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Study on the water resistance performance of floor rockmass under different fracture combinations

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To obtain the water resistance performance of floor strata under different rock layers and fracture combinations, the propagation mechanisms of different crack combinations in floor strata under mining conditions were simulated by using singular elements. The propagation path of twin cracks under different situations was given by the minimum plastic zone theory according to the change of the fracture factor and the plastic strain of different strata combination cracks under the influence of fault, water pressure and mining. The shortest length of the rock bridge between twin cracks after bursting in different strata combination was obtained. The water resistance performance of every strata combination was analyzed. It was shown that the water resistance performance of the floor strata under the combination soft-soft-hard-hard upward is the worst while the combination of alternating soft-hard is the best. The fracture factor combination and the plastic strain of the crack will reach maximum when mining near to it, and the crack is mostly easy to extend. The shortest length of the rock bridge between the twin cracks after bursting is under the combination of soft rock layers below and hard rock layers above while it is the longest under the combination of alternating soft-hard. The length of the rock bridge between the twin cracks after bursting will be shortened when considering the water pressure inside the crack and fault, which results in a decrease in rock water resistance performance. This paper will provide a reference for floor water inrush prediction in fractured rock mass.

Keywords: Floor strata, Fracture combination, Minimum plastic zone, Propagation path, Water resistance performance

INTRODUCTION

Since the floor aquifuge in pressure mining plays a role of blocking the confined water, the water resistance performance of the aquifuge is a very important parameter. Due to the difference of the comprehensive petrofabric, physical, mechanical, and hydraulic characteristics between the floor strata and the engineering geology, their mechanism and characteristics of rock mass failure are different under various geological stress; the mechanism, physical process and genetic types of the strong seepage channel formation which could induce the ordovician limestone water inrush are different too, then the water resistance performance differences between different strata combination are shown [1-2]. Floor water inrush is the interaction result of various factors, such as the geological structure, mining pressure, water pressure, the characteristics of aquifuge, etc. [3-4]. The fracture in the floor strata combination will cause plastic failure under the influence of mining, fault and water pressure; the further expansion of plastic zone leads to an increase in the permeability of rock mass near the cracks, making the cracks interconnected, and a water inrush channel will form under the action of high-pressure water. To realize the mining safety on the confined water, the influence of various factors should be comprehensively considered. Domestic and foreign scholars put forward a lot of theories such as "water inrush coefficient" [5-6], "concept of relative thickness of aquifuge" [7], "strong seepage channel" [8-9], "water-rock stress" [10], "zero position destruction and *in-situ* fissures" [11] ," key stratum theory" [12], "down three zone theory" [13-14] and so on. In these theories the mechanism and prediction methods of water inrush were revealed from all aspects, and the direction of mining fissure extension search becomes critical in the formation mechanism of water inrush channel. In this paper, the crack in different floor strata combinations was simulated using the singular unit in the finite element, considering the influence of mining, strata construction, high-pressure water. Propagation direction of cracks in different floor strata combination was searched using a minimum criterion of the plastic zone, and the crack and rock combination was obtained which is the most easy to form the water inrush channel. It has important

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theoretical significance for many mining cracks extension mechanism analysis, coal floor strata's water resistance performance evaluation and accurate analysis, and to ensure the mining safety under pressure.

Criterion of crack propagation and the simulation method

Crack fracture criterion selection

The underground rock fracture is I-II mixed mode fracture under combined compression-shear loading, as shown in Fig. 1.

