HONGJUN GUO
MING JI
YIDONG ZHANG
HUIQIN WANG
KUN ZHANG
and
AOXIANG LIANG

Prediction on surrounding rock deformation of roadway based on a neural network model

The measured data are taken as training samples, and the surrounding rock deformation of ventilation roadway of the 21175 working face in Huopu coal mine is predicted by building a wavelet neural network time series model whose network structure is 4-18-1. The result shows that there is high coincidence degree between the prediction deformation and the field monitored data. The maximum relative error is less than 1%, and the average relative error is less than 0.5%. Therefore, the prediction values provide the theoretical basis of support design and safe production for roadways with the same conditions.

Keywords: *Wavelet neural network; time series; surrounding rock deformation of roadway; prediction on surrounding rock deformation.*

1. Introduction

The stress environment of underground engineering is very complicated, especially coal mines [1]. As the vessel of coal mine underground production, the surrounding rock stability of roadway is of great importance to safe and efficient mining. During a roadway is excavation, the original rock stress is destroyed. Under the action of natural conditions and human factors (support), the rock stress rebalances. In this process, the most conspicuous characteristics are surrounding rock deformation of roadway [2,3]. There is a positive connection between the final convergence deformation and the previous deformation. If the mathematical relationship is found, based on the field monitored data of surrounding rock deformation, it can help to establish related models to predict the surrounding rock deformation of roadway [4], which will have a positive effect on the understanding of the lawson surrounding rock deformation of roadway [5, 6].

Since the 1950s, the state of underground chambers, roadways surrounding rock and support structures has been monitored. The field data are used to modify design and improve the safety of construction. When a roadway is excavated, the monitoring of surrounding rock deformation plays an important role. The measured data can be used to find the potential laws and to predict and analyze the possible behaviours of surrounding rock structures. This information can then be used to guide the production design and plan adjustment or to take emergency measures [7,8]. The methods used for predicting are various, including regression analysis [5], grey prediction [1, 9~12], support vector machine [13~15] and time series analysis [16]. However, for these methods, the ability of nonlinear mapping is poor, and there is no strong self-learning, self-organization, association, high fault tolerance and anti-interference ability for dealing with the complex nonlinear relationships [17, 18].

In the late 1980s, artificial neural networks are rapidly developed, and its theory had been greatly improved. As a type of nonlinear dynamic system, artificial neural networks are suitable for solving various nonlinear problems and overcoming the disadvantages of above methods. In recent years, artificial neural networks have been widely used in geotechnical engineering [19~24].

Therefore, in this paper, the monitored data on surrounding rock deformation of ventilation roadway of 21175 working face in Huopu coal mine is used to reconstructa time series, and a neural network model is built to predict and research the surrounding rock deformation of roadway.

2. Time series model of wavelet neural network

A wavelet neural network [25] is a kind of neural network based on the topological structure of BP neural network. The wavelet neural network uses wavelet basis function as the node transfer function of hidden layer, and its signal is forward-propagated, whereas the error is back-propagated. The topological structure of wavelet neural network is shown in Fig.1.

In Fig.1, $X = \{X_1, X_2, ...X_k\}$ is the input parameter of wavelet neural network; $Y = \{Y_1, Y_2, ...Y_k\}$ is the prediction output of wavelet neural network; and ω_{ij} and ω_{jk} are the

Mrssrs. Hongjun Guo, Ming Ji, Huiqin Wang, Kun Zhang, Aoxiang Liang, Key Laboratory of Deep Coal Resource Mining, Ministry of Education of China; School of Mines; China University of Mining & Technology, and Mr. Yidong Zhang, State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology, Xuzhou, 221116, China. Corresponding author: e-mail: jiming@cumt.edu.cn

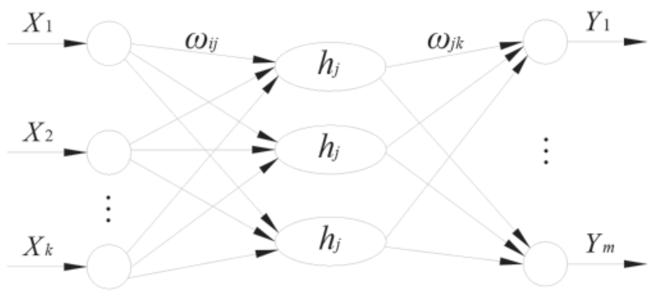


Fig.1 Wavelet neural network

weights of wavelet neural network.

