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TECHNICAL ARTICLE

The Feasibility of Mining Under a Water Body Based on a Fuzzy Neural Network

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Abstract

The burial depth and dip angle of a coal seam, the size of the working face, mining height, structure of the overlying strata, coal mining method, and the number of mining slices all significantly affect the amount of water flowing in a fractured zone. Combined with these seven factors, a predictive model for the height of water flowing in a fractured zone was established based on a fuzzy neural network, and 49 typical cases were chosen to train and test the network. The test error of the network was small and the match degree was high. Furthermore, the predicted height of water flowing in a fractured zone of working face 2309 in the Guozhuang coal mine, China was found to be within the range of the results calculated by more traditional (the empirical formula, the key stratum, and numerical simulation) predictive methods. After a safety coefficient of 1.2–1.5 was incorporated, a 183–211 m thick coal/rock safety pillar was required. In addition, a 98 m rock pillar with original permeability was left between the protective layer and the weathered zone. Therefore, under normal conditions, the mining of working face 2309 beneath Jianghe River was assessed to be safe and feasible.

Keywords Fuzzy neural network · Mining under a water body · Height of the fractured zone · Rock pillar

Introduction and Background

Before a coal seam is mined, coal and rock are in a natural stress state (Fig. 1). After it is mined, the overlying strata of a working face moves in response to ground pressure, resulting in the cracking and fracturing of rock. According to the degree of destruction, the rock is divided into three zones: a caving zone, a fractured zone, and a bending subsidence zone in the vertical direction, and a markable destruction outline is formed in the advance direction (Fig. 2). As water channels are generated in the caving and fractured zones, the water at the surface or in an aquifer can flow into the working face, causing an inrush of water (Beijing Mining Research Institute 1981; Macfarlane et al. 2007; Shi et al. 2012). Meanwhile, the normal flow of surface or ground water can be dramatically disrupted (Fig. 3).

Many studies have been carried out to determine the height of water flowing through a fractured zone and on the relationship between the surface water and inrush events, using various methods. Some of these are briefly summarized below to provide a background for interested readers.

1. Because the Wuyang coal mine is threatened by the Zhuozhang River, Du and Gao (2017) used numerical simulation software, the Universal Distinct Element Code (UDEC), to investigate water flowing in a fractured zone. Through field measurements, the height of the water flowing in a fractured zone during longwall caving mining of thick coal seams was verified, providing significant theoretical insights for effectively preventing water hazards to mine roofs, especially when mining beneath water bodies.
2. Wei and Chen (2010) used the empirical formula to judgee the feasibility of different mining methods below the Lanshui River, one of the tributaries of Zhuozhang River in the Gaohe coal mine. Theoretically, fully mechanized slice and fully mechanized caving mining were judged to be feasible. Comparing the

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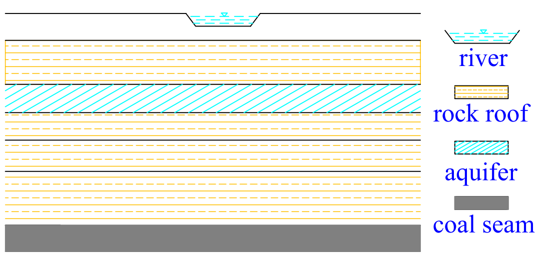


Fig. 1 The state of coal and rock strata before coal seam mined

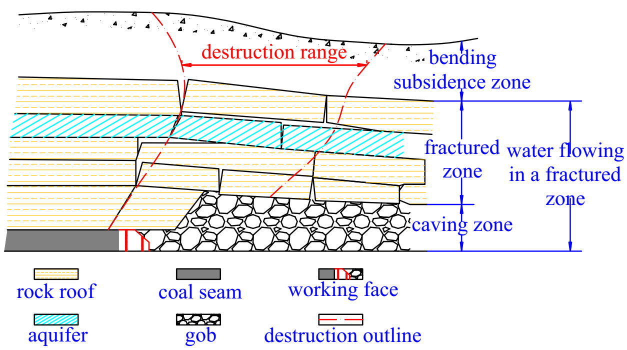


Fig. 2 "Three-zone" structure of overlying strata in working face

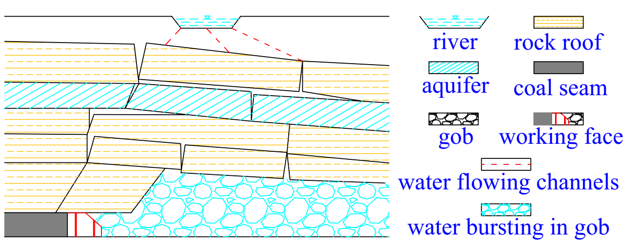


Fig. 3 The state of coal and rock strata after coal seam mined

advantages and disadvantages of the two methods, the fully mechanized, full-thickness caving mining method was chosen.

