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ORIGINAL PAPER

Analysis of Prediction Model of Failure Depth of Mine Floor Based on Fuzzy Neural Network

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Abstract To obtain the law of failure depth of mine floor and its influencing factors during coal mining process, a large amount of field measured data of floor failure depth was collected, and five influencing factors were summarized based on the analysis of data and years of field experience. The five main influencing factors were the length of working face, mining depth, mining height, dip angle and floor anti-sabotage ability. Based on fuzzy math membership and membership function, the five factors were preliminarily processed, then the sensitivity ranking was obtained according to the weight of influencing factors, and the prediction model of failure depth of mine floor was established based on the fuzzy neural network. It was shown that the order of the weight of the five factors was the length of working face > dip angle > floor anti-sabotage ability > mining depth > mining height. The maximum weight of the length of working face was 0.3678. The accuracy of the model was high and the prediction results were in good agreement with the engineering practice according to verification results. To ensure the maximum economic benefit of mine, some measures and methods through human intervention to reduce the failure depth of floor and ensure mine safety were suggested.

Keywords The failure depth of floor · Fuzzy neutral network · Influence factor · Weight · Prediction model

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1 Introduction

In recent years, with the gradual expansion of the mining degree of coal resources, the phenomenon of the polarization of coal mining was becoming more and more obvious, especially in the old mining area of North China, the coal resources were gradually depleted, and the depth of mining was increasing. The increasing of mining depth made the mine more and more threatened by the floor confined water. The floor was more easy to water inrush accident owing to the large stress, high water pressure and strong disturbance in deep mining. However the general law of mechanical adaptability in deep mining had limitations. The adaptability of a large number of conclusions became poor. Therefore, In an overall analysis of the bottom damage depth development during the mining of shallow and deep coal seams, it was very important to obtain a prediction model of the floor failure depth with high accuracy and adaptability to ensure mine safety and exploit coal resources threatened by water hazard.

A large number of scholars have done a lot of research on the failure depth of coal seam floor. Li (1999) put forward the down three zone theory, Yu et al. (2006) and Shi and Han (2005) put forward the four zone theory based on the down three zone theory. Cheng et al. (1999) and Dong (2005) obtained the range of floor guide zone based on the geophysical survey data. Liu et al. (2017a, b) and Lu et al. (2017) put forward many calculation formula according to the plastic slip line field and damage theory. In addition, many scholars analyzed the development law of mine floor failure depth by using numerical simulation and similar material experiments (Feng et al. 2009; Li et al. 2017; Zhang et al. 2013). The study of prediction accuracy of shallow and deep buried coal seam floor failure depth was low. Therefore, we adapt BP neural network algorithm to predict the mine floor failure depth, in order to get a strong adaptability and high accuracy method to predict the mine floor failure depth. The BP neural network algorithm had good robustness, generalization and strong learning ability for solving the complicated internal mechanism, and its structure was simple and easy to be realized (Zhang et al. 2015, 2017; Li et al. 2017).

A large number of data about mine floor failure depth were collected and summed up the five main factors by combining with years of mine work experience. The fuzzy neural network model was established by choosing the reasonable initial parameters and enough learning samples in the fuzzy mathematics theory and neural network. Through the model learning, the weights of all the factors were obtained, and the absolute impact coefficient was used to determine the contribution weight of each factor to the floor failure depth, and the sensitivity ranking was made for all the influencing factors. The prediction model of the failure depth of the mine floor was established, and the accuracy of the model was verified by the field measured data.

2 Summary of Influencing Factors and Pretreatment

2.1 Summary of Influencing Factors

In this paper, more than 20 mine floor failure depth data and various types of geological data were collected. By analyzing the geological conditions of each working face, mining methods and the failure depth of floor under mining influence, five main factors were summarized as follows, buried depth, dip angle, mining height, inclined face length, floor anti-sabotage ability. The buried depth and dip angle were geological factors. The inclined length of working face and mining height were man-made subjective factors in coal seam mining process. The damage resistance of the floor was the comprehensive consideration of the damage resistance of floor by the factors of comprehensive mining method and geological conditions. The above factors are coupled and interact. And it was impossible to solve the nonlinear mathematical problem accurately by the conventional linear mathematical method. Therefore, the fuzzy neural network system which continuously updated the error by error back propagation was used to predict failure depth of coal seam floor under different conditions.

