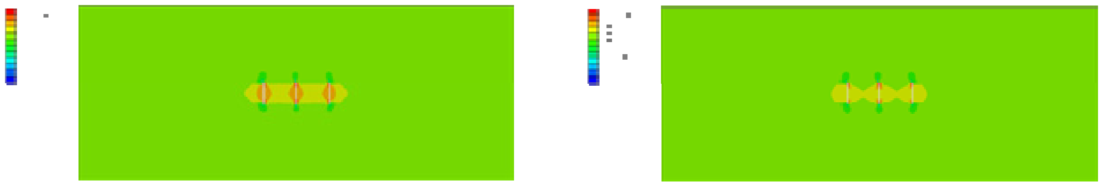
It is known from above simulation that the horizontal impacting distance of a single vertical circular slot is about 1.2 m. The following simulation studies the spatial distribution characteristics of internal stress and energy density of the coal elements affected by a group of slots consisting of different spaces (0.5 m, 1.0 m, and 1.5 m), as shown in Fig. 9.



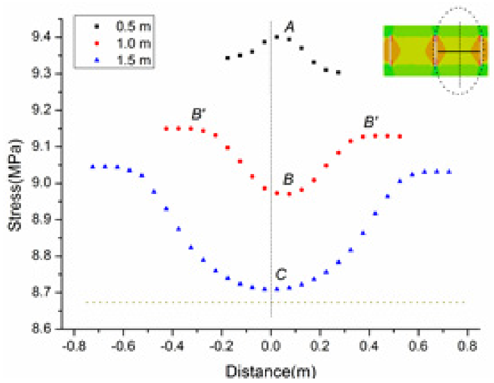
(a) 0.5 m



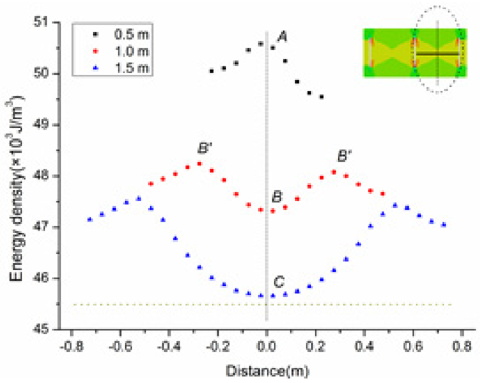
(b) 1.0 m



(c) 1.5 m



(d)



(e)

Fig. 9 Distributions of stress and energy density of coal elements around the group of annular slots: (a), (b) and (c) are the distributions of stress and energy density of coal elements affected by 0.5 m, 1.0 m, and 1.5 m slot spacings; (d) and (e) are the changes in stress and energy density of coal elements between the middle and right slots

From Fig. 9, it can be seen that the effects of slots of different spaces on the distributions of stress and energy density in the coal elements just above the group of slots are very small. In the horizontal direction, there are different degrees of stress concentration and energy accumulation phenomenon between different intervals of slots, among which, the smaller the spacing of the slot, the more obvious the impacting degree. By comparing the stress values of non-affected regions by the slots in Figs. 9(d)-(e), the coal element between the slots of 0.5 m spacing obviously produce the superposition of their stress concentration zones, the stress just in between two slots reaches its maximum value (A point); the stress peaks produced by the two slots of 1.0 m spacing are located in the center line close to their own side (B' point); but the stress concentration still affects the location of the centerline (B point higher than the normal); the two slots of 1.5 m spacing also cause the stress concentration, respectively, but the centerline position is almost not influenced (C point). In fact, it can be seen from the figure, the unilateral impacting range of the circular vertical slot is about 0.75 m.

Because the strength of coal elements is bigger, the applied load is not sufficient to cause the free space provided by the coal elements of slot walls for the slots to be bent, or even damaged. The presence of a number of slots makes the coal mass form a small-scale "layered energy reservoir structure" that has a considerable stability and is capable of accumulating a lot of stress and elastic energy (Dyskin and Germanovich 1993, Zhang and Miao 2002, Zuo *et al*. 2005). When the storage layer is thin, the superposition of stress concentration and energy accumulation on its both sides will happen; with the thickness of energy storage layer increasing, the superposed area gradually shrink; when its thickness increases to a certain extent, the superposition parts of stress and energy accumulation will separate away. In this case, the energy storage layer is most stable. In practical applications, the spacing of two annular slots should be appropriately determined to drive the energy storage structure in the action of the external force to be destroyed, so that those excess stress and elastic energy could be released.

