Research Article

Determining the Height of Water-Flowing Fractured Zone in Bedrock-Soil Layer in a Jurassic Coalfield in Northern Shaanxi, China

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The height of the water-flowing fractured zone is the most important technical parameter for water prevention and control in a coal mine. Due to the numerous factors affecting the water-flowing fractured zone, it is difficult to accurately identify the zone. Currently, no effective way exists for determination of the water-flowing fractured zone in a soil layer. To accurately determine the development law of the water-flowing fractured zone in the bedrock-soil layer of a Jurassic coalfield in northern Shaanxi, China, we conducted a comprehensive study using microresistivity scanning imaging technology, apparent density logging, long-range gamma logging, observation on drilling flushing fluid consumption, physical simulation, and numerical simulation. The following results were obtained: (1) The ratio of the height of the water-flowing fractured zone to the mining height was 28.3–28.5, which was obtained by microresistivity scanning imaging technology, whereas the ratio of the height of the water-flowing fractured zone to the mining height was 28.1–29.1, determined by apparent density logging, long-range gamma logging, physical simulation, and numerical simulation. The microresistivity scanning imaging results were consistent with those obtained by other methods. (2) Based on the thickness of the soil layer and the bedrock, the height model of the water-flowing fracture zone was divided into four regions, that is, the thick bedrock-thick soil layer region, thick bedrock-thin soil layer region, thin bedrock-thin soil layer region, and thin bedrock-thick soil layer region. A mathematical model describing the difference between the thickness of the water-flowing fractured zone and the bedrock and the thickness of the soil under the condition of bedrock-soil was established. (3) We conclude that microresistivity scanning imaging technology can accurately detect the height of the water-flowing fractured zone in a soil layer, and the apparent density logging and long-range gamma logging can precisely detect the height of the water-flowing fractured zone in bedrock. This is a new comprehensive method for research on the height of the water-flowing fractured zone that can provide a reliable basis for water prevention and control in mines.

1. Introduction

China ranks third in the world in terms of its reserve of coal resources. The Jurassic coalfield in northern Shaanxi is the seventh largest coalfield in China. Northern Shaanxi coal production base is one of the fourteen billion-ton coal production bases with high coal seam occurrence condition and excellent coal quality, which is planned and

constructed in China. However, the ecological environment is fragile, because the aquifer Salawusu Formation aquifer is overlying the coal seam that is not only the chief water supply source in the region but also the main water source used to maintain the fragile ecological environment in the desert region [1–3]. The water-flowing fracture in coal seam mining is easy to communicate with this aquifer, resulting in mine water disaster accidents, leading

to the decline of groundwater level and the degradation of supergene ecology.

It is very important to determine the height of the water-flowing fractured zone because it concerns the coordination and balance between coal mining, water resources protection, and mine safety. The theoretical analysis, empirical formulas, physical and numerical simulations, field measurement, and other methods have been used to research the water-flowing fracture and obtained a great deal of encouraging results. The “key layer theory” proposed by Qian et al. [4] is the most widely used theoretical analysis method for calculating the water-flowing fractured zone [5]. Mathematical statistics is predominantly used to study the development height of a water-flowing fractured zone and compare the applicability with construction, water body, railway and main roadway coal pillar retention, and coal pressure mining rules [6–8]. Wang et al. [9] and Zhao et al. [10, 11] determined the height of the water-flowing fractured zone by examining the relationship between the water-flowing fractured zone and the coal mining parameters, which has laid the foundation of water-retaining coal mining. Underground mine water injection leakage measuring method with overhead borehole, transient electromagnetic method, drilling TV, and numerical simulation were previously applied to investigate the height of the water-flowing fractured zone in the roof above that was fully mechanized one passing full seam mining face [12, 13]. Yang and Teng [14] observed the borehole flushing fluid consumption and determined the maximum height of the water fractured zone by three boreholes of 6206 working face in Wangzhuang coal mine. Based on the physical simulation method, the law of the cracked zones in the overburden strata of the Western mining area was also revealed by Huang et al. [15–17] and Cao et al. [18]. In recent years, the microseismic monitoring technique has been increasingly applied to examine the heights of water-flowing fractured zones [19, 20].

However, due to the existence of a thick loess layer in the ecologically fragile area of northern Shaanxi, the following difficulties were faced in determining the height of the water-flowing fractured zone. First, theoretical analysis, empirical formula, physical simulation, numerical simulation, and other methods are used to obtain the height of the water-flowing fractured zone indirectly, but the accuracy is low. Second, the observation method of borehole flushing fluid consumption is widely used in field measurements. However, due to the water insulation effect of the flushing fluid mixed with loess and the insignificant change of the flushing fluid leakage, no accurate determination of the height of the water-flowing fractured zone is possible. Third, the detection of the drilling TV method has good applicability in field measurements in bedrock. In loess, since the water-flowing fracture is filled by loess itself during drilling, it is difficult to directly and clearly observe the fracture, and the height of the water-flowing fractured zone cannot be determined. Currently, the borehole flushing fluid consumption observation method is the most direct, accurate, and widely applied method for the development height of water-flowing fractured zone in the bedrock, but its disadvantage is its great

time consumption. Another detection technology utilized to compare and verify the detection result obtained by the observation method of borehole flushing fluid consumption can increase the reliability of the final result. Therefore, in this paper, the microresistivity scanning imaging technology was employed to elucidate the development law of the water-flowing fracture in the soil layer of this area. The apparent density logging and long-range gamma logging are used to detect the development height of the water-flowing fracture zone in the bedrock. Auxiliary physical simulation and numerical simulation, as well as a comprehensive study of the water-flowing fractured zone, were carried out to fill the gaps in research on determining the height of the water-flowing fractured zone in the soil layer. The methods to identify the height of the water-flowing fractured zones in different types of bedrock-soil layers were extended, and the research results concerning the development law of water-flowing fractured zone were further improved.

