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Analysis and Prediction of Foundation Settlement of High-Rise Buildings under Complex Geological Conditions

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Abstract

Based on an example of a project in Tangshan, the high-rise buildings are built in karst area and mined out affected area which is treated by high pressure grouting, and foundation is adopted the form of pile raft foundation. By long-term measured settlement of high-rise buildings, It is found that foundation settlement is linear increase with the increase of load before the building is roof-sealed, and the settlement increases slowly after the building is roof-sealed, and the curve tends to converge, and the foundation consolidation is completed. The settlement of the foundation is about 80% - 84% of the total settlement before the building is roof-sealed. Three layer BP neural network model is used to predict the settlement in the karst area and mined affected area. Compared with the measured data, the relative difference of the prediction is 0.91% - 2.08% in the karst area, and is 0.95% - 2.11% in mined affected area. The prediction results of high precision can meet the engineering requirements.

Keywords

Complex Geological Conditions, Settlement Law, Settlement Prediction, The BP Neural Network

1. Introduction

In recent years, the construction area of high-rise buildings has become more and more complex, such as: Karst area, mined out area, mined out affected area, subsidence area, tidal flat area, filling area, etc. The complexity of geological conditions will lead to instability of the ground in the field area, the security of the building is seriously threatened, coupled with the increase of the height of the building, the load also increases, and the foundation is prone to uneven settlement. In order to ensure the safety of the building, the use of modern information equipment to monitor the settlement of the foundation and the collected data analyzed for future settlement prediction are important parts of engineering construction indispensable under complicated geological conditions [1] [2].

There are many methods for predicting the settlement of foundation, which can be reduced to two kinds. One is a purely theoretical method of calculation, which is more difficult to predict when calculating the relevant parameters. The other is the prediction method based on measured data, the method to establish the model with the measured data, the prediction results of higher accuracy, such as regression analysis, time series method, hyperbola method, grey theory method, artificial neural network method [3].

The construction in complex geological conditions of the high-rise buildings, because the underground situation is unknown, leading to many parameters difficult to define, coupled with its perplexing changes, and it is difficult to give a mathematical formula for each stage of the construction, but due to the influence of human factors, in various stages of settlement monitoring will have errors, these with the increase of time continuous superposition error. If the prediction model cannot eliminate the human error and the system error in the observation result, the result will be very different from the actual situation. For the prediction of settlement data of high-rise building foundation under complicated geological conditions, BP neural network has its unique advantages, the traditional function of the independent variables can be used as the inputs of the model, and the traditional function of the dependent variable can be used as the output of the model, and this function is transformed into multi dimensional nonlinear mapping, through the network like the brain the information processing process of parallel processing, will not affect the results of the whole small part because the loss of data. The network contact between the contact behavior between the simulated brain neurons, adaptive, self-organizing and self-learning characteristics, error information can eliminate the settlement monitoring results in the continuous learning of the correct information simulation, through the simulation to predict the future settlement [4] [5].

A neural network consists of a large number of neurons interconnected by certain rules. The interaction between neurons connection to play the role of information processing, distributed information and knowledge reserves by neurons, automatic change of weight in neural network is the core part of the whole network, through the network automatically changing the weights, until it reaches the desired output. Its basic characteristics are: nonlinear function's extreme approximation, fault tolerance, learning adaptability and parallel processing [6].

Rumelhart and McCelland [7] in the writings for the first time proposes the error back-propagation algorithm, this algorithm called BP algorithm, which is three layer feed-forward neural network BP the typical network consists of input layer, hidden layer and output layer three components. Between the adjacent layers, the neurons are all connected, the neurons of the same layer are not connected, and the information is transmitted between neurons. BP neural network learning mode is divided into supervised learning and unsupervised learning mode in supervised learning mode, the relationship between output by the instructor to set expectations and the information into the network is composed of input layer, processing only plays the role of input layer's data transfer, the data from the hidden layer after training, data import and output layer, output data and mentor the expectations set the difference for output error, if the output data does not meet the expectations of the mentor is to reverse error to the input layer, the network will automatically adjust the weights and thresholds for training the data again, stop the iteration error until the wireless approaches 0. The final output data meets the requirements [8] [9] [10].