When the signal series of network input is $x_i = (i = 1, 2, ..., k)$, the output of hidden layer is

$$h(j) = h_j\left(\frac{\sum_{i=1}^{k} \omega_{ij} x_i - b_j}{a_j}\right) \quad j = 1, 2, \cdots, l \qquad \text{... (1)}$$

In formula (1), $h(j)$ is the output of the j^{th} node of hidden layer; h_j is the wavelet basis function; ω_{ij} is the connection weight of input layer and hidden layer; b_j is the translation factor of wavelet basis function h_j; and a_j is the contraction-expansion factor of wavelet basis function h_j.

In this model, the *Morlet* wavelet basis function is used, and its mathematical expression is

$$y = \cos(1.75x) e^{-\frac{x^2}{2}} \qquad \text{... (2)}$$

The formula of output layer of wavelet neural network is

$$y(k) = \sum_{i=1}^{l} \omega_{ik} h(i) \quad k = 1, 2, \cdots, m \qquad \text{... (3)}$$

In formula (3), ω_{ik} is the weight from output layer to hidden layer; $h(i)$ is the output of the i^{th} node of hidden layer; l is the node number of hidden layer; and m is the node number of output layer.

The weight parameter correction algorithm of wavelet neural network is similar to the weight correction algorithm of BP neural network, and it uses gradient correction method to modify the weights of network and the parameters of wavelet basis function. The predicted output of wavelet neural network continuously approximates the expected value. The modification process of wavelet neural network is as follows.

(1) The prediction error of network is calculated by

$$e = \sum_{k=1}^{m} yn(k) - y(k) \qquad \text{... (4)}$$

(2) According to the prediction error e, the weights of wavelet neural network and the coefficients of wavelet basis function are corrected.

Because the gradient training algorithm evolves slowly and easily falls into the minimum, this model chooses a method of increasing the momentum unit, and the formulas are

$$\omega_{n,k}^{(i+1)} = \omega_{n,k}^{i} + \Delta\omega_{n,k}^{(i+1)} + k \cdot (\omega_{n,k}^{i} - \omega_{n,k}^{i-1}) \qquad \text{... (5)}$$

$$a_k^{(i+1)} = a_k^i + \Delta a_k^{(i+1)} + k \cdot (a_k^i - a_k^{i-1}) \qquad \text{... (6)}$$

$$b_k^{(i+1)} = b_k^i + \Delta b_k^{(i+1)} + k \cdot (b_k^i - b_k^{i-1}) \qquad \text{... (7)}$$

In formula (5)~(7), $\Delta\omega_{n,k}^{(i+1)}$, $\Delta a_k^{(i+1)}$ and $\Delta b_k^{(i+1)}$ are obtained based on the prediction error of network; the expressions are

$$\Delta\omega_{n,k}^{(i+1)} = -\eta \frac{\partial e}{\partial \omega_{n,k}^{(i)}} \qquad \text{... (8)}$$

$$\Delta a_k^{(i+1)} = -\eta \frac{\partial e}{\partial a_k^{(i)}} \qquad \text{... (9)}$$

$$\Delta b_k^{(i+1)} = -\eta \frac{\partial e}{\partial b_k^{(i)}} \qquad \text{... (10)}$$

In formula (9)~(10), η is the training rate.