2. General Geological Parameters of the Study Area

The northern Shaanxi coal production base lies in the semiarid areas at the border between the Maowusu Desert and the Loess Plateau and has an annual precipitation of approximately 400 mm and evaporation of approximately 2,000 mm. In this study, we selected Zhangjiamao and Caojiatan coal mines as the research area (Figure 1). We investigated the height of the water-flowing fractured zone in the soil layer and in the bedrock.

The Zhangjiamao coal mine is dominated by loess of the Quaternary Middle Pleistocene Lishi Formation. The general thickness is 20–30 m, whereas the maximum thickness is 90.5 m. The loess lithology is silty clay with large porosity, loose structure, and a small amount of sandy soil in the area. Vertical joints are developed, which are easy to be eroded by surface water, and thus the immersion can easily lose stability. Under the influence of water erosion, gully development in loess area, and gully slope formation, collapse often occurs, resulting in a prevalence of gully head erosion. According to the soil test data, the loess void ratio is 0.818, the plastic limit is 17.7%, the liquid limit is 29.0%, the natural water content is 5.3%, and the liquid index is 0. The soil is in a hard or hard-plastic state. The compression coefficient is within $0.04\text{--}1\text{ MPa}^{-1}$, the compression modulus is 45.4 MPa, and the collapse coefficient is 0.010 with no collapsibility.

The overlying bedrock of Caojiatan coal mine consists mainly of Jurassic Yan'an Formation (J_2y) and Zhiluo Formation (J_2z) strata with a thickness of 164.33–294.48 m. The rock mechanics test results showed that the saturated compressive strength of the direct roof of the coal seam is 24.80–37.90 MPa with an average value of 31.35 MPa. The tensile strength is 0.39–0.56 MPa, with an average value of 0.48 MPa. The saturated compressive strength of the basic top is within the range of 27.60–37.90 MPa, with an average value of 33.25 MPa. The tensile strength is 0.23–1.14 MPa, with an average value of 0.71 MPa. The immediate roof and basic roof of the coal seam are medium-hard rocks that are easy to soften.

FIGURE 1: Map of the study area.

The relationship between the coal seam and the overlying bedrock and soil layer is illustrated in Figure 2.

3. Determination of Water-Flowing Fractured Zone by Physical and Numerical Simulation

3.1. Physical Simulation Study on the Height of the Water-Flowing Fractured Zone. Taking 5^{-2} coal seam mining in Zhangjiamao coal mine as an example, the 12-2 drilling columnar located in the drilling exploration area 9 of the water-flowing fractured zone was selected as the experimental prototype. Using a plane model frame, the length of the model was determined to be 3.0 m and the width was 0.2 m with a geometric similarity ratio of 1 : 120. The mining height of 5^{-2} coal seam was 4.88 m, the overlying bedrock thickness was 96.12 m, and the loess thickness was 48.16 m. Table 1 represents the material matching scheme of the model.

The simulation test showed that the working face advanced to a total of 240 m, and the initial weighting step was 36 m, which can be observed in Figure 3(a). At the end of the working face mining, the height of the water-flowing fractured zone developed to the middle of the soil layer, and the height was roughly 137 m. The ratio of the water-flowing fractured zone to the mining height was approximately 28.1 (Figure 3(b)).

Caojiatan coal mine uses the 2^{-2} coal seam. The D1 drilling columnar located in the area of the exploration drilling DZ1 of the water-flowing fractured zone was

selected as the experimental prototype. Using a plane model frame, we determined the length of the model, which was 3.0 m, and the width was 0.2 m, with a geometric similarity ratio 1 : 200. The mining height of the 5^{-2} coal seam was 6 m; the overlying bedrock thickness was 173.3 m, and the loess thickness was 75.9 m. Table 2 displays the material matching scheme of the model.

The simulation test revealed that the working face advanced 400 m in total, and the initial weighting step was 42 m. At the end of the working face mining, the height of the water-flowing fractured zone developed to approximately 162 m. The ratio of the water-flowing fractured zone to the mining height was about 27 and did not communicate with the soil layer (Figure 4).

3.2. Numerical Simulation Study on the Height of the Water-Flowing Fractured Zone. A numerical simulation model with a length of 500 m and a height of 191 m was established based on the drilling histogram of the area of the Zhangjiamao coal mine, where the N15203 working face 9 was located. A 100 m boundary coal pillar was set on both sides of the model. The mining height of 5^{-2} coal seam was 5.5 m, the overlying bedrock thickness was 105 m, and soil thickness was 60 m. Table 3 lists the physical and mechanical properties of the rock coal seam overlying strata of the 5^{-2} coal seam of the model.

The simulation test results showed that the initial weighting step was 55 m. After the overlying strata of 5^{-2} coal seam were stabilized, the height of the water-flowing fractured zone was approximately 160 m, and the ratio of the water-flowing fractured zone to the mining height was 29.1 m (Figure 5).

A numerical simulation model with a length of 500 m and a height of 286 m was established according to the drilling histogram of the area, where 122106 working face D1 was located in Caojiatan coal mine. A 100 m boundary coal pillar was set on both sides of the model. The mining height of the 2^{-2} coal seam was 6 m, the overlying bedrock thickness was 168 m, and the soil thickness was 90 m.

Table 4 shows the physical and mechanical properties of rock coal seam overlying strata of 2^{-2} coal seam for the model.

The simulation test showed that the initial weighting step was 90 m. After the overlying strata of 2^{-2} coal seam were stabilized, the height of the water-flowing fractured zone was established to be roughly 162 m, and the ratio of the water-flowing fractured zone to the mining height was 27 m (Figure 6).

