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REVIEW PAPER

Seepage problems on fractured rock accompanying with mass loss during excavation in coal mines with karst collapse columns

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Abstract
Under the background of China as a big coal-hungry country lasting till 2050, deep mining becomes more and more significant. However, deep coal seams usually have a very complex geological structure like Karst collapse columns, and excavation is often accompanied with water-inrush accidents, restricting the development of the coal industry. In order to study on seepage problems on fractured rock accompanying with mass loss during excavation in coal mines with karst collapse columns, researchers studied on water-inrush mechanism in karst collapse columns directly, researched on seepage behavior of fractured rock with pressure as the basis of studying on water-inrush mechanism indirectly, studied the fluid flow change in fractured rock regarding the change of liquid flow type in fractured rock as seepage instability, and observed and studied the phenomenon of mass loss during seepage in succession. In the following research, (1) the cementation, lithology, and match rate of testing samples, which are the foundation of the simulation study, need to be determined in more detail; (2) migrated particles in fractured rock should be distributed which are from migration, corrosion, erosion, and abrasion; (3) multi-permeate agents in the fractured geological structure, their diffusion and convection, and the related chemical reactions should be involved; (4) more and more contemporary mathematical methods will be introduced to help us to study the complex dynamic system; and (5) experimental equipment needs to be designed and improved. What we did before, do now, and will do later is to penetrate the mysteries of seepage problems on fractured rock accompanying with mass loss during excavation in coal mines with karst collapse columns.

Keywords Seepage problems · Fractured rock · Karst collapse columns · Mass loss

Background

Today, China is a big coal-hungry country; the total amount of coal has reached 3.88 billion tons in 2016, and coal will still be the major energy source in China from now on to 2050. Due to the increasing demand for coal resources and gradual exhaustion of the shallow resources, deep excavation is more and more common in most coal mines in China.

However, deep coal seams usually have very complex geological structure (Xie et al. 2015), such as faults and Karst collapse columns (see Fig. 1), and the excavation is often accompanied with water-inrush accidents, which seriously restricts the development of the coal industry (Miao and Qian 2009; Dong 2010).

A major water-inrush accident in karst collapse column happened in Fangezhuang Coal Mine, Kailuan, on June 2, 1984, the largest accident in the world's mining history. The maximum water inflow reached 2053 m^3/min, and the poured-out collapse column fillings were about 65,653 m^3, which contained clay, coal-rock waste, and rock blocks. Rock blocks were rubbed and scoured as round pebbles in the transportation process with water flow. The accident caused not only hundreds of thousands of people's difficulties in water for production and living but also ground collapse and buildings' collapse, resulting in a direct economic loss of 500 million RMB. The existence of the typical fractured geological structure of karst collapse column is the root of a water-inrush accident in this mine.

Karst collapse columns are fractured rock with variable porous and fracture structures, which are formed by mixing various fractured rock blocks of different sizes and cemented together through muddy and siliceous thin layers on their

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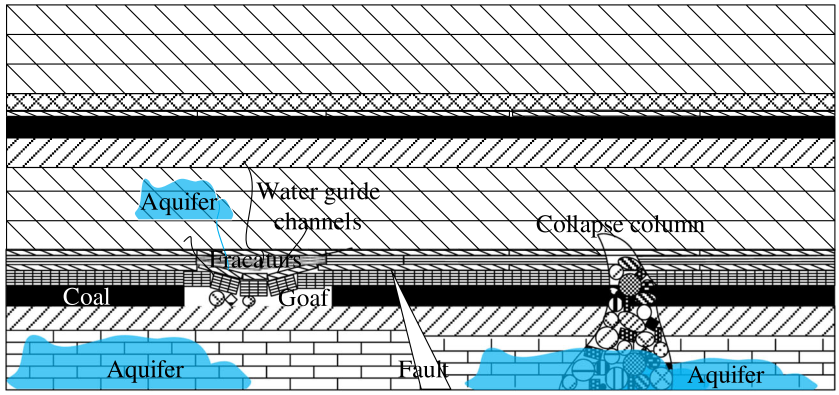


Fig. 1 Complex geological structure of deep coal seam

surfaces under the self-gravity of collapse columns or ground pressure. Mining in coal mines with karst collapse columns is often accompanied with water-inrush accidents, the main influence factors, and the mechanism of which needs to be researched to ensure the safe production of the coal industry. This is not a trivial question, but one that we are willing to explore in the current paper.

The main influence factors of water inrush in karst collapse columns are high water pressure, the through-flow channels, and certain mining stress. On one hand, pores and fractures in surrounding rock develop and expand under mining, and the stress field and the seepage field inside and around Karst collapse column change; subsequently, the network of cracks in the surrounding rock and the porous structure change evidently. On the other hand, fractured rock blocks undergo dissolution, erosion, and abrasion, and the resultant fine particles migrate and lose with the interior coal-rock waste and grains under the entrainment of water flow. As a consequence, the density, porosity, and permeability parameters are time-varying during the mass loss. When mass loss develops to a considerable degree, regional-connected pipe flow channels are formed inside the fractured rock and the confined water penetrates the roof and floor of coal seams through these channels. As the mass loss is going on, flow type changes from seepage to pipe flow, resulting in water-inrush accidents. Hence, the research on seepage problems of fractured rock mass accompanying with mass loss during excavation in a coal seam penetrated by a karst collapse column is of great scientific significance for revealing the water-inrush mechanism and prevention of water-inrush accidents.

The water-inrush mechanism in karst collapse columns

Water inrush in karst collapse columns is mostly considered to result from mining (Yin et al. 2008). During mining, fractures are developed and expanded in the surrounding rock and connected with the fractured geological structure, then water flow channels are formed; finally, water inrush happens indirectly.

Theoretical researches

In order to predict and prevent water inrush in Karst collapse columns, scholars studied water inrush in coal mines with karst collapse columns theoretically, using elastic mechanics (including thin plate theory and thick plate theory), elastoplastic mechanics, fluid mechanics, nonlinear dynamics, and so on.