The training steps of wavelet neural network algorithm are shown in Fig.2.

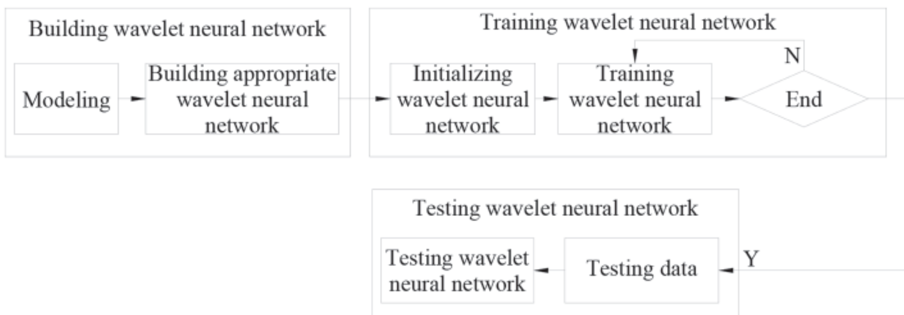


Fig.2 Training process of the wavelet neural network

3. Analysis of project case

3.1 MONITORING OF SURROUNDING ROCK DEFORMATION OF ROADWAY

(1) Layout of monitoring station

The 21175 working face in Huopu mine is the first mining face in the south of 21 mining area, and both sides of ventilation roadway are solid coal. The section of roadway is an arch, and its width and middle height are respectively 4.6 m and 2.9 m. The roadway is supported by a U29 arch shed with inclined legs. To determine the weighting laws of mining roadway in 17# coal during excavation, the monitoring station of surrounding rock deformation is arranged in 21175 ventilation roadway, and the details are shown in Fig.3.

