Research Article

A Study on the Seepage Flow Characteristics and Disaster-Causing Mechanism of Collapse Column

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Factors such as the hydrogeological conditions, the lithological characteristics of the columns' components, and the lithological characteristics and stress conditions of the coal seam roof and floor are interrelated and jointly affect column collapse. In this study, the disaster-causing mechanism of column collapse was studied. Based on the system theory, a collapsed column is divided into the column and the surrounding fissure zone as two subsystems for analysis. And, the permeability coefficient of the broken rock under different conditions was measured by a self-designed equipment. The variations of the permeability coefficient for rock samples with different particle diameters, different axial pressures P_a , and different seepage velocities were further studied. Through phenomena analysis and experimental data processing, it was concluded that, under the same pressure state, smaller particle diameter meant smaller permeability coefficient; with the increase of axial pressure, the permeability coefficient decreased; and the larger the water flow velocity was, the smaller the permeability coefficient became. For particle diameter $\Phi = 2.5\text{--}5\text{ mm}$ or larger, the tiny particles formed by randomly washing and breaking in the water flow blocked some of the channels. For particle diameters smaller than $\Phi = 2.5\text{--}5\text{ mm}$, the smaller permeability coefficient was attributed to the turbulence resulting from non-Darcy flow. The study on the permeability of the fractured rock mass clarified the mechanism of water inrush from the fissure zone of the collapsed column: the collapsed column itself was impermeable, and the permeability of the fissure zone around the collapsed column was related to the lithological characteristics of the rock within the fissure zone and the sequencing of rock strata. When mining coal in areas with collapsed columns, experiments on collapsed columns and fissure zones are prerequisites. This study has a certain referential value for coal mining in this region.

1. Introduction

According to incomplete statistics, from January 2001 to December 2017, there were a total of 182 water inrush accidents in China, resulting in 1807 deaths and 73 missing. During the four years from December 2013 to December 2017, there were 32 floor water inrush accidents (42.1% of all water inrush accidents), causing 153 deaths (45.1% of deaths from water inrush accidents) [1]. Column collapse accounted for more than 90% of these accidents [2, 3]. In developed coal-producing countries [4, 5], it is usually possible to locate coalfields in regions with simple hydrogeological conditions and adopt the method

of open-pit mining or room [6] and pillar mining [7] to reduce or totally avoid the occurrence of such water hazards. However, for countries with relatively few coal resources, it is necessary to mine coal above the karst aquifer [8, 9]. Karst collapsed columns are distributed in more than 20 coalfields in North China, as well as in the provinces of Shandong, Jiangsu, Shanxi, etc. [10]. There are four main types of collapsed columns: conical collapsed columns, cylinder collapsed columns, leaning tower collapsed columns, and irregular collapsed columns [11, 12], as shown in Figure 1. Column collapse can destroy the coal seam and affect fully mechanized coal mining [13, 14], directly impairing the safety and efficiency of coal production.

FIGURE 1: Four types of collapsed columns.

In recent years, scholars have conducted much research on water inrush from collapsed columns, and a systematic approach has gradually been formed. Qian [15] studied the discovery, nomenclature, distribution, and forms of collapsed columns in North China and proposed that collapsed columns were a product of gypsum karsts and explained their formation mechanisms in detail. Based on years of investigations, Yu et al. [16] designed their own system to test the permeability of cemented broken rocks and analyzed the impact of different factors on their water-resisting ability, providing a new perspective for research on the fissure zone of collapsed columns. Liu et al. [17] performed a numerical simulation with a plastic damage model based on seepage theory and studied the mechanism of water inrush from karst column collapse under confining pressure as a cascade disaster caused by geological and coupled hydromechanical factors. Zhang et al. [18] developed a physical test system for the seepage model of column collapse and formulated similar materials for fluid-solid coupling tests that can be used for permeability adjustment, providing new test materials, equipment, and related methods for the discovery of mining's influence on the seepage mechanism evolution of column collapse.

In the abovementioned studies, the connection between mining wall rocks and aquifers has been fully considered, but the structure and permeability characteristics of collapsed columns are ignored. The structure characteristics of rock are

the basis for studying water inrush from the coal seam floor, and the abrupt change of the rock's permeability is an important piece of information for predicting water inrush in a coal mine. As a defect structure in the rock, the karst collapsed column is the main path through which the coal seam comes into contact with the underlying aquifer. In its affected zone, the rock cracks or becomes loose. In this study, we employ an experimental method to study the permeability characteristics of the floor rock, including the permeability characteristics of the intact coal seam floor, the collapsed columns, and the fissure zone around the collapsed columns and the permeability variation with confining pressure imposed on the rock samples. This provides the basic parameters for research on water inrush from column collapse under an intact coal seam floor.