Based on the Tangshan A plaza including A tower in karst area and E4 high-rise residential building in the mined out affected area. Combined with their long-term measured settlement data, analysis of building foundation settlement rule, and establish the BP neural network prediction model, to predict the foundation settlement.

2. Model Establishment

Three layer feed-forward BP neural network prediction model is adopted, and the learning steps of the network are as follows: [11] [12]

2.1. Node Output

Middle layer node operation formula:

$$x_j = f\left\{\sum w_{ij} x_i - q_j\right\} \tag{1}$$

Output layer node operation formula:

$$y_k = \left\{\sum w_{jk} x_i - q_k\right\} \tag{2}$$

where, f is a nonlinear function; q is the neuron threshold; w_{ij} is the connection weight of the j^{th} neuron and the i^{th} neuron; x_i is the input values; w_{jk} is the connection weight of the k^{th} neuron and the j^{th} neuron.

2.2. Transfer Function

The transfer function, also known as the stimulus function, is the stimulus intensity between the feedback layer and the layer node. In the (0, 1) continuous value, the Sigmoid function is one of the most commonly used transfer functions. The formula is as follows:

$$f(x) = \frac{1}{\left(1+e^{-x}\right)} \tag{3}$$

2.3. Operational Error

The difference between the output of the output layer and the expectation is the error of the network. The formula is as follows:

$$E_p = \frac{\sum (t_{pi} - O_{pi})^2}{2} \quad (4)$$

where, t_{pi} is the expected output value of the i node; O_{pi} is the i node that calculates the output value.

2.4. Self-Learning Process

Through error back propagation, the network adjusts the weights and thresholds of each layer automatically, and the error continues to decrease until the infinity tends to 0. The process is called self learning process:

$$\Delta w_{ij}(n) = \eta \times \varphi_i \times O_j \quad (5)$$

where, η is learning factor; ϕ_i is calculation error of output node *i*; O_j is calculated output value of output node *j*.

3. Settlement Analysis

A square in Tangshan is located in Lunan District of Tangshan City. The area includes karst development, goaf wave and seismic fracture zone. According to the engineering characteristics and physical and mechanical properties of the soil layer, the soil layer in the field area can be divided into 14 layers from top to bottom (as shown in Table 1).

The A tower is in karst area, underground karst develops. The main building is 23 storey frame shear wall structure, the underground two layers are underground garage and the frame structure. From April 2010 to July 2011, during the period, a total of 18 monitoring were conducted, the accumulation settlement data of eight settlement observation points of the high building was obtained. E4 building is adjacent to the former site of Fengnan coal mine. It is affected by the influence of mined out area. E4 high-rise residential buildings is a 34 storey

Table 1. Characteristic values of soil bearing capacity and table of main parameters.

Layer number	Name of rock soil	Unit weigh (kN/m^3)	Void ratio e	Water content (%)	Shear strength		Modulus of compressibility Es (MPa)	Characteristic value of subgrade bearing capacity f_{ak} (kPa)
					internal friction angle	Cohesion C(kPa)		
2	Silty clay	18.0	0.615	27	23.0	25.0	5.2	140
3	Silty sand	19.0	0.594	22	*21.0	*4.5	9.0	160
4	Fine sand	20.0	0.593	23	*24.0	*5.5	9.5	190
5	Silty clay	20.5	0.598	25	13.0	8.0	5.3	160
6	Fine sand	19.5	0.589	20	*28.0	*5.5	13	230
7	Silty clay	20.5	0.604	26	23.0	43.9	5.5	160
8	Fine sand	20.1	0.596	22	*27.0	*5.5	14.5	250
9	Silty clay	20.6	0.574	24	23.2	48.2	5.7	170
10	Residual soil	18.0	0.654	25	*23.5	*13.5	7.0	260

shear wall structure, and the underground two layer is an underground garage. From March 2010 to May 2011, during the period, a total of 30 monitoring were conducted, the accumulation settlement data of eight settlement observation points of the high building was obtained. The P-v-t curves are shown in Figure 1 and Figure 2.