Yin et al. (2008; Liu et al. 2007a, b) simplified the water-rich collapse column into an infinite thick wall cylinder under the uniformly distributed pressure; divided water inrush in karst collapse columns into two modes, the shear failure water-inrush mode occurred at the bottom and the water-inrush mode for thick wall cylinder occurred at the side face; and gave theoretical criterions for water inrush in water-rich collapse column. For the shear failure water-inrush mode that occurred at the bottom, the limit value of ground water pressure was (Yin et al. 2008; Liu et al. 2007a)

$$p = \frac{1}{a}h^2\gamma_g\lambda\tan\theta + \frac{2}{a}(H_0\gamma_d\lambda\tan\theta + c)h - Q + W \tag{1}$$

While for the water-inrush mode for thick wall cylinder that occurred at the side face, the plastic limit pressure was (Yin et al. 2008; Liu et al. 2007b)

$$p_s = \sigma_{st0}\left[H_{t_1}K^2 - \frac{1}{1-\alpha} - \left(H_{t_1} - \frac{1}{1-\alpha}\right)\left(\frac{r_b}{r_a}\right)^B\right] \tag{2}$$

Based on thick plate theory, a mechanical model for water inrush of collapse columns was established, which indicated that the boundary conditions and strength of water-resisting strata played important roles in influencing water inrush of collapse pillars and determined the critical water-inrush pressure by both relative thickness and absolute thickness of water-resisting strata (Tang et al. 2011).

Song et al. (2011) derived the criteria of water inrush in collapse columns by the equations of an elliptical cross-section of a thick cylinder mechanical model (see in Fig. 2) by using complex functions, elastoplastic mechanics, and other related theories.

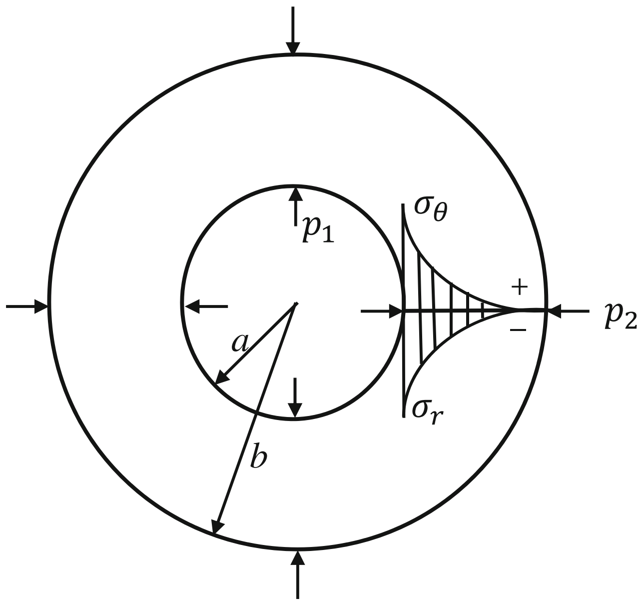


Fig. 2 Thick-walled cylinder model and stress distribution (Song et al. 2011)

Xu et al. (2005, 2006) analyzed the mechanism to conduct water in karst collapse columns by the limit equilibrium principle; studied the stress distribution in the karst collapse column by the gravity, the pressure of ground water, and the other stress around; deduced the criterion of conducting water; and revealed the factors resulting in conducting water in karst collapse columns.

Wang and Li (2010) analyzed the changes of stress, strain, and plastic zone of the collapse column and its surrounding rock based on the theory of elastic-plastic mechanics and fluid mechanics, established a physical model of predicting water inrush caused by collapse columns, identified the hazardous area, and picked up the water-inrush criterion as follows:

$$\begin{cases} L_1 = \dfrac{M}{2f}\left(\ln\sigma_y - \ln N_0\right)\dfrac{1-\sin\phi}{1+\sin\phi} \\ L_2 = r_0\left\{\left[\dfrac{2+m-(2+m)\sin\phi}{3+\sin\phi}\cdot\dfrac{P}{P_W}\right]^{\frac{2+m-(2+m)\sin\phi}{2[1-m+(3+m)\sin\phi]}} - 1\right\} \\ L_3 = \dfrac{h}{h'}\cdot\dfrac{k_j}{k_p}\cdot r_0\cdot\exp\left[\dfrac{\pi k_p\left(h'^2-h^2\right)}{Q}\right] - R_0 \\ L_1 + L_2 + L_3 \geq L \end{cases} \qquad (3)$$

Bai et al. (2013) established a mechanical model (a plug model) to describe the behavior of water seepage flow in coal mines with karst collapse columns. Considering the nonlinear relationship between groundwater inflow and factors, such as geological structure, aquifer, groundwater pressure, etc., Ma and Bai (2015) established a groundwater inflow prediction model of karst collapse column and presented a new parameter optimization scheme of nonlinear gray Bernoulli model using the genetic algorithm. Ma et al. (2015a) also created a numerical fast Lagrangian analysis of continua in a three-dimension model to understand the mechanical state of a coal seam penetrated by a karst collapse column during extraction.

Numerical simulations

Numerical simulation is the main method for researching water-inrush mechanism in fractured geological structures. Scholars use the FEM method and software, such as, RFPA, FLAC, and ANSYS, to simulate water inrush in coal seams with karst collapse columns.

Song et al. (2011) verified the analytical solution of stress distribution on the edge of the thick cylinder inside uniformly distributed pressure by FEM method. Zhang et al. (2009) used the FEM method to simulate the deformation of surrounding rock and seepage field of pore water with a full-water karstic collapse column during mining and discussed the influence of pore water pressure on the plastic deformation of surrounding rock (see Fig. 3).

Li et al. (2009) investigated the activation of Karstic collapse columns by combined FEM method and RFPA^{2D}-Flow, studied the influence of the height of karstic collapse columns and the magnitude of water pressure on the delayed time of water inrush, and illuminated the transformation of floor rock mass from water-resisting strata to inrush pathway.

Yin and Wang (2003) simulated the full excavation process in the coal seam existing in a collapse column by FLAC^{3D} to study the effect of karstic collapse columns on surrounding rock mass yield and water inrush from coal floor. Wang and Yang (2009) simulated the full-water filling and non-water filling collapse columns and the collapse column in coal floor by FLAC^{3D} to analyze the change in stress, strain, and plastic area of collapse column and its surrounding rocks. Li et al. (2013) used the rising level of confined water head and the change of seepage quantity as simplified criterion, simulated the whole water-inrush process of karst collapse columns which was water filled and water conducted in edge above confined water by the further developed FLAC^{3D}, and acknowledged the characteristics of seepage and the dangerous water bursting area in the collapse column. Ma et al. (2015a) studied the mechanical behavior of a coal seam penetrated by a karst collapse pillar by FLAC^{3D} based on a numerical fast Lagrangian analysis of continua in a three-dimensional model to understand the mechanical state of a coal seam penetrated by a karst collapse pillar during mining panel extraction, and analyzed the plastic zone development, as displayed in Fig. 4.