2. Materials and Methods

2.1. Experimental Methods and Principles. In this study, with an MTS815.02 electrohydraulic servo rock mechanics system and the transient-state method, the stress-strain process and the permeability with changing ambient pressure for an intact rock sample were analyzed. The experiment mechanism is shown in Figure 2. Water pressure was simultaneously imposed on the top and bottom of the rock sample, and by reducing water pressure from the bottom, the initial pressure difference was

obtained. The existence of fissures inside the rock sample led to the rapid attenuation of pressure difference; the control system recorded the signals of pressure difference, based on which the permeability k of the rock sample was calculated. Due to the large permeability of the fracture medium, adoption of the transient-state method may result in the immediate disappearance of the pressure difference between the two ends of the rock sample or reduce it to a particularly small value. Therefore, the steady-state method was more appropriate for the experiment on a broken rock mass. The permeability apparatus for compacting broken rocks could provide axial pressure and allow water exchange, and based on the steady-state method, the stress-strain process and the permeability with changing ambient pressure for broken rocks of varied particle diameters were tested [19–21]. The experiment mechanism of the steady-state method is shown in Figure 3. The water pressure difference at both ends of the rock sample when seepage flow was in a stable state was recorded. The permeability coefficient was calculated based on the deformation formula of Darcy's law, as shown in Equation (1):

$$K = \frac{QL}{A(h_1 - h_2)}, \quad (1)$$

where Q is the amount of water flow, which can be obtained via the plunger velocity, cm^3/s ; A is the cross-sectional area of the rock sample, cm^2 ; L is the height of the rock sample, cm ; and $h_1 - h_2$ is the water level difference of the rock sample.

2.2. Experiment Material. The samples were divided into three groups: the rock of the collapsed column, the rock of the fissure zone around the collapsed column, and the rock of the intact coal seam floor. The sampling sites were the X-187-08 collapsed column revealed by the track of the 10-108 working face of the Tuanbai Coal Mine of Huozhou Coal electricity Group Co. Ltd., the fissure zone around the collapsed column, and the intact coal seam floor 150 m in height above the collapsed column.

Considering that the degree of cementation and compaction at different strata of the collapsed column varies, the core of the collapsed column was divided into three sections: upper (0–5 m), middle (5–10 m), and lower (10–15 m). 5 samples were taken from each section, totaling 15 samples.

In testing the permeability of the broken rock, the rock sample was crushed into particles that were further classified into five groups based on their diameters: particle diameter 1 ($\Phi = 15 \text{ mm} - 20 \text{ mm}$), particle diameter 2 ($\Phi = 10 \text{ mm} - 15 \text{ mm}$), particle diameter 3 ($\Phi = 5 \text{ mm} - 10 \text{ mm}$), particle diameter 4 ($\Phi = 2.5 \text{ mm} - 5 \text{ mm}$), and particle diameter 5, representing the particle diameter of a broken rock mixture of the previous four types in the same mass ratio (1 : 1 : 1 : 1).

2.3. Experimental Apparatus. The stress-strain process and the permeability with changing ambient pressure for an intact rock sample were tested using the MTS815.02 electrohydraulic servo rock mechanics system. The ambient pressure was set as $p_c = 4 \text{ MPa}$. The seepage flow was water with the following characteristics: mass density $\rho = 1000 \text{ kg/m}^3$, kinematic viscosity $\mu = 1.01 \times 10^{-3} \text{ Pa}\cdot\text{s}$,

FIGURE 2: The experimental principles of the MTS815.02 electrohydraulic servo rock mechanics system.

FIGURE 3: The permeability apparatus for compacting broken rocks.

compressibility $c_f = 0.475 \times 10^{-9} \text{ Pa}^{-1}$, and voltage stabilizer volume $B = 0.332 \times 10^{-3} \text{ m}^3$.

According to the time series of the pore pressure difference collected in the experiment, the permeability coefficient K of the Darcy flow was calculated by Formula (1). The test work of the rock sample was accomplished with a permeability apparatus. Images of the rock sample and the permeability apparatus are shown in Figure 4. In the experiment, the loading process was controlled, and the axial loads were classified into 4 levels: 11 MPa, 22 MPa, 33 MPa, and 44 MPa; the corresponding velocities of the supercharger pistons for the axial

FIGURE 4: (a) Rock samples and (b) the experimental apparatus.

loads were 5.6×10^{-5} m/s, 11.2×10^{-5} m/s, 22.4×10^{-5} m/s, and 33.6×10^{-5} m/s, respectively.

