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A DATA-DRIVEN INTELLIGENT EARLY WARNING METHOD FOR TRANSMISSION TOWER TILT

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Abstract

Aiming at the problem of transmission tower tilt caused by unstable geological structure, this paper proposes a data-driven intelligent early warning technology for transmission tower tilt. First, by introducing the static finite element theory of the transmission tower structure, the finite element model of the transmission tower structure is constructed. Then, the load loading method and calculation process in the transmission tower structure model are described in detail. Second, we analyse the deployment of the tower structure monitoring system and the execution process of the finite element program and introduce the monitoring and early warning workflow, and finally give a judgement and early warning strategy for the deflection and tilt of the tower structure. The proposed early warning technology can use various monitoring data to perform real-time calculation of finite element program, and realise real-time early warning evaluation according to deflection and tilt thresholds. The experimental results show that the error between the actual measured value and the predicted value of the Tensile steel pipe rod tower by the early warning system is only 0.2%, which exceeds 125.25% of the threshold value, and it successfully predicts that its state is in a dangerous state.

Key Words

Data-driven, transmission tower, inclination, warning, finite element

1. Introduction

With the completion of many ultra-high voltage (UHV) transmission lines in my country, the requirements for safe operation of transmission lines are becoming increasingly strict. Transmission towers are an important part of transmission lines and play a pivotal role. The working environment of transmission towers is mostly exposed and complex outdoor environment, which will be affected by various natural factors, such as wind, rain, and snow. The transmission pole tower line system is a large-span and high-flexible structure, and the wind load acts frequently, which will lead to more disasters caused by the wind [1], [2]. More serious damage may lead to the destruction or collapse of transmission towers, especially in areas with loose geology. These situations will cause large-scale power outages and inevitable economic losses [3], [4]. Therefore, it is very meaningful to carry out data-driven intelligent early warning technology of transmission tower tilt. It is of great practical significance to study the real-time damage detection, identification, and evaluation of structural safety of transmission towers under the action of wind loads [5].

In the past research, some progress has also been made in the wind resistance research and wind resistance monitoring design of transmission towers. According to the basic theory of random vibration, Zhang *et al.* [6] established a multi-degree-of-freedom system calculation method for the analysis of coupled vibration dynamic characteristics of large-span transmission tower-line systems. Wang *et al.* [7] obtained the influencing factors, such as the distribution of transmission poles and towers according to the characteristics of the structure and the power spectrum characteristics of the pulsating wind field. At the same time, the literature [8] established a numerical simulation method of fluctuating wind speed time history. Li *et al.* [9] studied the correlation between high-voltage transmission tower body-cable and wind excitation and provided a new early warning and forecast service method for power meteorology. Yang *et al.* [8] and Zhao *et al.* [10], [11] carried out a one-dimensional multivariable pulsating wind field simulation for a transmission tower, and then proposed a more effective simulation method. Liu *et al.* [12] constructed a spatial–temporal vulnerability model of transmission corridor in the framework of grid resilience assessment under extreme weather, which provided a basis for the planning and design of wind resilience in the later period. Zhou *et al.* [13] proposed the method of extracting the side edges of iron towers through RANSAC fitting and established a common tower head model library, which can match and identify different types of iron towers according to feature points.

Although the above literature have done a lot of research on the tilt of transmission towers, there are few researches on the data-driven intelligent early warning

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technology of transmission tower tilt. Based on multi-source monitoring data, this paper analyses the structural damage of transmission towers that may be caused by wind loads. The specific innovations are as follows:

1. The static finite element theory of the transmission tower structure is introduced, and the finite element model of the transmission tower structure is constructed.
2. The load loading method and calculation process in the transmission tower structure model are proposed.
3. The deployment of the tower structure monitoring system and the execution process of the finite element program are analysed.
4. The monitoring and early warning workflow is introduced, and the judgement and early warning strategy for the deflection and inclination of the tower structure is given.

