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Analysis and Prediction of Soft Foundation Settlement for Expressway Based on BP Neural Network

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***Abstract*—This paper introduced the principle of BP neural network and established the model of foundation settlement prediction. To analyze the rules of soft foundation settlement, the BP neural network was used to fit and optimize the settlement data of one expressway project. And the one-dimensional consolidation theory and the BP neural network are compared with measured data respectively. The analysis results show that the one-dimensional consolidation theory are more conservative in security while the BP neural network method more accurate and more economical in the practical engineering. It indicates that the BP neural network is an effective method and can be widely used in practical engineering.**

Keywords-soft foundation; the BP neural network; settlement prediction

I. INTRODUCTION

With the development of transportation industry, expressway gradually becomes the main force. And the condition of foundation is closely related to foundation, embankment design, road construction and the normal operation after completion, especially for soft foundation with complicated engineering properties. Soft oil features in large porosity, higher natural water content, long consolidation time, large amount of settlement and low load-carrying capacity etc, which is not conducive to engineering construction. Constructed on soft soil foundation, its potential of post-construction settlement will cause serious harm to the transportation security. However, soft soil is widely distributed in our country. Limited to the geographical conditions, many expressways have to be built on soft soil foundation, which increases the difficulty of design and construction. At present, the design of the subgrade of many expressways are mostly adopted rigid or semi-rigid base, thus there are strict requirements for settlement after construction. In order to design cut-fill volumes reasonably and further guide the construction, it is necessary to predict the final settlement of foundation accurately [1].

There are many methods of foundation settlement prediction. In recent years, with the development of science and technology, as well as the widely used of computer, the method of foundation settlement prediction has further developed. According to pertinent literature, there are three methods of soft soil foundation settlement prediction as follows [2]:

- Method of theoretical equation. Based on one-dimensional consolidation theory of soil, it is the method combined with the constitutive relation model of soil.
- Method of numerical analysis. It is the method based on the finite element analysis by computer.
- The measured data analysis. It is the method based on the observed settlement data and calculates the relationship between settlement and time, thus predict final settlement.

Due to the complex constitutive relation of soil, although the traditional theory method can predict the final settlement of the foundation roughly to some extent, there is large difference with the actual result. For the method of finite element numerical analysis, it is theoretically possible with high prediction accuracy, but the actual operation is difficult, thus rarely used in practical engineering. Then using limited settlement observation data to predict the final settlement is of great significance. Its prediction methods are mainly included exponential curve, hyperbolas, Asaoki, grey prediction and Artificial Neural Network, etc. According to related literature [3]-[4], the foundation settlement prediction based on artificial neural network method is of the highest accuracy compared with the traditional curve fitting and exponential curve method, etc.

Artificial neural network is a new practical method integrated with a variety of modern science and technology and a nonlinear, adaptive information processing system combined with a large number of processing units. It has high ability of self-learning and self-organization in Lenovo reasoning and adaptive recognition, which suitable for processing all kinds of nonlinear problems. Back Propagation network, referred to as 'BP network' [5] is currently the most widely used neural network. This paper will analyze the foundation settlement using BP neural network, combined with an engineering example.

II. Foundation Settlement Prediction Based on BP Neural Network

A. The Principle of BP Neural Network

The BP neural network consists of input layer, hidden layer and output layer. Using the error back propagation algorithm to learn, the connection between two layers is neural, and there are no connections between neurons.

For a network X with input layer of m and dimensionality of n, the input value of the layer of k and the neural of i can be expressed as the linear combination of the output for $k-1$ layers neurons signal U_i^k.

$$U_i^k = \sum W_{ij} X_j^{k-1} \tag{1}$$

Where W_{ij} is weight coefficient, the positive value represents the strength is promoted, and the negative value represents the strength is restrained.

According to activation function $f(x)$, the output value is calculated as follows:

$$X_i^k = f\left(U_i^k\right) \tag{2}$$

There are p output signals X_p^m in the output layer, and compare it to the expected output Y^{m}, the error signal e is obtained.

$$e = \frac{1}{2}\sum_i \left(X_i^m - Y_i\right)^2 \tag{3}$$

Based on negative gradient of the error function, modify the weights of the two output signals

$$\Delta W_{ij} = -\eta \frac{\partial e}{\partial W_{ij}} \tag{4}$$

Where η is learning rate, the value of which varies between 0 and 1. And the adjustment formula of weight is given as in Eq. (5). α is weights fixed constant.

$$\Delta W_{ij}\left(t+1\right) = -\eta d_i^k X_i^{k-1} + \alpha \Delta W_{ij}\left(t\right) \tag{5}$$

When the error signal of each sample meets the accuracy requirement or maximum number of learning, the algorithm terminates.