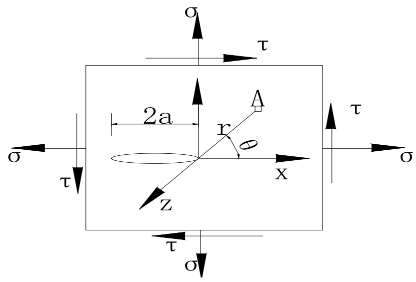

Fig.1. Mechanism of crack under compression-shear combination conditions

According to the Griffith criterion, when the maximum stress intensity factor K_{max} reaches KIC, the energy released by the crack propagation is enough to provide for all its extension needs, and the cracks will further extend, the total strain energy release rate G_C and the crack propagation resistance R_C should meet the formula below:

$$G_t = G_I + G_{II} + G_{III} \geq R_c \qquad (1)$$

For Ⅰ-Ⅱ type combined loading：

$$\begin{cases} G_I = \dfrac{(1-v^2)K_I^2}{E} \\ G_{II} = \dfrac{(1-v^2)K_{II}^2}{E} \\ G_{III} = 0 \end{cases} \qquad (2)$$

So the criterion of fracture is the formula:

$$K_I^2 + K_{II}^2 = K_{\max} = K_C^2 \qquad (3)$$

Where: K_I and K_{II} are the type I and type II stress intensity factors of crack, respectively. When meeting $K_I^2 + K_{II}^2 \geq K_C^2$, crack extension will occur.

From the energy conservation and transformation of the crack propagation, we can conclude that the existence of the crack tip plastic zone is an important factor to anti-crack, the plastic work of the crack propagation has close relationship with the material fracture toughness, and in the same plastic zone, in which direction the plastic zone width is the shortest (refers to the shortest distance between the crack tip and the edge of the plastic zone), the crack will propagate most easily from this direction [15].

Under the combined stress state, the stress field of a certain point near the crack tip is as below:

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}) - \frac{K_{II}}{\sqrt{2\pi r}}\sin\frac{\theta}{2}(2+\cos\frac{\theta}{2}\cos\frac{3\theta}{2}) \qquad (4)$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}) + \frac{K_{II}}{\sqrt{2\pi r}}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \qquad (5)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2} + \frac{K_{II}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}) \qquad (6)$$

Where: A is a certain point in the stress-strain field near the crack tip; r is the distance from point A to the crack tip; θ is the angle between A and X axis.

As the normal stress at the crack tip is equal to or greater than the effective yield stress, the material near this area enters the plastic state, the plastic deformation will take place, and the plastic zone will be formed eventually. The range of the plastic zone can be determined by yield condition of the material.

According to the Von Mises yield condition:

$$(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 = 2\sigma_s^2 \qquad (7)$$

Using the relationship of the stress invariants:

$$\sigma_1 + \sigma_2 + \sigma_3 = \sigma_x + \sigma_y + \sigma_z$$

$$\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1 = \sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2$$

$$\sigma_1\sigma_2\sigma_3 = \sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{xz}^2 - \sigma_z\tau_{xy}^2$$

the function (7) changes to:

$$(\sigma_x-\sigma_y)^2 + (\sigma_y-\sigma_z)^2 + (\sigma_z-\sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) = 2\sigma_s^2 \qquad (8)$$

Substituting the functions (4-6) into the equation (8), the mini-plastic zone displacement can be expressed as:

$$r = \frac{9}{2\sigma_s^2}\left[\begin{array}{l}\left(\frac{5}{36}+\frac{1}{18}\cos\theta-\frac{1}{12}\cos^2\theta\right)K_{\blacklozenge}^2 + \left(\frac{1}{3}\cos\theta\sin\theta-\frac{1}{9}\sin\theta\right)K_{\blacklozenge}K_{\blacklozenge} + \\ \left(\frac{5}{36}-\frac{1}{8}\cos\theta+\frac{1}{4}\cos^2\theta\right)K_{\blacklozenge}^2\end{array}\right] \qquad (9)$$

Under this yield condition, the crack will develop along the direction of the shortest distance $r_{\min}$, namely, the crack extension direction will be determined by the conditions below:

$$\begin{cases} \dfrac{\partial r}{\partial \theta} = 0 \\ \dfrac{\partial^2 r}{\partial \theta^2} > 0 \end{cases} \qquad (10)$$

For the multiple crack penetration, in this paper, according to the calculated extension direction of crack, the extended distance of two adjacent crack tip after fracture was obtained, then the minimum distance between the rock bridge of the cracks after fracture in different strata combination was determined by its coordinates.