3. By considering geological and hydrogeological conditions, recent observational data, and theoretically calculated results from the Dongpo coal mine, Jiang and Gong (2010) analyzed the feasibility of mining below waterbodies and developed safe technical measures for such mining.
4. The empirical formula, a downhole plugging, water injection, crack measurement system, and a downhole televised detection system were used to detect the development of water flowing in a fractured zone by Gao et al. (2014), which provided theoretical support for mining the Sitai coal mine beneath Shili River and a way for other mines to detect water flowing in a fractured zone.
5. The process of mining coal below the Beizao sea area was simulated using UDEC 4.0 software by Chen et al. (2014), who combined field observations, rules on fracture propagation of overlying strata, and the height of water flowing in a fractured zone.
6. A feasibility of mining beneath composite water bodies in the no. 2 Nalinhe mine area in the Dongsheng coalfield was studied by Fan (2013). Some technical measures were drawn up to delineate the danger zone and a comprehensive waterproofing technology was proposed.
7. An in-situ hybrid packer system was designed to measure the thickness of the fractured zone and a 3-D hydrogeological model of the coal seam, associated aquifers, artificial lake, and surface water was established to simulate the groundwater flow field to evaluate the potential impact of induced fractures between a lake and the aquifers and coal seams below (Dong et al. 2016).
8. In the Laowuji coal mine of the Panjiang mining area, Mao and Shi (2009) explored how to safely mine beneath water from Qiutian and Ditch. The 131,211 working face was successfully mined, laying a good foundation for future working faces.
9. Research on the height of water flowing in a fractured zone in the Gaotouyao coal mine was carried out by Li et al. (2011) using similar material simulation. They showed that when $\frac{H}{h} \geqslant 19$ (where H is the thickness of the water-separated bedrock and h is the mining height), mining could proceed safely below surface water from two seasonal water bodies, the Shuiduohuchuan River and Dahata ditch.
10. Through an analysis of the empirical formula and numerical simulation (by FLAC^{3D}4.0), Zhang (2015) concluded that mining coal below the Santaizi reservoir would be safe, and would not cause an inrush of surface water.
11. Based on the empirical formula and overburden structure, it was concluded that mining was safe in most areas of the Xin'an coalfield below the Xiaolangdi reservoir, and that mining height did not need to be limited (Li 2010a, b). Moreover, he designated the area with a risk of water inrush.

At present, the height of water flowing in a fractured zone in China's coal mines is calculated mainly based on regulatory formulas (State Bureau of Coal Industry 2000). Since few factors and only an ideal model are considered by these other methods, their results often differ significantly from measured values. In general, the measured values are more reliable, but its implementation incurs a heavy workload and high costs (Li et al. 2012; Luan et al. 2010; Xu et al. 2010).

However, these formulas are mainly focused on the influence of aquifers on coal mining, with little attention paid to the potential influence of surface water bodies. The key to solving engineering roadblocks impeding safe mining and water resource protection in that situation is accurate prediction of the height of water flowing in the fractured zone and objective evaluations of mining feasibility.

The Guozhuang coal mine is in the Lu'an mining area; the length of working face 2309 is 208 m and its advance length is ≈800 m (Figs. 4, 5). However, safe mining of the working face is threatened by the fact that the land surface above the working face is comprised of hilly terrain (at an elevation of 905–925 m, and averaging 910 m) and is split in half by the Jianghe River. The floor elevation of the coal