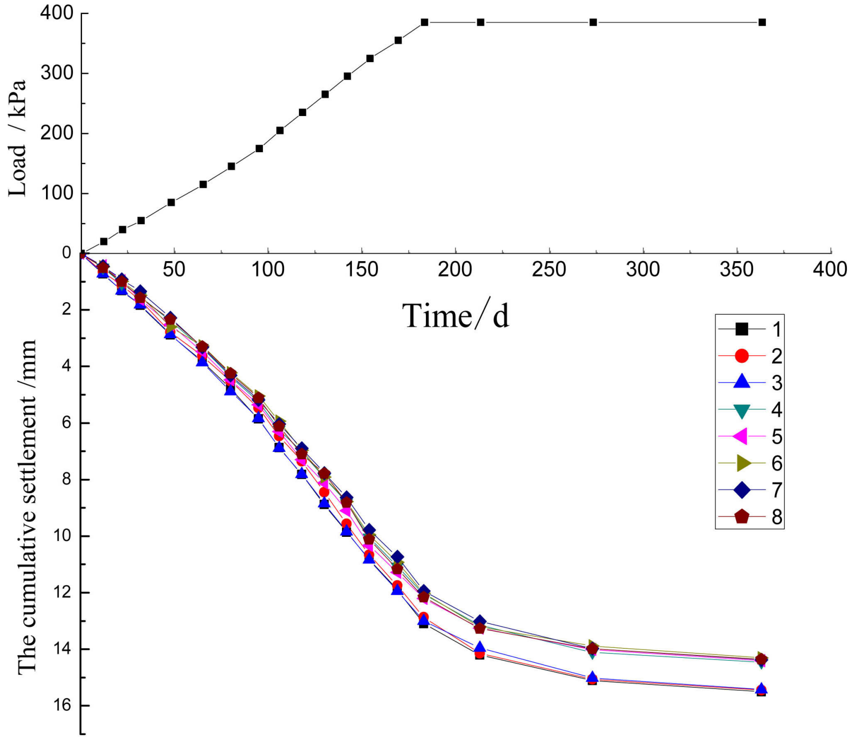

Figure 1. A tower p-v-t curve.