2. Theory and Method

2.1 Analysis Theory of Tower Structure

The randomness of environmental loads will lead to real-time changes in the operation state of transmission lines, which in turn affects the reliability and safety of the operation of transmission towers. The state analysis of the transmission tower structure is based on the simulation of the load effect of the tower structure under the action of environmental loads (such as wind load, unbalanced force of conductors, etc.). The structural state is analysed through the calculation results. In the simulation modelling, it is necessary to accurately simulate the structural characteristics of the tower steel structural members and the accurate loading method of external loads. According to the modeling requirements of finite element mechanical analysis, it is necessary to select the correct tower element and set the material properties close to the actual. By establishing a fine simulation model of the tower structure, the force of the tower is analysed according to the mechanical finite element calculation. Therefore, it is necessary to first understand and analyse the mechanical properties of the steel materials used to construct the tower steel structure. The second step is to correctly select the finite element model element, and carry out the tower structure modelling and finite element analysis and calculation. The above is the basis for the analysis and evaluation of the mechanical properties of the tower under the action of environmental loads. According to the general mechanical properties of materials, we establish a finite element model of the tower structure and describe the load loading method and calculation process in the model.

The beam element of the tower steel member is simulated based on the Euler–Bernoulli beam theory, which can realise the cross-section simulation by defining the cross-section and the definition point of the cross-section direction. Its function can well simulate the cross-section of a variety of materials and is suitable for analysing beam structures ranging from slender to medium stubby. In the research on reliability and safety of transmission lines in natural disaster environments, beam elements can be used to simulate towers. The nodal displacement of Euler–Bernoulli beam element in three-dimensional form has a total of 12 degrees-of-freedom, namely:

$$\mathbf{q} = \left[u_i \; v_i \; w_i \; \theta_{\mathrm{xi}} \; \theta_{\mathrm{yi}} \; \theta_{\mathrm{zi}} \;\; u_j \; v_j \; w_j \; \theta_{\mathrm{xj}} \; \theta_{\mathrm{yj}} \; \theta_{\mathrm{zj}} \right]^T \tag{1}$$

The corresponding cell shape function form (natural coordinates) is in equation to, shown at the bottom of page.

The strain matrix (natural coordinates) of the beam element is in equation to, shown at the bottom of page.

According to the principle of virtual displacement, the internal force work is equal to the sum of the external force work. According to this principle, the corresponding beam element stiffness matrix can be obtained. Using the 3D beam element model, the stiffness matrix of the elastic beam element with standard constant cross-section is obtained as shown below (Equation 4), shown at the bottom of next page.

The beam element coordinate axes in 3D space are shown in Fig. 1. The $X–Y–Z$ three-axis direction conforms to the right-hand rule.

When analysing the space system problem, it is necessary to transform the element characteristic matrix in the element coordinate system, and its coordinate transformation matrix can be expressed as (5):

$$\lambda_0 = \begin{bmatrix} \lambda_{01} & 0 \\ 0 & \lambda_{01} \end{bmatrix} \tag{5}$$

$$\mathbf{N} = \begin{bmatrix} 1-\xi & & & & & & \xi & & & & & \\ & 1-3\xi^2+2\xi^3 & & & & \left(\xi-2\xi^2+\xi^3\right)l & & 3\xi^2-2\xi^3 & & & & \left(-\xi^2+\xi^3\right)l \\ & & 1-3\xi^2+2\xi^3 & & -\left(\xi-2\xi^2+\xi^3\right)l & & & & 3\xi^2-2\xi^3 & & \left(\xi^2-\xi^3\right)l & \\ & & & 1-\xi & & & & & & \xi & & \end{bmatrix} \tag{2}$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{B}_a & 0 \\ 0 & \mathbf{B}_b \end{bmatrix} = \begin{bmatrix} \frac{\partial \mathbf{N}_a}{\partial x} & 0 \\ 0 & \frac{\partial^2 \mathbf{N}_b}{\partial x^2} \end{bmatrix} = \begin{bmatrix} -\frac{1}{l} & & & & & & \frac{1}{l} & & & & & \\ & -\frac{6}{l^2}+\frac{12\xi}{l^2} & & & & -\frac{4}{l}+\frac{6\xi}{l} & & \frac{6}{l^2}-\frac{12\xi}{l^2} & & & & -\frac{2}{l}+\frac{6\xi}{l} \\ & & -\frac{6}{l^2}+\frac{12\xi}{l^2} & & \frac{4}{l}-\frac{6\xi}{l} & & & & \frac{6}{l^2}-\frac{12\xi}{l^2} & & \frac{2}{l}-\frac{6\xi}{l} & \\ & & & -\frac{1}{l} & & & & & & \frac{1}{l} & & \end{bmatrix} \tag{3}$$