3. Results and Discussion

The relationship between the strength and the permeability coefficient of the rock at three strata of the collapsed column with the strain is shown in Figure 5.

The data showed that the rock strength and permeability coefficient varied at the three sections of the collapsed column in a similar trend. In the early stage, the uniaxial compressive strength of the rock sample increased at nearly a constant speed, and after reaching 50 MPa, it decreased sharply. When it dropped to approximately 22 MPa, the decrease slowed down. The corresponding permeability coefficient of the rock sample began to increase when the strain reached approximately 9%. It increased slowly in the early stage and surged to $(75-95) \times 10^{-12} \text{ m}\cdot\text{s}^{-1}$ when the strain reached 1.3%; then, it drastically dropped to $15 \times 10^{-12} \text{ m}\cdot\text{s}^{-1}$ and basically remained unchanged. Rocks from three sections showed similar deformation rules, indicating that there was no significant difference among them. For strain from 0.3% to 0.9% (AB segment), the axial pressures of rocks from the three sections gradually increased, and their permeability coefficients declined to a certain extent. At this stage, the original fissures in the rock were closed, and the gap between the specimen and the

FIGURE 5: The changes for the rock strength and permeability coefficient with the strain of the collapsed column.

pressure plate was adjusted. For strain from 0.9% to 1.23% (BC segment), the axial pressure of rocks from the three sections gradually increased to an extreme value; the ultimate strength of rocks from the middle section was 53 MPa, slightly larger than the 47 MPa of the upper and lower sections; the permeability coefficient of rocks from the three sections also increased gradually, and the increasing slope was not a definite value, indicating that it was a stage in which the original fissures were closed and a few new fissures came into being. For strain from 1.23% to 1.5% (CD segment), the axial pressure of rocks from the three sections decreased sharply with the increase of strain, and there was an obvious macroscopic structural failure plane forming on the rock; additionally, the permeability coefficient increased sharply, indicating that new fissures increased sharply within the rock. The extreme values of the permeability coefficients of rocks from the three sections were as follows: $95.41 \times 10^{-12} \text{ m}\cdot\text{s}^{-1}$ in the upper section $> 82.72 \times 10^{-12} \text{ m}\cdot\text{s}^{-1}$ in the middle section $> 76.85 \times 10^{-12} \text{ m}\cdot\text{s}^{-1}$ in the lower section, indicating that the permeability of the lower section was inferior to that of the upper section. The reason was that the lower section had better cementation and compaction; the result was consistent with the shape and structure of the collapsed column, and the three did not show significant differences because they were all of the same order of magnitude. For strain from 1.5% to 1.65% (DE segment), the axial pressure of rocks from the three sections decreased with the increase of strain, the rate of decline decreased, and the permeability coefficient decreased sharply and dramatically. For strain greater than 1.65% (EF segment), the axial pressure of rocks from the three sections decreased with the increase of strain, and the permeability coefficient was almost constant and tended to be a constant. The peak value of the permeability coefficient lagged behind the peak

value of the rock strength. The reason was that, in the BD stage, the dislocation of the broken rock masses along the fracture plane and the climbing effect of the asperity body increased the gap in the macrofissures direction, and the permeability coefficient of the rock reached a peak. Subsequently, within the confining pressure limit, the intensifying deformation of the sample led to the compression and closure of the dislocation and the fissures, resulting in a sharp decrease in the permeability coefficient. The entire process was a process of fissure generation and closure.

With the same method, we analyzed the sandstone and mudstone from the fissure zone around the collapsed column and the intact coal seam floor to clearly show the trend of variation; the value of the mudstone's permeability coefficient was multiplied by 10^3 , as shown in Figures 6 and 7.

The trend and principle of the axial pressure and permeability coefficient varying with the strain are similar to what have been discussed above. Experiments with samples from the fissure zone around the collapsed column and the intact coal seam floor mainly manifested the following aspects. The variation slope of the axial pressure of rock from the fissure zone was not stable, and the permeability coefficient showed a significant and relatively long-term decline at the initial stage of the experiment, indicating that there was a large number of nonuniform primary fissures within the rock [22–24].