Special element method of stress intensity factor

Too much degrees of freedom are needed to solve the stress intensity factor by using a general element, only by increasing the element number to make the approximate displacement field and its first derivative field infinitely approach the corresponding real field, the convergence can be guaranteed. General finite element cannot satisfy the convergence condition, because the displacement derivative of the exact solutions is unbounded in the crack tip. To make the displacement model reflecting the singularity, at the crack tip to switch to a special finite element. Thus there is no need to refine the grid, but the accuracy of the solution can greatly improve. In ANSYS, the stress intensity factor under plane strain conditions uses a special isoparametric element “PLANE82” which has mid-side nodes. "PLANE82" element around the crack tip degenerates into "PLANE2" element, each one has a node at the crack tip, at the same time removes the middle node to the quarterpoint, which can make the corner into singularity. The stress intensity factor of the crack tip can be determined by this element, as is shown in Figs. 2 and 3.

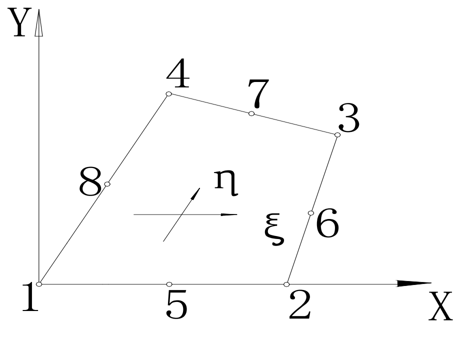

Fig. 2. Isoparametric element

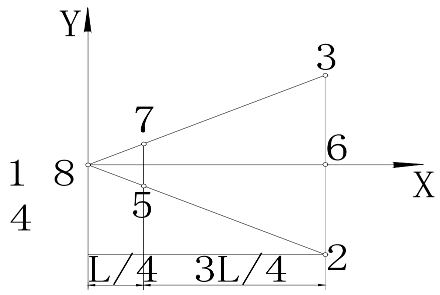

Fig. 3. Singular element

By the transformation below:

$$\begin{cases} x = \sum_{i=1}^{8} N_i(\xi\eta)x_i \\ y = \sum_{i=1}^{8} N_i(\xi\eta)y_i \end{cases} \tag{11}$$

To map the element to regular square space (ξ , η), $-1 \le \xi \le 1$, $-1 \le \eta \le 1$, the corresponding shape functions of node *i* are:

$$\begin{aligned} N_i = {} & \begin{bmatrix} (1+\xi\xi_i)(1+\eta\eta_i)-(1-\xi^2)(1+\eta\eta_i)- \\ (1-\eta^2)(1+\xi\xi_i) \end{bmatrix} \xi_i^2\eta_i^2/4 + \\ & (1-\xi^2)(1+\eta\eta_i)(1-\xi_i^2)\eta_i^2/2 + \\ & (1-\eta^2)(1+\xi\xi_i)(1-\eta_i^2)\xi_i^2/2 \end{aligned} \tag{12}$$

The coordinate of node *i* in the XY coordinate system is (x_i, y_i), but in the transformation system (ξ , η) is (ξ_i, η_i). The corner node is $\xi_i, \eta_i = \pm 1$, the middle node is $\xi_i, \eta_i = 0$, the displacement is as below:

$$\begin{cases} u = \sum_{i=1}^{8} N_i(\xi\eta)u_i \\ v = \sum_{i=1}^{8} N_i(\xi\eta)v_i \end{cases} \tag{13}$$

The η is -1 in the side 1-2, the shape function is:

$$\begin{cases} N_1 = \frac{1}{2}\xi(1-\xi) \\ N_2 = \frac{1}{2}\xi(1+\xi) \\ N_5 = 1-\xi^2 \end{cases} \tag{14}$$