Xu et al. (2006) studied the stress distribution in the Karst collapse column by ANSYS. Liu and Xiong (2007) studied the water-inrush mechanism and law using ANSYS through translating solid-fluid coupling equations (Yang and Zhao 1998) into thermal analysis problem.

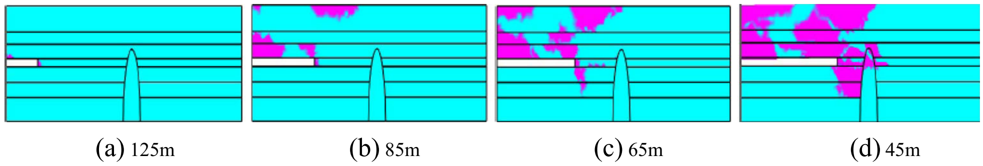


Fig. 3 Extension of plastic deformation region varying with mining (Zhang et al. 2009)

Later, with the upsurge of multiphase flow research, COMSOL and PFC were widely used to simulate water-inrush problems in coal mines with karst collapse columns.

Yang et al. (2008) considered the water inrush due to karst collapse columns to be a coupled process and studied the complete fluid flow process in a confined aquifer, fractured zone, and tunnel using COMSOL Multiphysics based on Darcy equation in a confined aquifer, Brinkman equation in the fractured zone, and Navier-Stokes's equation in the tunnel. Zhu et al. (2009) proposed a constitutive law for rock failure under coupled rock heterogeneity, deformation, and seepage; reproduced the complete water-inrush process in Fangezhuang Coal Mine by COMSOL; assessed the possibility for water inrush; and clarified the associated mechanical mechanism. Zhang et al. (2013) used COMSOL Multiphysics to obtain the distribution of the porosity and seepage velocity in the collapse column at different times and calculate the seepage discharge (see Fig. 5). Liu and Zhang (2017) analyzed the distribution of column pressure and different moment shear forces and obtained the corresponding curves at a different time by COMSOL.

Hu (2015) established a PFC/FLAC coupling model of coal floor with fractured geological structure; simulated meso-crack initiation during workface advancing; and investigated the rise, expansion, and inrush from the floor of the confined water.

Experimental researches

Experimental research is the most direct method to study water inrush in coal mines with karst collapse columns, which is always combined with theoretical study or numerical simulations.

Based on a TXFC-3 triaxial permeability instrument, Xiang (1993) carried out experiments on water inrush from natural hydraulic fracturing and pointed out that the natural hydraulic fracturing effect was an important reason of water inrush in a full-water Karstic collapse column. Based on the geological condition and mining technical conditions of the object workface, Wang et al. (2010) established a similar simulation using a self-developed special test system and studied the water-inrush process of collapse column both in the floor and through the coal seam by the similar simulation and numerical simulation software. To investigate the seepage mutation mechanism in the hidden collapse column, Zhang et al. (Zhang 2016; Zhang et al. 2016a, b) developed a fractured

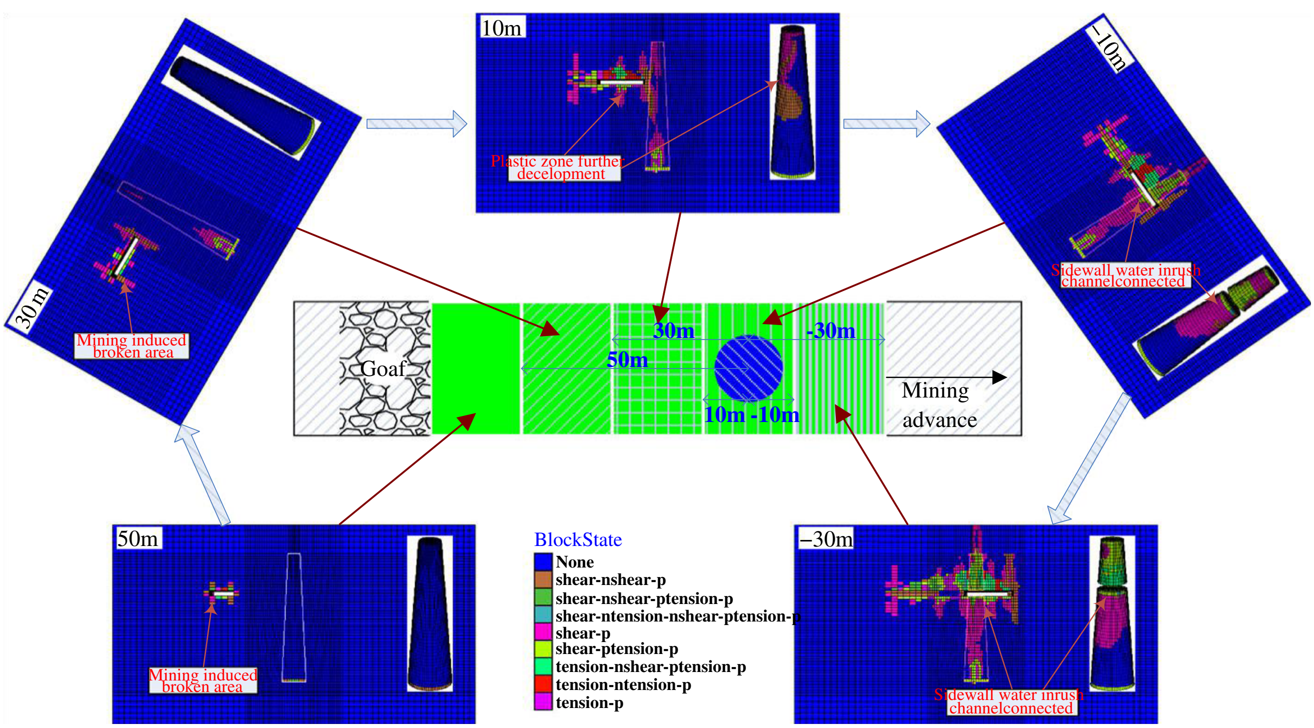


Fig. 4 The plastic zone development of a coal seam penetrated by a karst collapse column (Ma et al. 2015a)