In the final analysis, it is determined by the mineral composition, particle, pore, and fracture structure of its internal structure rock. The load on the rock sample, including pore pressure and confining pressure, is only an external condition that causes the microstructure of the rock sample to change. Due to the gray nature of the rock material structure, the rock permeability has a strong disorder. The permeability coefficient of the fissure zone was much larger than that of the intact complete floor. The experimental results and existing literature [25–27] all show that the key to research on the mechanism of water inrush from collapsed columns is the permeability coefficient of the broken rock. Table 1 lists the variations of the permeability coefficients of the broken sandstone and broken mudstone under different axial pressures P_a , different seepage velocities, and different particle diameters ϕ of the rock samples.

Table 1 shows that the broken sandstone and broken mudstone had the minimum values of permeability coefficients, $0.11 \times 10^{-8} \text{ m}\cdot\text{s}^{-1}$ and $0.11 \times 10^{-10} \text{ m}\cdot\text{s}^{-1}$, respectively, when the gradation was 1:1:1:1, the pressure was 44 MPa, and the loading velocity was $6v_1$; they had the maximum values, $154.76 \times 10^{-8} \text{ m}\cdot\text{s}^{-1}$ and $175.14 \times 10^{-10} \text{ m}\cdot\text{s}^{-1}$, respectively, when the particle diameter Φ was 15–20 mm, the pressure was 11 MPa, and the loading velocity was $1v_1$. With the increase of the water flow velocity, the permeability coefficients K of the broken sandstone and broken mudstone decreased slightly. φ was defined as the influence coefficient, i.e., the ratio between the difference of $1v_1$ and $6v_1$ and the permeability coefficients when $1v_1$. $\varphi = (K_{v_1} - K_{6v_1}) / (K_{v_1})$, and the influence coefficient obtained is shown in Figure 8.

The value of the influence coefficient mainly lies in the range of 0.1–0.95 and was smaller than 0.6 in most cases. The influence coefficients of broken sandstone and broken

FIGURE 6: The relationship curve for the rock strength and permeability coefficient with the strain of the fissure zone.

FIGURE 7: The relationship curve for the rock strength and permeability coefficient with the strain of the intact floor.

mudstone with particle diameter $\Phi = 15\text{--}20 \text{ mm}$ showed a synchronized changing trend with the increase of the water flow velocity. For particle diameter $\Phi = 10\text{--}15 \text{ mm}$, the influence coefficient of broken sandstone showed a slightly smoother changing trend than that of broken mudstone but still fluctuated explicitly. The influence coefficients of broken sandstone and broken mudstone with particle diameter $\Phi = 10\text{--}15 \text{ mm}$ and gradation 1:1:1:1 tended to stabilize and remain approximately 0.4. The main reason was that, for particle diameter $\Phi = 15\text{--}20 \text{ mm}$, broken rocks were composed of large particles and formed many effective fissures, and thus the influence coefficient

TABLE 1: Permeability coefficients of broken sandstone and broken mudstone/ $v_1 = 5.6 \times 10^{-5} \text{ m}\cdot\text{s}^{-1}$.

Particle sizes and axial pressure		Broken sandstone ($\times 10^{-8} \text{ m}\cdot\text{s}^{-1}$)				Broken mudstone ($\times 10^{-10} \text{ m}\cdot\text{s}^{-1}$)			
		$1v_1$	$2v_1$	$4v_1$	$6v_1$	$1v_1$	$2v_1$	$4v_1$	$6v_1$
$\Phi = 15\text{--}20 \text{ mm}$	11	154.76	151.66	149.52	137.34	175.14	157.15	154.86	126.26
	22	121.25	116.71	117.13	41.98	34.92	48.06	33.15	29.85
	33	69.56	23.27	12.45	3.33	14.04	17.67	16.86	3.17
	44	1.37	1.06	0.73	0.51	2.95	2.05	2.55	1.45
$\Phi = 10\text{--}15 \text{ mm}$	11	82.69	77.89	75.4	62.72	251.47	201.36	140.77	140.82
	22	20.75	8.92	9.43	7.63	89.44	65.08	47.11	21.86
	33	1.19	1.01	0.92	0.89	6.39	5.56	3.04	1.78
	44	1.24	0.62	0.56	0.52	1.45	0.97	0.58	0.66
$\Phi = 5\text{--}10 \text{ mm}$	11	44.32	40.78	35.12	30.63	52.84	42.7	36.37	29.92
	22	15.6	7.12	6.98	5.3	25.12	23.92	19.12	12.84
	33	1.08	0.87	0.68	0.54	9.7	8.67	7.89	5.3
	44	0.79	0.54	0.51	0.48	2.07	1.77	1.25	1.23
$\Phi = 2.5\text{--}5 \text{ mm}$	11	15.27	12.02	9.42	8.69	36.26	32.18	25.52	20.77
	22	1.8	1.79	1.16	0.92	9.87	8.35	7.23	6.19
	33	0.49	0.33	0.32	0.28	3.02	2.31	2.05	1.75
	44	0.23	0.19	0.17	0.14	0.93	0.74	0.66	0.54
Mixture of different particle sizes: 1:1:1:1	11	7.04	5.76	4.72	3.24	16.05	13.47	10.85	7.72
	22	1.42	1.29	1.09	0.84	6.48	5	4.13	3.87
	33	0.37	0.31	0.28	0.24	2.12	1.78	1.55	0.98
	44	0.17	0.15	0.14	0.11	0.55	0.43	0.33	0.29