2.2 Preprocessing of Influencing Factors

Of the five factors, there were one qualitative factor (floor anti-sabotage ability) and four quantitative factors. Firstly, the corresponding membership of seam depth, dip angle, mining height and face length was obtained by the data collected in the field and years of mining experience. The membership function of coal seam inclination, mining depth, mining height, the length of the working face was determined. They was expressed as

$$R_a = \begin{Bmatrix} 0 & a \le 8 \\ \frac{a-8}{14} & 8 < a < 22 \\ 1 & a \ge 22 \end{Bmatrix} \quad R_m = \begin{Bmatrix} 0 & m \le 1.5 \\ \frac{m-1.5}{6.5} & 1.5 < m < 8 \\ 1 & m \ge 8 \end{Bmatrix}$$

$$R_s = \begin{Bmatrix} 0 & s \le 80 \\ \frac{s-80}{520} & 80 < s < 600 \\ 1 & s \ge 600 \end{Bmatrix} \quad R_l = \begin{Bmatrix} 0 & l \le 120 \\ \frac{l-120}{160} & 120 < l < 280 \\ 1 & l \ge 280 \end{Bmatrix}$$

where a was the coal seam dip angle, m was the mining height, s was the mining depth, l was the length of coal face, R_a, R_m, R_s, R_l, respectively represented the membership of various factors.

Fuzzy evaluation was made on the size of the floor anti-sabotage ability. The comprehensive analysis was made on the influence of coal mining, floor strength and floor strata combination. The failure resistance of the floor wais divided into 4 categories, and the results were shown in Table 1.

3 The Establishment and Analysis of Fuzzy Neural Network Model

3.1 A Brief Introduction to Fuzzy Neural Network

BP neural network was a kind of error back-propagation learning process. The minimum square error of the network was obtained by constantly adjusting the network weights and threshold by back propagation error. It had strong nonlinear mapping capability. BP neural network could realize any nonlinear mapping from input to output layer. Fuzzy neural network based on fuzzy theory and neural network technology improved the learning ability and expressive power of BP system, and had good generalization and robustness.

3.2 Model Establishment

The neural network model of Matlab platform contained five input elements and one output layer, which represented five main control factors affecting the failure depth of the floor and failure depth of mine floor respectively. The number of hidden layer neuron was determined as 11. The momentum and adaptive gradient descent function traingdx was selected. The logsig-purelin function was the mechanism function. And the msereg was the performance function. The step length was 0.2. The momentum factor was 0.9. The initial weight of the network was set to a fixed value. The learning rate was 0.05. The expectation error was 0.01. The maximum training period was 50,000.

(1) Significant coefficient

$$r_{ij} = \sum_{k=1}^{P} W_{ki}(1 - \mathrm{e}^{-x})/(1 + \mathrm{e}^{-x}) \quad x = w_{jk}.$$

(2) Correlation coefficient

$$R_{ij} = |(1 - \mathrm{e}^{-y})/(1 + \mathrm{e}^{-y})| \quad y = r_{ij}.$$

(3) Absolute influence coefficient

$$S_{ij} = R_{ij} / \sum_{i=1}^{m} R_{ij}.$$

where i was the input layer neuron, i =1, …, m. j was the output layer neuron, j =1, …, n; k was the hidden neuron, k =1, …, p. w_{ki} was the weight coefficient between the input layer neuron i and the hidden layer neuron k. w_{jk} was the weight coefficient between the output layer neuron j and the hidden layer neuron k. And the absolute influence coefficient S was the required weight.

3.3 The Training of Fuzzy Neural Network

The data of the factors affecting failure depth of the mine floor were collected, as shown in Table 2. The training error curve of fuzzy neural network was shown in Fig. 1. It was shown that the model had better learning effect and higher accuracy. The weight matrix was processed according to the learning result, and the final weight of the influencing factors was obtained according to the weight of the each factor, as shown in Table 3.