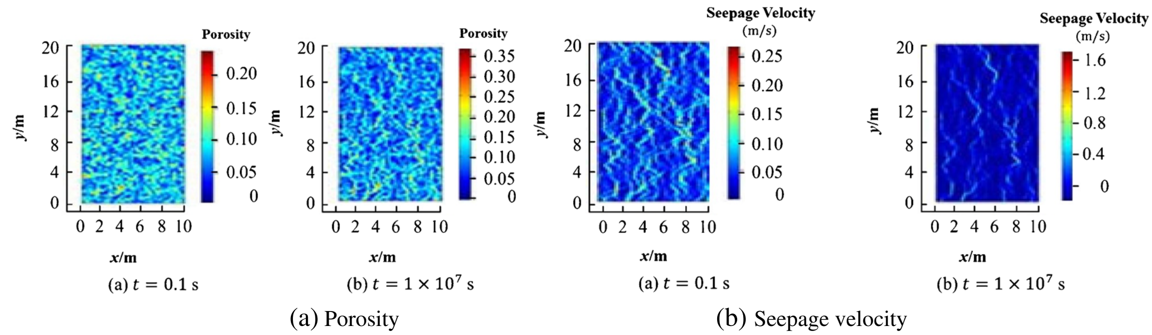


Fig. 5 Distribution of porosity and seepage velocity in the collapse column (Zhang et al. 2013)

rock permeability test system, the experimental loading system of which was shown in Fig. 6, and conducted a series of experiments to examine the seepage in the collapse column under different floor damage conditions.

With the deepening of research, a single method cannot meet the needs any longer; scholars studied the field of water inrush in Karstic collapse column comprehensively using theoretical research, numerical simulation, experimental research, and so on.

The above studies expressed concern on the relationship between water inrush in coal seams with the fractured geological structure and the mining effect in surrounding rock but ignored the structural characteristics of the fractured geological structure itself. Taking the karst collapse column as an example, the columns are mainly accumulated by fractured rock blocks and silt, with high porosity and complex pore and fissure structure.

Water permeate behavior in fractured rock

In essence, water inrush in karst collapse columns is divided into two types. In the first type, due to mining, fractures are developed and expanded in the surrounding rock and connected with the fractured geological structure, then water flow

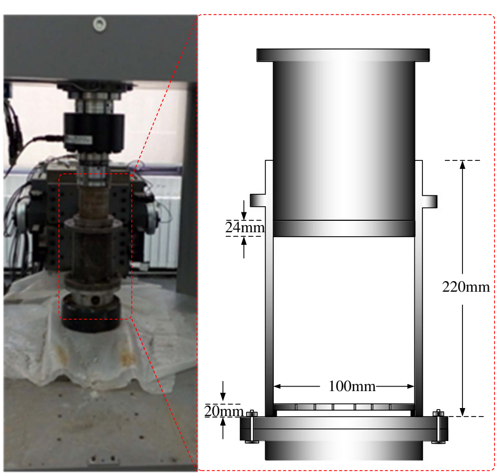


Fig. 6 Experimental loading system (Zhang 2016; Zhang et al. 2016a, b)

channels are formed; finally, water inrush happens indirectly. In the second type, the fractured geological structure itself is the water flow channel, and water inrush happens directly (Yin et al. 2008). Researches in the second type mostly use the seepage theory of fractured rock as the research foundation.

Scholars (Kogure 1976; Mc Corquodal et al. 1978; Stephson 1984; Pradeep Kumar and Venkataraman 1995; Xu et al. 1998; Qiu et al. 2004; Gao and Wang 2007; Ding et al. 2010) firstly started their experimental researches on a non-pressure fractured rock since the 1970s, which could be taken as references for researches on fractured rock with pressure, even though the action of rock mass deformation and axial loading had not been considered.

Researches on seepage behavior of fractured rock with pressure are the basis of studying on the second type of water-inrush mechanism in coal mines with karst collapse columns. The research team (Miao et al. 2003, 2004, 2009; Sun et al. 2003; Ma et al. 2007a, b; 2009; Liu et al. 2003, 2012; Huang et al. 2005; Li et al. 2008; Miao et al. 2011; Ma et al. 2014, 2015b; Yu et al. 2016; Wang et al. 2014a; 2013a, b, c; Kong et al. 2013; Yu et al. 2015) in China University of Mining and Technology had carried out a series of related theoretical and experimental researches on the permeability of fractured rock with pressure.

Miao et al. (2003, 2004, 2009) thought that seepage in fractured rock mass disobeyed Darcy's Law and considered it as a nonlinear dynamic system and analyzed the stability and bifurcation of the system by Lyapunov's first method (see Fig. 7).

Based on the test system measuring seepage properties of broken rock (see Fig. 8), permeability of fractured rocks with pressure were tested by loading control method and porosity control method (Sun et al. 2003; Ma et al. 2007a, 2007b, 2009; Liu et al. 2003, 2012; Huang et al. 2005; Li et al. 2008; Miao et al. 2011; Ma et al. 2014, 2015b; Yu et al. 2016), as listed in Table 1; the former was used to test permeability under different seepage velocities when the axial loading keeps stable, while the later was used to test permeability and non-Darcy β factor under different seepage velocities when the porosity keeps stable.

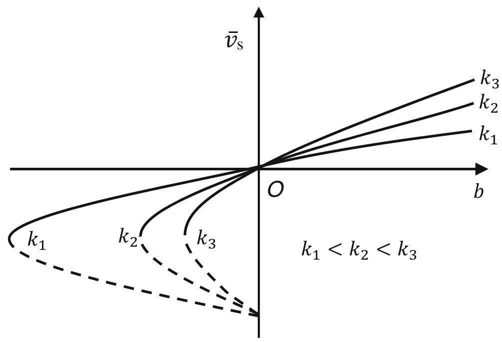


Fig. 7 Bifurcation curve for the flow systems with different controlling parameter (Miao et al. 2004, 2009)

Wang et al. examined the permeability characteristics of disc-shaped sandstone during bending and shearing deformation, analyzed variation characteristics of the peak load (Wang et al. 2014a, 2013a), measured the permeability and non-Darcy flow β factor of fractured coal samples under five different porosity levels, studied on the type change of liquid flow in fractured coal samples (Wang et al. 2013b), tested the permeability characteristics of fractured coal with different grain sizes under two experimental schemes (Wang et al. 2013c), and tested the permeability of crushed gangues with six different particle sizes during compaction (Kong et al. 2013).

Yu et al. (2015) used the original designed compacting device and seepage experiment system of fractured rock to complete the seepage experiment of cemented fractured mudstone and analyzed the influence of cementing material, water pressure, fractured mudstone size distribution, and initial porosity on seepage characteristics.

