Safety Prediction of Deep Foundation Pit Based on Neural Network and Entropy Fuzzy Evaluation

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Abstract: The monitoring data can effectively reflect the safety status of the project during the construction of deep foundation pit, and the risks existing in the project can be discovered in time and the development trend can be reasonably predicted through the processing and analysis of the existing monitoring data. In this paper, a deep foundation pit in compound soil area of a coastal city was taken as an example, the BP neural network was taken to predict the monitoring data in the next stage, the entropy method was utilized to determine the weight of the evaluation index according to the predicted value, and the fuzzy comprehensive evaluation method was used to quantitatively describe the future safety status, so as to formulate targeted countermeasures and improve the construction safety.

1 Introduction

The subway is favored by major cities in China because of its advantages of saving land, low noise, efficient construction speed, and low pollution. Due to the large number of deep foundation pit engineering generated by subway construction, the construction safety issues have become the focus and difficulty in the current field of basic engineering. At present, the construction safety of deep foundation pits of subway stations in China is greatly affected by the subjective judgment of operators, which is reflected in the analysis of on-site monitoring data based on their own engineering experience. Before an engineering hazard develops into an engineering disaster, there are often abnormal reactions in monitoring data. If corresponding measures are taken, engineering risks can be reduced at a small cost^[1].

To improve the safety and precautions of deep foundation pit engineering, Yin Shengquan, and others combined on-site monitoring data with neural networks to give corresponding risk levels^[2]. Wei Xinjiang et al. used the entropy method to determine the evaluation index weight and took into account the relationship between the index value and the rate of change^[3]. Liu Junwei et al. established a foundation pit safety evaluation model based on the fuzzy evaluation theory and obtained the membership functions of deep foundation pits under different safety conditions^[4]. Integrating the advantages of a neural network, entropy method, and fuzzy comprehensive evaluation method, this paper forecasts the evaluation indicators of the next phase based on the existing monitoring data, so as to predict the safety status of the foundation pit and quantitatively describe the risks in the project.

2 BP Neural Network

BP neural network is also called error backpropagation neural network. The weight adjustment adopts the backpropagation learning algorithm, which is a multilayer feedforward neural network composed of nonlinear transformation units, including an input layer, hidden layer, and output layer.

Foundation pit deformation is a nonlinear process with time-space effects, and it can use BP neural network technology with time domain. It exerts its powerful nonlinear mapping, evaluates indicators based on existing monitoring data, and builds a MATLAB-based BP neural network prediction model to predict the monitoring data within a short period.

3 Entropy Method

The entropy method is a utility value method developed on the basis of entropy theory, which reflects the information entropy value of each evaluation index. Foundation pit excavation is a complex and dynamic process. As the excavation progresses, the weight of each evaluation index in the safety evaluation of the foundation pit will continue to change. The entropy method is used to determine the evaluation index weight, which can fully consider the timeliness of the monitoring data. At present, this is more in line with the actual situation of foundation pit construction. When evaluating the safety status of the current foundation pit, if a certain index changes more widely in the current construction situation, the more weight is assigned to the evaluation index.

1) There are m groups of monitoring data in chronological order during the excavation, and each group

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of monitoring data contains n evaluation index. Use x_{ij} to represent the measured value of the j evaluation index in the monitoring data of the i group.

2) The proportion of each measured value in the j evaluation index:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (1)$$

3) Calculate the entropy value of each evaluation index:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \ln p_{ij} \quad (2)$$

4) Calculate the weight of each evaluation index:

$$w_i = \frac{g_i}{\sum_{i=1}^n g_i} = \frac{1 - e_i}{n - \sum_{i=1}^n e_i} \quad (3)$$

4 Fuzzy Comprehensive Evaluation Theory

A fuzzy comprehensive evaluation method is a method to comprehensively evaluate the evaluation object. It is based on fuzzy mathematics and replaces traditional logical thinking with dialectical thinking.

When evaluating the safety status of a foundation pit, all evaluation indexes must be considered comprehensively. In actual engineering, the evaluation indexes are interrelated but with vague evaluation standards. The fuzzy comprehensive evaluation method introduces the degree of membership and the membership function to quantitatively evaluate the safety status of the foundation pit. This contributes to describing the many influencing factors with precise mathematical language and clarifies the excessive amount of fuzzy information in the intermediary, which helps comprehensively evaluate the safety status of the foundation pit.

Assuming that n evaluation indexes are used to evaluate the safety state of the foundation pit, the evaluation index set is $U = \{u_1, u_2, u_3, \dots, u_n\}$.