4. Apparent Density Logging and Long-Range Gamma Logging for Detection of the Height of the Water-flowing Fractured Zone in the Bedrock

4.1. Detection Principles of Apparent Density Logging and Long-Range Gamma Logging. Rock fractures are developed by mining damage, reducing the density of the rock mass and the resistivity value. This method can explain the

stratigraphic age		thickness (m) min~max /average	lithological description	aquifer/ aquifuge
Quaternary	Alluvial-pluvial	0.9~60/10.49	mainly for modern aeolian sand, sand and sub-sand soil.	aquifer
	Salawusu formation	3~22.8/8.44	gray yellow-brown black silty sand, subsandy soil, sandy clay.	
	Lishi formation	4~88.74/27.12	light brown-yellow - brown subclay sandy soil, silty sand, paleosol, calcareous nodule	
Neogene	Baode formation	1.7~77.35/27.4		
Jurassic	Zhiluo formation	3.71~49.78/24.1	brown-purple red clay or sandy clay with calcareous nodules	aquifuge
		9.01~68.58/32.66		
	2 ⁻² coal	1.85~10.6/7.75		
		23.68~38.7/30.42	purple mudstone, sandy mudstone, sandstone, sometimes at the bottom of the conglomerate.	aquifer
	3 ⁻¹ coal	2.1~3.4/2.81		
		37.96~47.36/42.1		
	4 ⁻² coal	1.25~4.75/3.63	shallow gray-dark gray sandstone and mudstone, sandy mudstone, containing multi-layer coal seam, is the main	aquifuge combination
		1.55~39.4/19.41		
	4 ⁻³ coal	0.1~1.9/1.28		
		2.56~35.65/14.57	coal-bearing strata of the basin, up to 13 layers of coal seam, generally 3~6 layers.	
	4 ⁻⁴ coal	0.1~1.2/0.79		
		28.95~79.23 /35.74		
	5 ⁻² coal	4.79~8.23/6.14		
		0.41~21/2.47		
	5 ⁻³ coal	0.45~1.1/0.73		

(a)

stratigraphic age			thickness (m) min~max /average	lithological description	aquifer/ aquifuge	
Quaternary	Aeolian sand		0~23.2/6.62	mainly for light yellow-brown yellow fine sand, powder sand, uniform texture. gray-yellow, gray-brown silt and sub-sand.	aquifer	
	Salawusu formation		0~49.37/10.9			
	Lishi formation		0~65/19.05			
Neogene	Baode formation		2.13~134.35 /70.51	light brown yellow sub-sandy soil, silt, light red-brown red clay and subclay.	aquifuge	
	Anding formation		0~96.67/42.74	mainly for purple red, dark, purple, purple miscellaneous mudstone, siltstone.		
Zhiluo formation		21.7~186.4 /116.91				
Jurassic	Yanan forma- tion		1 ¹ coal	0~1.76/0.63	gray-green blue-gray, purple lacustrine deposits. mainly for gray-white to light gray coarse, medium and fine feldspar quartz sandstone, lithic feldspar sandstone and calcareous sandstone are the main lithology, followed by gray to gray black siltstone, sandy mudstone, mudstone and coal seam, a small amount of carbonaceous mudstone.	aquifuge combin- ation
				27.15~35.7 /30.56		
			1 ² coal	0~2.24/0.93		
				6.29~39.9/28.93		
			2 ⁻² upper coal	1.02~3.61/1.62		
				0.8~17.09/3.78		
			2 ⁻² coal	9.89~10.73 /10.41		
				26.67~40.43 /35.69		
			3 ⁻¹ coal	1.93~3.7/2.36		
				23.22~34.17 /26.34		
			4 ⁻¹ coal	0~0.84/0.36		
				11~24.52/19.66		
			4 ⁻² coal	0~2.35/0.87		
				10.42~25.33 /17.12		
	4 ⁻³ coal	1.07~4.13/2.14				
		9.2~22.97/16.89				
	4 ⁻⁴ coal	0~1.6/0.54				

(b)

FIGURE 2: Relationship between the coal seam and the vertical distribution of the bedrock and the soil layer ((a) Zhangjiamao coal mine and (b) Caojiatan coal mine).

TABLE 1: Material matching scheme of the physical simulation model for 5⁻² coal seam mining in Zhangjiamao coal mine.

No.	Lithology	Accumulated thickness of the original rock (m)	Thickness of the original rock (m)	Thickness of the model (cm)	Accumulated thickness of the model (cm)	Sand (g/ cm)	Gypsum (g/cm)	Big white powder (g/cm)
19	Loess	48.16	48.16	40.13	124.90	—	—	—
18	Medium grained sandstone	52.56	4.4	3.67	84.77	8640	288	672
17	Fine grained sandstone	55.43	2.87	2.39	81.10	7680	384	1536
16	Medium grained sandstone	56.7	1.27	1.06	78.71	8640	288	672
15	Siltstone	65.96	9.26	7.72	77.65	7680	384	1536
14	4 ⁻³ coal seam	69.58	3.62	3.02	69.94	—	—	—
13	Siltstone	71.2	1.62	1.35	66.92	7680	192	1728
12	Siltstone	72.14	0.94	0.78	65.57	8640	288	672
11	4 ⁻⁴ coal seam	73.05	0.91	0.76	64.79	—	—	—
10	Siltstone	75.4	2.35	1.96	64.03	8640	384	576
9	Fine grained sandstone	82.8	7.4	6.17	62.07	7680	384	1536
8	Siltstone	93.6	10.8	9.00	55.90	7680	576	1344
7	Fine grained sandstone	96	2.4	2.00	46.90	8640	384	576
6	Fine grained sandstone	104.8	8.8	7.33	44.90	7680	576	1344
5	Siltstone	113.35	8.55	7.13	37.57	7680	384	1536

TABLE 1: Continued.

No.	Lithology	Accumulated thickness of the original rock (m)	Thickness of the original rock (m)	Thickness of the model (cm)	Accumulated thickness of the model (cm)	Sand (g/cm)	Gypsum (g/cm)	Big white powder (g/cm)
4	Siltstone	127.5	14.15	11.79	30.45	7680	576	1344
3	Fine grained sandstone	129.6	2.1	1.75	18.65	7680	384	1536
2	Siltstone	144.28	14.68	12.23	16.90	7680	576	1344
1	5 ⁻² coal seam	149.88	5.6	4.67	4.67	—	—	—

FIGURE 3: Characteristics of overburden failure after the extraction by physical simulation in the Zhangjiamao coal seam.

fracture development of the drilling wall, so as to determine the top interface position of the water-flowing fractured zone.