In the above researches, water flow in fractured rock was considered as stable in the seepage process, which obeyed or disobeyed Darcy's Law. Actually, it can be observed that when a water-inrush accident happens, large numbers of rock blocks, coal, and rock blocks with different sizes rush out with water, and suddenly the water flow type changes.

Fluid flow change in fractured rock

Scholars' studies on fluid flow change started at the beginning of this century, experimentally and theoretically.

In the beginning, scholars could not study further on fluid flow change using the MTS testing system but could only discuss seepage stability by the sign of the non-Darcy β factor theoretically (Li 2006; Li et al. 2007; Chen et al. 2010). Whether the non-Darcy flow β factor is negative, is the flag for the theory of seepage instability to explain water inrush (Li 2006; Li et al. 2007; Chen et al. 2010), because when the non-Darcy flow β factor is positive, the permeability of non-Darcy flow is less than that of Darcy's flow, and the seepage system is stable; the seepage flow would be instable when the non-Darcy flow β factor is negative, and water inrush may happen. The formula is as follows:

$$4\sum_{i=1}^{n}\frac{\rho_0(p_0-p_n)}{c_a^i}\cdot\sum_{j=1}^{n}\frac{\beta_j h_j}{c_a^j}-\left(\sum_{i=1}^{n}\frac{\mu h_i}{c_a^i k_i}\right)^2=0 \tag{4}$$

Based on the traditional theory of seepage mechanics, the non-Darcy flow β factor cannot be negative, so seepage instability cannot occur. Restricted by the supercharger volume in the seepage circuit in the MTS815 rock mechanics servo system, deficiencies existed in references (Li 2006; Li et al. 2007; Chen et al. 2010). Therefore, if the loaded axial pressure is lower or the specimen's porosity is larger, the variable range of seepage velocity is small, the test time is short, the pressure gradient is little,

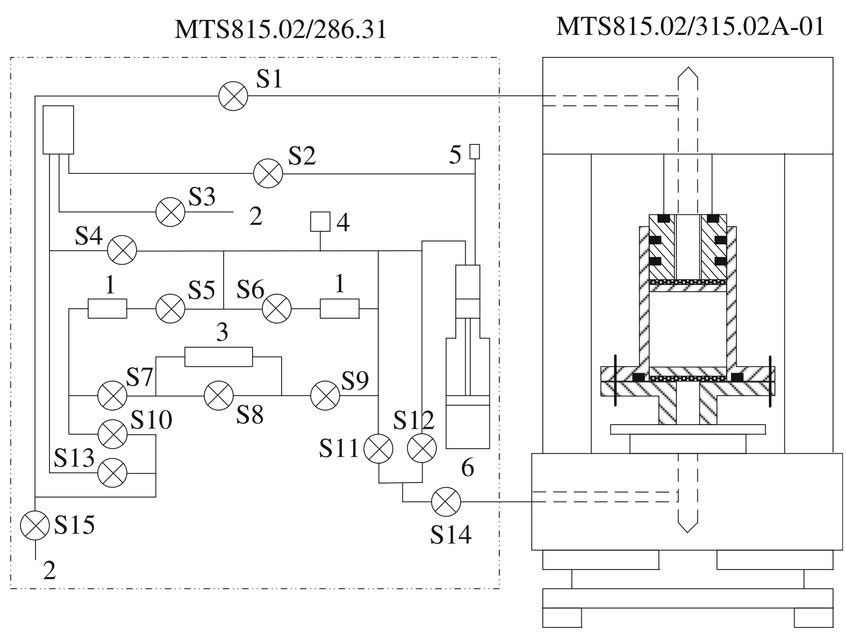


Fig. 8 Test system measuring seepage properties of fractured rock (Miao et al. 2004)

Table 1 Tests of seepage properties of broken rock

Testing methods	Testing objects	Scholars	Year
Loading control method	Broken sandstone	Sun, Li, Huang et al. (2003)	2003
	Broken shale	Ma, Miao, Li et al. (2007a)	2007
	Broken mudstone	Ma, Miao, Zhang et al. (2007b)	2007
	Broken coal	Ma, Miao, Chen et al. (2009)	2009
Porosity control method	Broken sandstone	Liu, Miao, Chen (2003)	2003
	Over-broken sandstone, shale, coal	Liu, Fei, Fang (2012)	2012
	Broken sandstone	Huang, Tang, Miao et al. (2005)	2005
	Broken sandstone, coal gangue, limestone	Li, Miao, Chen et al. (2008)	2008
	Broken sandstone	Miao, Li, Chen et al. (2011)	2011
	Crushed mudstone, limestone, sandstone	Ma, Miao, Jiang et al. (2014)	2014
	Crushed mudstone	Ma, Bai, Chen et al. (2015b)	2015
	Broken gangue, mudstone, sandstone, limestone	Yu, Chen, Ding et al. (2016)	2016

and seepage is difficult to reach turbulence state, so the phenomenon of piping and breakdown does not occur.

In order to overcome the defect of the small supercharger volume in the seepage circuit, Yao (2012) designed an equipment and the experiment system (see Fig. 9); tested the seepage mutation rule under the conditions of different proportion, axial pressure, and so on; and obtained the filling material flow velocity, porosity, water pressure, and flow volume as the time for fractured rock mass, but the equipment can test the fluid flow change for only about 3 min (see Fig. 10), which is the greatest shortage of this equipment. Ma (2013) improved Yao's design, shortened the piston, and lengthened the overflow tank. The common defect of the above two test systems is that the precision of pressure control is not high enough.

Considering that the collapse column has experienced quite a long time of mass loss before water inrush, the test system should adapt to the requirement of longer time penetration and the inlet pressure of rock sample must keep stable. In accordance with these requirements, subsequently, Wang et al. (2013b, 2013c; Kong et al. 2013) measured the permeability and non-Darcy flow β factor of specimens under five different porosities; found that when the overall pressure of the relief valve was continuously increased until the specimen was broken down, the flow type of liquid in the specimen changed from seepage to pipe flow; and analyzed the correlation between the breakdown pressure gradient and the porosity and the relationship between the breakdown pressure gradient and the critical pressure gradient at seepage instability. However, water flow changing in fractured rock had been realized, but it could not be tested lasting for a long time under a stable pressure.