had larger values [28, 29]. When the water flow velocity increased, the small particles resulting from the edge crush or particle break were randomly washed to fill in the fissures, blocking some of the channels, and therefore the influence coefficient at this stage had larger values and fluctuated in a wider range; when the particles composing the broken rock gradually decreased, the probability of such random filling and clogging of the fissures was reduced, so the influence coefficient generally had smaller values and showed small fluctuation [30, 31]. When the particles composing the broken rock were much smaller or in a more balanced proportion (a mixture composed of various particles with different diameters in a mass ratio of 1:1:1:1), the effective fissures within the rock sample were more uniform, and the value of the influence coefficient tended to be a constant. The possible reason for the existence of the influence coefficient was that laminar flow became turbulent with the increase of the water flow velocity, and the non-Darcy flow characteristics of the rock were more prominent. The influence coefficient was a constant consumption lessening the water flow velocity in the turbulent flow state [32, 33]. The influence coefficient began to stabilize when the particle diameter $\Phi = 2.5\text{--}5 \text{ mm}$, which can be regarded as a critical value dividing Darcy flow and non-Darcy flow in this state.

In short, under the same conditions, the permeability coefficient of broken sandstone was nearly 1-2 orders of magnitude larger than that of broken mudstone. The permeability coefficient of broken sandstone was 1-2 orders of magnitude higher than that of intact sandstone. The permeability coefficient of broken mudstone was 2-3 orders of magnitude higher than that of intact mudstone. When the axial pressure imposed on the broken sandstone exceeded 22 MPa and the axial pressure imposed on the broken

FIGURE 8: The influence coefficient curve of the broken sandstone and broken mudstone.

mudstone exceeded 11 MPa, their permeability coefficients were different than that of the intact rock of their own type, but they approximated or were smaller than the upper limit of the permeability coefficient of the aquifer. Considering the actual process of water inrush, the fissures were affected by different hydraulic pressures; after long-term continuous erosion and expansion, the water guiding channels were finally formed. Because the water inrush channels of the collapsed column were mainly composed of a series of fissures with the maximum permeability coefficient, the ultimate strength and permeability coefficient of various rocks were jointly analyzed, as shown in Table 2.

The ultimate strength of the rock in the upper section of the collapsed column was 48.01 MPa, and the permeability

TABLE 2: Maximum strength and permeability coefficient of each sample.

	Collapse column-upper	Collapse column-middle	Collapse column-lower	Fissure zone-sandstone	Fissure zone-mudstone	Intact floor-sandstone	Intact floor-mudstone
Maximum axial pressure	48.01	52.01	48.01	69.63	28.81	89.63	48.01
Maximum permeability coefficient	0.95	0.84	0.77	262.39	0.47	27.9	4.9

coefficient was 0.95×10^{-10} ; the ultimate strength of the rock in the middle section of the collapsed column was 52.01 MPa, and the permeability coefficient was 0.84×10^{-10} ; the ultimate strength of the rock in the lower section of the collapsed column was 48.01 MPa, and the permeability coefficient was 0.77×10^{-10} ; the ultimate strength of the sandstone in the fissure zone was 69.63 MPa, and the permeability coefficient was 262.39×10^{-10} ; the ultimate strength of the mudstone in the fissure zone was 28.81 MPa, and the permeability coefficient was 0.47×10^{-10} ; the ultimate strength of the sandstone in the intact coal seam floor was 89.63 MPa, and the permeability coefficient was 27.90×10^{-10} ; the ultimate strength of the mudstone in the intact coal seam floor was 48.01 MPa, and the permeability coefficient was 4.9×10^{-10} .

