Simulation And Prediction Of the Safety Risk Of Tower Crane For Super High-rise Buildings Through Back Propagation Neural Network

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Abstract. High-rise buildings especially super high-rise buildings are booming with the rapid urbanization because the urban population increases dramatically. For the sustainable development of super high-rise buildings, construction safety is an important issue. Since tower cranes are widely applied on the construction of super high-rise buildings as the lifting and transportation equipment, their safety is closely related to the safety of construction sites. In this study, a reasonable safety evaluation system with clear input and output indicators was first established. Then, the input index was quantified, and their weights were determined according to their importance which were ranked based on the fourth-class division method of safety grade. Subsequently, the neural network model was developed. 90 tower crane accidents were evaluated quantitatively which provided the data to train and verify the model. The results show that prediction of neural network model is reliable. The trained neural network model is capable to predict the tower crane risks of high-rise buildings, which can be helpful to the construction safety management.

1. Introduction

With the advancement of urbanization, the urban population is increasing, and the urban land area is limited. High-rise buildings, especially super high-rise buildings, continue to emerge. However, due to the large scale of high-rise buildings, long construction period, complex technology, and numerous risks, the accident rate on site has increased, and construction safety issues have become an important issue affecting the sustainable development of super high-rise buildings [1]. There are many operations in high-rise buildings. Tower cranes are the preferred lifting and transportation equipment for the construction of high-rise and super high-rise buildings. The reasonable layout, type selection, lifting weight and other factors in the project construction will directly affect the construction safety issues [2]. In order to meet complex building functions and improve the economic benefits of high-rise construction enterprises, construction safety evaluation and management have become the core part of construction project management [3].

Construction safety evaluation is a predictive work. It evaluates the safety status of a construction site through the collected index data and predicts where the problems occur on the site. It is of great help to the management personnel of the construction site. Related work is carried out in advance to stifle potential safety hazards in the bud stage. However, the traditional evaluation method has its own deficiencies that are difficult to overcome. For example, the safety checklist method relies on experience and lacks systematic analysis. The index evaluation method treats various factors by addition or multiplication, and does not distinguish the important degree of different factors [4]. Artificial neural networks, which simulate the human brain for nonlinear parallel processing of data, can effectively solve
complex problems. Neural networks have been used in various industries [5]. BP (Back-Propagation) neural network is a type of artificial neural network with a strong ability to deal with problems. By adjusting the weight of each layer, it can learn and memorize the learning sample set [6]. Compared with traditional evaluation methods (such as safety checklist method, index evaluation method, probabilistic risk evaluation method, etc.), neural network can better overcome the shortcomings of traditional evaluation methods, and obtain better safety evaluation results quickly and accurately. Thereby, the casualties of construction safety accidents can be reduced or avoided, thereby improving the safety management level of high-rise construction enterprises, and improving the market competitiveness and comprehensive strength of construction enterprises.

2. Tower crane construction safety evaluation

2.1. Introduction to the neural network method

The BP (Back Propagation) network is a feedforward multi-layer network with guided training. Its training algorithm is the BP algorithm, which relies on adjusting the weight of each layer to make the network learn the characteristics of the training group composed of input and output pairs.

The weight matrix between the input layer and the hidden layer:

\[ W_{ij} = (V_{1j}, V_{2j}, \ldots, V_{nj}) \in \mathbb{R}^{n \times m}, j = 1, \ldots, m \]  

Where the column vector \( V_j \) is the weight vector corresponding to the \( j \)th neuron in the hidden layer, \( V_j = (V_{1j}, V_{2j}, \ldots, V_{nj})^T \in \mathbb{R}^n, j = 1, \ldots, m \).

The weight matrix from the hidden layer to the output layer:

\[ W_{kl} = (W_{1l}, W_{2l}, \ldots, W_{nl}) \in \mathbb{R}^{m \times l}, k = 1, \ldots, l \]  

Where the column vector \( W_k \) is the weight vector corresponding to the \( k \)th neuron in the output layer, \( W_k = (W_{1k}, W_{2k}, \ldots, W_{mk})^T \in \mathbb{R}^m, k = 1, \ldots, l \).