The apparent density is expressed as

$$\text{apparent density} = \frac{\text{mass}}{\text{external actual volume} + \text{internal closed pore volume}} \quad (1)$$

Note that the expression does not include the opening pore volume on the surface of the object.

Long-range gamma logging is a well-recognized logging method for geological engineering research, including stratigraphic lithology, mineral composition, density, porosity, and fluid migration. Its detection mechanism is based on the radiation field generated by natural or artificial gamma sources in formations and boreholes to measure and analyze the intensity and energy spectrum of the gamma line.

4.2. Results of Apparent Density Logging and Long-Range Gamma Logging for Water-Flowing Fractured Zone Detection. Two exploration drillings and one control drilling were performed in Caojiatan coal mine, denoted as DZ1, DZ2, and D1, respectively. They were located in 122106 goaf of the first working face (Figure 7). No. 2⁻² coal seam with a mining thickness of 6 m was employed as the main mining coal seam. The bedrock thickness of DZ1 drilling was 175 m; of DZ2 drilling, it was 178.9 m. The working face was mined out. After the full mining of the coal seam, the water-flowing fractures in the overlying strata of the coal seam were detected.

From Figure 8, the following can be seen: (a) The apparent density of DZ1 drilling suddenly decreases at a depth of 131.39 m compared with that of D1 drilling, and there is a large sword-front anomaly in each interval below the depth of 131.39 m, indicating that there is a gap in the drilling wall leading to a sudden decrease in the apparent density. The apparent density of DZ2 drilling suddenly becomes smaller than that of D1 drilling at a depth of 144.65 m, with a sharp sword-like anomaly at each interval below a depth of 144.65 m, indicating the presence of a gap in the hole wall, leading to the sudden decrease of the apparent density. (b) The long-range gamma of DZ1 drilling suddenly becomes larger than that of D1 drilling at a depth of 130.19 m, and there is a sword-front anomaly in each interval below the depth of 130.19 m, indicating that there is a gap in the drilling wall, resulting in the sudden enlargement of the long-range gamma. Compared with drilling D1, the long-range gamma of DZ2 drilling suddenly becomes larger at a depth of 145.54 m, and there is a sword-front anomaly in each interval below the depth of 145.54 m, indicating that there is a gap in the borehole wall, which leads to the sudden enlargement of the long-range gamma.

TABLE 2: Material matching scheme of the physical simulation model of the 2⁻² coal seam mining in Caojiatan coal mine.

No.	Lithology	The thickness of the original rock (m)	The accumulated thickness of the original rock (m)	The thickness of the model (cm)	The accumulated thickness of the model (cm)	Sand (g/cm)	Gypsum (g/cm)	The big white powder (g/cm)
1	2 ⁻² coal seam	12.0	10.0	5.0	5.0	—	—	—
2	Siltstone	2.0	12.0	1.0	6.0	8640	288	672
3	Fine grained sandstone	14.0	26.0	7.0	13.0	7680	576	1344
4	Coarse grained sandstone	18.0	44.0	9.0	22.0	7680	384	1536
5	Medium grained sandstone	6.0	50.0	3.0	25.0	7680	768	1152
6	Siltstone	22.0	72.0	11.0	36.0	8640	288	672
7	Coarse grained sandstone	22.0	94.0	11.0	47.0	7680	384	1536
8	Medium grained sandstone	10.0	104.0	5.0	52.0	7680	768	1152
9	Coarse grained sandstone	14.0	118.0	7.0	59.0	7680	384	1536
10	Siltstone	2.0	120.0	1.0	60.0	8640	288	672
11	Fine grained sandstone	6.0	126.0	3.0	63.0	7680	576	1344
12	Siltstone	6.0	132.0	3.0	66.0	8640	288	672
13	Fine grained sandstone	2.0	134.0	1.0	67.0	7680	576	1344
14	Siltstone	4.0	138.0	2.0	69.0	8640	288	672
15	Sandy mudstone	2.0	140.0	1.0	70.0	8640	192	768
16	Siltstone	2.0	142.0	1.0	71.0	8640	288	672
17	Medium grained sandstone	6.0	148.0	3.0	74.0	7680	768	1152
18	Fine grained sandstone	4.0	152.0	2.0	76.0	7680	576	1344
19	Siltstone	14.0	166.0	7.0	83.0	8640	288	672
20	Sandy mudstone	4.0	170.0	2.0	85.0	8640	192	768
21	Medium grained sandstone	2.0	172.0	1.0	86.0	7680	768	1152
22	Fine grained sandstone	2.0	174.0	1.0	87.0	7680	576	1344
23	Siltstone	6.0	180.0	3.0	90.0	8640	288	672
24	Medium grained sandstone	4.0	184.0	2.0	92.0	7680	768	1152
25	Fine grained sandstone	2.0	186.0	1.0	93.0	7680	576	1344
26	Laterite	36.0	222.0	18.0	111.0	8640	96	864
27	Loess	40.0	262.0	20.0	131.0	8640	96	864
28	Drift sand	18.0	280.0	9.0	140.0	8640	96	864

According to the aforementioned characteristics, the top boundary position of the water-flowing fractured zone for DZ1 drilling is 130.19 m, and the top boundary position of

the water-flowing fractured zone for DZ2 drilling is 144.65 m. The depth of 2⁻² coal in DZ1 drilling and DZ2 drilling is 269.8 m and 273.4 m, respectively. Then, the height

FIGURE 4: Characteristics of overburden failure after the extraction by physical simulation in Caojiatan coal seam.

TABLE 3: Physical and mechanical properties of the rock coal seam overlying the strata of the 5⁻² coal seam in Zhangjiamao coal seam.