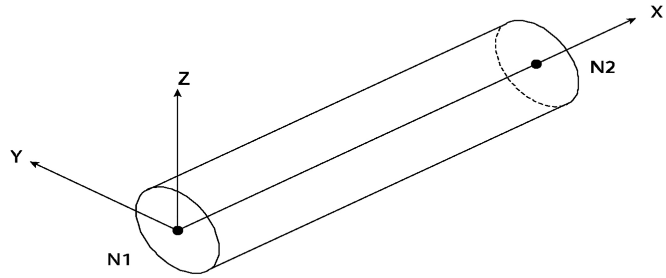

Figure 1. Schematic diagram of three-dimensional spatial coordinate system of the beam element.

In the formula, λ_{01} is represented as (6):

$$\lambda_{01} = \begin{bmatrix} l_{x\overline{x}} & l_{x\overline{y}} & l_{x\overline{z}} \\ l_{y\overline{x}} & l_{y\overline{y}} & l_{y\overline{z}} \\ l_{z\overline{x}} & l_{z\overline{y}} & l_{z\overline{z}} \end{bmatrix} \tag{6}$$

2.2 Wind Load of Tower Structure

Wind load is the main load in the structural design of the transmission pole and tower line system, and it controls the structural design. Wind load is usually divided into two parts: average wind load and fluctuating wind load. The average wind load refers to: the wind speed with a long propagation period (generally more than 10 min) in the atmospheric turbulence in the atmospheric boundary layer, and the wind pressure formed on the surface of the structure. Since the transmission period of wind speed is much larger than the natural vibration period of the transmission tower, the effect on the structure can be regarded as a static load [10], [11]. According to the building structure load specification [14], [15], the standard value of the wind load when the tower itself (tower body, cross arm, and support) is covered with ice can be calculated by (7)–(9):

$$W_s = W_0 \mu_z \mu_s \beta_z A_s \tag{7}$$

where W_s is the standard value of the wind load of the tower, and the unit is kN; W_o is the basic wind pressure; β_z is the adjustment coefficient of the wind load of the tower; μ_s is the shape coefficient of the component; μ_z is the wind pressure height variation coefficient; A_s is the projected area of the component subjected to wind pressure.

For the construction of buildings in areas where basic wind pressure is not given, basic wind speed should be calculated according to the local wind speed data, and then converted to basic wind pressure by the following formula:

$$W_0 = \frac{1}{2}\rho\nu^2 = \frac{1}{2}\frac{\gamma}{g}\nu^2 \tag{8}$$

At standard atmospheric pressure, suppose the air capacity γ is 0.012018 kN/m^3, gravitational acceleration g is 9.81 m/s^2. In general:

$$W_0 = v^2/1600 \tag{9}$$

2.3 Local Implementation of Finite Element Calculations

The finite element method is an important component in the field of numerical calculation and is a powerful tool for structural analysis. However, after analysis and calculation, people are faced with a large number of discretised calculation results. Therefore, it is very necessary to use the finite element method to selectively extract the results. The post-processing system of the finite element is to perform model analysis and result calculation on the finite element with graphics. In this way, the tower data can be checked and understood intuitively, comprehensively, and quickly. Object-oriented design is a concrete realisation for the system, which includes two aspects of work. The first is to move the model of object-oriented analysis directly into object-oriented design. The second is to