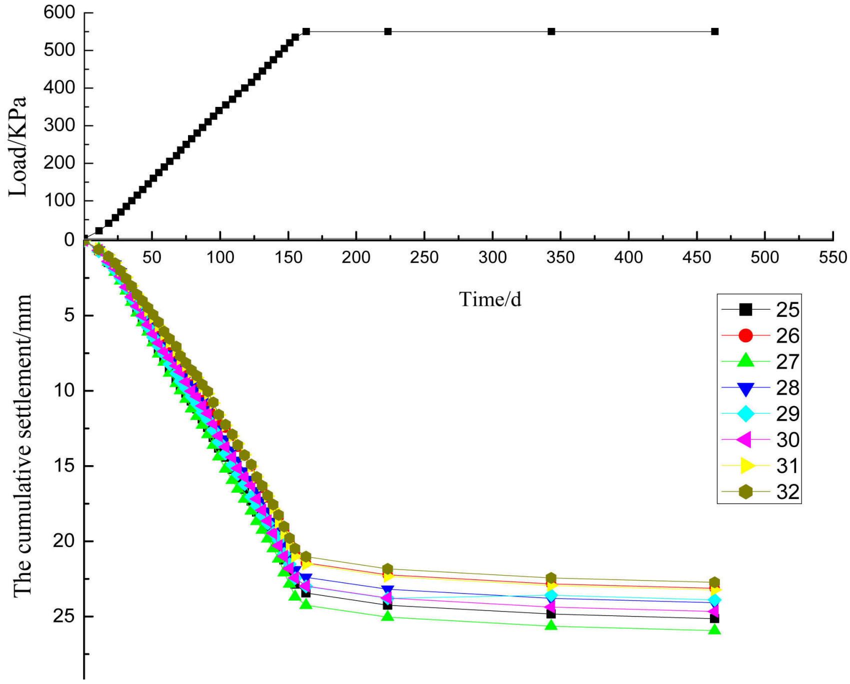

Figure 2. E4 high-rise residential building p-v-t curve.

The following conclusions can be drawn from Figure 1 and Figure 2:

1) A tower cumulative settlement observation point the highest point for the point 1, the cumulative settlement is 15.50 mm, the cumulative settlement minimum point for settlement observation point 6, the cumulative settlement is 14.31 mm. High-rise residential buildings cumulative settlement observation point the highest point for the point 27, the cumulative settlement is 26.0 mm, the cumulative settlement minimum point for settlement observation point 32, the cumulative settlement is 22.5 mm. All conform to the standard [13] requirement.

2) A tower and E4 high-rise residential building, the monitoring points are basically the same trend, no more than the standard allowed uneven settlement occurred. The pile raft foundation has good applicability in the mined out area of the karst area after grouting treatment. It can basically eliminate the adverse effects of the mined out area on the ground.

3) The total settlement of the A tower at each settlement observation point is 81% - 83% of the total settlement, and the accumulated settlement accounts for 17% - 19% of the total settlement after the cap is completed. Before the settlement of the E4 high-rise residential building, the accumulated settlement accounts for 82% - 83% of the total settlement, and the accumulated settlement accounts for 18% - 19% of the total settlement. Most of the settlement of the foundation occurred before loading.

4) From the P-s-t curve of A tower and E4 high-rise residential buildings can be seen in stories with the increase of load settlement is increasing linearly, constant load after the cap, the settlement curve increased slowly convergent, complete consolidation.

5) Tilt of the building body are calculated, respectively A and E4 tower high-rise building settlement difference between the two observation points of maximum calculated inclination values, calculated A tower tilt value is 0.0015, E4 value of 0.0018 high-rise residential building tilt, all meet the requirements of the standard [13] 0.0025.

4. Settlement Prediction

The maximum cumulative sedimentation rate of point 16 is chosen as the settlement prediction. The cumulative sedimentation value of the original observations is shown in Table 2. This section takes the most representative of the cumulative settlement of the cumulative settlement of point 27 as the case analysis. The cumulative settlement value of the observed cumulative settlement is shown in Table 3.

4.1. Settlement Data Processing and Prediction in Karst Area

For the measured settlement data of karst area foundation, selects 18 issues of settlement observation data in the first stage 8 data as the analysis sample, predict 10 period after sedimentation value, the predicted results with 10 phase of the measured data, after discussing the model accuracy. The predictions are shown in Table 4 and Figure 3.

4.2. Settlement Data Processing and Prediction in Mined Out Area

The 30 issue of settlement observation data is selected in the first 20 period as the training sample data, to predict the settlement of 10 period, the 10 period after prediction results and the measured data, the prediction results are shown in Table 5 and Figure 4.