No.	Lithology	The thickness (m)	The buried depth (m)	The density (g/cm ³)	Uniaxial compressive strength (MPa)	Modulus of elasticity (MPa)	Tensile strength (MPa)	Cohesion (MPa)	Angle of internal friction (°)
1	Loess	60	60	1620	700	600	0.2	0.32	20
2	Fine grained sandstone	10	70	2600	4500	3800	1.2	1.8	20
3	Sandy mudstone	6	76	2400	4000	3200	1.2	1.6	25
4	Siltstone	4	80	2400	4500	3800	1.2	1.8	20
5	Medium grained sandstone	6	86	2400	4000	3200	1.2	1.6	25
6	Fine grained sandstone	5	91	2600	4500	3800	1.2	1.8	20
7	Medium grained sandstone	12	103	2520	4000	3200	1.2	1.6	25
8	Fine grained sandstone	10	113	2600	6000	4800	1.5	1.9	34
9	Siltstone	16	129	2400	4000	3200	1.2	1.6	25
10	Fine grained sandstone	12	141	2600	5600	4200	1.5	1.9	28
11	Siltstone	18	159	2400	4500	3800	1.2	1.8	20
12	Medium grained sandstone	6	165	2520	4000	3200	1.2	1.6	25
13	2 ⁻² coal seam	5.5	170.5	1420	2000	1800	1.0	1.0	15
14	Fine grained sandstone	20.5	191	2600	5600	4200	1.5	1.9	28

FIGURE 5: Characteristics of the overburden failure after the extraction by numerical simulation in Zhangjiamao coal mine (measurement unit: m).

TABLE 4: Physical and mechanical properties of rock coal seam overlying strata of coal seam in Caojiatan coal mine.

No.	Lithology	Thickness (m)	Buried depth (m)	Bulk modulus (MPa)	Shear modulus (MPa)	Angle of internal friction (°)	Adhesion stress (MPa)	Tensile strength (MPa)
1	Loess	90	1900	—	—	—	—	—
2	Sandy mudstone	5	2570	3380	3150	39	5.6	5.9
3	Medium grained sandstone	10	2670	3830	3750	40	6.7	6.3
4	Fine grained sandstone	24	2700	3300	3160	32	6.5	6.8
5	Siltstone	15	2500	3600	3670	24	6.8	6.7
6	Medium grained sandstone	40	2100	3380	3150	20	5.6	6.8
7	Fine grained sandstone	16	2600	3300	3160	27	6.5	6.7
8	Medium grained sandstone	20	2500	3740	3570	24	6.3	6.8
9	Fine grained sandstone	32	2400	3600	3660	20	6.3	6.8
10	Siltstone	6	2500	3720	4630	24	8.6	5.7
11	2 ⁻² coal seam	12	1400	1480	1480	17	2.5	3.8
12	Siltstone	16	2500	3920	3700	23	8.5	5.5

FIGURE 6: Characteristics of the overburden failure after the extraction by numerical simulation in Caojiatan coal mine (measurement unit: m).

FIGURE 7: Layout of the detection drilling in the water-flowing fractured zone of Caojiatan coal mine.

of the water-flowing fractured zone in DZ1 and DZ2 drilling is 139.61 m and 128.75, correspondingly. The ratio of the water-flowing fractured zone to mining height is 23.27 and 21.46, respectively.

5. Microresistivity Scanning for Detection of the Height of Water-Flowing Fractured Zone in the Soil Layer

5.1. Detection Principle of Microresistivity Scanning Imaging Technology. Microresistivity scanning imaging is an important drilling wall imaging method, which uses small electrodes like multirow of buttons a multipolar plate to emit current to a borehole wall stratum. When a difference exists in the rock composition, structure, and fluid contained at the electrode contact place, a change in the current occurs. This current change reflects the alteration of the rock resistivity around the drilling wall, which can display the resistivity imaging of the drilling wall.

A drilling wall microresistivity scanning imaging logging tool (MCI) is used to detect fractures in the soil layer [21–23]. An alternating current is emitted by the polar plate body of the thruster so that the current is returned to the loop electrode of the upper part of the instrument through the loop composed of the mud column and the formation in the well. The equipotential of the thruster and the metal connection of the plate focus the current flowing from the array button in the middle of the plate perpendicular to the outer surface of the plate into the formation. The measured array spike current intensity reflects the change in the microresistivity caused by rock structure or electrochemical heterogeneity in the stratigraphic field, where the spike is opposite (Figure 9).

5.2. Microresistivity Scanning Imaging Exploration. Two detection drillings, drilling 8 and drilling 9, were constructed in Zhangjiamao coal mine, which were located in the goaf of N15203 working face in the northern wing panel of Zhangjiamao coal mine (Figures 10 and 11). This was the

FIGURE 8: Apparent density logging and long-range gamma logging curve. (a) Apparent density. (b) Long-range gamma.

FIGURE 9: Microresistivity scanning imaging. (a) Measurement scheme. (b) Scanner plate morphology.

FIGURE 10: Layout drawing of exploration drilling with microresistivity scanning imaging in Zhangjiamao coal mine.

location of drilling 9 area exploration of the water-flowing fractured zone. No. 5⁻² coal seam, with a mining thickness of 4.5 m and a buried depth of 149 m, was used as the main mining coal seam. The soil thicknesses of drilling 8 and

drilling 9 were, respectively, 21.92 and 58.89 m. The working face was mined. After the full mining of the coal seam, the water-flowing fractures in the soil layer of approximately 100 m above the coal seam were detected.

FIGURE 11: Construction site of the microresistivity scanning imaging in Zhangjiamao coal mine.

The measurement section of drilling 8 was 7.5–33.0 m, and two water-flowing fractures were detected, of which two complete high-angle fractures were developed in the range 21.8–29.9 m (Figure 12). The simple hydrological observation results (Table 5) of the drilling showed that there was no water level total pump loss; it was observed to enter the water-flowing fractured zone. Based on this result, the ratio of the water-flowing fractured zone to the mining height was calculated to be 28.5. The main related characteristics are presented in Table 6.

The measurement section of drilling 8 was 7.5–33.0 m, and two water-flowing fractures were detected, of which two complete high-angle fractures were developed in the range of 21.8–29.9 m (Figure 12). The simple hydrological observation results (Table 5) of the drilling showed that there was no water level total pump loss; it was observed to enter the water-flowing fractured zone. Based on this result, the ratio of the water-flowing fractured zone to the mining height was calculated to be 28.5. The main related characteristics are presented in Table 6.