$$K^e = \int_0^1 B^T \mathrm{HB} \bullet \iota \lceil \varepsilon = \begin{bmatrix}
\frac{\mathrm{EA}}{\iota} \\
0 & \frac{12EI_{\ddagger}}{\iota^3} \\
0 & 0 & \frac{12EI_y}{\iota^3} \\
0 & 0 & 0 & \frac{\mathrm{GJ}}{\iota} \\
0 & 0 & \frac{6EI_y}{\iota^2} & 0 & \frac{4EI_y}{\iota} \\
0 & \frac{6EI_{\ddagger}}{\iota^2} & 0 & 0 & 0 & \frac{4EI_z}{\iota} \\
-\frac{\mathrm{EA}}{\iota} & 0 & 0 & 0 & 0 & 0 & \frac{\mathrm{EA}}{\iota} \\
0 & -\frac{12EI_{\ddagger}}{\iota^3} & 0 & 0 & 0 & -\frac{6EI_z}{\iota^2} & 0 & \frac{12EI_{\ddagger}}{\iota^3} \\
0 & 0 & -\frac{12EI_y}{\iota^3} & 0 & -\frac{6EI_y}{\iota^2} & 0 & 0 & 0 & \frac{12EI_y}{\iota^3} \\
0 & 0 & 0 & -\frac{\mathrm{GJ}}{\iota} & 0 & 0 & 0 & 0 & 0 & \frac{\mathrm{GJ}}{\iota} \\
0 & 0 & \frac{6EI_y}{\iota^2} & 0 & \frac{2EI_y}{\iota} & 0 & 0 & 0 & \frac{6EI_y}{\iota^2} & 0 & \frac{4EI_{\ddagger}}{\iota} \\
0 & \frac{6EI_{\ddagger}}{\iota^2} & 0 & 0 & 0 & \frac{2EI_z}{\iota} & 0 & -\frac{6EI_{\ddagger}}{\iota^2} & 0 & 0 & 0 & \frac{4EI_y}{\iota}
\end{bmatrix} \tag{4}$$

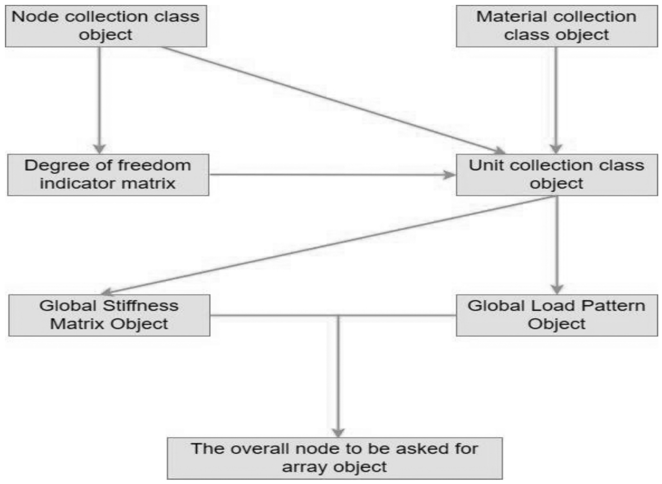

Figure 2. Object-oriented design process for JAVA finite element analysis.

supplement some specific implementation parts for human–machine interface, data storage, task management, and other factors. Most of the computational work in this abstract architecture alternates between entity classes and unit classes, the whole process is as follows:

Step 1: We first read data from a data file, and then use these data to generate entities. At this time, entity classes are all adding nodes and units to operations.

Step 2: Elements and nodes are managed during the experiment, and boundary conditions, such as loads and displacements, are stored in the nodes.

It is worth noting that once the entire solid is generated, the solid class calculates the element stiffness matrix for each element.

