J. Earth Syst. Sci. (2020)129 4
https://doi.org/10.1007/s12040-019-1284-5

Evolution of the hydraulic properties of deep fault zone under high water pressure

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MS received 7 September 2017; revised 13 May 2019; accepted 13 August 2019

Repeated water injection tests with varied injection flow rates are conducted on a fault zone under the roadway floor to study the evolution of the hydraulic properties of fault zone under high water pressure. Based on the analysis of test results, the evolution process of the hydraulic properties of fault zone under high water pressure can be divided into three successive stages: the initial infiltration stage, the splitting stage, and the scouring infiltration stage. It is found that in the splitting stage and the scouring infiltration stage, the hydraulic conductivity of fault zone increases rapidly under the condition of sufficient water supply, and this is likely to evolve into a large-flow-rate water inrush accident. Therefore, the safety factor e of fault zone should be defined as the ratio of the splitting pressure of fault zone P_f over the aquifer pressure P_h, i.e., $e = P_f / P_h$; when $e < 1$, water inrush may occur in the fault. Based on the results in this study, a new method is proposed for assessing the risk of fault.

Keywords. Fault zone; water injection test; splitting pressure; equivalent hydraulic gap width; safety factor.

1. Introduction

China has the largest proven reserve of coal in the world, and is the world's largest coal producer and consumer (Miao and Qian 2009). However, the extraction of this important resource is often associated with groundwater inrush accidents (Zhang *et al.* 2014; Ma *et al.* 2017). The hydraulic properties behaviour of the rocks around the working face is a key factor in determining the chance of water inrush from the floor (Huang *et al.* 2014a). The borehole water injection test is an *in-situ* hydraulic properties test conducted in the borehole, with the main purpose of measuring the hydraulic conductivity of rock mass to provide the basic data for formulate seepage control measure (Zhang 2002). According to China's current 'Water Conservancy and Hydropower Engineering Rock Test Rules' (The industry standard Editorial committee of the People's Republic of China 2003), the recommended maximum water pressure of injection test is 1.0 MPa. However, the mining depths of current coal mines are generally larger than a few hundred meters, or even more than 1000 m, and the water injection test under less than 1.0 MPa cannot accurately reflect the hydraulic properties of rock mass under the actual water pressure, so it is necessary to test the rock mass under higher water pressure. The high pressure water injection test can reflect the actual hydraulic properties of rock mass, and can also be used to assess the critical pressure value for all kinds of

Published online: 19 December 2019

Figure 1. Location of the study area.

rock mass to resist hydraulic splitting, providing the evidence for assessing the safety of a project (Yin *et al.* 2005; Jiang *et al.* 2007, 2010). Compared with intact rock mass, the fault zone has low strength and weak seepage resistance. According to the statistics, 80% coal mine water inrush accidents are related to fault (Huang *et al.* 2010; Song *et al.* 2013). Hence, the hydraulic properties of fault zone are important to coal mining, particularly when a confined karst aquifer is underlying the coal seams (Huang *et al.* 2014b, 2016). In this paper, *in-situ* high pressure water injection tests are conducted in two boreholes drilled in a fault of buried 550 m deep in Yanzhou Coalfield, Shandong province of China (figure 1). The test results are presented and the relationship between the obtained parameters are analyzed.

2. *In-situ* high pressure hydraulic testing

2.1 *Fault zone*

The tested fault is a normal fault numbered 'FP2', its displacement is about 7.5 m with dip of about 70° and fault zone thickness of about 1.0 m (figure 2). The strata on both sides of the fault zone are mainly mudstone and sandstone with low hydraulic conductivity. The fault zone consists mainly of extremely fractured mudstone, sandstone and fault gouge with a small amount of coal. The test site is located in a roadway at buried depth of about 550 m, and the roadway has exposed the FP2 fault zone before the test. Seepage is absent in the exposed fault zone, and the fault zone is dense and has certain cementation strength. The distance between the exposed fault of the roadway and the main aquifer (Ordovician limestone) is 57 m.