B. The Model of Settlement Prediction

The theoretical calculation method of foundation settlement prediction has great limitations due to the complex engineering properties of soil. BP neural network has high ability of self-learning and self-organization, suitable for processing all kinds of nonlinear problem. Using BP neural network, the change rule of settlement can be obtained just according to the observation data without the consideration of property of soil and the actual project conditions. Then the ultimate settlement in a certain period of time can be obtained. It is generally believed that increase the number of hidden layer can reduce prediction error of network, thus improve accuracy. But increasing the number of hidden layer can make the network more complicated, thus increase the training time and lowered the generalization ability due to over fitting. According to the theorem of Kolmogorov, A three-layer neural network with a hidden layer can approximate any nonlinear continuous function with arbitrary precision on closed set. For settlement prediction of soft soil foundation, the topological structure is single hidden layer, and there is no efficient way in selecting the number of hidden layer nodes. According to the empirical formula and test method, the number of hidden layer nodes is determined in n, and set up the network topology structure of 1 - n – 1. The hidden layer function is adopted as tansig and the output layer function is adopted as purelin. Set up the biggest training cycles of 3000, the performance target value of 0.001 and the initial learning coefficient of 0.9. Using MATLAB2013b, part of the data is selected as training set to train the neural network and the other part is used in simulation test. Then the ultimate settlement in a certain period of time can be obtained according to simulation fitting.

III. Engineering Project Based on Hubei Huang Expressway

A. Project Profile

Mainly distributed in the accumulation plain of middle and lower reaches of Yangtze River, the topographic relief of Hubei Huang Expressway is not big. The route mainly passes through farmland. And the strata are mainly quaternary alluvial cohesive soil, mud and silt soil and silty-fine sand, etc. The underlying bedrock is mainly cretaceous glutenite. Buried shallow, the groundwater is rich, and local groundwater was confined. The distribution of soft soil is mainly mucky soil, the depth of which is between 2.2 and 9.3 meters and thickness vary 0.6 to 9.3 meters. Thus effective measures must be taken during foundation construction. Because the subgrade is longer, many sections are selected in practical engineering observation. In this case, to simplify the calculation, there are three typical sections selected to analyze the settlement of foundation. The three cross sections are K6+930, K7+750, K8+750 respectively, the engineering geological conditions of which are shown in table 1.

TABLE I. ENGINEERING GEOLOGICAL CONDITIONS

Section	Worksite Type	Design Filling Height(m)	Distribution of Soft Soil
K6+930	bridgehead	5.80	The first layer: silty clay; burial depth of 1.4m, thickness of 9.2m. The second layer: mucky soil; burial depth of 9.2m, thickness of 7m.
K7+750	General section	6.08	burial depth: 3.1~7.0m, thickness : 6.0~8.3m
K8+750	General section	5.40	The first layer: silty clay; burial depth of 1m, thickness of 1.7m. The second layer: fine sand; burial depth of 1.6m, thickness of 5.5m. The third layer: mucky soil; burial depth of 5.4m, thickness of 3.5m.

B. The Engineering Geological Conditions

Considering the great differences of engineering geological conditions of the three sections and the observation time is not the same, then this paper established network respectively.

Taking the section K6+930 for example, for the 39 groups of settlement data measured, some part are selected for training of network, and the other part are selected for testing. The value of maximum training cycles is set to 3000. The performance target is 0.001. And the initial learning coefficient is 0.9. Constantly adjust the topology network parameters such as the number of hidden layer nodes, it won't meet the requirements until the accuracy of the training and testing reaches 0.001. After several adjustments, it found that, to guarantee the stability of neural network, the training set should contain at least the former 30 sets of data, and according to Pruning Method, there must be at least 10 nodes in hidden layer. According to training of the former 30 sets of data with 31 convergences, the settlement for the later 9 sets are obtained, as shown in figure 1.