Step 3: After each element class calculates the stiffness matrix, until the overall stiffness matrix is assembled, all the solution work at this time is undertaken by the entity class.

Step 4: After the displacement of the node is obtained, the stress and strain of each element are solved between the element class and the node class. Object-oriented design is actually to formulate the above tasks to complete the transfer and delegation of information and data between classes, so that the overall program can be executed correctly and clearly. The specific process is shown in Fig. 2.

3. Experiment

3.1 Deployment Principle of Transmission Tower Structure Monitoring System

The transmission tower online monitoring system mainly monitors the towers on the transmission line. In order to be widely applicable to various power transmission and transformation projects, the following principles must be realised:

1. *Real-time:* The transmission tower online monitoring system is supported by the underlying hardware of the Internet of Things to monitor the main data of the tower. It is necessary to realise real-time acquisition of various values, such as tension, inclination, inclination acceleration, foundation displacement, and micro-meteorology of the tower.
2. *Innovation*: It provides scalable detection algorithms for the online monitoring system of transmission towers. The algorithm installed should be able to alarm and process abnormal data to avoid major power transmission accidents and ensure the safety of power transmission.
3. *Effectiveness:* It is required that the data sources of the online monitoring system for transmission towers and distribution civil construction facilities be authentic and reliable. At the same time, it is necessary to carry communication modules, battery packs, and photovoltaic panels to ensure that data transmission remains unaffected even in harsh environments such as rainy days.

3.2 Implementation of the Finite Element Program for Early Warning of Transmission Towers

Finite element program execution is divided into three steps:

3.2.1 Pretreatment

This process is the beginning of the early warning finite element program analysis process, and its purpose is to establish a structural finite element analysis model that conforms to the actual situation. The judgement is made by introducing the boundary conditions of the actual structure and the coupling relationship between the degrees of freedom.

3.2.2 Calculation Settings and Solutions

This process is mainly to define the element type and its related parameters that need to be used in the analysis process. The point is to specify the material model used in the analysis and the corresponding material parameters (such as elastic modulus, Poisson's ratio, density, etc., for linear elastic materials).

3.2.3 Post-processing

This process is mainly to analyse and evaluate the obtained solution according to the relevant criteria. Post-processing can make it easier for users to extract information and understand the calculation results. The specific execution steps are shown in Fig. 3.

3.3 Judgement Basis of Early Warning System

According to the actual situation of the transmission tower and the existing technical means and specifications, the health technical index system is proposed in a targeted manner. Then, the test results and the index system are analysed and evaluated by means of structural analysis,

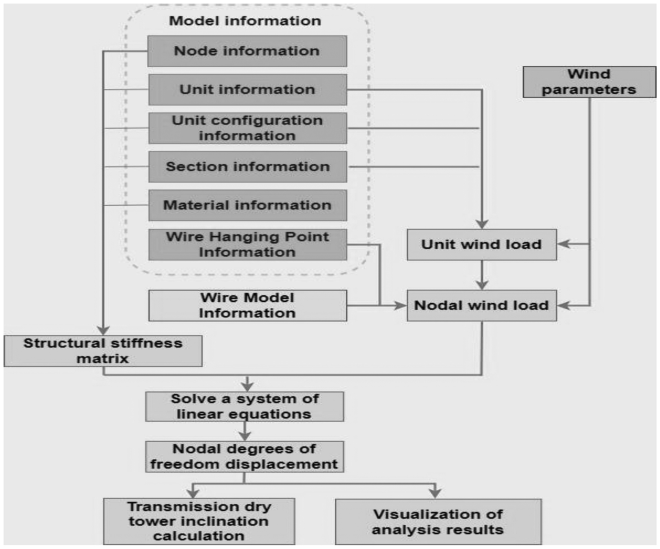

Figure 3. Process of finite element analysis for transmission tower.