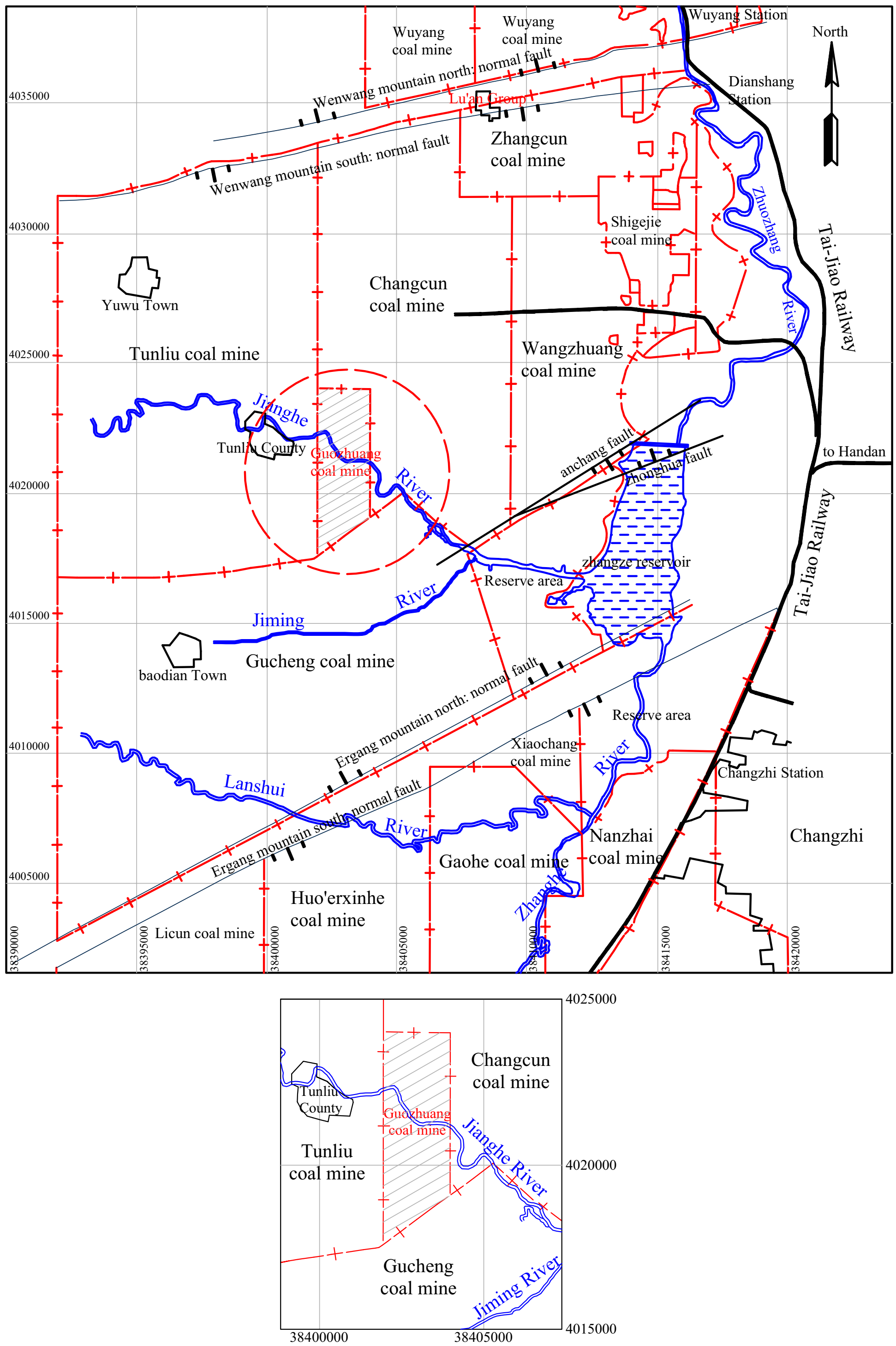


Fig. 4 Geographical position of Guozhuang coal mine

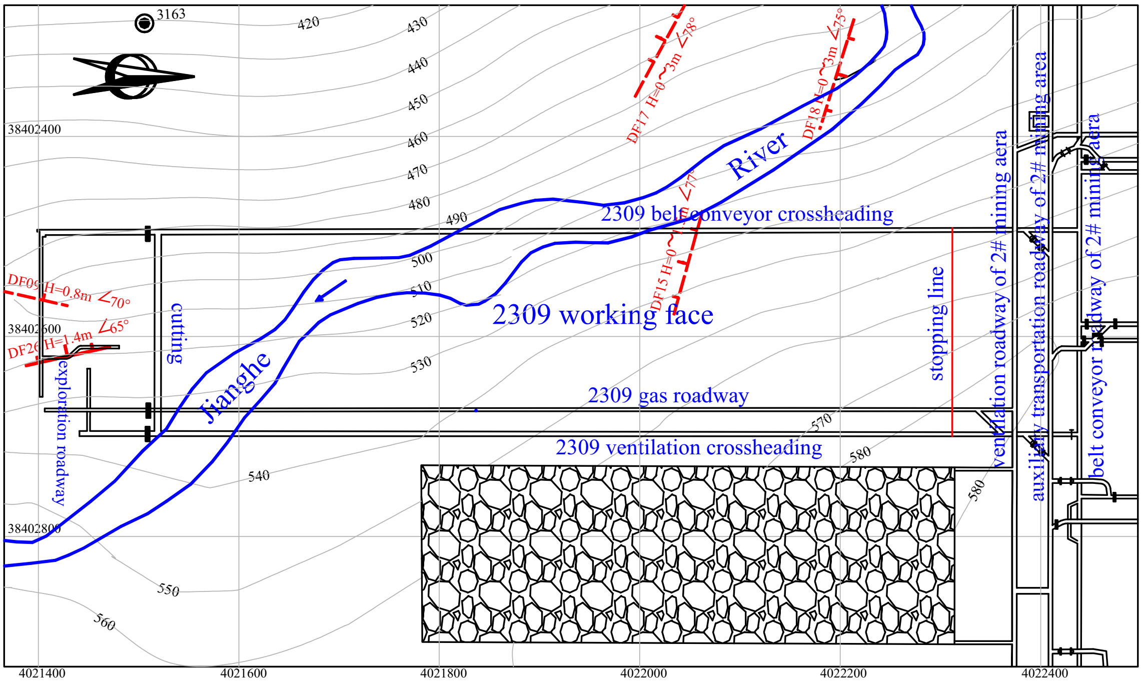


Fig. 5 Engineering plan for mining and excavation of 2309 working face

seam is 480–580 m and the mining depth is 359–419 m below the riverbed; the unconsolidated aquifer is 50 m thick in the study area (Fig. 6).