The measurement section of drilling 9 was 7–46 m. Here, four water-flowing fractures were detected, of which the complete high-angle fractures were developed in the range of 7.8–18.4 m (Figure 13). Our comparison between the results obtained by microresistivity scanning imaging and simple hydrology observation of soil layer (Table 5) revealed that the water level decreases rapidly from the depth of 18.4 m, and the total pump leakage was gradually lost. The depth of 22.4 m enters the water-flowing fractured zone; the ratio of the water-flowing fractured zone to the mining height was 28.3. The data are shown in Table 7.

5.3. Comparative Analysis of Microresistivity Scanning Imaging and Other Methods. Microresistivity scanning imaging technique detected water-flowing fractures in the soil layer at a depth of 7.8–21.8 m. Comprehensive borehole flushing fluid consumption indicated that the ratio of the water-flowing fractured zone to the mining height was 28.3–28.5. The water-conducting fractures obtained by physical simulation and numerical simulation were all developed to the soil layer, and the ratio of the water-flowing fractured zone to the mining height was within 27–29.1. According to the ratio of the water-flowing fractured zone, the physical simulation surface fracture

FIGURE 12: Microresistivity scanning imaging characteristic of drilling 8.

development depth was calculated to be 7.28 m, which is consistent with the results obtained by microresistivity scanning imaging technology.

6. Comprehensive Research on the Height of Bedrock-Soil Composite Water-Flowing Fractured Zone

6.1. Relationship between Water-Flowing Fractured Zone Specifics and Geotechnical Characteristics. We performed fitting of the difference between the height of the water-flowing fractured zone and the bedrock and soil thicknesses to examine the development of the water-flowing fractured zone horizon and degree, soil, or bedrock. The correlations between the parameters of the fractured zone and the geotechnical characteristics of the zone need to be analyzed. Therefore, the differences between the height of the water-flowing fracture and the bedrock and soil layer thicknesses were taken as variables to conduct the bivariate correlation

TABLE 5: Comparison between the results obtained by microresistivity scanning imaging and simple hydrology observation of soil layer.

Drilling	Interpretation of fractures by microresistivity scanning imaging		Fractures of simple hydrological observation				Comparative results	Ratio of the water-flowing fractured zone to the mining height
	Depth of the fractures (m)	Fracture numbers/article	Depth of the fractures (m)	Water level existence	Rate of water level decline ($\text{m}\cdot\text{min}^{-1}$)	Drilling flushing fluid consumption per unit time ($\text{L}\cdot\text{s}^{-1}$)		
Drilling 8	21.8	2	21.92	No	—	1.3	No water level; total pump leakage. The rock mass is broken. Those two methods confirm each other better	28.5
	29.9		29.12	No	—	1.3		
Drilling 9	7.8–7.9	4	7.79	Yes	0.026	0.6933	The water level declines to zero and the rate of decline suddenly changes	28.3
	18.4		16.67	Yes	0.380	0.7917	No water level; total pump leakage. Those two methods confirm each other better	
	22.4		22.97	No	—	2.0742	No water level; total pump leakage. Those two methods confirm each other better	

TABLE 6: Types, characteristics, and depth range of the main fracture for drilling 8.

Geological stratification	Depth (m)	Inclination ($^{\circ}$)	Towards ($^{\circ}$)	Scope (m)
Soil	21.8	85.8	143–323	20.7–23.8
Bedrock	29.9	57.3	68.6–249	28.7–30.2

TABLE 7: Types, characteristics, and depth range of the main fracture for drilling 9.

Geological stratification	Depth (m)	Inclination ($^{\circ}$)	Towards ($^{\circ}$)	Scope (m)
Soil	7.8	84.4	155–335	7.5–9.0
	7.9	84.4	155–335	7.5–9.0
	18.4	83.7	9.1–189.1	17.5–19.2
	22.4	80.8	126.1–306.1	21.8–23.2

FIGURE 13: Microresistivity scanning imaging characteristic of drilling 9.

analysis. A significant correlation was present at the set significance level of 0.01, indicating that the two groups of variables can be subjected to correlation analysis.

Time series analysis is a statistical method for dynamic data processing. This approach is based on the random process theory and mathematical statistics and is employed to study the statistical laws followed by random data sequences for solving practical problems. Classical statisticians assume that data sequences are independent, whereas time series analysis focuses on the interdependence of data sequences. In this paper, we subjected the two groups of data to the time series analysis method.

First of all, the soil layer data was processed; based on the change of the soil layer, 20 m was set as a section point. Then, the data group was divided into seven sections, forming seven groups of continuous time series data. The data in each group of time were not unique and were clustered to select a data group that was most representative of the region. Finally, seven groups of data were formed.

Second, the seven groups of data variables were analyzed by trend analysis (Figure 10) using the exponential smoothing method. We concluded that the difference between the height of the water-flowing fractured zone and the bedrock first increased and then leveled off before declining

as the soil layer increases. The difference between the height of the water-flowing fractured zone and the bedrock increased within the thickness range of 0–20 m soil layer in the first sequence. In the range of 20–100 m soil layer thickness, namely, the second, third, fourth, and fifth section sequences, moderate differences were observed between the height of the water-flowing fractured zone and the bedrock. Logistic analysis showed that the inflection point of the group data appeared in the second section of the time series, namely, in the range of 20–40 m the soil layer thickness. In the soil layer thickness in the range of 100–140 m, specifically, in the sixth and seventh sequences, the difference between the height of the water-flowing fractured zone and the bedrock showed a downward trend.

Figure 14 can be divided into four blocks (I, II, III, and IV) by two lines: a horizontal line marking no height difference between the water-flowing fractured zone and the bedrock and a vertical line marking the soil thickness at 20 m.

6.1.1. Thick Bedrock and Thick Soil Region (I). Only two isolated points existed in the region, which indicated that this situation in the study area is uncommon, and the development of the height of the water-flowing fractured zone was limited, not leading to the bedrock.