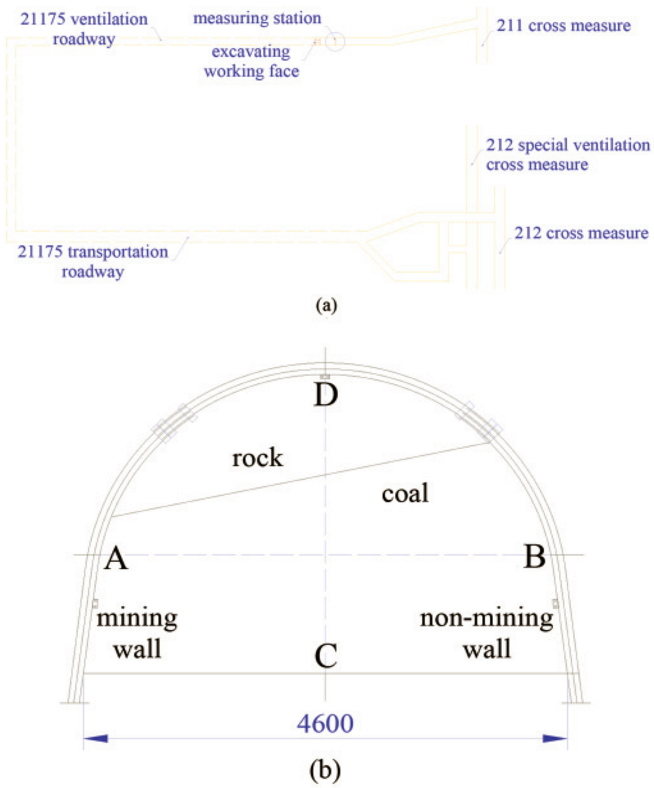


Fig.3 Layout of the monitoring station of surrounding rock deformation

TABLE 1 STATISTICS OF SURROUNDING ROCK DEFORMATION OF ROADWAY

Time /d	Distance working face/m	Roof and floor /mm	Roof /mm	Floor /mm	Both mining sides/mm	Mining side /mm	Non-mining side /mm
1	7	0	0	0	0	0	0
2	10	112	87	25	61	34	27
3	11	205	168	37	101	59	42
4	12	264	218	46	130	77	53
5	12	313	259	54	155	93	62
6	12	345	284	61	173	104	69
8	12	385	317	68	196	121	75
10	12	412	338	74	211	130	81
11	12.5	436	356	80	224	138	86
13	16	459	373	86	237	147	90
15	22	480	388	92	249	154	95
17	22	501	405	96	261	162	99
19	22	517	418	99	272	169	103
21	22	537	434	103	282	175	107
22	22	549	443	106	290	180	110
24	23.5	560	452	108	298	185	113
26	24.5	571	460	111	306	189	117
28	24.5	583	469	114	312	193	119
32	31	592	476	116	319	197	122
34	37	599	481	118	324	200	124
38	37	605	485	120	329	203	126
42	48	611	490	121	334	206	128
46	70	616	494	122	337	208	129

(2) Surrounding rock deformation of roadway

The data of surrounding rock deformation are listed in Table 1.

3.2 PREDICTION OF SURROUNDING ROCK DEFORMATION OF ROADWAY

(1) Modelling

The research shows that the surrounding rock deformation at a certain time is closely related to the former deformation, which has a significant excavation influence. A wavelet neural network time series prediction model was established according to the characteristics of surrounding rock deformation. In the model, the former n deformation of current time is taken as input layer, and the node of hidden layer consisted of wavelet basis function. The current prediction deformation is given by output layer.

A time series $X = \{x(1), x(2), ...x(n)\}$ $n = 23$ is formed by the data in Table 1. In the time series X, $x(2)$, was surrounding rock deformationon the 1st day, and $x(n)$ is deformation on the 46th day. The step of time series X is 4, and the 5th deformation is predicted through four continuous monitored values. The input and output of roadway deformation time series prediction model are shown in Table 2.

The nodes of hidden layer were 6, 12 and 18. Through training the model, the errors produced by different nodes were compared. Then, the ultimate structure of wavelet neural network is obtained as 4-18-1. That is to say, there are 4 nodes in input layer, 18 nodes in hidden layer and 1 node in output layer. The monitored data are repeatedly trained for 200 times (the increase of train times can improve prediction accuracy but add extra calculation time and memory share), and the surrounding rock deformation of roadway is predicted with the trained wavelet neural network.

(2) Verification and analysis of prediction model

The 1~25th-day data are regarded as training sample, and the surrounding rock deformation of roadway in the 26~46th days is predicted. The prediction is compared to the monitored value, and the results are shown in Figs.4 and 5.

From Figs.4 and Fig.5, it can be observed that there is a strong goodness of fit between the surrounding rock deformation of roadway predicted by wavelet neural network time series model and the field measured data. The maximum relative