Subsequently, a new designed sustainable pressurized osmosis device for seepage test of rock mass was established, as shown in Fig. 11, which could control pressure stability. Based on this seepage test system, Wang carried out a series of seepage tests (Wang et al. 2014b, 2015a; Wang 2014), which could last for a longer time (about 18,000 s) with a stable water pressure (see Fig. 12).

Based on the collection of the mine typical fault and sinkhole, late-type water-inrush cases and the analysis of the features, Li et al. (2011) designed and conducted a water-inrush simulation experiment from structure of fractured zone under high water pressure, found that the water inrush from the structure fractured zone under high water pressure condition would be a conversion process of the "pore flow to crack flow to pipeline flow" with the inner composition structure variation, and pointed out that the vadose conversion would be the inherent mechanism of the late-type water inrush from the structure fractured zone, but which was not described qualitatively and quantitatively. Based on the example analysis of water inrush through fault in the fully mechanized top-coal caving face, Qiao et al. (2013) designed similar material

Fig. 9 Yao's seepage test system (Yao 2012)

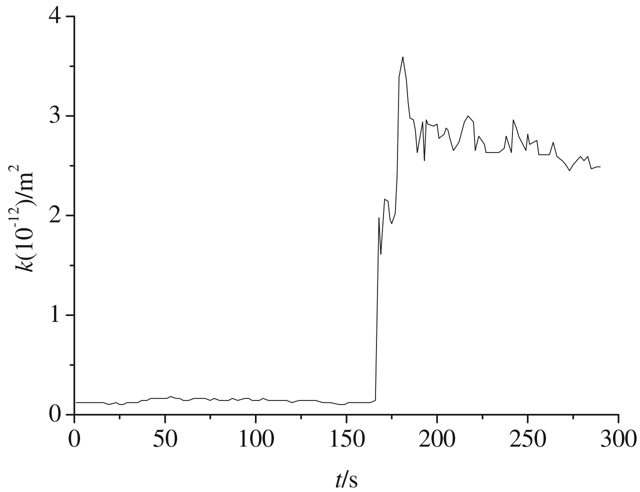


Fig. 10 The permeability evolution in Yao's research (Yao 2012)

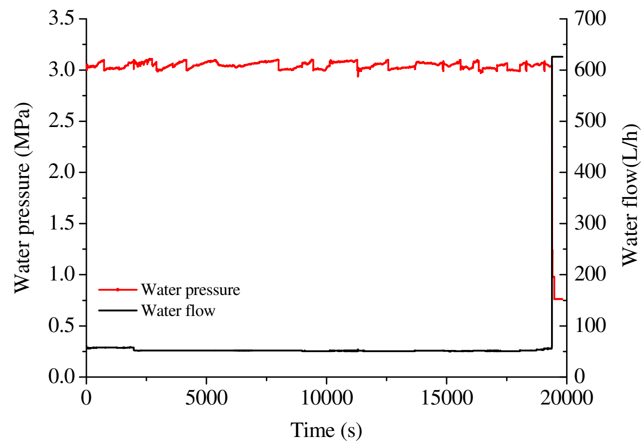
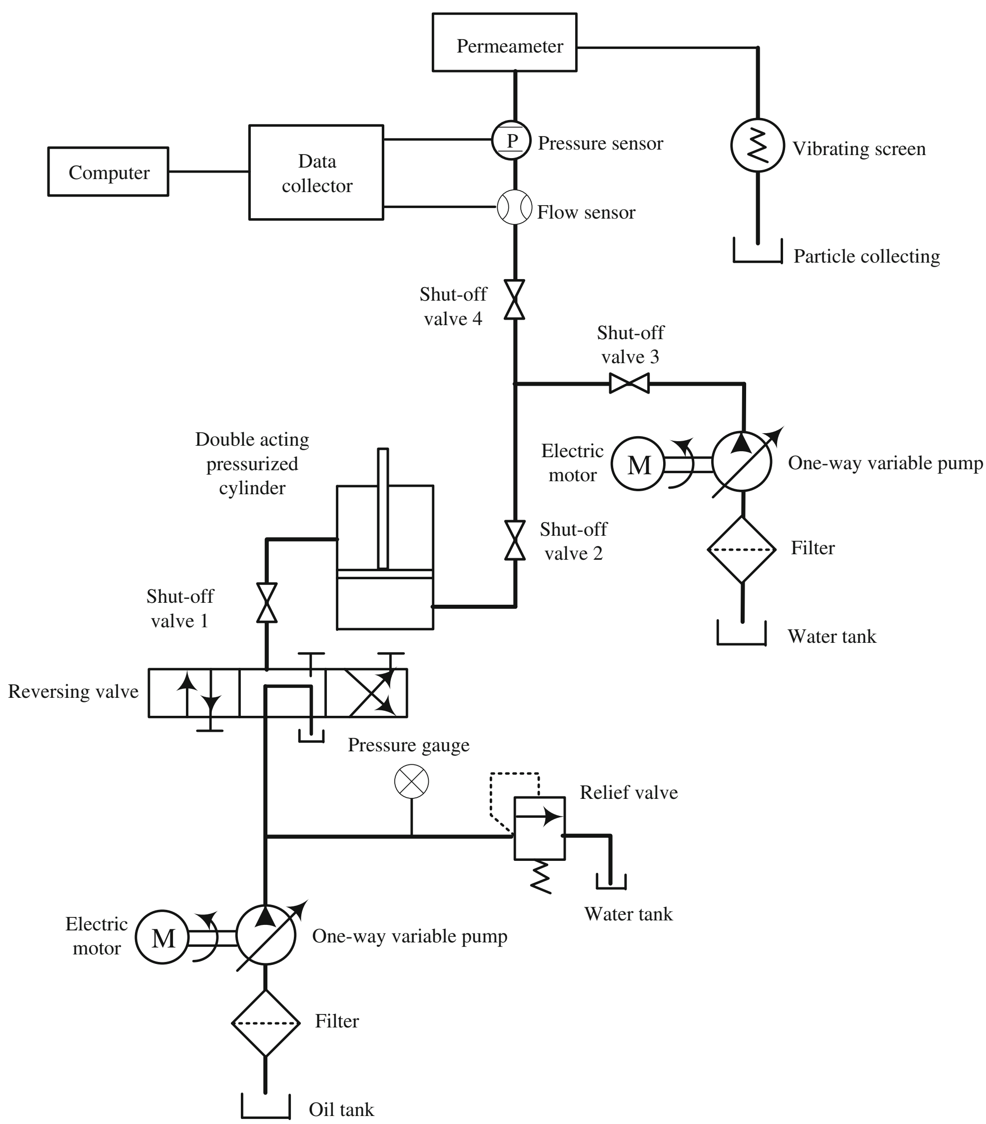