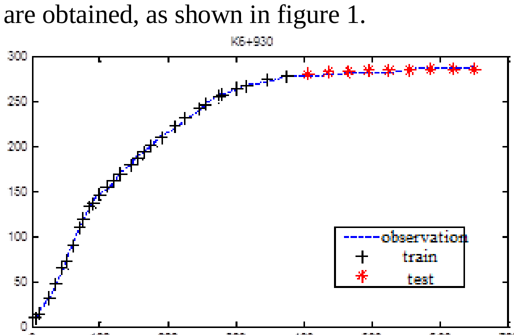

Figure 1. Prediction results of K6+930

As shown in figure 1, it took about 400 days until the settlement of foundation began to stabilize. And for three consecutive months, the settlement of three sections is all less than 3mm, which shows that the settlement is basically stable [6]. According to the network trained, it can be easy to predict the settlement of foundation at any time in the future.

TABLE II. STATISTICAL ANALYSIS OF SECTION K6+930

Observation Day (t)	The Cumulative Settlement Measured (mm)	Predicted Settlement (mm)	Relative Error(%)
405	278.5	280.91	0.87
435	280.1	282.65	0.91
465	281.6	283.76	0.77
495	281.7	284.46	0.98
525	282.3	284.91	0.92
555	286.3	285.19	-0.39
585	287.1	285.37	-0.60
615	287.9	285.50	-0.83
645	288.5	285.56	-1.02

As shown in table 1, using BP neural network to predict the settlement of the cross section, the mean square error of training group and experimental group is 1.93 and 2.40 respectively. The relative error maintains at about 1.02%. The precision of prediction for training set is higher. The precision decreases in the late due to the accumulation of error. With the increase of observation days, the error also decreases gradually, which makes the prediction of final settlement smaller than the measured values. But it still has very high precision, applicable to the engineering prediction.

For the section of K7+750 and K8+750, the simulation results can be obtained according to similar methods. And the comparison between predicted value, calculated value and the measured value of the three sections are shown in table 3.

TABLE III. CONTRASTIVE ANALYSIS OF THREE SECTIONS

Section	Measured Value(mm)	BP Neural Network (relative error %)	Theory Calculation (relative error %)
K6+930	288.5	285.4(-1.07)	318.0(10.2)
K7+750	253.2	250.1(-1.22)	291.0(15.0)
K+850	300.4	292.3(-2.60)	346.0(14.2)

Using the network that has been trained, the settlement of foundation at any time in the future can be obtained. In the 600 days after construction, the settlement of each section has been basically stable. In this paper, the last observed data is taken as the ultimate settlement.

As shown in table 3, the prediction of settlement based on theoretical calculation method is generally much larger than the measured values, and the relative error is greater than the neural network. Post-construction settlement is mainly secondary consolidation settlement, and then the settlement is slow after 200 days. And the settlement before 200 days is immediate settlement and consolidation settlement, which has a high settling volume and quick settling velocity. Thus the ultimate settlement obtained according to one-dimensional consolidation theory is often greater than the measured settlement. And the relative error is less than the theoretical calculation method compared with BP neural network. The predicted value is generally less than the measured values using BP neural network. In the practical engineering, the final settlement according to theoretical calculation is security but uneconomical. According to BP neural network, it can predict the settlement of any point within a certain time, speculate residual subsidence of foundation and determine the further fill and preloading scheme. At the same time, put forward reasonable suggestions timely to construction process by prediction can prevent the engineering accidents effectively.

IV. CONCLUSION

Artificial neural network is widely used in various kinds of curve fitting and forecasting for its high performance of self learning and self organizing. Using artificial neural network in prediction of foundation settlement has a good application prospect. Combined with an engineering project, this paper compared the method of BP neural network and the theory calculation method. The results show that predicting foundation settlement using the traditional calculation method based on one-dimensional consolidation theory will have higher error, and it is conservative and not economic. In contrast, the BP neural network has high accuracy and economic applicability. Using the prediction method presented in this paper, the settlement of the foundation within a certain time can be obtained according to the early part of the observation data in practical engineering. The results show that the precision of predictions is very high, which has certain application value in guiding later construction, the determination of and further digging fill and preloading scheme, etc.

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