6.1.2. Thick Bedrock and Thin Soil Region (II). The bedrock in the region was thick, and the height of the water-flowing fractured zone increased rapidly with the elevation of the soil layer, indicating that the key layer had not been broken at that time point. The soil layer exerted a load, and a thicker soil layer led to a greater height of the water-flowing fractured zone.

6.1.3. Thin Bedrock and Thin Soil Region (III). The bedrock in the region was thin, and the water-flowing fracture height penetrated through the bedrock, while the key layer was broken. With the increase of the thickness of the soil layer, the height of the water-flowing fractured zone rose rapidly, which implied that the soil layer still exerted its load layer that accelerated the rise of the height of the water-flowing fractured zone. However, compared with region II, the rising rate decreased, showing that the soil layer had an inhibitory effect on the development of the height of the water-flowing fractured zone as compared with bedrock.

6.1.4. Thin Bedrock and Thick Soil Region (IV). The bedrock was thin in the region, and the height of the water-flowing fracture penetrated the bedrock, and the key layer was broken. The increase in the thickness of the soil layer basically did not change the height of the water-flowing fractured zone, which reveals that the rise in the height of the water-flowing fractured zone was suppressed by the soil layer. As can be seen from Figure 14, when the thickness of the soil layer was greater than 70 m, the height of the water-

FIGURE 14: Relationship between the difference between fissure zone and bedrock thickness and soil thickness.

flowing fractured zone could not lead through the soil layer, indicating that when the thick soil layer exists, the height of the water-flowing fractured zone would not directly communicate with the overlying water on the soil layer. The fitting trend line shows that a 70 m soil layer was the boundary: the thickness of the soil layer at a depth lower than 70 m increased with the rise in the loess content, whereas the soil layer at a depth greater than 70 m decreased with the increase in the loess amount.

In summary, the development of the height of the water-flowing fractured zone was initially regulated by the thickness of the bedrock. When the bedrock was thick, the soil layer acted mainly as a load, whereas when the bedrock was thin, the soil layer exerted both load and inhibitory effect.

6.2. Study on the Relationship between the Height of the Water-Flowing Fractured Zone and Multifactor Fitting. In this paper, multiple regression analysis was used to predict the height of the water-flowing fractured zone. Regression analysis is a method applied to establish the mathematical relationship between statistical observations, which explains the change of dependent variables by the change of independent variables. It also predicts the possible value of dependent variables by the value of independent variables [24]. Multiple regression analysis is employed to establish a prediction model by analyzing the correlation between two or more independent variables and one dependent variable. A linear relationship between independent and dependent variables is called multiple linear regression analysis. Many nonlinear regressions can be solved by multiple linear regressions, and thus the linear regression method can be used to solve nonlinear regression prediction problems.

Multivariate linear regression analysis was utilized to analyze the correlation between n independent variables and dependent variables. Its basic model is described by

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + u. \quad (2)$$

We used the least square method to calculate the regression coefficients $\beta_1, \beta_2, \dots, \beta_n, \beta_0$, and the process is as follows:

$$f(x_i) = \sum (y_i - \hat{y}_i)^2 = \sum (y_i - \beta_0 - \beta_1 x_{1i} - \beta_2 x_{2i} - \cdots - \beta_n x_{ni})^2 = \min, \quad (3)$$

where $x_{1i}, x_{2i}, \dots, x_{ni}$ are independent variables and y_i is dependent variables. The independent variables and the dependent variables are all specific known observed values. To find a pair of regression coefficients, the following formula is derived for $\beta_0, \beta_1, \beta_2, \dots, \beta_n$, and its first derivative is 0.

$$\begin{cases} L_{11}\beta_1 + L_{12}\beta_2 + \cdots + L_{1n}\beta_n = L_{1y}, \\ L_{21}\beta_1 + L_{22}\beta_2 + \cdots + L_{2n}\beta_n = L_{2y}, \\ \dots \\ L_{n1}\beta_1 + L_{n2}\beta_2 + \cdots + L_{nn}\beta_n = L_{ny}. \end{cases} \quad (4)$$

Here,

$$\begin{aligned} L_{ij} &= L_{ji} = \sum (x_{ij} - \bar{x}_i)(x_{ij} - \bar{x}_j), \\ L_{iy} &= \sum (x_{ij} - \bar{x}_i)(y_i - \bar{y}_1). \end{aligned} \quad (5)$$

Because $L_{i1}, L_{i2}, L_{in}, \dots, L_{iy}$ ($i = 1, 2, \dots, n$) are known values, that is, $x_{ij}, y_i, \bar{x}_1, \bar{y}_1$ ($i = 1, 2, \dots, n$) are specific known observed values, $\beta_1, \beta_2, \dots, \beta_n$ are n unknown values and to solve n equations. Therefore, $\beta_1, \beta_2, \dots, \beta_n$ can be solved by determinant or elimination methods, and then β_0 can be obtained. When judging a close degree of the linear relation between variables in the regression equation, a quantitative index, correlation coefficient, is needed:

$$R \left(R^2(y, 1, 2, \dots, n) = \frac{\sum (\hat{y}_1 - \bar{y}^2)}{\sum (y_i - \bar{y}^2)} \right). \quad (6)$$

A value of R closer to 1 indicates that the so-called regression equation is more accurate.

The correlation between the height of the water-flowing fractured zone and various factors was assessed by SPSS. This software provides a simple statistical description to a complex multivariate statistical analysis. When analyzing the correlation between the height of the water-flowing fractured zone and the single-factor indexes, considering that other influencing factors were similar, representative data were selected to establish the multiple regression model with the largest correlation coefficient.

The multifactor fitting model is as follows:

$$y = 24.73x_1 + 0.135x_2 + 0.149x_3 + 1.946, \quad (7)$$

where y is the height of the water-flowing fractured zone, x_1 is the thickness of mining, x_2 is the thickness of soil, and x_3 is the difference between the height of the water-flowing fractured zone and the thickness of bedrock. Table 8 lists the proposed parameters and their values.