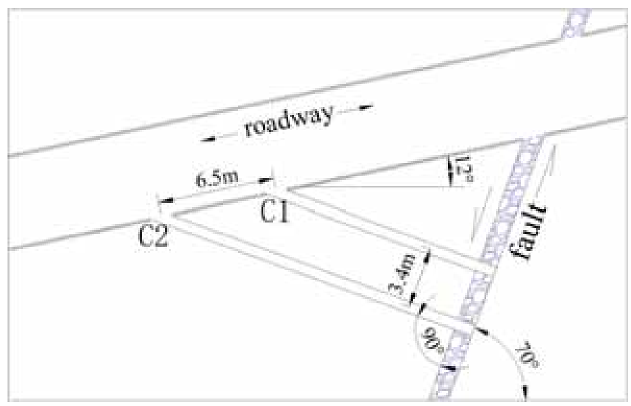

Figure 2. The layout of test boreholes.

2.2 *Test boreholes*

A total of two testing boreholes C1 and C2 are designed, which are extending in the direction perpendicular to the fault plane, the spacing is 6.5 m, the locations of the testing holes are shown in figure 1. The testing boreholes have the form of bare hole in the fault zone, with diameter of ϕ, 75 mm.

2.3 *Test equipment*

Water injection was conducted by piston propulsion using a 2ZBQ-3/21 type pneumatic water injection pump with rated pump pressure of

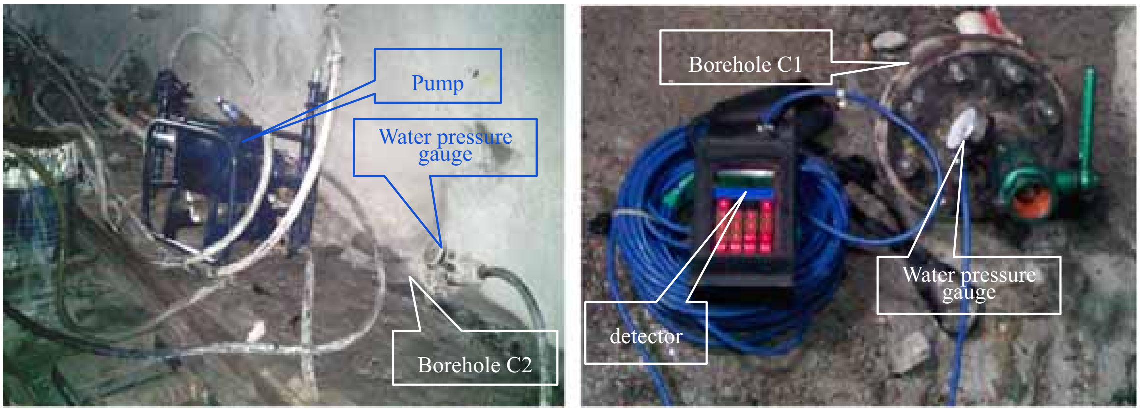

Figure 3. Water injection and monitoring devices.

21 MPa. The hydraulic pressure in C1 is measured using a vibrating string-type water pressure sensor, the water pressure is collected using a GSJ-2A type intelligent detector, and the pressure of water injection is recorded by a pressure gauge. The water injection test system is shown in figure 3.

2.4 *Test process*

The method of water injection test is to inject water into the C2 hole, and to monitor the water pressure in the C1 hole. The water injection flow rate (q) is artificially controlled when the water is injected in. A total of five rounds of continuous water injection tests are conducted, the same variation of q is kept in each round; q is first increased and then decreased. The tests last for a total of 355 min, and a set of data is recorded in every 5 min. The pressure of injected water (P), water injection flow rate (q) and water pressure in the monitor borehole (P') are recorded continuously in the water injection process.

2.5 *Test analysis*

2.5.1 *P–t relationship*

Figure 4 shows the changes of water injection pressure (P) in the C2 hole and water injection flow rate (q) as well as water pressure (P') in the C1 hole with test duration (t).

As shown in figure 4, in the first round, the q–t curve during water injection is different from the curves in the other four repeated rounds. The first round lasts 75 min; the first 40 min is the increase stage of injection q, and the later 35 min is the decrease stage. In the increase stage of q, P varies in the way of 'increasing–decreasing–increasing'. In the