Substitution of the functions (14) into the equations (6, 7),

$$x = -\frac{1}{2}\xi(1-\xi)x_1 + \frac{1}{2}\xi(1+\xi)x_2 + (1-\xi^2)x_5 \tag{15}$$

Taking $x_1 = 0$, $x_2 = L$, and removing the middle node 5 from the usual position to the quarter, taking $x_5 = L/4$, then

$$x = \frac{L}{4}(1+\xi)^2 \tag{16}$$

$$\xi = -1 + 2\sqrt{\frac{x}{L}} \tag{17}$$

The displacement is:

$$u = -\frac{1}{2}\xi(1-\xi)u_1 + \frac{1}{2}\xi(1+\xi)u_2 + (1-\xi^2)u_5$$
$$= -\frac{1}{2}(-1+2\sqrt{\frac{x}{L}})(2-2\sqrt{\frac{x}{L}}) + \frac{1}{2}(-1+2\sqrt{\frac{x}{L}})(2\sqrt{\frac{x}{L}})u_2 + \tag{18}$$
$$(4\sqrt{\frac{x}{L}} - 4\frac{x}{L})u_5$$

So the strain of x direction is:

$$\varepsilon_x = \frac{\partial u}{\partial x} = \frac{\partial \xi}{\partial x}\frac{\partial u}{\partial \xi} = -\frac{1}{2}(\frac{3}{\sqrt{xL}} - \frac{4}{L})u_1 +$$
$$\frac{1}{2}(-\frac{1}{\sqrt{xL}} + \frac{4}{L})u_2 + (\frac{2}{\sqrt{xL}} - \frac{4}{L})u_5 \tag{19}$$

Reducing the side 1-4 of the quadrilateral in Fig. 2 into a tip, then the quadrilateral turned into a six nodes triangle whose mid-side nodes are at the quarter, as shown in Figure 3.

The η is equal to the zero on the X axis,

$$x = -\frac{1}{4}(1+\xi)(1-\xi)L - \frac{1}{4}(1+\xi)(1-\xi)L + \frac{1}{2}(1-\xi^2)\frac{L}{4} + \tag{20}$$
$$\frac{1}{2}(1+\xi)L + \frac{1}{2}(1-\xi^2)\frac{L}{4} = \frac{L}{4}(1+\xi^2)$$

For the opening mode crack:

$$\begin{cases} U = \dfrac{K_I}{8G}\sqrt{\dfrac{2\rho}{\pi}}\left[(2k-1)\cos\dfrac{\theta}{2} - \cos\dfrac{3\theta}{2}\right] \\ V = \dfrac{K_I}{8G}\sqrt{\dfrac{2\rho}{\pi}}\left[(2k-1)\sin\dfrac{\theta}{2} - \sin\dfrac{3\theta}{2}\right] \end{cases} \tag{21}$$

For the shear crack in plane:

$$\begin{cases} U = -\dfrac{K_{II}}{8G}\sqrt{\dfrac{2\rho}{\pi}}\left[(2k+3)\sin\dfrac{\theta}{2} + \sin\dfrac{3\theta}{2}\right] \\ V = -\dfrac{K_{II}}{8G}\sqrt{\dfrac{2\rho}{\pi}}\left[(2k-3)\cos\dfrac{\theta}{2} + \cos\dfrac{3\theta}{2}\right] \end{cases} \tag{22}$$

Where: G is shear elastic modulus $k = 3 - 4\nu$, ν is Poisson ratio; ρ is the distance from crack nearby to the crack tip (not more than 10-2L); θ is the rupture angle of crack.

Substituting the node displacement obtained into functions (9) and (10), the stress fracture factor of the crack could be estimated. This isoparametric element algorithm which contains rigid motion and constant strain mode meets the necessity of convergence, in that it can get very good effect only needing a few elements.