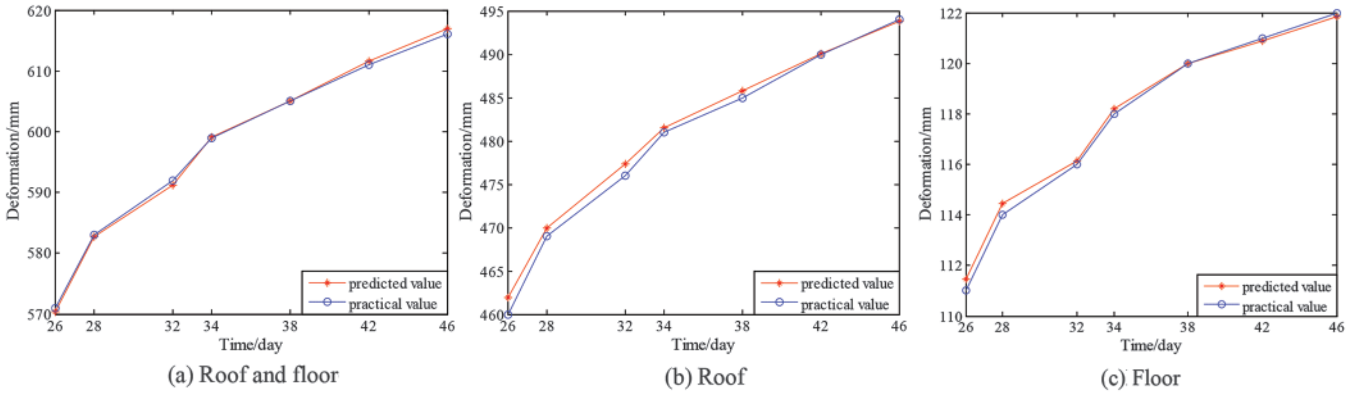


Fig.4 Displacement of roof and floor of roadway

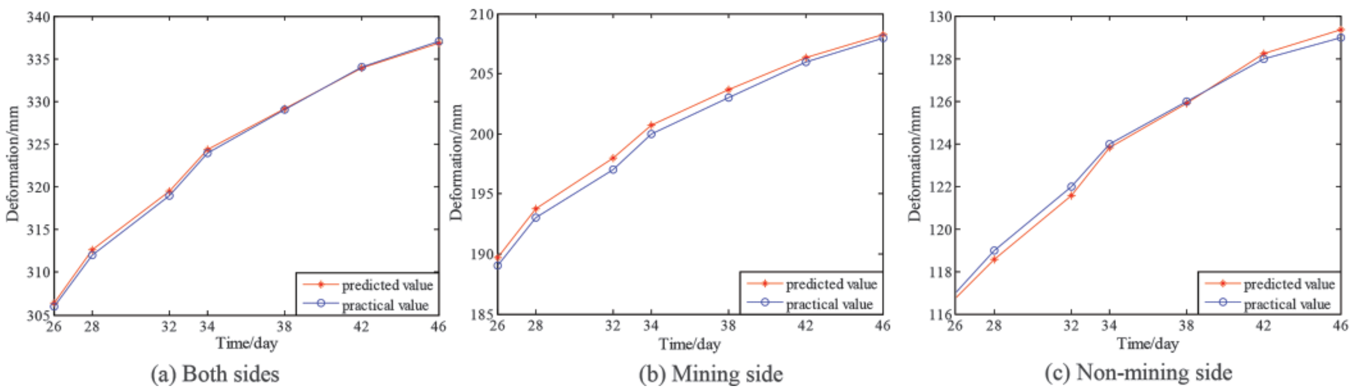


Fig.5 Displacement of both sides of roadway

Table 2 Input and output of time series prediction model

Four input	One output
$x(1)$, $x(2)$, $x(3)$, $x(4)$,	$x(5)$
$x(2)$, $x(3)$, $x(4)$, $x(5)$,	$x(6)$
|	|
$x(n–4)$, $x(n–3)$, $x(n–2)$, $x(n–1)$,	$x(n)$

Table 3 Relative error

Item/ error	Roof and floor	Roof	Floor	Both mining sides	Mining side	Non-mining side
Maximum relative error /%	0.15	0.41	0.41	0.19	0.51	0.26
Average relative error /%	0.08	0.17	0.19	0.08	0.32	0.10

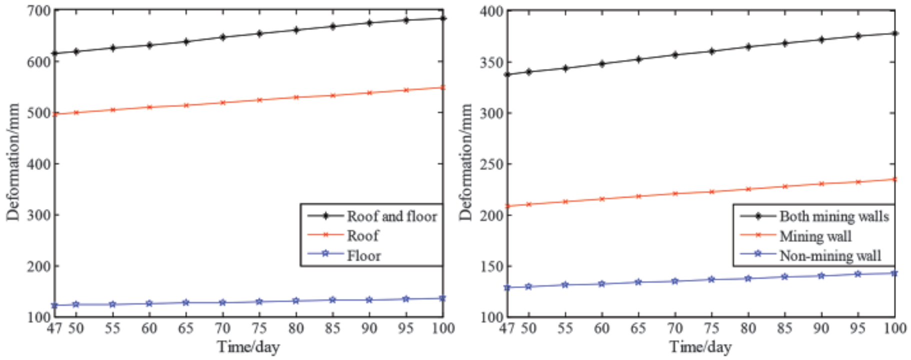
error is less than 1%, and the average relative error is less than 0.5%. The results are given in Table 3. Therefore, the model can predict the surrounding rock deformation of roadways with the same geological conditions.