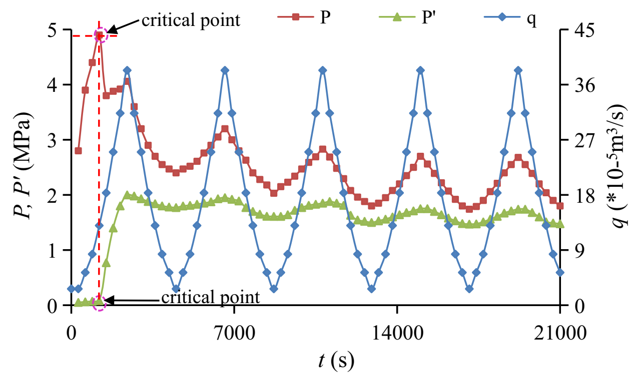

Figure 4. Temporal variations of flow rate (q) and pressures (P).

initial stage of water injection, P increases rapidly, and when P is increased to a certain value, P decreases rapidly, and then increases gradually. Such process of variation has the characteristics of a typical pressure curve during the hydraulic splitting, suggesting that the fault zone is split and the hydraulic properties is changed abruptly. Thus, it can be determined that the splitting pressure of the tested fault zone is 4.9 MPa. In the initial stage of q increase in the 1st round, P' in C1 keeps increasing slowly, and when the fault zone split after P is higher than the splitting pressure, P' in the C2 hole increases rapidly, indicating that the C1 and C2 holes are connected by the split cracks.

As shown in figure 4, the later four repeated rounds of water injection tests show similar characteristics under the same flow rate gradient. Both P and P' show synchronized variation with q.

2.5.2 *P–q relationship*

Figure 5 shows the relationship between water injection flow rate (q) and injection pressure (P).

During the 1st round of water injection, initially with the increase of q, P increases rapidly; after the splitting pressure is reached, the fault zone is split and P decreases rapidly; then with the increase of q, P increases slowly, indicating that the cracks expand after the splitting. In the stage of decreasing q, P is reduced synchronously with the decrease of q, indicating that the cracks are closed at lower q. In the process of repeated injections, P also show synchronous increase and decrease with q. After the fault zone is split, the P–q curves of all the water injection processes show good linearity, i.e., $P = \mathrm{a}q + b$, with correlation coefficient (R^2) above 0.95, and the fitting data in each stage are listed in table 1.

Comparison of P at the same q before and after the fault zone split shows that P in the stage with decreasing q is less than that in the stage with increasing q; P in later rounds of water injection is also lower than that in the former rounds. These results suggest that the cracks formed when the water is injected into the fault zone are gradually scoured, and the hydraulic properties are enhanced. In all the water injection tests, concentrated water seepage occurs at the location of fault zone, and the water is turbid, suggesting that the cracks formed by splitting have been scoured. The scouring of cracks should be caused by the shear stress acting on the crack walls when the water flows through.

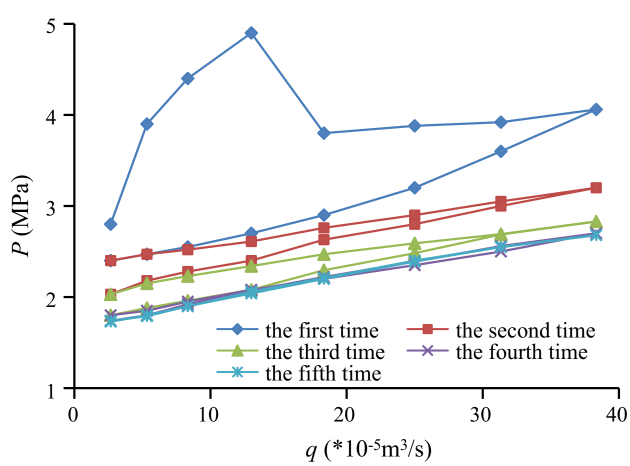

Figure 5. Changes of water injection pressure (P) with flow (q).

3. Discussion and summary of test results

3.1 *Evolution process of the hydraulic properties*

For the original fault zone which contains no water and has very weak permeability, the hydraulic property evolution may be caused by the increase of water pressure in the aquifer on both sides of the fault zone (for example, water storage in the reservoir area, water level recovery in the aquifer at the bottom floor of coal mine, etc.), may lead to the occurrence of water inrush accidents. Under high water pressure, the hydraulic properties evolution of fault zone can be divided into three stages: the initial infiltration stage, the splitting stage and the scouring infiltration stage. They will be further illustrated based on the data obtained in the water injection tests.