Propagation mechanism of multiple cracks under different floor strata structure

Establishment of numerical model

The numerical model width is 400 m and the height is 295 m considering that the 6th coal thickness is 3 m, buried depth is 375 m and the inclination nearby horizontal. Overburden thickness of 6th coal is 170 m, the overburden-pressure according to the gravity load $p = \gamma H$, and this is the free boundary. The floor strata of the 6th coal are 125 m, the aquifuge h is 55 m, the confined water pressure $P_w = 3MPa$, the bottom boundary is the limit vertical displacement, applying level constraints on the model lateral boundary. In order to consider the water resistance performance of the strata comprehensively, different combination models containing strata, fault, fissure and water pressure were set up, asshown in Figure 4. The length of each crack is 6 m, located in the two bottom layers, respectively. The coordinates of crack tip 2 are (198.0， 108.08), the crack tip 3 is (198.04, 113.78). The inclination of crack 1-2 is 59.470. The inclination of crack 3-4 is 58.50. There are four procedures of rock combination from bottom to top: a) 2346 (soft rock, hard rock, hard rock, soft rock), b) 4326 (soft rock, soft rock, hard rock, hard rock), c) 2364 (soft rock, hard rock, soft rock, hard rock), d) 2643(hard rock, hard rock, soft rock, soft rock). Divided into two kinds of working conditions, respectively, considering fault and water pressure in the fracture of 1 Mpa. The length of work face along the incline direction is 200 m, the step length of the step excavation is 10 m, so there are 21 steps to mine the work face. The changes of the stress intensity factor and the plastic strain of the crack under different conditions were obtained.

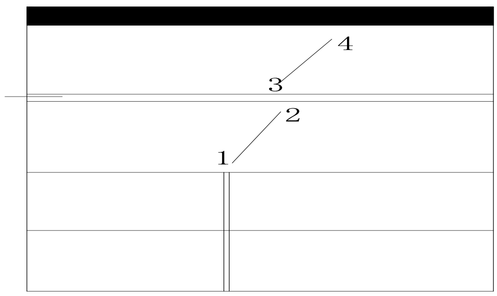

Fig. 4. Schematic diagram of the two arbitrary angle cracks in the aquifuge containing fault

Selection of rock mechanic parameters

The Drucker-prager yield criterion is used for the rock layers. The computational mechanic parameters of each strata are shown in Table 1.

Calculation results analysis

Fracture factor change rule of the crack under different condition

The fracture factor change curves of the crack under different conditions are shown in Figs. 5-8, by the graphs it can be seen:

(1) For the fracture factor value K_I of crack tip 2, it increases gradually, reaches the maximum value when the working face advances to 20 m distance from the crack tip, and then it suddenly decreases, and achieves the minimum when the working face advances to the middle of it. Then, the value of the K_I increases gradually and levels off. The value of K_{II} slowly decreases at first, reaches the minimum when the working face advances 40 m. Then, K_{II} increases slowly, achieves the maximum value when the working face advances to 30 m distance from the crack tip. Finally, it decrease gradually, achieves the minimum value at a distance from the crack s about 10 m. When the working face advances to the middle, K_{II} suddenly increases to the maximum and then tends to be stable. Considering K_I, K_{II} comprehensively, the value of Kc reaches maximum when the working face advances to a 20 m distance from the crack tip, that is to say, the crack will be destroyed most easily here. When the working face advances to the middle, the Kc is at the minimum, then it increases and tends to be stable. The change trends of fracture factors K_I and K_{II} at crack tip 3 are similar to the crack tip 2, only the value of K_I and K_{II} reaches the maximum at 10 m from the crack tip.

(2) For the same kind of rock combinations, the crack propagation will change greatly, when considering the effect of 1 MPa water pressure in the crack and the fault below the crack. Under the action of fault and water pressure, the fracture factor values K_I and K_{II} of the crack will increase and the crack is easier to break, just the change of the trend curve pattern is small. The effect order from large to small is: the combination action of fault and hydraulic pressure, bearing 1 MPa water pressure in the crack, only affected by faults, only affected by mining. It can be seen that when there are fault and water pressure in the crack in the floor strata, it is easier to damage the crack.