The following points can be seen from (7):

- (i) The largest coefficient of mining thickness shows that the height of the water-flowing fractured zone in coal seam mining is affected mainly by the mining thickness; the larger the mining thickness is, the higher the height of the water-flowing fractured zone is.

- (ii) The contribution of the soil layer to the height of the water-flowing fractured zone is slightly smaller than that of the bedrock. Both increase with the rise in the bedrock and soil layer thicknesses, indicating that they mainly exert load action.
- (iii) The constant term is smaller, indicating that the variation range of the height of the water-flowing fractured zone is larger, and different mining and geological conditions cause certain differences in the height of the water-flowing fractured zone.

In addition, the results of the single-factor analysis showed that different thicknesses of the bedrock and soil layer contributed to variations in the height of the water-flowing fractured zone. Therefore, multifactor fitting analysis was performed following the aforementioned zoning as follows.

- (1) In area I, the geological conditions in the study area had a lower impact, with no statistical significance.
- (2) In area II, when the soil layer was less than 20 m, if the height of the water-flowing fractured zone did not penetrate the bedrock, the calculation formula is as follows:

$$y = 18.68x_1 + 0.356x_2 + 0.058x_3 + 10.714, \quad (8)$$

where y is the height of the water-flowing fractured zone, x_1 is the thickness of coal seam mining, x_2 is the thickness of the soil layer, and x_3 is the thickness of bedrock. Table 9 lists the proposed parameters.

It can be seen from (8) that when the bedrock is thick, but the soil layer is thin, the following characteristics are evident:

- (a) Mining thickness is still the main influencing factor. The larger the mining thickness is, the higher the height of the water-flowing fractured zone is.
 - (b) The contribution of the soil layer to the thickness of the bedrock is much greater, and the load action of the soil layer also plays a part.
 - (c) The constant term is larger, indicating that the variation range of the height of the water-flowing fractured zone is smaller, and all of them are greater than 10.714 m.
- (3) The following calculation formula is suggested for area III, where the height penetrates the bedrock to reach the soil layer, and the soil layer is less than 20 m:

$$y = -6.654x_1 + 2.99x_2 + 1.378x_3 - 12.357, \quad (9)$$

where y is the height of water-flowing fractured zone, x_1 is the thickness of the coal seam mining, x_2 is the thickness of the soil layer, and x_3 is the thickness of

TABLE 8: Proposed parameters.

R	R^2	Standard estimate error	F	D-W
0.915	0.837	12.486	54.97	1.39

TABLE 9: Proposed parameters of the calculation formula for area II.

R	R^2	Standard estimate error	F	D-W
0.949	0.901	9.97	24.3	2.13

the bedrock. The proposed parameters are presented in Table 10.

It can be seen from (9) that when the bedrock is thin and the soil layer is thin, it has the following characteristics:

- (a) The contribution of the mining thickness to the height of the water-flowing fractured zone is negative; that is, a larger mining thickness results in a smaller height of the water-flowing fractured zone. As visible from the original data of the corresponding area, the height of the water-flowing fractured zone in this region reached the surface. Thus, the observation value of the height of the water-flowing fractured zone is small. A larger mining thickness leads to a greater error of the height of the water-flowing fractured zone; that is, the observation values are mainly related to the buried depth, namely, the thicknesses of the bedrock and the soil layer.
- (b) In this case, the contribution of the soil layer is larger than that of the bedrock, and both exerted a positive contribution.
The reason for this effect is that the height of the water-flowing fractured zone penetrated the surface. Greater thicknesses of the soil layer and the bedrock have resulted in a greater height of the water-flowing fractured zone.
- (c) The constant term is negative, whereas y is positive, which indicates that the range of the height of the water-flowing fractured zone is very large.
- (4) The calculation formula for area IV, where the height of the water-flowing fractured zone penetrated the bedrock and reached the soil layer and the soil layer was greater than 40 m, is as follows:

$$y = 32.7x_1 + 0.292x_2 + 0.428x_3 - 78.995, \quad (10)$$

where y is the height of water-flowing fractured zone, x_1 is the thickness of coal seam mining, x_2 is the thickness of the soil layer, and x_3 is the thickness of the bedrock. Table 11 lists the suggested parameters. It can be seen from (10) that when the bedrock is thin and the soil layer is thick, the following characteristics are evident:

TABLE 10: Proposed parameters of the calculation formula for area III.

R	R^2	Standard estimate error	F	D-W
0.964	0.93	12.31	13.318	2.2

TABLE 11: Proposed parameters of the calculation formula for area IV.

R	R^2	Standard estimate error	F	D-W
0.968	0.937	8.67	54.45	1.459

- (i) Most of the water-flowing fractured zone is developed by the soil layer, and most of them do not reach the surface, so the mining thickness contributes considerably to the height of the water-flowing fractured zone.
- (ii) In this case, the soil layer exerts both load and an inhibitory effect, and thus its contribution rate is lower than that of the bedrock.
- (iii) The constant term is negative, whereas y is positive, which indicates that the range of the height of the water-flowing fractured zone is very large.

7. Conclusion

- (1) Research on the height of the water-flowing fractured zone for water-retaining coal mining in the area is of great practical significance.
- (2) For the first time, the microresistivity scanning imaging technology was applied to study the development law of the water-flowing fracture in the soil layer under the mining conditions in Zhangjiamao coal mine. The detection results are more accurate than those of the physical and numerical simulations, which can further expand the detection area and fully confirm the reliability of the detection results.
- (3) The water-flowing fracture of the soil layer was found in this study, which lays a foundation for research on the development law of water-flowing fractures in soil layers.
- (4) The development height of the bedrock-soil water-flowing fractured zone was systematically studied, and a mathematical model for its prediction with different bedrock and soil thicknesses was established, which provided a theoretical basis for determining the development height of the water-flowing fractured zone.

Data Availability

There are eleven tables providing the data used to support this study. All these data were obtained from geological prospecting, field test, laboratory test, indoor test, and mathematical calculations and any details about them are indicated in this paper. The exploration, experimental, and

original data used to support the findings of this study are included within this article. No additional data are available.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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