3.1.1 *Initial infiltration stage*

The initial hydraulic conductivity of the fault zone is K, the porosity is n, the seepage starting pressure is P_s, and the thickness of the fault zone is L. The water is injected at a given flow rate q, $q = f(t)$, and then after the water is injected continuously for time t, the diffusion radius of water injection R is

$$R = \sqrt{\frac{\int_0^t d(f(t))}{\pi n L}}. \tag{1}$$

According to the Darcy's law,

$$q = KAJ, \tag{2}$$

where J is the water head gradient, $J = \frac{dH}{dr}$ and A is the cross-sectional area of passage, $A = 2\pi RL$. Bringing both into equation (2) and rearranging and integrating both sides finds:

Table 1. *Data fitting results for different water injection stages.*

	1st time		2nd time		3rd time		4th time		5th time	
Parameter	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease
a	0.020	0.068	0.037	0.053	0.035	0.049	0.041	0.045	0.045	0.045
b	3.564	2.224	2.337	1.994	2.034	1.719	1.735	1.685	1.678	1.673
R^2	0.955	0.978	0.998	0.995	0.985	0.996	0.998	0.994	0.992	0.994

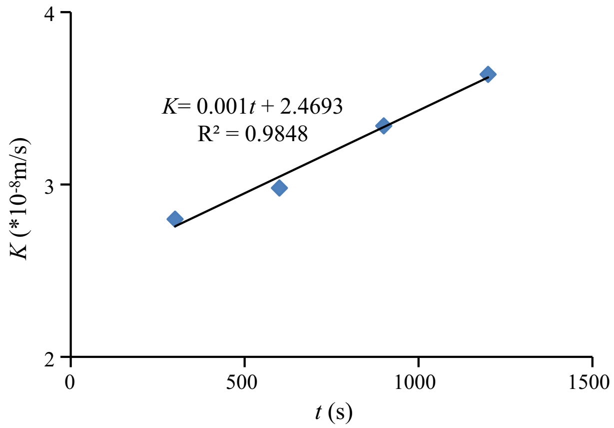

Figure 6. Temporal variations of hydraulic conductivity (K) in the initial stage of water injection pressures.

$$\frac{q}{2\pi L}\int_{r_0}^{R}\frac{dr}{r} = K\int_{H_0}^{0} dH, \tag{3}$$

then

$$K = \frac{q\ln\left(\sqrt{\frac{\int_0^t d(f(t))}{\pi n L} + r_0^2} - r_0\right)}{-2\pi H_0 L}, \tag{4}$$

where r_0 is the radius of water injection hole; H_0 is the water head height of water injection hole; n is the porosity, set to be 0.1.

The hydraulic conductivity (K) of the tested fault zone in the initial infiltration stage is obtained by calculation and is shown in figures 6 and 7. In this stage, K of the fault zone is 0.245 ~ 0.316 cm/d, and the overall change is not large. K increases with t and also with the increase of P.

3.1.2 *Splitting stage*

According to the theory of the tensile strength of rock mass (figure 8), the critical stress condition for the splitting of rock layer is when the water injection pressure P is equal to or higher than the extension stress P_f, which is the sum of the minimum principal stress σ_3 and the tensile strength T_c of the rock, i.e.,

$$P \geq P_f = T_c + \sigma_3. \tag{5}$$

With the increase of P, when P is larger than P_f of the fault zone, the fault zone is split to form the dominant permeable cracks. The water then quickly enters into the cracks, resulting in a rapid decrease in P.

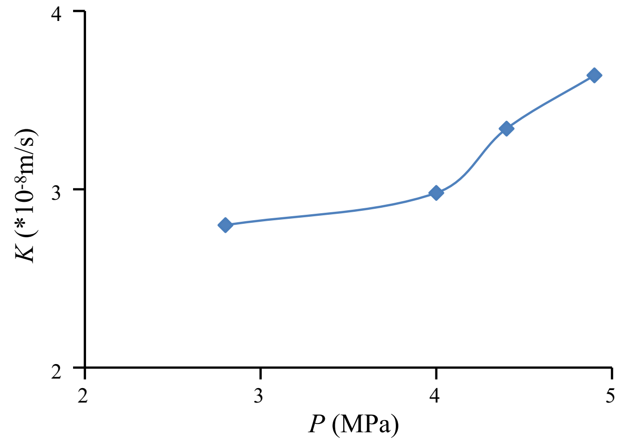

Figure 7. The hydraulic conductivity (K) of fault zone under different water injection pressures.