Takagi and Sugeno (T–S) (1985) first proposed a method for fuzzy modeling. A T–S fuzzy model is a system that is strongly self-adaptive, that can be automatically updated, and is able to continuously modify the membership function of a fuzzy subset. Gradually, the approach has developed into an effective method to analyze complex problems and it is widely applied in various fields. A T–S fuzzy neural network model was therefore developed to predict the height of the water flowing in the fractured zone, based on multiple factors (Sun et al. 2013; Zhang et al. 2012; Zhou 2007), and the feasibility of safely mining a working face (2309) beneath Jianghe River was assessed.

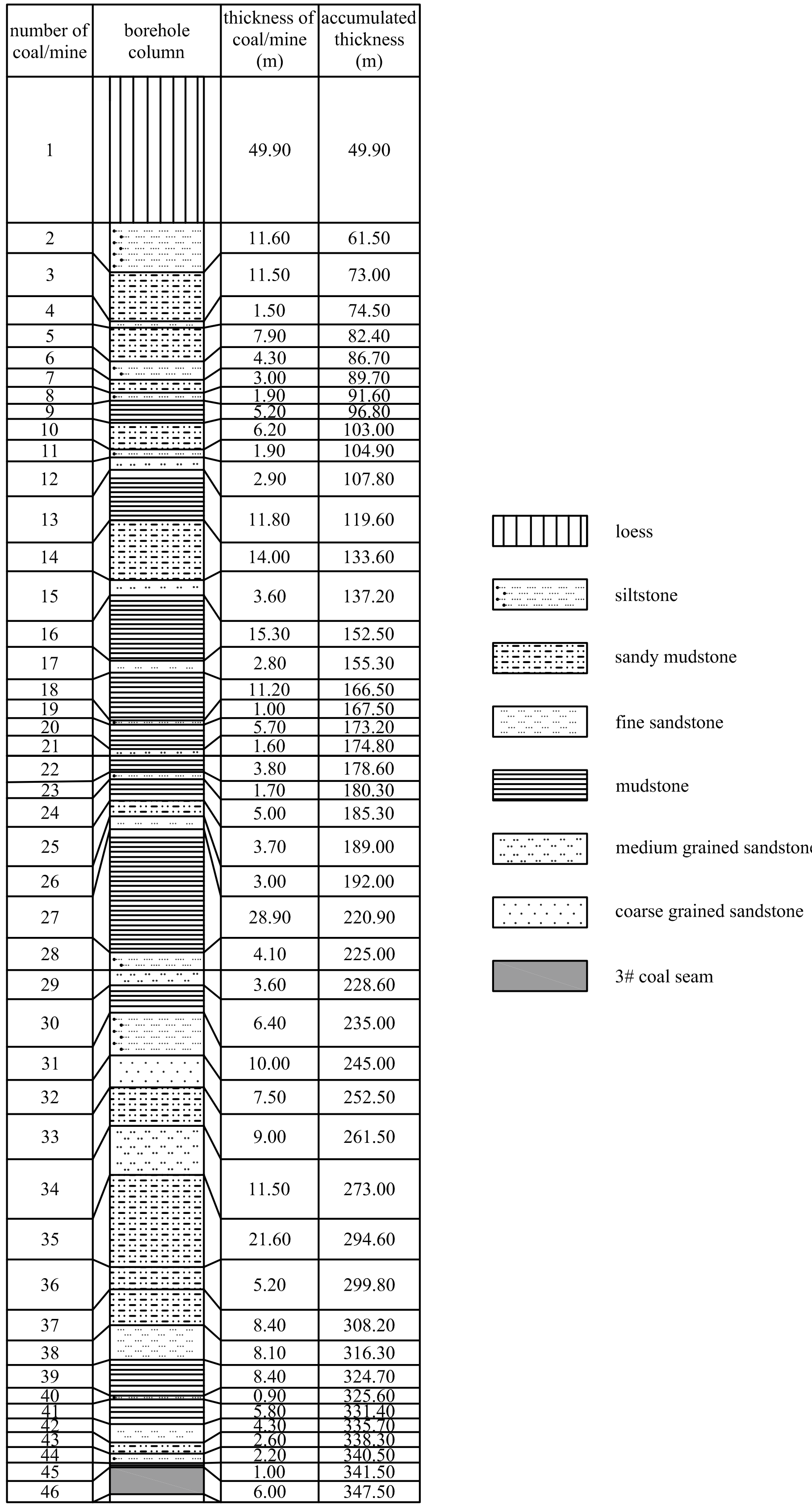
Modeling for the Height of Water Flowing in a Fractured Zone Based on T–S Fuzzy Neural Network

A predictive algorithm for the height of water flowing in a fractured zone based on a T–S fuzzy neural network is shown in Fig. 7. The number of input and output nodes as well as the function of the fuzzy membership degree are determined according to the dimension of the training samples (Gan et al. 2005; Jiang 2005; Shi et al. 2010). Research proves that the height of water flowing in a fractured zone of a working face is closely related to the burial depth, the angle of the coal seam, the size of the working face, the mining height, the structure of the overlying strata, the coal mining method, and the number of mining slices (Li 2010a, b). Consequently, the risk of water inrush through the working face roof can be predicted based on these parameters.