Table 2. The cumulative settlement of the observation points 16 of A tower.

nper	date	Number of days (d)	Cumulative Settlement (mm)	nper	date	Number of days (d)	Cumulative Settlement (mm)
1	2010/04/12	0	0	10	2010/08/11	121	8.80
2	2010/04/25	13	0.47	11	2010/08/21	131	9.74
3	2010/05/28	26	1.00	12	2010/08/31	141	10.45
4	2010/05/16	34	1.48	13	2010/09/10	151	11.44
5	2010/06/06	55	2.97	14	2010/09/20	161	12.49
6	2010/06/24	73	4.35	15	2010/09/30	171	13.66
7	2010/07/09	88	5.43	16	2010/10/30	201	14.16
8	2010/07/20	99	6.86	17	2011/01/30	293	14.46
9	2010/07/31	110	7.95	18	2011/07/30	476	14.66

Table 3. The cumulative settlement of the observation points 27 of E4 high-rise residential building.

nper	date	Number of days (d)	Cumulative Settlement (mm)	nper	date	Number of days (d)	Cumulative Settlement (mm)
1	2010/03/21	0	0	16	2010/05/31	72	9.98
2	2010/04/01	11	0.56	17	2010/06/04	76	10.54
3	2010/04/08	18	1.43	18	2010/06/08	80	11.18
4	2010/04/13	23	2.10	19	2010/06/12	84	11.68
5	2010/04/17	28	2.68	20	2010/06/16	88	12.27
6	2010/04/21	32	3.35	21	2010/06/20	92	12.90
7	2010/04/25	36	4.11	22	2010/06/24	96	13.60
8	2010/04/29	40	4.83	23	2010/06/29	101	14.37
9	2010/05/03	44	5.46	24	2010/07/04	106	15.18
10	2010/05/07	48	6.08	25	2010/07/09	111	15.93
11	2010/05/11	52	6.79	26	2010/07/13	115	6.52
12	2010/05/15	56	7.54	27	2010/07/18	120	17.19
13	2010/05/19	60	8.08	28	2010/08/18	150	17.98
14	2010/05/23	64	8.82	29	2010/11/19	240	18.67
15	2010/05/28	69	9.49	30	2011/05/20	420	19.25

Table 4. Comparison between measured and predicted data at No. 16 observation point.

nper	Cumulative settlement (mm)	The BP neural network	Residual (mm)	Relative difference (%)
9	7.95	8.0377	0.0877	1.10
10	8.80	8.8932	0.0932	1.06
11	9.47	9.5748	0.1048	1.11
12	10.45	10.5532	0.1037	0.97
13	11.44	11.5436	0.1036	0.91
14	12.49	12.6477	0.1577	1.26
15	13.66	13.8313	0.1713	1.25
16	14.16	14.4136	0.2536	1.79
17	14.46	14.7343	0.2743	1.90
18	14.66	14.9417	0.2817	1.92

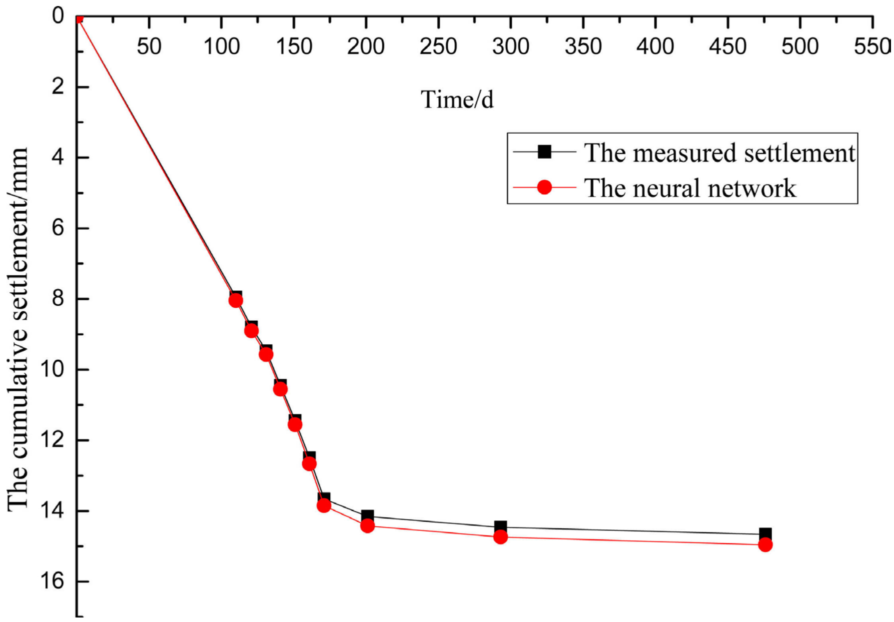

Figure 3. The prediction curve of the point 16 observation curve and the measured graph.