The experimental results showed that the ultimate strength of the sandstone in the intact coal seam floor was greater than that of the fissure zone, which was in turn greater than that of the collapsed column; the ultimate strength of the mudstone in the intact coal seam floor was equivalent to that of the collapsed column, which was greater than that of the sandstone in the fissure zone. In terms of the permeability coefficient, the permeability coefficient of the sandstone in the fissure zone was much larger than that in other regions. According to the gradation for rock and earth in the National Standard GB 50487–2008 “Code for Engineering Geological Investigation of Water Resources and Hydropower,” [34] the permeability coefficient of sandstone in the fissure zone has reached the “slightly permeable” level, as shown in Table 3.

The fact that the permeability coefficient of the mudstone in the fissure zone around the collapsed column was small, and even smaller than the permeability coefficient of the sandstone in the floor, indicates two problems. (1) The fissure zone around the collapsed column was the main water-permeating channel, while the collapsed column with relatively high compaction and cementation was impermeable in normal conditions. (2) The permeability of the fissure zone around the collapsed column was related to the lithological characteristics of the rock constituting the fissure zone and the sequencing of rock strata. When the lithological characteristics include complete water-resistance or the aquiclude lay under the hard rock stratum, forming a floor of “rigid upper layer and soft lower layer,” the damage of mining would have a shallow depth, and the height of the confined water permeation was low, which is the most favorable condition for coal mining above confined water. On-site detection showed that there was water seepage from the collapsed

TABLE 3: Permeability gradation for rock and earth.

Grade of permeability	Standard		Soil type
	Permeability coefficient K (m/s)	Permeability q (Lu)	
Mostly impermeable	$K < 10^{-8}$	$q < 0.1$	Clay
Slightly permeable	$10^{-8} \leq K < 10^{-7}$	$0.1 \leq q < 1$	Clay-silt
Weakly permeable	$10^{-7} \leq K < 10^{-6}$	$1 \leq q < 10$	Silt-fine sand
Moderately permeable	$10^{-6} \leq K < 10^{-4}$	$10 \leq q < 100$	Sand-sand gravel
Strongly permeable	$10^{-4} \leq K < 10^{-2}$	$q \geq 100$	Sand gravel- gravel
Very strongly permeable	$K \geq 10^{-2}$		Boulder

column and a small amount of water seepage and moisture in the surrounding fissure zone, which was consistent with the analysis results.

4. Conclusion

In this study, the disaster-causing mechanism of column collapse was studied. Based on the system theory, a collapsed column is divided into the column and the surrounding fissure zone as two subsystems for analysis. The experiment showed that the average ultimate strength of the collapsed column was approximately 50 MPa and the average peak value of the permeability coefficient was 0.85×10^{-10} m/s; the ultimate strength of the sandstone fissure zone was 69.63 MPa, and the peak value of the permeability coefficient was 262.39×10^{-10} m/s; the ultimate strength of the mudstone fissure zone was 28.81 MPa, and the peak value of the permeability coefficient was 0.47×10^{-10} m/s, which proved that the fissure zone of the collapsed column was the main water-conducting channel and that the collapsed column had a relatively good degree of compaction and did not allow for water flowing under normal circumstances. The permeability coefficient of the broken rock under different conditions was measured by a self-designed equipment. The variations of the permeability coefficient for rock samples with different particle diameters, different axial pressures P_a and different seepage velocities were further studied. Through phenomena analysis and experimental data processing, it was

concluded that, under the same pressure state, smaller particle diameter meant smaller permeability coefficient; with the increase of axial pressure, the permeability coefficient decreased; and the larger the water flow velocity was, the smaller the permeability coefficient became. For particle diameter $\Phi = 2.5\text{--}5\text{ mm}$ or larger, the tiny particles formed by randomly washing and breaking in the water flow blocked some of the channels. For particle diameters smaller than $\Phi = 2.5\text{--}5\text{ mm}$, the smaller permeability coefficient was attributed to the turbulence resulting from non-Darcy flow. The study on the permeability of the fractured rock mass clarified the mechanism of water inrush from the fissure zone of the collapsed column: the collapsed column itself was impermeable, and the permeability of the fissure zone around the collapsed column was related to the lithological characteristics of the rock within the fissure zone and the sequencing of rock strata. When mining coal in areas with collapsed columns, experiments on collapsed columns and fissure zone-s are prerequisites. This study has certain referential value for coal mining in this region.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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