4.3 Comparison between radial and annular slots

Both radial and annular slots could efficiently induce pressure relief and energy dissipation in the vertical direction, i.e., they have the pressure relief effect. However, their impacts on stress concentration and energy accumulation are different.

Radial slot is horizontal, perpendicular to the vertical stress direction (most time it is the maximum principal stress direction). Coal mass above the slot may collapse under the action of gravity, while coal mass below the slot may heave. That is, the slot supplies space for the deformation of coal mass around, leading to greater degree of damage, so its pressure relief effect is much better. Annular slot is parallel to the maximum principal stress direction, the main influencing regional of which is the two sides of slot surface. On the one hand, the coal mass moving to the space generated by the slot mainly depends on the horizontal stress, which is far less than maximum principal stress because of roadway excavation; on the other hand, "layered energy storage structure" between slots developed, resulting in poor pressure relief effect to some extent. So, the impacting scope of radial slotting is much wider than that of annular slotting.

Table 2 shows the comparison between radial and annular slots.

After radial slotting and annular grooving by WJC, in coal rock mass form a large number of slot groups, they play a role in causing coal rock mass to release pressure and in shielding or weakening stress and deformation energy transfers. Among them, the horizontal radial slots are equivalent to mining a very thin protective layer in coal and rock mass, capable of effectively

Table 2 Comparison between radial and annular slots

Ways of coal-breaking	Parameter	Vertical direction		Horizontal direction	
		Impacting scope (m)	Max impacting extent (%)	Impacting scope (m)	Max impacting extent (%)
Radial slotting	Stress	3.0	−52.28	1.0	+44.58
	Energy density	3.0	−71.24	1.5	+59.94
Annular slotting	Stress	1.0	−6.72	1.2	+4.51
	Energy density	1.0	−11.10	1.2	+4.62

freeing stress and elastic energy in the coal rock mass. The annular grooves form a strong - weak - strong structure in the coal rock mass can also release part of the stress, more importantly, they are capable of effectively shielding or weakening elastic energy or stress transfer in the coal rock mass and eliminating or diminishing the risk of rock outbursts, etc.

5. Conclusions

In this paper, theoretical analysis of WJC pressure relief are presented, and the distribution characteristics of stress and energy fields in roadway wallrock after cutting radial and annular slots in hard coal seams are studied. The conclusions are as follows:

- The important roles of the radial slotting are: (a) the impact from the water jet directly breaks the nearby coal mass, making it release its pressure and dissipate its excessive energy; (b) the cutting slots provide great space for coal to deform and further induce the deeper compressed coal mass to rebound, unload, and dissipate energy. Besides, the annular slots can effectively shield or weaken elastic energy or stress propagation.
- The WJC pressure relief in hard coal seams in both radial and annular slotting are simulated using ABAQUS software, and found the followings:

  (1) Stress release and energy dissipation in the vertical direction of a single horizontal radial slot are significant, with the max of the effect distance about 3 m, and the two biggest changes appear in the vicinity of slot walls; The "beam structure" formed after cutting results in stress concentration or energy accumulation near at the slot's ends, with the effect distance 1.5 m. After three radial slots of same size cut on the same horizontal layer face, the influential scope and extent of the slots in the vertical direction increase differently; the combined effects of the " beam structure" and "the small pillar skeleton" between two neighboring slots make stress concentration and energy accumulation more significant.

  (2) The annular slots in the vertical direction have limited influence, and the stress concentration and energy accumulation on both sides of the slots wall surface in the horizontal direction tend to increase, with the scope of 1.2 m. For three annular vertical slots cut on the same horizontal face, the interslot "layered energy storage structure" leads to the increase in stress concentration and energy accumulation in coal element mass.

Acknowledgments

This work is supported by the Youth Science Foundation of the National Natural Science Foundation of China (51304205), the China Postdoctoral Science Foundation (2014T70678) and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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