(3) Prediction and analysis on the surrounding rock deformation of roadway

After completing the field monitoring, the deformation characteristics of roadway are comprehensively analyzed and more surrounding rock deformation is predicted. As an example, the prediction deformation of the 47~100th days are shown in Fig.6.

The study shows that (1) when the roadway section decreases by 25%, wind age increases by more than once, increasing the burden of mine ventilation; (2) when the decrease of roadway section is over 50%, the roadway would become paralyzed in ventilation and transportation and even blocked [26]. In Fig.6, the surrounding rock deformation rate of roadway is approximately zero but not convergent. The deformation is continually increasing with time. On the 100th day, the roadway section has reduced by 30%, significantly affecting the ventilation of working face. Therefore, some measures should be taken to improve surrounding rock conditions of roadway. High-strength support is implemented in the form of initiative support, effectively controlling the stability of surrounding rock and ensuring safe and efficient production for coal mine.

For the problem on the support difficultly of ventilation roadway of 21175 working face, acombined support of shed and anchor (cable) is proposed. After the roadway section is excavated, a hanging metal net and building contractible U29 shed are constructed. The distance of shed is 700 mm. Secondly, the anchor is added to the whole section in the center of every two sheds. The anchor is a sinistral no-longitudinal bar thread steel whose dimensions are Φ 20×2500



(a) Displacement of roof and floor ofroadway (b) Displacement of both sides of roadway

Fig.6 Deformation prediction of the roadway surrounding rock

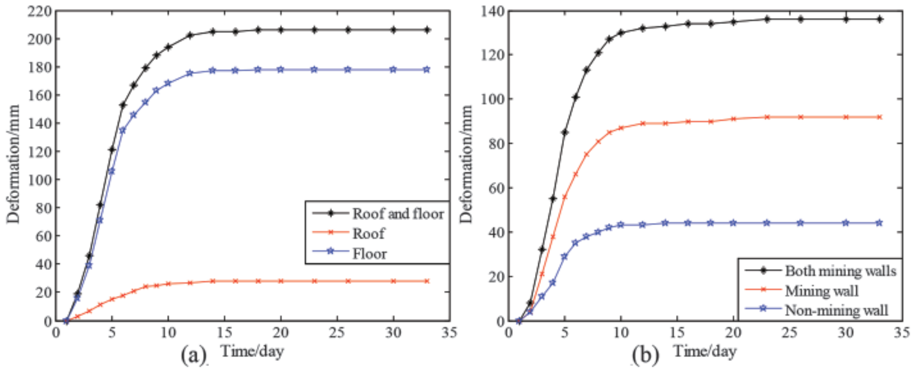
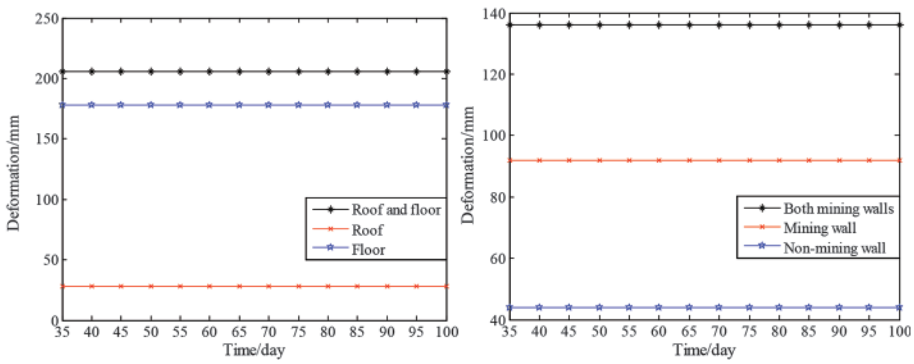