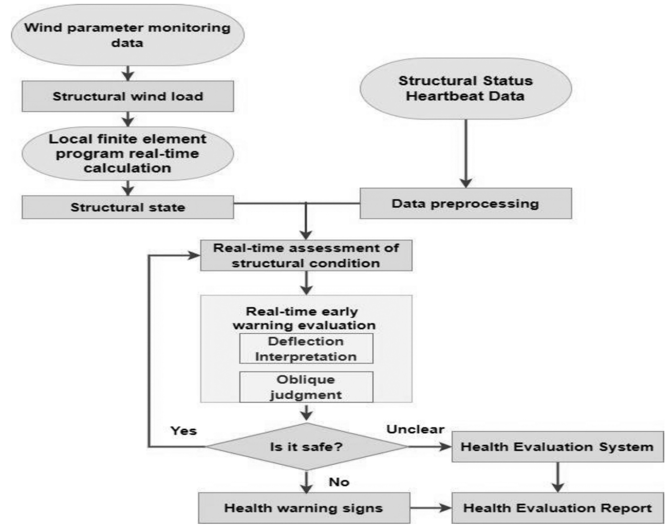

Figure 4. Process of monitoring and evaluation system for transmission tower.

so as to realise the evaluation and early warning of the health status of the structure. The early warning system can be divided into three functional modules: structural health assessment, structural early warning, and assessment report. The overall process is shown in Fig. 4.

The first evaluation indicator is the structural health evaluation. According to all the monitoring information, the structural state is evaluated through the localised structural analysis program, and the safety state of the structure is obtained comprehensively. The second evaluation indicator is structural early warning. When the test data exceeds the threshold of health technical indicators, the early warning system will issue different health early warning signals in time. In addition, the early warning system will also provide managers with corresponding disposal suggestions. Finally, the early warning system will generate a health assessment report, which aims to visualise and data output the structural evaluation and early warning results.

3.4 Early Warning Judgement and Result Output

The deflection of the tower refers to the horizontal distance that the tower structure deviates from the centre line due to the load. The calculated deflection of the tower shall comply with the specified limits in Table 1.

This calculated deflection does not include foundation tilt and stay point displacement. In this paper, $3h/1000$ is selected for the straight tower, $5h/1000$ for the corner tower, and $7h/1000$ for the tensile tower. It can be seen from the laboratory results that the deflection limit of the tensile steel pipe rod has reached $25h/1000$, which obviously exceeds the specified threshold of $20h/1000$. The judgement result of the early warning system is consistent with the actual situation. In addition, the deflection limit of the pendant corner steel pole and the self-supporting tension tower has reached $7h/1000$, ranking second in all these indicators. But it did not exceed the specified threshold of $20h/1000$. The judgement result of the early warning system is also consistent with the actual situation.

In the next experiment, two types of towers h and h_1 were analysed. For the tower of type h, the results calculated by the early warning system, the real results, and the standard reference results are shown in Table 2. It can be concluded from Table 2 that the predicted value of the Tensile steel pipe rod is $25h/1000$, the threshold is $20h/1000$, and the predicted value exceeds 125% of the threshold. According to the results of the early warning system, such towers have been seriously tilted and need to be repaired immediately. In order to determine whether the results from the early warning system are correct, it is also necessary to compare them with the actual measured values in the field. The actual measured value of the Tensile steel pipe rod is $25.05h/1000$, and the error with the predicted value is 0.2%. The actual measurement result is compared with the threshold, and it exceeds 125.25% of the threshold. Therefore, the predicted value for the Tensile steel pipe rod is quite accurate. In this experiment, a total of six groups were tested for the h-type towers, of which only one group exceeded the threshold. The prediction results of the early warning system are consistent with the actual results. The other five sets of experiments in this experiment all showed that the predicted results did not exceed the threshold. The predicted results of the Suspended corner steel pole are the closest to the real results. The two are $7h/1000$ and $7.03h/1000$, respectively, with an error range of 0.42%. At the same time, both the predicted and real results of the Suspended corner steel pole show that the tower is in a safe range. It is worth noting that the predicted value of the Free-standing suspended vertical line tower is also very close to the real value, $3h/1000$ and $3.05h/1000$, respectively, with an error range of 1.6%. It can be seen from the above experiments that the accuracy of the early warning system is quite reliable.