Given the seven-dimensional input parameters and a one-dimensional output parameter, a 7-14-1 T-S fuzzy neural network model was established, with 14 functions of membership degree. Eight sets of coefficients were chosen; the center and width of the function of fuzzy membership degree were randomly obtained. After data input, the fuzzy neural network was repeatedly trained 500 times, and then the height of water flowing in the fractured zone was predicted by the well-trained network.

Referring to the measured heights of water flowing in fractured zones in China's coal mines (Ma et al. 2008), 49 sets of measured data from working faces were chosen for the training sample and the test sample of the fuzzy neural network (see Table 1). In Table 1, the datasets 1–45 were used as the training sample and the remaining four sets served as the test sample. The test results from the training of the fuzzy neural network are shown in Fig. 8, from which we can see that the output of the network is basically consistent with the measured data. The average absolute error is 1.86 m, and the average relative error is 6.5%, indicating that the model is reasonable. Thus, the prediction value is reliable and can be used to evaluate the feasibility of mining coal safely beneath a water body.

Fig. 6 Geological column



number of coal/mine	borehole column	thickness of coal/mine (m)	accumulated thickness (m)
1		49.90	49.90
2		11.60	61.50
3		11.50	73.00
4		1.50	74.50
5		7.90	82.40
6		4.30	86.70
7		3.00	89.70
8		1.90	91.60
9		5.20	96.80
10		6.20	103.00
11		1.90	104.90
12		2.90	107.80
13		11.80	119.60
14		14.00	133.60
15		3.60	137.20
16		15.30	152.50
17		2.80	155.30
18		11.20	166.50
19		1.00	167.50
20		5.70	173.20
21		1.60	174.80
22		3.80	178.60
23		1.70	180.30
24		5.00	185.30
25		3.70	189.00
26		3.00	192.00
27		28.90	220.90
28		4.10	225.00
29		3.60	228.60
30		6.40	235.00
31		10.00	245.00
32		7.50	252.50
33		9.00	261.50
34		11.50	273.00
35		21.60	294.60
36		5.20	299.80
37		8.40	308.20
38		8.10	316.30
39		8.40	324.70
40		0.90	325.60
41		5.80	331.40
42		4.30	335.70
43		2.60	338.30
44		2.20	340.50
45		1.00	341.50
46		6.00	347.50

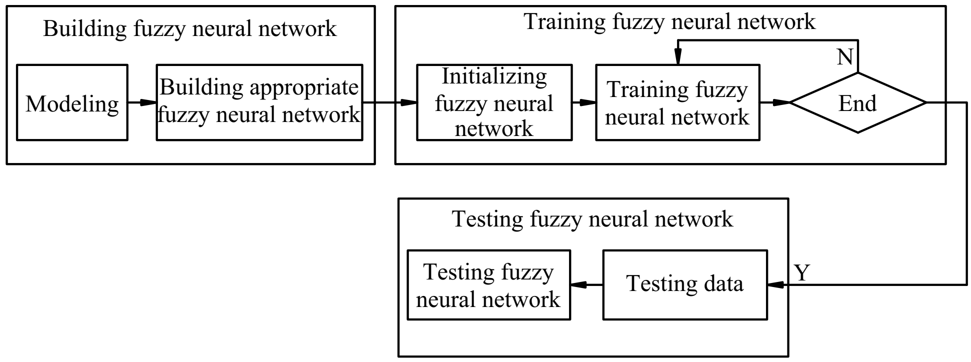


Fig. 7 The prediction algorithm for the height of water flowing in a fractured zone based on a fuzzy neural network

Analysis of the Feasibility of Mining Beneath a Water Body

Prediction for the Height of Water Flowing in a Fractured Zone

The data in Table 2 were substituted into the well-trained network to predict the height. Since different outputs are obtained from the network every time, 30 continuous predictions was carried out (Table 3). The maximum height of water flowing in the fractured zone was 104.52 m, the minimum 87.25 m, and the average 95.55 m. The height of water flowing in the fractured zone was calculated using more traditional predictive methods, and compared to the predicted value from the fuzzy neural network model.

1. Empirical formula (Deng and Peng 2015; State Bureau of Coal Industry 2000)

The structure of the overlying strata above a working face is type h–h (see Tables 1, 2), and the height of water flowing in a fractured zone can be calculated by the following formulae.

$$H = \frac{100 \sum M}{1.2 \sum M + 2} \pm 8.9 \quad (1)$$

$$H = 30\sqrt{\sum M} + 10 \quad (2)$$

where $\sum M$ is the cumulative mining height. A cumulative height of $\sum M = 6$ m was inserted into formulae (1) and (2) to calculate the height of water flowing in a fractured zone, giving 74.1 and 83.5 m, respectively.