Fig.7 Deformation of roadway surrounding rock with combined support



(a) Displacement of the roadway roof and floor (b) Displacement of both roadway sides

Fig.8 Prediction on surrounding rock deformation of roadway with combined support

mm. The row and line space of anchor is 1000×700 mm, and each row had 10 anchors.Thirdly, every two-row bolt had a row of cable. The cable used steel strands whose dimensions are Φ17.8×7000 mm. The row and line space of cable is 2000×2100 mm, and each row has 3 cables. Through field monitoring, the surrounding rock deformation of roadway with the combined support is shown in Fig.7.

The surrounding rock deformation of roadway in the 34~100th days are predicted using wavelet neural network time series model, and the result is displayed in Fig.8.

As shown in Fig.7, after using the combined support of shed and anchor (cable), the surrounding rock deformation rate of roadway gradually converged and basicaly tended to zeroon the 14th day. Moreover, Fig.8 further shows that the surrounding rock deformation of roadway tended to be stable. Additionally, the roadway does not show rheology and creep phenomena, and good support results are achieved.

4. Conclusions

According to the field monitored data of the surrounding rock deformation of roadway, the deformation state of roadway is predicted using wavelet neural network time series model. The result shows that the prediction deformation is consistent with the measured values. The maximum relative error is less than 1%, and the average relative error is less than 0.5%. The prediction values can successfully describe the surrounding rock deformation of other roadways with the same geological conditions during excavation. Therefore, this method is reasonable and feasible, and the predicti results are of practical significance to underground roadway engineering.

Conflict of Interests

The authors declare that there is no conflict regarding the publication of this paper.

Acknowledgements

This paper is supported by "Priority Academic Program Development of Jiangsu Higher Education Institutions", and "the Fundamental Research Funds for the Central Universities (2017XKQY044)".

Reference

1. Gong K.Y. (2006): "Application of Grey System Theory in Roadway Tunneling and Prediction of Surrounding Rock," *Qingdao: Shandong University of Science and Technology*, 2006.
2. Graves J.P., Chapman I.T., Coda S., et al. (2010): "Deformation and Broken Rule and Supporting Countermeasure of Coal Roadway with Large Section," *Nuclear Fusion*, 2010 (50.5): 1211-1469.

3. Yang S.Q., Chen M., Jing H.W., et al. (2016): “A Case Study on Large Deformation Failure Mechanism of Deep Soft Rock Roadway in Xin'an Coal Mine,” *China Engineering Geology,* 2016.

4. Wang H.C., Guo S.Z. and Deng L.M. (1997): “Application on Neural Network Theory in Predicting Surrounding Rock Deformation of Roadway,” *Mine Construction Technology*, 1997(18.4): 38-40.

5. Shi G. P., Han L.J., Wei Z.M., et al. (2013): “Building and Application of Coal Roadway Surrounding Rock Deformation Prediction System,” *Metal Mine*, 2013(1): 27-29.

6. Yang Z.G., Gao Q. (2007): "Application of Neural Network in Mine Tunnel Safety Prediction," *Mining R&D,* 2007 (27.3): 75-76.

7. Dwivedi R.D., Singh M., Viladkar M.N., et al. (2013): "Prediction of Tunnel Deformation in Squeezing Grounds," *Engineering Geology*, 2013(161.4): 55-64.

8. Guo W. (2009): "Prediction of Rock Deformation and Analysis of Rock Stability of Tunnel Based on the Neural Network," *Chongqing: Chongqing University,* 2009.