For the output layer, the activation function is as follows:

\[ O_k = f(u_k), k = 1, \ldots, l \]  

The relatively commonly used activation function is the non-linear activation function unipolar Sigmoid function, referred to as the sigmoid function:

\[ f(x) = \frac{1}{1 + e^{-x}} \]  

The method for determining the number of nodes in the hidden layer of the BP neural network structure is:

\[ x = (n + m)^{0.5} + a \]  

Where, \( x \) represents the number of intermediate nodes; \( n \) represents the number of input nodes; \( m \) represents the number of output nodes.
2.2. Tower crane construction safety evaluation index system

Constructing a reasonable evaluation index system is the basis for evaluating the construction safety of high-rise buildings. Whether the selection index is appropriate or not directly affects the final safety evaluation result. In view of the content of tower crane construction safety management and many influencing factors of high-rise building projects, combined with 90 domestic tower crane safety accidents, the details of some accidents are shown in Table 1.

| Number | Project Name                                                                 | Accident type           | Casualties | Accident time |
|--------|------------------------------------------------------------------------------|-------------------------|------------|---------------|
| 1      | A tall building in Shenyang                                                  | Tower crane breaks      | 3 dead 3 hurt | 2012.04       |
| 2      | A high-rise residential building in Shanghai                                  | Tower crane collapsed   | 2 dead 0 hurt | 2009.08       |
| 3      | B-04 Block Project in Nantong City, Jiangsu Province                         | Tower crane overturned  | 3 dead 1 hurt | 2013.09       |
| 4      | A construction site in Hohhot                                                 | Tower crane collapsed   | 5 dead 0 hurt | 2011.06       |
| 5      | The tallest building in Dongguan                                              | Tower pendant           | 3 dead 5 hurt | 2009.12       |
| 6      | A super high-rise building of Hangzhou Wanyin Real Estate Co., Ltd.           | Tower crane breaks      | 1 dead 0 hurt | 2010.05       |
| 7      | China Communications Group Southern Headquarters Base Area B Project          | Tower crane collapsed   | 7 dead 2 hurt | 2017.07       |
| 9      | A building in Hangzhou                                                       | Tower crane collapsed   | 2 dead 6 hurt | 2009.05       |
| …      | …                                                                             | …                       | …          | …             |

The three factors that human factor R1, mechanical equipment R2, and environmental factor R3 are considered. In the human factor, 7 items directly related to people are given. R11 is safety operation, emergency rescue and other system establishment. R12 is safety management organization and position setting. R13 is safety training for drivers and commanders. R14 is status of holding special job certificate for special operations. R15 is check the rectification of hidden dangers. R16 is operating proficiency of the driver and commander. R17 is driver playing mobile phones, listening to the radio or working after drinking.

In the mechanical factors, five influencing factors directly related to the tower crane are given. R21 is tower crane installation. R22 is tower crane removal. R23 is tower crane repair and maintenance. R24 is tensile strength of tower body. R25 is the quality of other auxiliary parts.

For the environmental factors, the following specific five factors are given. R31 is climatic conditions on the day. R32 is material stacking at the construction site. R33 is lifting material quality. R34 is construction site environment (lighting conditions, etc.). R35 is humanities and social environment.

2.3. Tower crane construction safety evaluation index weight

Four scaling methods of the analytic hierarchy process are shown in Table 2. The product scaling method is a weight determination method, which can reflect the relative importance of each evaluation index. The idea of the product scaling method is that in the pairwise comparison of the importance of each evaluation index, it does not divide too many levels first, but only sets two levels. The importance of the evaluation index A and the evaluation index B is "same" or "Slightly larger", and then use this as a basis for progressive product analysis.

| Degree distinction | 1～9 Scaling method | 9/9～9/1 Scaling method | 10/10～18/2 Scaling method | Exponential scaling |
|--------------------|--------------------|------------------------|---------------------------|---------------------|
| the same            | 1                  | 9/9 (1.000)            | 10/10 (1.000)             | 9^0 (1.000)         |
The scale weights of the 7 indicators of human factors are:

\[ \omega_1 = (\omega_{11} : \omega_{12} : \omega_{13} : \omega_{14} : \omega_{15} : \omega_{16} : \omega_{17}) = (0.155, 0.155, 0.085, 0.210, 0.155, 0.155, 0.085) \]  

(6)

The scale weights of the five indicators of mechanical equipment are:

\[ \omega_2 = (\omega_{21} : \omega_{22} : \omega_{23} : \omega_{24} : \omega_{25}) = (0.223, 0.223, 0.223, 0.165, 0.165) \]  

(7)

The scale weights of the five indicators of environmental factors are:

\[ \omega_3 = (\omega_{31} : \omega_{32} : \omega_{33} : \omega_{34} : \omega_{35}) = (0.280, 0.207, 0.153, 0.207, 0.153) \]  

(8)

The range of 90-100 is excellent, and the range of 80 is excellent. -89 is good, interval 70-79 is fair, and interval 70 is bad. The index score of each factor is multiplied by its respective weight, which is the weighted calculation to obtain the score of each factor. This score is the input parameter calculated by the neural network, as shown in Table 3. The construction process of super high-rise buildings has greater risks, and after an accident occurs at the construction site, the casualties of personnel are generally regarded as a more intuitive judgment. Therefore, this case develops the output index score standard and the value standard combined with the sample project, as shown in Table 4.