Table 5. Comparison between measured and predicted data at No. 27 observation point.

nper	Cumulative settlement (mm)	The BP neural network	Residual (mm)	Relative difference (%)
21	12.90	13.0225	0.1225	0.95
22	13.60	14.0057	0.1357	1.00
23	14.37	14.5275	0.1578	1.10
24	15.18	15.3337	0.1537	1.01
25	15.93	16.0895	0.1595	1.00
26	16.52	16.7037	0.1837	1.11
27	17.19	17.4025	0.2125	1.24
28	17.98	18.2718	0.2918	1.62
29	18.67	19.0087	0.3387	1.81
30	19.25	19.6125	0.3625	1.88

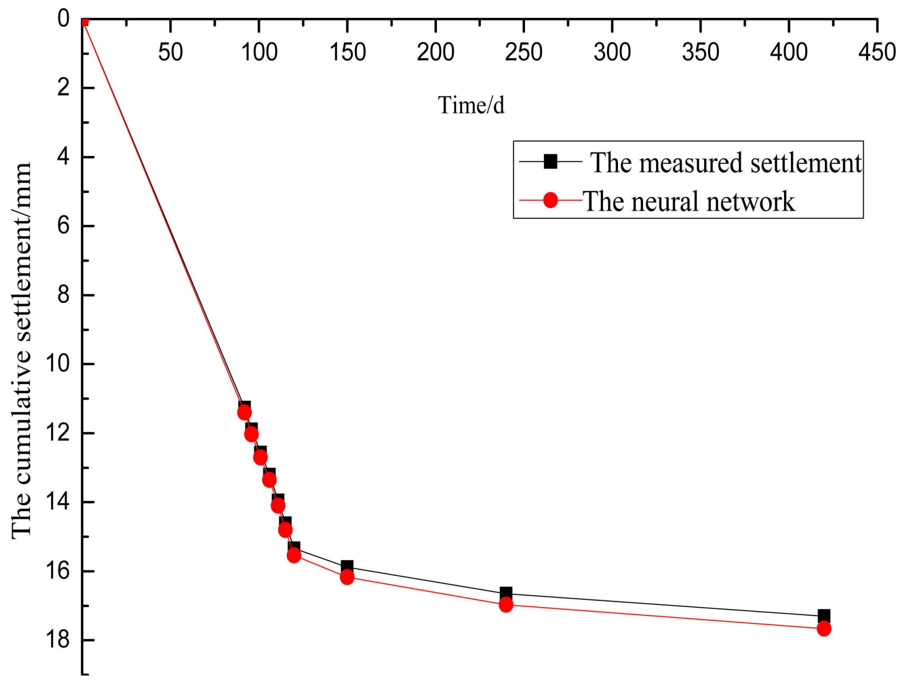

Figure 4. The prediction curve of the point 27 observation curve and the measured graph.

4.3. Result Analysis

Table 4 and Figure 3 show, predicting curve fitting degree is higher, predicted values and measured values is relatively close, and the maximum value of the relative difference is 1.92%, the minimum value of the relative difference is 0.91% in the karst area. Table 5 and Figure 4 show, predicting curve fitting degree is higher, predicted values and measured values is relatively close, and the maximum value of the relative difference 1.88%, the minimum value of the relative error is 0.95% in mined out affected area. The late prediction difference is more common than previous predicts, shows that the precision of the model as time growth will reduce, so the BP neural network prediction model in the prediction of subsidence in the short term advantages are more obvious.