9. Bai N., Jin L.Z. and Zhan Z.N. (2013): "Design and Relization of Coal Mine Accident Prediction Mofulr Based on B/S and Grey Model," *Journal of Safety Science & Technology*, 2013(9).

10. Liu X.S., Tan Y.L. and Ning J.G. (2014): "Chaotic Prediction of Surrounding Rock Deformation Speed in Coal Roadway Supported by Bolt," *Journal of Mining & Safety Engineering,* 2014(31.3): 385-389.

11. Özf?rat M.K. (2012): "A Fuzzy Method for Selecting Underground Coal Mining Method Considering Mechanization Criteria," *Journal of Mining Science*, 2012(48).

12. Shen J.B., Qu J.G. and Zhan Z.W. (2011): "Prediction of Surrounding Rock Deformation of Roadway with Soft Rock Based on Grey Theory," *Coal Mining Technology,* 2011(16.1): 22-24.

13. Li X.L., Wang F.M. and Cai Y.C. (2009): "Predicting Deformations of Tunnel Surrounding Rock by Using Least Squares Support Vector Machine," *Journal of Highway and Transportation Research and Development,* 2009(26.7): 80-84.

14. Wang X.M. (2009): "Predietion Research of the Surrounding Rock Deformation in Engineering by the Support Vector Machine," Shenyang, Northeastern University, 2009.

15. Zhao H.B. (2005): "Predicting the Surrounding Deformations of Tunnel Using Support Vector Machine," *Chinese Journal of Rock Mechanics and Engineering,* 2005(24.4): 649-652.

16. Bhattacherjee A., Ramani R.V. and Natarajan R. (1994): "Time Series Analysis of Coal Mine Accident Experience," *Journal of Safety Research,* 1994(25).

17. Wu Y.L. (2005): "Study on Prediction Forecast of Rock Burst Based on Matlab Neural Networks," *Qingdao: Shandong University of Science and Technology,* 2005.

18. Zhang J.Y., Feng S.Z. and Liu D.H. (2005): "A Forecasting Method for Tunnel Surrounding Rock Deformation Using RBF Neural Networks," *Engineering Science,* 2005(7.10): 87-90.

19. He G.H., Wang X.Y. and Zhang Y. (2008): "The Application of Neural Network Technology in the Forecast of Tunnel Wall Rock Deformation," *Shanxi Architecture,* 2008(34.4): 364-35.

20. Kher A. (2016): "Application of Forecasting Models on Indian Coal Mining Fatal Accident (Time Series) Data." *International Journal of Applied Engineering Research*, 2016(11).

21. Li P.N., Liu J. and Zhang H.H. (2009):"Research on Prediction of Surrounding Rock Deformation in Tunnel Based on RBF Neural Network," *Sichuan Architecture*, 2009(29.6): 79-80.

22. Li Y.S., Li X.P. and Zhang C.L. (2006): "Displacement Prediction Method of Surrounding Rock in Tunnel Based on BP Neural Network, *"Chinese Journal of Rock Mechanics and Engineering,* 2006(25): 2971-2973.

23. Ma W.Q., Wang X.P. and Cheng C.G. (2003): "Application of Neural Network Technique in the Prediction of Roadway Surrounding Rock Deformation in Yangzong Tunnel," *Technology of Highway and Transport*, 2003(2): 56-58.

24. Sheng J.L. and Zhao J.H. (2005): "Model of Neural Network Predicting the Deformation of Surrounding Rock in Tunnel," *Blasting*, 2005(22.1): 16-19.

25. Shi F., Wang X.C., Yu L., et al. (2010): "30 Cases Analysis of MATLAB Neural Network," *Beijing: Beihang University Press*, 2010.

26. Wang B.S. (2001): "Effect of Reduction and Deformation of Air Duct Section on the Mine Windage," *Safety in Coal Mines*, 2001(1): 37-39.