The site-measured data of water flowing in a fractured zone undergoing fully mechanized top coal caving mining in the Lu'an mining area was considered, and the maximum height of water flowing in a fractured zone was calculated using the method of linear regression, as follows:

$$H = 15.9M + 17.6 \quad (3)$$

where M is the effective mining height. When an effective mining height of 6 m was inserted into formula (3), the height of water flowing in the fractured zone was calculated as 113 m.

2. Key stratum prediction method (Li 2007; Xu et al. 2012)

According to the drilling results and physical mechanics parameters of the overlying strata, and based on the key stratum theory, the key stratum for the fine sandstone was calculated to be 74 m from the coal seam. Since the key stratum was not located in the range of 7–10 m from the coal seam, the height of water flowing in the fractured zone was calculated as 74 m.

3. Numerical simulation method (Chen et al. 2006; Li 2007)

Based on the site conditions and the parameters of the overlying strata, Rock Failure Process Analysis (RFPA) software (Liu et al. 2005; Tang et al. 2003; Wang et al. 2011) was used to simulate water flowing in the fractured zone. For a working face undergoing fully mechanized top coal caving with an effective mining height of 6 m, the final height of water flowing in the fractured zone should be ≈ 120 m. Thus, the predicted result for the network obtained using the above methods ranged from 74 to 120 m, showing that the predicted height based on the fuzzy neural network model was reasonable, and that its predictive output is of high credibility and actual reference value. Given the uncertainty of a mine's geological conditions, good engineering practice dictates that a safety coefficient should be incorporated when predicting the height of water flowing in a fractured zone.

Analysis of Feasibility

The Jianghe River flows from west to east and lies in the middle of the Guozhuang mining area, just above working face 2309, and the water flows for a distance of ≈ 4.8 km near the mine. The river is 30–70 m wide and flows at a

Table 1 Statistics of the height of water flowing in a fractured zone in working face

Serial number	Buried depth (m)	Dip angle of coal seam (°)	Length of working face (m)	Mining height (m)	Structure type of overlying strata	Mining method	Number of slicing mining	Height of water flowing in a fractured zone (m)
1	150	23	174	6	11	1	3	58.4
2	168	5.5	137	3.1	11	2	1	27.8
3	418	6	198	8.7	21	3	1	65.5
4	434.6	8	153	8.7	22	2	1	71
5	359	2.3	146	3.6	11	3	1	30
6	56	0	55	4.5	22	2	1	42.5
7	49	5	135	4	11	2	1	45
8	458.9	7.5	227	12.42	11	3	1	205.9
9	516.3	8	195	7.54	11	3	1	185.1
10	458	7.5	207	11.4	11	3	1	211.2
11	433	8	227	15.17	11	3	1	234
12	784	6	230	10.95	11	3	1	219
13	420	23	70	3.7	21	2	1	56.8
14	43	60	30	3	22	2	1	35
15	173	20	70	3.38	22	3	1	25.3
16	89	7	69	2.03	22	1	1	45.86
17	1024	32	180	6.5	22	3	1	75.6
18	225	23	174	6	11	4	3	58.4
19	270	18	100	1.8	22	1	1	33
20	479	4	170	6.6	21	3	1	66.6
21	209.5	30	77	4.5	22	4	2	47.3
22	391	25	230	5.6	22	4	2	57.3
23	113.3	14.5	188.8	2.45	12	2	1	34.98
24	350	9	136	4	11	2	1	35
25	350	5	135	2.5	12	2	1	20
26	282	8	71	4.8	21	2	1	33
27	89	7	69	2.1	22	2	1	45.86
28	213	8	167	6.2	22	4	2	91.7
29	400	5.75	154	5.77	22	3	1	70.7
30	446	17	143	3.8	21	2	1	40
31	520	12	174	3	21	2	1	102.3
32	550	15	180	2.4	21	2	1	55.32
33	230	37	85	2	11	1	1	52.5
34	125	5	150	8	11	3	1	22
35	262.8	2.5	143	8.8	11	4	2	39
36	101	1	158	3.2	11	2	1	63
37	290	8	645	8.4	11	3	1	85.6
38	329	8	134	8.1	11	3	1	83.9
39	475	28	147	5.13	12	2	1	45
40	409	9	193	8.13	21	3	1	72.9
41	450	8	170	8	21	3	1	86.8
42	117	2	200	3.4	12	2	1	72
43	590	6.5	230	9.97	11	3	1	199
44	320	6	65	1.7	21	1	1	27.5
45	272	11.5	120	8	22	3	1	62
46	285	6	180	1.6	21	1	1	30.8
47	93	62	73	1.8	21	1	1	16.6
48	120	8	75	1.2	12	1	1	31
49	130	5	136	6.3	21	4	2	52.2