5. Conclusions

1) A tower and E4 high-rise residential building, the monitoring points are basically the same trend, no more than the standard allowed uneven settlement occurred. The pile raft foundation has good applicability in the mined out area of the karst area after grouting treatment. It can basically eliminate the adverse effects of the mined out area on the ground.

2) The cumulative sedimentation of a tower settlement is 81% to 83% of the total settlement. The cumulative settlement volume of E4 high-rise residential buildings is 82% to 83% of the total settlement. Most ground subsidence occurs during loading in front of the cap.

3) Three layer feed forward BP neural network prediction models are adopted to predict foundation settlement prediction in the karst area and mined out affected area in high-rise buildings. The predicting results are close to the meas-

ured values and the difference between 1% and 2%. So the predicting model can be applied in high-rise building foundation settlement analysis and prediction.

4) The BP neural network prediction model will be more advantageous in the short-term settlement prediction, as the model of the growth model becomes less accurate over time.

References

[1] Long, X.Q. (2010) Analysis and Treatment of Uneven Settlement of Building Foundation in a Karst Area. *Building Technology*, No. 2, 168-171. (In Chinese)

[2] Tang, H. and Zhou, Z.R. (2013) Research on Complex Foundation Treatment and Uneven Settlement Control in Karst Area. *Construction Technology*, **42**, 93-95. (In Chinese)

[3] Zou, J.G., Xiao, Y.X. and Zhang, S.Y. (2014) Study on Application of Combined Model Based on ARIMA-BP Neural Network in Prediction of Settlement of Foundation. *Surveying and Mapping Bulletin*, No. S2, 99-104. (In Chinese)

[4] Cheng, S., Sui, B.B., Shen, Y. and Wang, T. (2015) Study on Prediction of Surface Subsidence in Mining Area Based on BP Neural Network. *Mapping and Geospatial Information*, No. 3, 18-20. (In Chinese)

[5] Fu, P.S. (2009) The Prediction and Dynamic Evolution Mechanism of Composite Foundation Settlement Deformation. Lanzhou University, Lanzhou. (In Chinese)

[6] Zhang, W.B. and Guo, Y.K. (2013) Study on Prediction Model of Building Subsidence Based on BP Neural Network. *Surveying and Mapping Engineering*, **22**, 52-56. (In Chinese)

[7] Rumelhart, D.E. and Mcclelland, J.L. (1986) Parallel Distributed Processing. Parallel Distributed Processing. The MIT Press, Cambridge, 45-76. (In Chinese)

[8] Li, T., Pan, Y., Lou, H.J., Li, B., Wang, H. and Zou, L.Z. (2005) Application of Artificial Neural Network to Land Subsidence Prediction in Tianjin City. *Geological Bulletin*, No. 7, 677-681. (In Chinese)

[9] Wang, L.W. (2012) Determination of the Number of Hidden Layer Neurons in Artificial Neural Networks. Chongqing University, Chongqing. (In Chinese)

[10] Zhu, D.Q. (2004) Research Status and Prospect of Artificial Neural Network. *Journal of Jiangnan University* (*NATURAL SCIENCE EDITION*), **3**, 103-110. (In Chinese)

[11] Liu, F.R. (2009) Discussion and Inversion Analysis of Settlement Calculation of High-Rise Building. China University of Petroleum, Beijing. (In Chinese)

[12] Peng, T., Yang, A.Y., Liang, X. and Yuan, Q. (2005) BP Neural Network Grey System Model for Predicting the Settlement of Soft Ground. *Rock and Soil Mechanics*, No. 11, 119-123. (In Chinese)

[13] Ministry of Construction of the People's Republic of China (2007) People's Republic of China National Standard. Building Deformation Measurement Code. China Construction Industry Press, Beijing. (In Chinese)