(3) For different rock combinations, the change trend curves of K_I, K_{II} are roughly the same, but have different values, different ease of crack fracture. When the rock combination from bottom to top is 4326 (soft rock, soft rock, hard rock, hard rock), the crack is the easiest to destroy. When the rock combination is 2643 (hard rock, hard rock, soft rock, soft rock), the crack is the most difficult to destroy.

(4) Considering K_I, K_{II} comprehensively, the value of K_I is much larger than of K_{II}, the crack destroy is mainly composed of tensile and compression failure. The crack 3-4 affected by mining is larger than crack 1-2.

Table 1. Mechanical parameters of each strata

Rock character	Thickness of layer /m	Elastic modulus /GPa	Poisson ratio	Density t/m^3	Cohesion /MPa	Angle of internal friction/ 0	Compressive strength /MPa	Tension strength /MPa	Number of rock characters
Limestone	70	14	0.24	2.76	4	38	30	1.79	1
Arenaceous shale	14.8	2.2	0.23	2.57	2.9	36	11	0.7	2
Kern stone	13.2	6.2	0.15	2.65	4	39	15	0.98	3
Fine sandstone	12.6	7.5	0.13	2.65	5	42	22	1.1	4
Weak interlayer	0.7	0.7	0.34	2.35	0.6	32	3.5	0.1	5
Mudstone	12.4	2.8	0.23	2.60	3	24	10	0.7	6
Coal	2.7	1.2	0.36	1.40	1	25	3.2	0.03	7
Mudstone	3.5	2.7	0.24	2.60	2.9	25	9.8	0.65	8

Coalescence mechanism of multi-cracks

Under the influence of mining and geological structure, multiple cracks will expand and interconnect each other, which makes the permeability greatly enhanced.

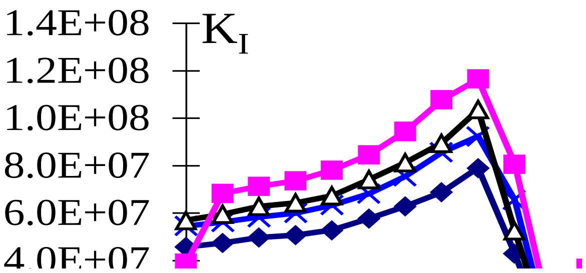

Fig. 5. Curve of the fracture factor (K_I) at crack tip2

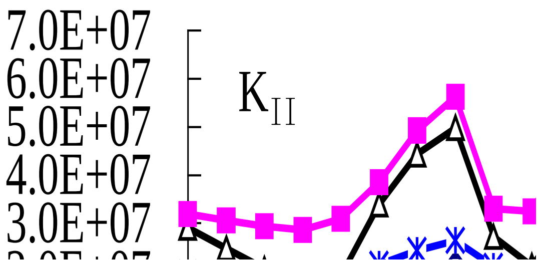

Fig. 6. Curve of the fracture factor (K_{II}) at crack tip2

This paper mainly studies the shortest length of the rock bridge of two cracks after damage under different conditions.