In the structure type of overlying strata, 11 represents soft–soft (s–s), 12 soft–hard (s–h), 21 hard–soft (h–s), and 22 hard–hard (h–h)

In mining method, 1 represents blasting mining, 2 fully-mechanized mining, 3 fully-mechanized top coal caving mining, and 4 slicing mining

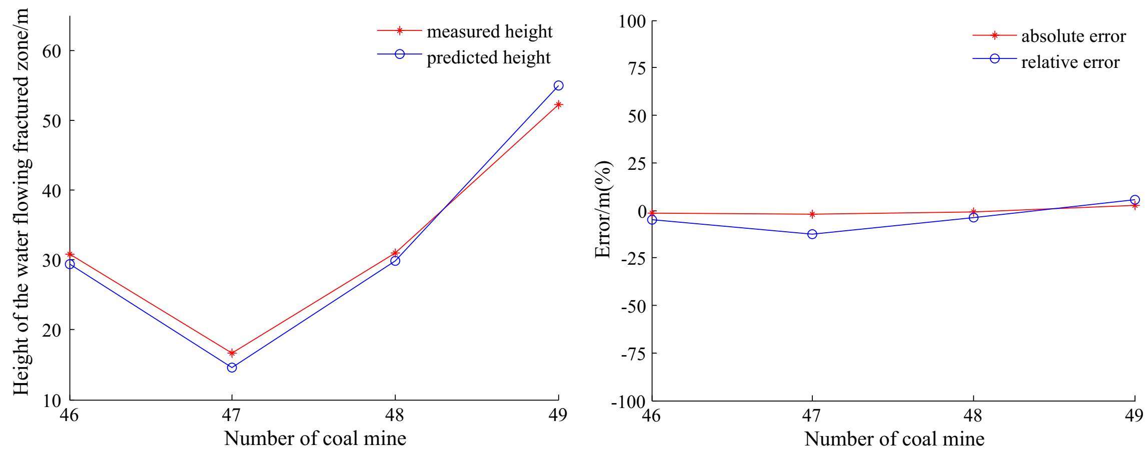


Fig. 8 Test error

Table 2 Factors influencing the height of water flowing in the fractured zone in the 2309 working face of Guozhuang coal mine

Buried depth (m)	Dip angle of coal seam (°)	Length of working face (m)	Mining height (m)	Structure type of overlying strata	Mining method	Number of mining slices
419	16	208	6	22 (h–h)	Type 3 (fully mechanized top coal caving mining)	1

Table 3 Prediction values for the height of water flowing in a fractured zone

Serial number	Prediction value	Serial number	Prediction value	Serial number	Prediction value	Serial number	Prediction value
1	89.84	9	102.45	17	90.13	25	94.20
2	87.25	10	93.02	18	92.54	26	102.69
3	95.86	11	98.21	19	90.17	27	97.21
4	89.66	12	101.43	20	98.25	28	97.35
5	94.31	13	94.39	21	98.53	29	91.57
6	96.27	14	104.52	22	98.04	30	90.34
7	95.60	15	98.98	23	91.13		
8	95.46	16	94.78	24	102.31		

velocity of ≈ 0.1–0.9 m^3/s. It contains water throughout the year; the river's depth is 1.7–5.2 m.

In the mining area, the Cenozoic unconsolidated aquifer is ≈ 50 m thick. The bedrock is deeply weathered to a depth of not more than 50 m. In addition, both strata are characterized by moderate, consistent, and strong abundance of water, which is typical when mining coal beneath composite water bodies. To ensure safe coal production, a waterproof rock pillar is necessary. The vertical height, H_{wp}, of this pillar, in m, can be calculated as:

$$H_{wp} = kH + H_p + H_{bw} \tag{4}$$

where H is the height of water flowing in the fracture zone after mining; k is the developmental uncertainty coefficient of the height of the water, generally 1.2–1.5 m; H_p is the thickness of the protective layer, which is equal to three times the mining height in a fully mechanized top coal caving mining operation; and H_{bw} is the penetration depth of a water body in the weathered bedrock, equal to 50 m.

The effective mining height of the #3 coal seam is 6 m. The parameters were put into formula (4), giving:

$$H_{wp} = (1.2 - 1.5) \times 95.55 + 3 \times 6 + 50 \approx (183 - 211)\ \text{m}$$

The resultant design of a coal and rock pillar for mining beneath Jianghe River is shown in Fig. 9. When the effective