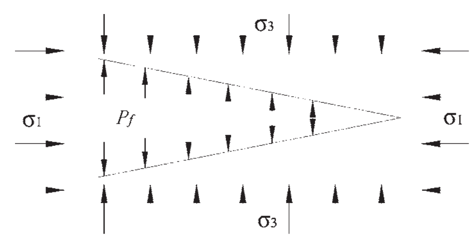

Figure 8. Mechanical model of the expansion of fractured surface.

3.1.3 *Seepage channel scouring infiltration stage*

It is assumed that a flat-plate-shaped crack with two smooth side surfaces is formed by splitting, and the crack penetrates into the C1 and C2 holes; the seepage flow in cracks is laminar and obeys the Darcy's law, so the equivalent hydraulic gap width b of the crack formed after splitting can be calculated by the following formula

$$b = \left(\frac{12\mu q}{JgL}\right)^{1/3}, \quad J = \frac{H_{C2} - H_{C1}}{d}. \tag{6}$$

where μ is the dynamic viscosity of water; g is the gravitational acceleration; H_{C1} is the water level in the C1 hole; H_{C2} is the water level in the C2 hole; d is the distance between the C1 and C2 hole.

Figure 9 shows b of the fault zone in the course of water injection, b increases with the increase of q. Figure 10 shows b at different q, it can be seen that at the same q, b increases with t. For example, when q is the maximum 0.383 L/s, b in the first round of water injection is 1.99 mm, and by the fifth round of water injection, b is increased by 2.58 mm, corresponding to an increase of 29.6%.

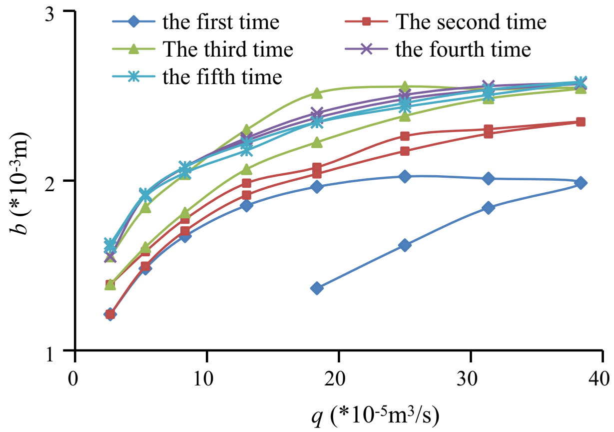

Figure 9. Equivalent hydraulic gap width (b) of the fault zone in the course of water injection.

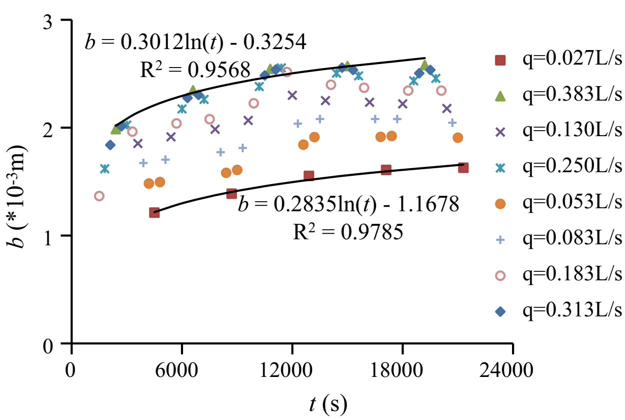

Figure 10. Equivalent hydraulic gap width (b) at different flow injection flow rates (q).

According to the cubic principle, under the same hydraulic gradient, the seepage flow rate can be increased by 117.9%. The above phenomena show that scouring has occurred in the split cracks in the process of water injection, leading to enhanced hydraulic conductivity of the fault zone. In addition, b increases at higher rate in the initial stage, and then the growth rate slows down. The relationship between b of cracks and t can be fitted by a logarithmic function.