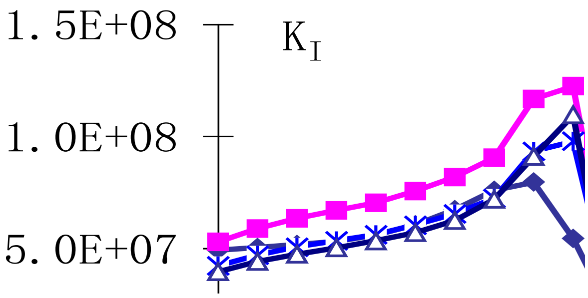

Fig. 7. Curve of the fracture factor (K_I) at crack tip3

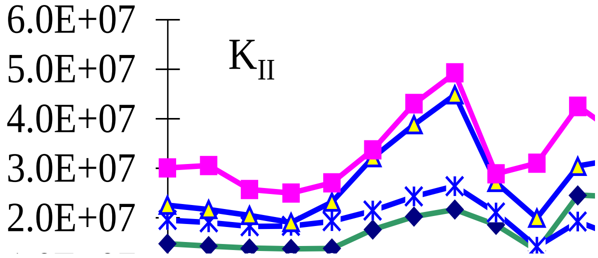

Fig. 8. Curve of the fracture factor (K_{II}) at crack tip3

Firstly, the maximum principal stress value of the factor combination $\sqrt{K_I^2+K_{II}^2}$ under different strata combination is substituted in equation (5) to obtain σ_s, then σ_s is substituted and the fracture factors K_I and K_{II} of the time step in equation (6), obtain any two floor strata crack propagation path under different rock combination according to equation (7), determine the coordinate after crack destroyed of point 2 and 3, according to which the shortest distance of rock bridge between the crack tip 2 and 3 after the crack damaged is obtained. The results are shown in Table 2.

Table 2. Results of propagation route under different floor combinations

Rock layer combination	Combination of construction	Failure angle of second crack tip $/^0$	Mini-plastic zone displacement /m	Failure angle of third crack tip $/^0$	Mini-plastic zone displacement /m	Displacement of rock bridge after failure /m
2346	Normal	68.58	1.28	51.57	1.30	3.715803
	Fault	65.94	1.29	51.15	1.31	3.65223
	Water pressure in crack	77.6	1.297	55.03	1.32	3.507769
	Fault, Water pressure in crack	78.37	1.30	54.85	1.33	3.483808
2364	Fault	63.09	1.24	60.11	1.28	3.685071
	Fault, Water pressure in crack	60.1	1.29	65.46	1.30	3.5991
2643	Fault	74.01	1.292	55	1.32	3.655416
	Fault, Water pressure in crack	61.99	1.305	59.53	1.34	3.530717
4326	Fault	67.38	1.298	57.51	1.33	3.591298
	Fault, Water pressure in crack	74.37	1.31	62.37	1.35	3.386976

As can be seen from the table:

(1) The fault and the water pressure in the crack have a certain influence on the crack propagation under the condition of the same rock combination. The minimum plastic zone is the maximum when the crack is affected by both the fault and the water pressure; when there is 1 Mpa water pressure in the crack takes the second place; and reaches the minimum when there is no structure in rock. It can be seen that the crack under the combined effect of fault and water pressure in the cracks is easiest to be damaged and the water resistance performance is the worst, however, the connection capacity of the cracks is worst when it is affected by mining only and the water resistance performance is best.

(2) The minimum plastic zone range of crack tip 3 is larger than of crack tip 2, that is to say, the upper crack is more strongly affected by mining.

(3) By comparison of different strata combinations, the minimum plastic zone range of the floor strata combination 4326 is the maximum under the same conditions and the length of the rock bridge between cracks after destroyed is the minimum; the combination 2643 takes the second place; the minimum plastic zone range combination 2364 is the minimum and the length of the rock bridge is the maximum. It can be seen that the water resistance performance of combination 4326 is the worst, on the contrary, the 2364 is the best.

CONCLUSIONS

In this paper different crack combinations in floor strata under mining conditions were simulated using a singular element, the two cracks propagation paths under different situations were given using the minimum plastic zone theory according to the change of the fracture factor and the plastic strain of different strata combination cracks under influence of fault, water pressure and mining, the shortest length of the rock bridge between the two cracks after bursting in different strata combination was obtained, and the water resistance performance of every strata combination was analyzed. The conclusion is that: the water resistance performance of the floor strata under the combination of soft-soft-hard-hard upward is the worst while the combination of alternating soft-hard is the best. The fracture factor combination and the plastic strain of the crack will reach maximum when mining is performed near to it, and the crack is the easiest to destroy. The length of the rock bridge between the two cracks after bursting is the shortest under the combination soft below and hard above, while it is the longest under the combination of alternating soft-hard. The length of the rock bridge between the two cracks after bursting will be shortened when considering the water pressure inside the crack and fault, which results in the decrease of rock water resistance performance. This paper provides a reference for floor water inrush prediction in fractured rock mass.