Dividing the foundation pit engineering into four safety

levels, the evaluation set is $V = \{v_1, v_2, v_3, v_4\}$, where u_i represents the evaluation index and v_i represents the safety level. According to the entropy method, the weight and the degree of membership of each index are obtained and expressed in vector form. The following mapping can be obtained through the membership matrix R :

$$U \xrightarrow{R} V \quad (4)$$

In the formula, three parameters of U , V , R are the elements of the evaluation model.

5 Engineering Case Analysis

A subway station in a coastal compound land area is a two-line transfer station. The deep foundation pit has a total length of 220m, a width of 45m, and an excavation depth of about 19.8m. The supporting scheme adopted for the envelope structure is a 1000mm-thick diaphragm wall along with 3 concrete walls as supports. According to the existing 12 sets of historical monitoring data in the six evaluation index monitoring points around the QCX-12 monitoring point, this paper will predict the evaluation index in the next phase and prejudge the safety status of the foundation pit. A simplified schematic diagram of monitoring points is shown in Figure 1.

Figure 1 Schematic diagram of monitoring points

5.1 Basic Flow of Foundation Pit Safety Prediction

The specific flow of predicting the safety status of deep foundation pit construction based on monitoring data is shown in Figure 2.

Figure 2 Flow chart of foundation pit safety prediction

5.2 Dynamic prediction of evaluation indexes

Chronologically, the first 9 groups of monitoring data were used as training samples, and the last 3 groups were used as test samples. Taking the first 4 groups in the training sample as input vectors and the next group as the target vector, the training samples were looped in turn. Then the trained network was used to predict the 10th group and the relative error was recorded. Afterward, the predicted value of the 10th group was replaced with the actual measured value to increase the number of original samples, and was retrained to predict the monitoring data of the 11th group, and so forth. As the excavation progressed, the number of training samples continued to increase, and the prediction under neural network training gradually became more reasonable. The training process is shown in Table 1.

Table 1 Schematic table of the training process

4 input vectors	1 target vector
Monitoring data of the 1 st , 2 nd , 3 rd , and 4 th groups	Monitoring data of the 5 th group
Monitoring data of the 2 nd , 3 rd , 4 th , and 5 th groups	Monitoring data of the 6 th group
Monitoring data of the 3 rd , 4 th , 5 th , and 6 th groups	Monitoring data of the 7 th group
.....	

Monitoring data of the 8th, 9th, 10th, and 11th groups

Monitoring data of the 12th group

The input vector of the network model contained 4 sets of monitoring data. There were 6 evaluation indexes in each group, so the number of neurons in the input layer was 24. Since the output vector was 1 group of monitoring data, the number of neurons in each output layer was 6. The neural network toolbox provided by MATLAB was adopted to write the BP neural network program. The training program was as follows:

1)[P,minp,maxp,T,mint,maxt]=premnmx(p,t)

Define the training input sample P and the expected output sample T, and normalize them;

2)net = newff(minmax(P),[5,6], {'tansig','purelin'}, 'traingdx')

Call the newff function to create a BP neural network, with the number of neurons in the hidden layer and output layer set to 5 and 6;

3)net.trainParam.lr = 0.01;
net.trainParam.epochs = 500;
net.trainParam.goal = 0.001;
net.trainParam.mc = 0.9;
net.trainParam.show = 50;

Set training parameters;

4)[net,tr] = train(net,P,T);

A = sim(net,p_test);

A1 = postmnmx(A,mint,maxt);

Apply the training input sample P and the expected output sample T to train the neural network, and use the test input sample p_test to get the predicted expected output sample A, and denormalize A.

Table 2 Error analysis table

Monitoring Index Relative Error		Deep horizontal displacement of walls (mm)	Brace force (×1000KN)	Underground water level (m)	Vertical displacement of surrounding surface (mm)	Vertical displacement of surrounding building (mm)	Deformation of surrounding pipeline(mm)
10	Predicted value	29.920	6.940	-1.236	-22.304	-9.175	-8.637
	Measured value	28.9	6.865	-1.26	-23.2	-9.1	-8.4
	Relative error	3.53%	1.09%	-1.94%	-3.86%	0.82%	2.82%
11	Predicted value	28.769	7.373	-1.197	-24.736	-9.777	-8.775
	Measured value	30.2	7.086	-1.24	-24.8	-9.5	-8.6
	Relative error	-4.74%	4.05%	-3.46%	-0.26%	2.92%	2.04%
12	Predicted value	34.302	7.166	-1.328	-28.182	-9.723	-9.062
	Measured value	32.8	7.200	-1.26	-27.2	-10.1	-8.9
	Relative error	4.58%	-0.47%	5.39%	3.61%	-3.73%	1.82%