3.2 *Evaluation of fault water inrush risk*

Regarding the *in-situ* hydraulic properties test of fault zone, Wu and Liu (2003) and Bai *et al.* (2009) study the hydraulic properties of the normal fault in the Yangzhuang coal mine and the reverse fault in the Liuxin coal mine using the double-hole arrangement similar to this study. Water is injected in one borehole, and another is for observation. When it is found that the double holes are connected (bubbles appear and the water becomes turbid in the observation hole), record the water injection pressure as P_b. The ratio of P_b over the distance d between the two holes is defined as the coefficient of water resistance Z, namely $Z = P_b/d$, and the water resistance coefficients of the tested faults mentioned above are 0.12 and 0.18 MPa/m. In assessing the safety of fault, if the distance between the fault point exposed in the roadway and the main aquifer lay is D along the fault zone, the water pressure in the aquifer is P, and the safety factor is n, then the fault is considered to be safe when $P < ZD/n$.

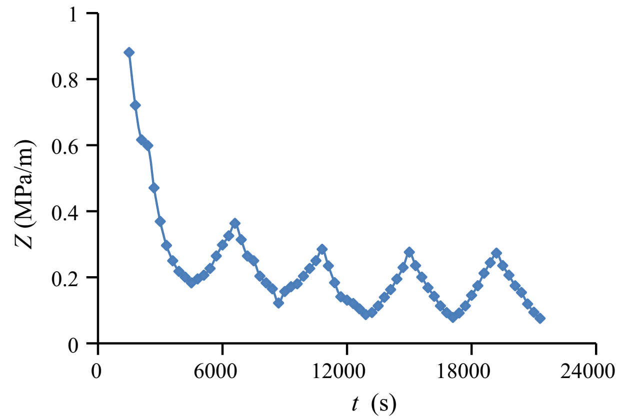

Figure 11. Calculated water resistance coefficient (Z) of the fault zone during water injection.

According to the above-mentioned ideas, the water resistance coefficient $Z = (P_{C2} - P_{C1})/d$, so Z of the fault zone during water injection is obtained and shown in figure 11. After the fault zone is split, salient water pressure increase is found in the C2 hole, indicating that the C1 and C2 holes are connected, and the derived Z is 0.88 MPa/m, the minimum Z is 0.076 MPa/m in the test, and Z changes synchronously with q and P. Given Z is 0.88 MPa/m when the holes are connected for the first time, and the safety factor n is 2, then the water resistance capacity of the fault can be 25 MPa. On the other hand, the test results show that the splitting pressure is only 4.9 MPa at the tested location of the fault zone, so under water pressure of 25 MPa, the fault zone has already split, and the hydraulic properties may change abruptly, further causing water inrush accidents. Hence it is not reasonable to use the method of water resistance coefficient to assess the safety of fault. Instead, the splitting pressure should be taken as the criterion for assessing the safety of fault zone. The safety factor e of fault zone should be defined as the ratio of the splitting pressure P_f

over the aquifer pressure P_h, i.e., $e = P_f / P_h$; when $e < 1$, water inrush may occur in the fault.

4. Conclusions

In-situ high-pressure water injection tests are conducted to study the hydraulic properties of fault zone. The injection flow rate (q) is artificially controlled during the water injection process to first increase and then decrease. The water injection pressure (P) and the pressure induced (P') in the observation hole are recorded continuously, and five successive rounds of tests were carried out. Analyses of the test results shows that the P–t curve during the first injection process is consistent with the pressure curve of typical rock hydraulic splitting, and the splitting pressure of fault zone can be obtained in the water injection test. The evolution process of the hydraulic properties of fault zone under high water pressure can be divided into three successive stages: the initial infiltration stage, the splitting stage, and the scouring infiltration stage. In the initial infiltration stage, with the increase of water pressure, although the hydraulic conductivity of the fault zone increases, the growth rate is slow and overall low, indicating that in this stage short-time, large flow inrush accidents will not occur. When the water pressure is greater than the splitting pressure, the fault zone is split and the hydraulic conductivity increases abruptly, scouring occurs in the split cracks and the hydraulic conductivity increases, water inrush accident is likely to occur under the condition of sufficient water supply. The safety factor e of fault zone should be defined as the ratio of the splitting pressure P_f over the aquifer pressure P_h, i.e., $e = P_f / P_h$; when $e < 1$, water inrush may occur in the fault. To solve this kind of engineering problems, the strength of the fault zone should be enhanced or the hydraulic pressure of the aquifer should be reduced through the drainage.

Acknowledgments

The authors wish to acknowledge the National Science Youth Foundation of China (No. 41602299) and the Talent Introduction Foundation of China University of Mining and Technology (No. 102519014) for funding and supporting the study.

Corresponding editor: Abhijit Mukherjee

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