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REFERENCES

1. M. Feng, X. Mao, Q. Zhu, *Journal of Mining & Safety Engineering*, **27**(3), 404 (2010).
2. Y. Gao, Sh. Liu, B. Lv, K. Li, *Journal of Mining & Safety Engineering*, **33**(4), 624 (2016).
3. S. Peng, J. Wang. Safety coal mining above the confined aquifer. Beijing: China Coal Industry Publishing House, 91−111, (2001).
4. Q. Wu, B. Li, *Journal of China Coal Society*, **41**(9), 2143 (2016).
5. W. Qiao, W. Li, C. Zhao, *Chinese Journal of Rock Mechanics and Engineering*, **28**(12), 2466 (2009).
6. B. Li, H. Liu, X. Liu, *Journal of Hebei University of Engineering (Natural Science Edition)*, **28**(3), 68 (2011).
7. Q. Liu, W. Li, H. Chai，Q. Guo，Sh. Sun, *Mining Safety ＆ Environmental Protection*, **42**(1), 64 (2015).
8. Zh. Li, C. Zhai, L. Li, *Journal of Central South University (Science and Technology)*, **46**(5), 1806 (2016).
9. R. Liu, D. Cao, D. Hu, *Hydrogeology ＆ Engineering Geology*, **43**(1), 105 (2016).
10. L. Shi, *Journal of Shandong University of Science and Technology (Natural Science)*, **28**(3), 17 (2009).
11. J. Sun, L. Wang, H. Hou, *Journal of china university of mining & Technology*, **42**(4), 560 (2013).
12. W. Li, J. Yang, *Coal Mining Technology*, **15**(5), 45 (2010).
13. X.Yu, L. Shi, J. Wei, *Journal of Shandong University of Science and Technology (Natural Science)*, **25**(4), 14 (2006).
14. W.Sun, Sh. Zhang, L. Zhu, *Mining Safety ＆ Environmental Protection*, **43**(3), 100 (2016).
15. Sh. Yin, The theory and application of fracture and damage. Beijing, Tsinghua University press, 1992.

ИЗСЛЕДВАНИЯ ВЪРХУ ВОДОУСТОЙЧИВОСТТА НА СТРАТИФИЦИРАНИ СКАЛНИ МАСИ ПРИ РАЗЛИЧНИ УСЛОВИЯ НА РАЗРУШАВАНЕ

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(Резюме)

За определяне на водоустойчивостта на дънни слоеве под различни скални пластове са симулирани механизмите на разпространение на пукнатините на слоевете при минна експлоатация с помощта на сингуларен елемент. Пътят на разпространение на двойни пукнатини при различни случаи е определен с помощта на теорията за минимална пластична зона според промяната на фактора на пропукване и пластичното напрежение на комбинации от различни слоеве под влияние на нарушения, водно налягане или минна експлоатация. Определена е най-късата дължина на скалния мост между двойни пропуквания при различни комбинации на слоевете. Анализирано е водното съпротивление на комбинации от различни слоеве. Показано е, че водното съпротивление на дънни слоеве при комбинация от меки-меки-твърди-твърди слоеве е най-лошо, а при комбинация меки-твърди – най-добро. Факторът на пропукване и пластичното напрежение на пропукването са максимални при близки минни дейности, като пропукването най-лесно се разширява. Дължината на скалния мост между две пропуквания е най-малка когато отдолу се намират меки скали, а отгоре – твърди скали и най-голяма когато се сменят последователно меки и твърди скали. Дължината на скалния мост намалява като се вземе предвид водното налягане в пукнатината и нарушението, което води до намаляване на водното съпротивление. Статията дава възможност за предсказване на водния напор в пропукани скални маси.