Table 3 Input value of indices (the number of columns increases with the number of samples)

| Index                  | Project | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | … |
|------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---|
| Human factor R1        |         | 81.8    | 83.8    | 87.1    | 76.7    | 83.8    | 81.7    | 77.8    | 95      | … |
| Mechanical equipment R2|         | 77.9    | 73.7    | 65.1    | 68.3    | 73.3    | 79.4    | 61.4    | 91      | … |
| Environmental factor R3|         | 70.9    | 83.5    | 81.3    | 81.4    | 83.5    | 78.6    | 82.6    | 93      | … |

Table 4 Standard of output values of indices

| Points | Standard                        |
|--------|---------------------------------|
| 90~100 | No injuries                     |
| 80~89  | Only minor injuries             |
| 70~79  | 1 person died, or 5 persons or less were seriously injured |
| 60~69  | 2 people died, or more than 5 people and less than 10 people were seriously injured |
| Under 60 | 3 or more people died, or more than 10 people were seriously injured |
3. Training and application of BP neural network model

3.1. BP neural network structure determination

After analysing each sample data in the data set, R1, R2, R3 are linearly related to the output index score Y, so multiple linear regression is used to fit the data. That is to satisfy the formula: \( aR_1 + \beta R_2 + \gamma R_3 = Y \).

A three-layer BP neural network structure of input layer-hidden layer-output layer is used. The input layer has 3 nodes, and the output layer has 1 node. In Eq. (5), \( a \) is a constant, usually a value of 2–6, and \( a=2 \) is in this case. The values of \( n, m \) and \( x \) are 3, 1 and 4, respectively.

3.2. Data set and evaluation indicators

After sorting and screening the existing collection of 90 tower crane safety accident project databases, according to the evaluation index system constructed, after scoring real projects, 90 data in the format such as \([R1, R2, R3, Y]\) are formed. The following is a display of real data: \([65.8, 64.9, 63.9, 53]\). Since the dimensions in the real data are not uniform, this paper uses z-score and min-max methods to normalize the data to reduce the error.

The mean square error (MSE) between the model output and the Y value is selected as the loss function, and the optimal solution of \( \alpha, \beta, \text{ and } \gamma \) is found by minimizing the mean square error.

\[
MSE(\theta) = \frac{1}{2m} \sum_{i=1}^{m} (\hat{y}^{(i)} - y^{(i)})^2
\]

3.3. Predictive simulation analysis based on neural network

30, 60, and 90 data set were randomly selected from the min-max normalized data set to conduct three sets of controlled experiments. In the three experiments, 80\% of the data was used as the training set, 10\% as the validation set, and 10\% as a test set. 30,000 iterations of training are performed, and the MSE change of the model is shown in Figure 2(a). When using 30 data for training, the model converged and terminated early after about 8000 iterations. However, due to the sparse data, the MSE at convergence was significantly higher than the other two experiments. When using 60 data for training, the model converges significantly faster, and terminates early after 13,000 iterations. The MSE during convergence is significantly lower than the first set of experiments. When using 90 data of the entire data set for training, the convergence speed is faster and the effect is better. This also proves that as the amount of data increases, the ability of neural network data fitting is qualitatively improved and the effect is very ideal.

In order to prove the effectiveness of the linear regression neural network model, a set of control experiments were carried out to remove the hidden layer of the network model. The same 30, 60, and 90 data were used for training, 80\% of the data was used as the training set, and 10\% was used as the training set. In the verification set, 10\% is used as the test set, and the model MSE changes are shown in Figure 2(b). When using 30 data for training, the model still does not converge after 20,000 iterations. When using 60 and 90 data for training, the model convergence speed is also much slower than the model with hidden layers.
The linear regression neural network model trained is used to predict the test data. The deviation between the predicted data and the real data is shown in Figure 3. The deviation value predicted by the model is low and fluctuates between [-15, 15], indicating the neural network model has certain reliability and can play a guiding role in the actual high-rise building tower crane construction safety evaluation.

![Figure 3 Prediction of Linear Regression Neural Network](image)

4. Conclusion
In the prediction and simulation of tower crane safety risks, the neural network model can achieve better prediction results, and the prediction deviation is within 15%. At present, with the application and promotion of high-tech methods such as smart construction sites in construction, construction engineering data will inevitably show an exponential growth, and neural network prediction models will have greater advantages in big data collection.

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