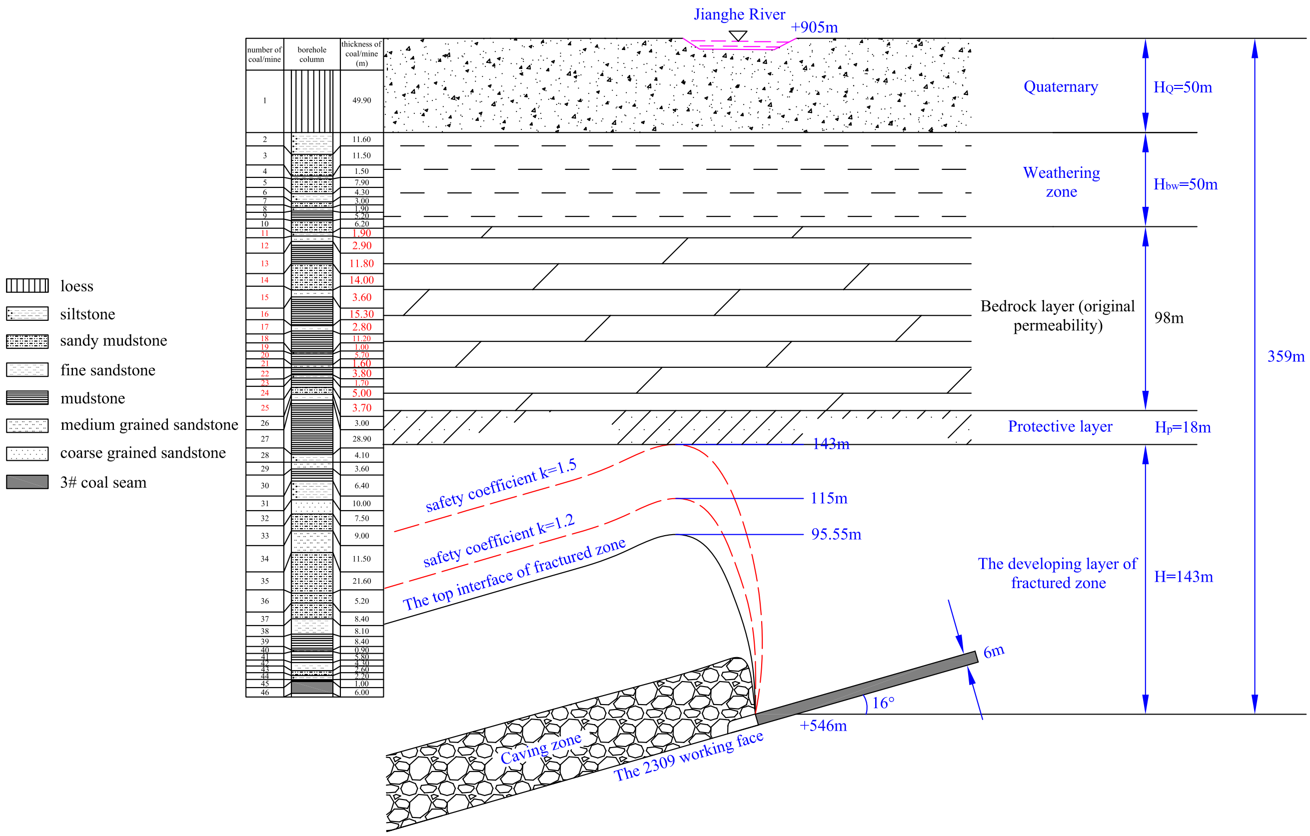


Fig. 9 The design of waterproof safety coal and rock pillar (considering the most dangerous case)

mining height of the working face was 6 m, the predicted height of water flowing in the fractured zone was 95.55 m. A safety coefficient of $k = 1.5$ was used to calculate the size of the waterproof safety coal and rock pillar, giving 211 m. The minimum thickness of the bedrock pillar between the roof of the coal seam in the working face and just above the riverbed measured 309 m, and a rock pillar 98 m high, above the protective layer and below the weathered zone, was retained, with its original permeability. Therefore, as long else nothing else occurred to threaten mine safety, it was judged feasible to mine working face 2309 by fully mechanized top coal caving beneath Jianghe River, without having surface water enter the mine.

Advanced detection and prevention should be strengthened and implemented in accordance with the relevant requirements if the working face encounters a collapse column of flowing water or the fractured zone of a fault, or if it is determined that there is a risk of a water inrush through the floor.

Conclusions

Based on the burial depth and dip angle of the coal seam, the size of the working coal face, the mining height, the structure of the overlying strata, the mining method, and the number of mining slices, a fuzzy neural network predictive model was established for the height of water flowing in a fractured zone with a network structure of 7-14-1. Data from 49 typical cases were chosen to train and test the model. The accuracy and reliability of the model was determined to be high, with an average absolute error of 1.86 m and an average relative error of 6.5%. Using the neural network model, the height of water flowing in a fractured zone above working face 2309 in the Guozhuang coal mine was predicted, and the results were compared with those obtained using more traditional methods (the empirical formula, key stratum prediction, and numerical simulations). The predicted height from the model was 95.55 m, which was in the range of the results calculated by the traditional methods.

After incorporating a safety coefficient of 1.5, a 98 m rock pillar, with its original permeability, was left above the protective layer and below the weathered zone. Therefore, it was determined that it was safe and feasible to mine working face 2309 beneath a water body.

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