Fig. 12 The stable water pressure in Wang's research

Fig. 11 A sustainable pressurized osmosis device for seepage test of rock mass (Wang et al. 2014b, 2015a; Wang 2014)



simulation models of water inrush aroused by fault activation under different water pressures, including the coal mining under the hanging wall and foot wall of fault; verified that the water inrush aroused by fault activation in fully mechanized top-coal caving had experienced the process of pore fluid, fracture flow, and pipe flow; and identified the time when the pore fluid converses into fracture flow according to the variation law of filling emission quantity along with time, obtaining the time when the fracture flow converses into pipe flow according to the change law of voidage along with time, which explained the conversion phenomenon from seepage to flow of water inrush aroused by fault activation in fully mechanized top-coal caving, and was anastomotic with the expressive characteristics of field examples.

Even though the change of liquid flow type in fractured rock is regarded as seepage instability, which supplies the seepage instability theory test supports, mass migration and loss during seepage in fractured rock has not been considered, which had been observed in seepage tests for fractured rock, and it is the main factor of fluid flow change in fractured rock.

Mass migration and loss in seepage process of fractured rock

The phenomenon of mass loss in the seepage process of fractured rock was ignored in those researches above. In fact, a large quantity of fractured rock and coal were rushed out in the process of water inrush in collapse columns; outthrust had a great disparity in diameters. Scholars observed the phenomenon of mass loss during seepage and studied on this field in succession.

To study the water-inrush mechanism of collapse column and complete testing basis for water inrush of collapse column, a new seepage testing system for variable mass of fractured rock to test the nonlinear seepage characters of variable mass of fractured mudstone was designed (Chen et al. 2014a; b; Wang et al. 2014c, d, e, 2016a, 2017; Kong et al. 2017a, b) (see Fig. 13), containing a sustainable pressurized osmosis device and an open penetration instrument, which could realize particle migration.

Fig. 13 The new seepage testing system for variable mass of fractured rock (Chen et al. 2014a, b; Wang et al. 2014c, d, 2016a, 2017; Kong et al. 2017a, b)

Chen et al. (2014a, b) established a method for calculating permeability parameters of the variable mass of fractured rock based on the time series of pressure gradient and seepage velocity and studied the time-varying rules of losing weight, porosity, permeability, non-Darcy flow β factor of mudstone during the seepage process. Wang and Kong et al. (Wang et al. 2014c, d, e, 2016a, 2017; Kong et al. 2017a, b) recorded and calculated the duration time of seepage burst, weight of gushed particle, change rate of gushed particle weight, and change rate of porosity and obtained the change rules under seepage pressure and initial porosity (see Fig. 14); they also established a non-Darcy seepage dynamic system for fractured rock with mass loss based on the accelerated experiment on permeability for fractured mudstone with mass loss and considered the effect of the accelerated factor on the rate of mass loss, but they had not considered the mass loss resulting from corrosion, erosion, and abrasion by water-rock interaction.

These researches are great steps forward to study the permeability of fractured rock with mass loss, but the test device was simple and still needs further improvement. Wang, Kong, and Chen et al. improved the test devices for seepage of fractured rock with mass loss (Wang and Kong 2017; Wang and Kong 2015; Wang et al. 2014f, 2015b, 2016b, c; Kong et al. 2016a, b, c, d; Wang and Kong 2018), such as the new test systems in Fig. 15, which provided an experimental basis for the further study on seepage in fractured rock with mass loss.

Besides, Bai (2008) picked up a seepage stability model (plug model) to describe the water-inrush mechanism in collapse columns; he thought that the changing of porosity resulted from the mass transfer in fractured rock, considering both mass loss and mass supply, but he had not analyzed the reason of mass loss further. Yao et al. (Yao 2012; Yao et al. 2013, 2014, 2018) thought that the varying of mass and permeability parameters of fractured rock were because of particle migration in collapse columns, which eventually led to water inrush; he coupled the deformation of fractured rock structure, seepage, and particle migration and established a fluid-solid coupling dynamic model of fractured rock

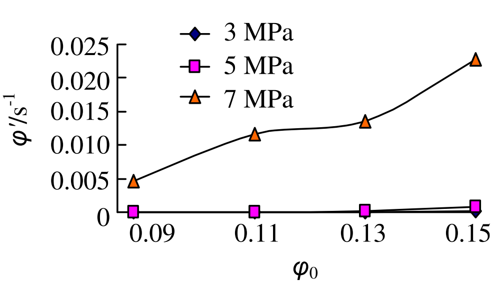


Fig. 14 The curve of the change rate of porosity φ' changing with initial porosity φ_0 (Wang et al. 2014e)