Note: Relative Error=(Predicted Value-Measured Value) / Measured Value

Table 3 Summary table of predicted values of evaluation indexes

Major Evaluation Index	Deep horizontal displacement of walls (mm)	Brace force (×1000KN)	Underground water level (m)	Vertical displacement of surrounding surface (mm)	Vertical displacement of surrounding building (mm)	Deformation of surrounding pipeline(mm)
Predicted Value	35.5	7.236	-1.26	-30.0	-10.5	-9.1

5.3 Determination of evaluation index weight

With the construction of the foundation pit progressing, the influence weight of each evaluation index in the safety evaluation of the foundation pit continued to change. The predicted value was listed as the 13th group of monitoring data, as shown in Table 4.

According to formulas (1)~(3) of the entropy method, 13 groups of monitoring data in Table 4 were calculated. The weight of each evaluation index for the next phase was obtained, as shown in Table 5.

Table 4 Summary Table of monitoring data

Monitoring Index Time	Deep horizontal displacement of walls (mm)	Brace force (KN)	Underground water level (m)	Vertical displacement of surrounding surface (mm)	Vertical displacement of surrounding building (mm)	Deformation of surrounding pipeline(mm)
1	20.1	3945	-1.10	-15.1	-5.6	-4.9
2	20.3	4267	-1.20	-15.5	-5.9	-5.1
3	21.0	4677	-1.19	-16.3	-6.6	-5.5
4	22.6	4980	-1.16	-16.5	-6.8	-5.9
5	23.5	5177	-0.99	-17.2	-7.2	-6.5
6	24.0	5280	-1.00	-17.5	-7.6	-6.9
7	24.6	5588	-1.11	-19.2	-7.9	-7.2

8	26.6	6050	-1.14	-20.1	-8.1	-7.7
9	27.5	6537	-1.22	-21.9	-8.9	-8.1
10	28.9	6865	-1.26	-23.2	-9.1	-8.4
11	30.2	7086	-1.24	-24.8	-9.5	-8.6
12	32.8	7200	-1.26	-27.2	-10.1	-8.9
13	35.5	7236	-1.26	-30.0	-10.5	-9.1

Note: The smaller the serial number, the earlier the time; the larger the serial number, the later the time.

Table 5 Summary table of index weights

Major evaluation index	Deep horizontal displacement of walls	Brace force	Underground water level	Vertical displacement of surrounding surface	Vertical displacement of surrounding building	Deformation of surrounding pipeline
Entropy e_j	0.99388	0.99275	0.99884	0.99051	0.99311	0.99220
Coefficient of difference g_i	0.00612	0.00725	0.00116	0.00949	0.00689	0.00780
Weight w_i	0.15799	0.18738	0.03006	0.24510	0.17809	0.20138

5.4 Prediction of the safety status of the foundation pit

The fuzzy comprehensive evaluation method was applied to predict the safety status of the foundation pit for the next phase.

5.4.1 Creation of weight set

According to the influence weight of the six evaluation indexes for the next phase obtained by the entropy method, the weight set was:

$$A = [A_1, A_2, A_3, A_4, A_5, A_6] \\ = [0.15799, 0.18738, 0.03006, 0.24510, 0.17809, 0.20138]$$

5.4.2 Creation of factor set

The factor set composed of the cumulative value of the six evaluation indexes was represented by U_1 , and the factor set composed of the rate of change was represented by U_2 :

$U_1 = \{u_{11}, u_{21}, u_{31}, u_{41}, u_{51}, u_{61}\} = \{\text{Cumulative value of deep horizontal displacement of walls, pit Cumulative value of brace force, Cumulative value of underground water level, Cumulative value of vertical displacement of surrounding surface, Cumulative value of vertical displacement of surrounding building, Cumulative value of deformation of surrounding pipeline}\}$

$U_2 = \{u_{12}, u_{22}, u_{32}, u_{42}, u_{52}, u_{62}\} = \{\text{Change rate of deep horizontal displacement of walls, Change rate of brace force, Change rate of underground water level, Change rate of vertical displacement of surrounding surface, Change rate of vertical displacement of surrounding building, Change rate of deformation of surrounding pipeline}\}$

Each factor in U_1 and U_2 was divided into four safety levels, including safety, attention, warning, and danger. The hierarchical control value of each factor was shown in Table 6.