3.4 Sensitivity Analysis of Influencing Factors

The sensitivity ranking of influencing factors was shown in Table 4. It can be seen that the length of working face was main factors affecting the failure depth of mine floor. The maximum weight of the length of working face was 0.3678. The following weights of the dip angle of coal seam and floor anti-sabotage ability were more than 0.2. The weight of mining depth and mining height were less than 0.1. According to the calculation results of the model, the main factors affecting the failure depth of mine floor were the length of working face, dip angle and anti-sabotage ability. Man-determined length of the working face had the most significant effect on the failure depth of the floor and was the primary consideration in preventing and controlling the water damage of the floor. The determination of the reasonable length of

Table 1 Membership function of floor anti-sabotage ability

Fuzzy constraint set	Description	Degree of membership
Floor anti-sabotage ability	Smaller, general, large and very larger	0–0.3, 0.3–0.5, 0.5–0.7, 0.7–1.0

Table 2 The Learning sample data of the factors affecting failure depth of the mine floor

No.	Working face	Mine depth (m)	Dip angle ( )	Mining height (m)	The length of the working face (m)	Floor anti-sabotage ability	Mine floor failure depth (m)
1	Jingxing No. 1 4707. 2	400	9.0	4.00	34	0.4	6.00
2	Jingxing No. 1 4707. 1	400	9.0	7.5	34	0.4	8.00
3	Xingtai 7802	259	4.0	3.00	160	0.6	16.40
4	Xingtai 7607N	320	4.0	5.40	60	0.6	9.7
5	Xingtai 7607W	320	4.0	5.40	100	0.6	11.7
6	Jingxing No. 3 5701(1)	227	12.0	3.50	30	0.4	3.50
7	Zhaogezhuang 1237(1)	900	26	2.00	200	0.6	27
8	Zhaogezhuang 1237(2)	1000	30	2.00	200	0.6	38
9	Hebi 3.128	230	26	3.5	180	0.4	20
10	Xinzhuangzi 4303(1)	310	26	1.8	128	0.2	16.8
11	Huafeng 41303	520	30	0.94	120	0.6	13
12	Fengfeng 2.2701(1)	145	16	1.5	120	0.4	14
13	Fengfeng 3.3707	130	15	1.4	135	0.4	12
14	Fengfeng 4.4804	110	12	1.4	100	0.4	10.7
15	Magouliang 1100	230	10.0	2.30	120	0.6	13.00
16	Chengtai 2.22510	300	8.0	1.80	100	0.4	10.00
17	Wangfeng 1951	123	15.0	1.10	100	0.2	13.40
18	Wangfeng1830	123	15.0	1.10	70	0.2	7
19	Liangzhuang 51101W	640	15.0	1.10	70	0.2	20.10
20	Baizhuang 7406	225	14.0	1.90	130	0.8	9.75
21	Caozhuang 9203	148	18	1.8	95	0.8	9.0
22	Shuanggou 1204	308	10.0	1.00	160	0.6	10.50
23	Wucun 32021(1)	375	14.0	2.40	70	0.6	9.70
24	WUcun 32031(1)	640	13.0	1.5	196	0.6	26.4
25	Wucun 3305	327	12	2.40	120	0.6	11.7

working face was an important factor to guarantee the safety of mine production in the exploitation of coal resources. The inclination and the anti-sabotage ability of coal seam floor as mine basic geological factors of the floor failure depth played an important role. The dip angle of coal seam inclination was not controlled artificially during mining process. The anti-sabotage ability of the floor can be controlled by grouting,