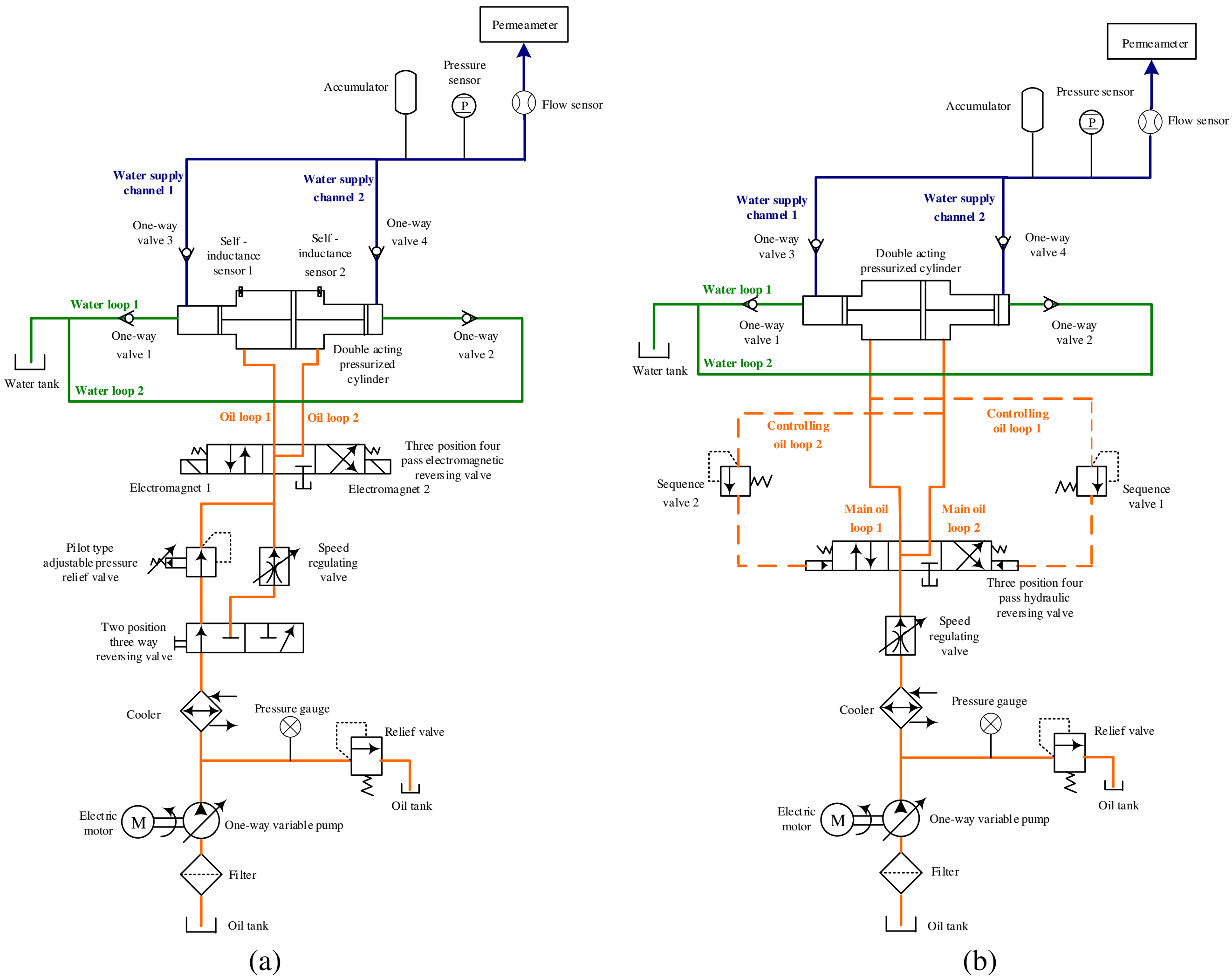


Fig. 15 The improved test systems for seepage of fractured rock with mass loss (Wang and Kong 2017; Wang et al. 2016b, c)

considering mass loss, but his research had certain limitations: it seemed water flow as linear Darcy flow, and its testing time was so short that it could not describe time-change rules of fractured rock with mass loss completely.

The above references studied the problem of mass loss of fractured rock in seepage process, which provides a reference for the seepage problem of fractured rock with mass loss during excavation in mines with karst collapse columns.

Expectations

Presently, the prepared samples in seepage tests are mainly un-cemented fractured rock, which is simulated by kinds of sizes of the single-lithology rock blocks in a certain match rate. Actually, fractured rock in karst collapse columns is mixed by various fractured rock blocks of different sizes, different lithology, and cemented together through muddy and siliceous thin layers on their surfaces. The cemented fractured rock has lower permeability and higher mechanical properties. After the external disturbance, the cementation is easily destroyed, the integrity of the rock declines rapidly, reappears loose, and the permeability increases. In addition, cemented fractured rock will hydrate with water, and the permeability will increase further. In further research, it is of great significance to research permeability characteristics and the mass loss and migration laws in cemented fractured rock, and it is very important to study the lithology and match rate of the testing samples, which will be much closer to the actual situation of fractured rock in karst collapse columns.

In previous research work, scholars studied the characteristics of physical quantities, for example, strain, stress, porosity, permeability, etc. More factors should be introduced to discuss the water flow in fractured rock, such as the triple effects of surface roughness (Zeng et al. 2018; Jin et al. 2017), self-affine fracture (Zeng et al. 2018; Jin et al. 2017), scale and size effects (Jin et al. 2017), and so on.

Currently, the mass migration and loss have been considered in the researches on water inrush in coal mines with karst collapse columns. In our previous studies, particle migration and loss were observed and tested, but we have not distributed migrated and lost particles clearly. How to distribute particles which are from migration, corrosion, erosion, and abrasion will be one of the most urgent problems to solve.

When studying the phenomenon of the mass migration and loss in fractured rock, we even took water as seepage agent and took the seepage as a single fluid. Actually, fine particles also permeate in the fractured geological structure, and perhaps the diffusion, convection of fine particles in water, and the related chemical reactions are involved, which is one of the directions of the next step. It is noteworthy that water that acted as the seepage agent now is the Newton fluid, while the mixed water-fine particles that acted as the seepage agent will be the non-Newton fluid (Du et al. 2017). If we took particle as another seepage agent, we have not described the movement of the migrated particles in fractured rock during the seepage process yet, which is complex, nonlinear, and time-varying. Confirming the fluid type of the seepage induced water-inrush accident in coal mines with karst collapse columns, establishing the movement equations of seepage agent(s) and analyzing the complexity, nonlinearity, and the time-varying characteristics of the movement of particles in fractured rock are our aims in our continuous researches.

The stability of the nonlinear dynamic model of a seepage system for fractured rock with mass loss is analyzed to determine whether water inrush happened in coal mines with karst collapse columns. In this nonlinear dynamic model, the movement equations of seepage agent(s); the constitutive relation of rock strata, stress-strain-seepage, etc.; the kinds of coupled relationships; the time-varying boundary conditions; and more and more equations and control parameters are involved. In further research, we should introduce more and more contemporary mathematical methods to help us to confirm these control parameters in the nonlinear dynamic model, such as genetic algorithm, gray theory, and fuzzy mathematics, perhaps which will help us to obtain the important achievements even if a breakthrough in water-inrush mechanism in coal mine with karst collapse columns.

The experiment is an important means of studying seepage problems on a fractured rock with mass loss during excavation in coal seams with karst collapse columns; it is necessary to improve the existing seepage testing system, which is also a hot point in further days.

In addition, micro-seepage and multi-scale seepage (Chen and Yu 2015) are new viewpoints on the research on the water-inrush mechanism in a coal mine with karst collapse columns. What we did before, do now, and will do later is to penetrate the mysteries of seepage problems on fractured rock accompanying with mass loss during excavation in coal mines with karst collapse columns.

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Compliance with ethical standards

Conflicts of interest The authors declare that there is no conflict of interest.

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