Table 6 Summary table of factor control values

Factor	Hierarchical control value	Safety	Attention	Warning	Danger
		70% warning	85% warning	100% warning level	110% warning level
Deep horizontal displacement of walls	Cumulative value u_{11} (mm)	21	25.5	30	33
	Rate of change u_{12} (mm/d)	2.1	2.55	3	3.3
Brace force	Cumulative value u_{21} (KN)	4831	5866	6902	7592
	Rate of change u_{22} (KN/d)	—	—	—	—
Underground water level	Cumulative value u_{31} (m)	1.4	1.7	2	2.2
	Rate of change u_{32} (m/d)	0.35	0.425	0.5	0.55
	Cumulative value u_{41} (mm)	21	25.5	30	33

Vertical displacement of surrounding surface	Rate of change u_{42} (mm/d)	2.1	2.55	3	3.3
Vertical displacement of surrounding building	Cumulative value u_{51} (mm)	14	17	20	22
	Rate of change u_{52} (mm/d)	1.4	1.7	2	2.2
Deformation of surrounding pipeline	Cumulative value u_{61} (mm)	7	8.5	10	11
	Rate of change u_{62} (mm/d)	1.4	1.7	2	2.2

5.4.3 Creation of membership function

The membership function of triangular distribution was selected as the membership function of each factor in U_1 and U_2 [6]. Taking the cumulative value of the deep horizontal displacement of walls U_{11} as an example, the expression of the membership function of the triangular distribution was briefly described here. It can be seen from Table 6 that the cumulative value U_{11} of the deep horizontal displacement of walls was divided into the control values of four safety levels, which were 21mm, 25.5mm, 30mm, and 33mm respectively. The membership function curve was shown in Figure 3.

Figure 3 Membership function of the cumulative value of deep horizontal displacement of walls

The membership function expression of the cumulative value U_{11} of the deep horizontal displacement of walls was:

Safety: $f_{11}^1 = \begin{cases} 1 & x \leq 21 \\ (25.5 - x) / 4.5 & 21 < x \leq 25.5 \\ 0 & x \geq 25.5 \text{ or } x > 30 \end{cases}$

Attention: $f_{11}^2 = \begin{cases} 0 & x \leq 21 \text{ or } x > 30 \\ (x - 21) / 4.5 & 21 < x \leq 25.5 \\ 0 & 25.5 < x \leq 30 \end{cases}$

Early-warning: $f_{11}^3 = \begin{cases} 0 & x \leq 25.5 \text{ or } x > 33 \\ (x - 25.5) / 4.5 & 25.5 < x \leq 30 \\ (33 - x) / 3 & 30 < x \leq 33 \end{cases}$

According to the predicted value of the deep horizontal displacement of walls, the corresponding membership degree of U_{11} under the four safety levels was calculated:

$$R_{11} = [r_{11}^1 \quad r_{11}^2 \quad r_{11}^3 \quad r_{11}^4]$$

5.4.4 Fuzzy comprehensive evaluation of a single index

The predicted value was used to predict the safety status of the foundation pit for the next phase. The values of each factor in U_1 and U_2 were shown in Table 7.

Table 7 Summary table of factor values

Factor \ Value	Factor set of cumulative value U_1						Factor set of change rate U_2					
	u_{11}	u_{21}	u_{31}	u_{41}	u_{51}	u_{61}	u_{12}	u_{22}	u_{32}	u_{42}	u_{52}	u_{62}
Predicted value	35.5	7236	-1.26	-30.0	-10.5	-9.1	2.7	—	0	-2.8	-0.4	-0.2
Factor value	35.5	7236	1.26	30.0	10.5	9.1	2.7	—	0	2.8	0.4	0.2

Liu Junwei [4] and Zhang Jin [7] found through research that, using the rate of change to prejudge the safety status of foundation pit construction was more accurate and timely than the cumulative value. Therefore, it was recommended that the weighted-average method be used to comprehensively consider the impact of these two combined. When calculating the membership degree of the evaluation index, if the rate of change factor was 4 times the cumulative value factor, it would be more in line

with the factor importance evaluation standard, and also in line with engineering practice. According to the values of various factors in Table 7 and the corresponding membership functions, the membership degrees of the six evaluation indexes were calculated as:

Deep horizontal displacement of walls

$$R_{11} = (0.2 \quad 0.8) \begin{pmatrix} R_{11} \\ R_{12} \end{pmatrix} \\ = (0 \quad 0.5336 \quad 0.2664 \quad 0.2000)$$

Brace force

$$R_2 = (1 \quad 0) \begin{pmatrix} R_{21} \\ R_{22} \end{pmatrix} = R_{21} \\ = (0 \quad 0 \quad 0.5160 \quad 0.4840)$$

Underground water level

$$R_3 = (0.2 \quad 0.8) \begin{pmatrix} R_{31} \\ R_{32} \end{pmatrix} \\ = (1 \quad 0 \quad 0 \quad 0)$$