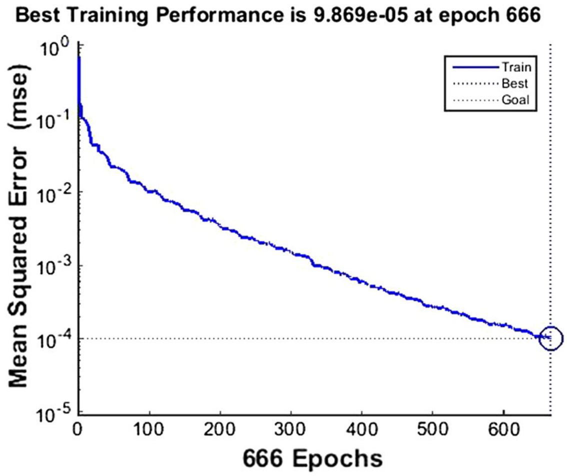

Fig. 1 The training error curve of fuzzy neural network

drainage pressure reduction. The reasonable length of working face was determined based on floor improvements. It could be seen from the order of influencing factors that, in the condition that the inclination of coal seam and the depth of buried water could not be changed, the safe and efficient production of the mine could be ensured by rational human intervention, and by selecting reasonable height and the length of working face on the basis of the management of the water barrier and the water pressure reduction of the aquifer.

4 Fuzzy Neural Network Model Verification

4.1 Example Validation

To verify the accuracy of the model, the author selected five sets of engineering example data as validation samples, and the validation samples and verification results were shown in Table 5.

4.2 Analysis of Case Verification Results

Under the confined water threat, the floor failure depth of working face water inrush prediction was critical. The paper selected three controllable factors and two uncontrollable geological factors to predict the failure depth of the mine floor. According to predictive analysis results of the fuzzy neural network, it could be seen that under the premise of coal seam dip angle and depth keeping unchanged, we could improve the floor anti-sabotage ability to increase the height and length of mining working face in coal seam. In order to ensure the rate of extraction of coal resources, the mining thickness of coal seam reached as much as possible occurrence thickness of coal seam. The determination of the treatment plan and the length of working face were important indexes to ensure the efficiency of mine. To get the optimal solution and to ensure the maximum economic benefit of mine, the paper could predict the failure depth of the floor with the combination of different floor anti-sabotage ability and the length of working face by constructing fuzzy neural network model.

5 Conclusion and Prospect

1. Considering the developmental characteristics of the failure depth of mine floor in some mining areas, the five main factors affecting the damage depth of mine floor were summarized by selecting some representative data of the failure depth of

Table 3 Contribution weight of each influence factor

Factor	Mining depth	Dip angle	Mining height	The length of the working face (m)	Floor anti-sabotage ability
Weight	0.1001	0.2316	0.0989	0.3678	0.2021

Table 4 Sensitivity ranking of influencing factors

Factor	Mining depth	Dip angle	Mining height	The length of the working face (m)	Floor anti-sabotage ability
Sensitivity sorting	4	2	5	1	3

Table 5 Validation sample

No.	Working face	Mine depth (m)	Dip angle (°)	Mining height (m)	The length of the working face (m)	Floor anti-sabotage ability	Mine floor failure depth (m)	Prediction of mine floor failure depth (m)	Deviation value (deviation rate)
1	Chensilou 21301	584	10.0	2.70	149	0.5	14.00	15.15	+ 1.15(8.2%)
2	Xingdong 2121	1000	10.0	3.75	150	0.8	32.50	35.33	+ 2.83(8.7%)
3	Dongjiahe 507	350	7.0	3.00	114	0.5	10.80	10.20	− 0.6(5.6%)
4	Xinglongzhuang 10302	466	7.0	8.91	200	0.6	16.00	15.81	− 0.19(1.2%)
5	Dongpang 9103	237	12.0	6.19	70	0.4	12.43	13.60.	+ 1.17(9.4%)

mine floor and combining with years of work experience. The five main influencing factors were the length of working face, mining depth, mining height, dip angle and floor anti-sabotage ability. The membership degree and dimensionality of 5 influencing factors were treated respectively.

2. According to the collected representative data of failure depth of floor, the sensitivity calculation of the factors on the floor failure depth was carried on by the introduction of fuzzy neural network. The weight of each factor was obtained. According to the influence degree of different factors, some measures and methods through human intervention to reduce the failure depth of floor and ensure mine safety were suggested.
3. The accuracy of the model was affected by the sample data. With the increase of data collected, the accuracy of the model could increase correspondingly. In subsequent research, we should continue to focus on the research of this direction and improve the accuracy of the model.

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