Vertical displacement of surrounding surface

$$R_4 = (0.2 \quad 0.8) \begin{pmatrix} R_{41} \\ R_{42} \end{pmatrix} \\ = (0 \quad 0.3552 \quad 0.6448 \quad 0)$$

Vertical displacement of surrounding building

$$R_5 = (0.2 \quad 0.8) \begin{pmatrix} R_{51} \\ R_{52} \end{pmatrix} \\ = (1 \quad 0 \quad 0 \quad 0)$$

Deformation of surrounding pipeline

$$R_6 = (0.2 \quad 0.8) \begin{pmatrix} R_{61} \\ R_{62} \end{pmatrix} \\ = (0.8000 \quad 0.1200 \quad 0.0800 \quad 0)$$

Taking the membership degrees of the six indicators into account, the membership matrix of the safety status

of foundation pit construction for the next phase can be obtained:

$$R = \begin{pmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \end{pmatrix} = \begin{pmatrix} 0 & 0.5336 & 0.2664 & 0.2000 \\ 0 & 0 & 0.5160 & 0.4840 \\ 1 & 0 & 0 & 0 \\ 0 & 0.3552 & 0.6448 & 0 \\ 1 & 0 & 0 & 0 \\ 0.8000 & 0.1200 & 0.0800 & 0 \end{pmatrix}$$

The membership degrees of foundation pit construction for the next phase were:

$$B = A \cdot R = [B_1, B_2, B_3, B_4] \\ = [0.36926, 0.19553, 0.31292, 0.12229]$$

The membership degree for the next phase corresponding to the four safety levels of safety, attention, warning, and danger of the foundation pit construction was 0.36926, 0.19553, 0.31292, and 0.12229.

The basic scores corresponding to the four safety levels were:

$$T = \{T_1, T_2, T_3, T_4\} = \{100, 80, 60, 40\}$$

The comprehensive evaluation score of the safety status of the foundation pit construction for the next phase was:

$$F = B \times T = 0.36926 \times 100 + 0.19553 \times 80 + 0.31292 \times 60 + 0.12229 \times 40 = 76.24$$

It can be seen in Table 8 that the corresponding relationship between the comprehensive evaluation score and the safety level of the foundation pit construction was $80 > 76.24 > 60$, and the safety level of the next stage can be prejudged as attention. Therefore, the foundation pit system was relatively safe at that time and can be constructed normally.

Table 8 Correspondence between comprehensive evaluation score and safety level of foundation pit construction

Comprehensive evaluation score F	Safety level of foundation pit	Description	Response
80~100	Safety	The foundation pit does not tend to deform or damage, and the foundation pit system is safe.	Normal construction
60~80	Attention	The foundation pit has the tendency and signs of deformation and damage, but relatively safe for now.	It is necessary to attract the attention of all parties involved in the construction and analyze the development trend of deformation.
40~60	Warning	The construction has certain safety hazards and is prone to danger in this state.	The construction unit shall hold a monitoring and warning analysis meeting, and take necessary emergency measures.
40	Danger	The safety risk is very high, and construction should be temporarily stopped.	The construction unit shall invite relevant experts to participate in the rescue meeting, and take relevant rescue measures based on the site conditions.

5.5 Risk Prediction of Foundation Pit

It can be seen from the membership matrix R that, in the foundation pit for the next phase, the membership degrees of the deep horizontal displacement of walls R_1 and the brace force R_2 under the danger level are 0.2000 and 0.4840 respectively, and other indexes are all 0. This indicates that the risks for the next phase are mainly the deformation of the enclosure structure and the excessive brace force of the concrete support. If it continues to develop, it may cause damage and endanger the safety of the foundation pit.

The prediction result helps all parties involved in the construction to formulate effective measures to control the deformation of the supporting structure in advance, so as to ensure the safety and stability of the foundation pit construction.

6 Conclusion

(1) The trained BP neural network prediction model can make a more accurate prediction of the evaluation index based on the monitoring data in a short time. Combined with the timeliness of the entropy method, it can obtain the influence weight of each evaluation index in the safety evaluation of the foundation pit for the next phase.

(2) Fuzzy comprehensive evaluation method introduces the concepts of membership degree and membership function, which better tackles with the ambiguity and relevance of safety risks in foundation pit excavation. Through the quantitative evaluation of the later construction safety status, the foundation pit engineering is divided into four safety levels, including safety, attention, warning, and danger, making the prediction results more realistic.

(3) The membership matrix quantitatively describes the construction risks for the next phase, contributing to control engineering risks and improving the function of safety predicting of foundation pits.

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