For the tower of type h_1, from Table 3, it can be concluded that the predicted value of Suspended straight steel pipe rod is $5h1/100$, the threshold is $6h1/100$, and the

Table 1
Calculated Deflection Limits for Loaded Transmission Towers [16], [17]

Structure and Member Type	Calculation of Deflection Limits
Free-standing suspended vertical line tower	$3h/1000$
Free-standing hanging corner tower	$5h/1000$
Self-supporting tension tower	$7h/1000$
Suspended vertical line tower	$4h/1000$
Tower top	$2h_1/1000$
Suspended vertical line tower	$5h_1/100$
The tower body below the pull line point	$7h/1000$
Suspended straight steel pipe rod	$25h/1000$

*h is the height of the tower from the base of the tower to the top surface, and h_1 is the height of the tower cable point to the ground.

Table 2
Results for Towers of Type h

Serial Number	Tower Type	Predictive Value	Actual Value	Standard Value
1	Free-standing suspended vertical line tower	$3h/1000$	$3.05h/1000$	$4h/1000$
2	Free-standing hanging corner tower	$5h/1000$	$5.1h/1000$	$5h/1000$
3	self-supporting tension tower	$7h/1000$	$7.21h/1000$	$20h/1000$
4	Suspended vertical wire tower	$4h/1000$	$4.81h/1000$	$6h/1000$
5	Suspended corner steel pole	$7h/1000$	$7.03h/1000$	$20h/1000$
6	Tensile steel pipe rod	$25h/1000$	$25.05h/1000$	$20h/1000$

Table 3
Results for Towers of Type h_1

Serial Number	Tower Type	Predictive Value	Actual Value	Standard Value
1	Suspended vertical wire tower	$2h_1/1000$	$2.01h_1/1000$	$6h_1/1000$
2	Suspended straight steel pipe rod	$5h_1/100$	$5.21h_1/100$	$6h_1/100$

predicted value exceeds the threshold by -16.7%. According to the results of the early warning system, such towers are in a safe state. In order to determine whether the result obtained by the early warning system is correct, it is also necessary to compare it with the actual measured value on site. The actual measured value of the Suspended straight steel pipe rod is $5.21h_1/100$, and the error with the predicted value is 4.03%. The actual measurements of the Suspended straight steel pipe rod are compared to the threshold and exceed the threshold by -13.2%. This shows that the predicted value for the Suspended straight steel pipe rod is suitable. In another set of experiments, the predicted value of the Suspended vertical wire tower was $2h_1/1000$, the threshold was $6h_1/1000$, and the predicted value exceeded the threshold by -66.7%. According to the results of the early warning system, such towers are also in a safe state. In order to determine whether the result obtained by the early warning system is correct, it is also necessary to compare it with the actual measured value on site. The actual measured value of the suspended vertical wire tower is $2.01h_1/1000$, and the error with the predicted value is 0.5%. The actual measurements of the suspended vertical wire tower were compared to the threshold and exceeded -66.5% of the threshold. This shows that the predicted value for the suspended vertical wire tower is also suitable.

4. Conclusion

The intelligent early warning technology of transmission tower tilt successfully predicts the problem of transmission tower tilt under dangerous conditions through data driven and draws the following conclusions:

1. For the early warning technology proposed in this paper, the error between the actual measured value and the predicted value of the tensile steel pipe rod tower is only 0.2%, which exceeds 125.25% of the threshold value, and it successfully predicts that its state is in a dangerous state.
2. The early warning system can use various monitoring data to perform real-time calculation of finite element programs and realise real-time early warning evaluation according to deflection and tilt thresholds.
3. In the future, the early warning technology proposed in this paper can be applied to the structural tilt program warning of the equipment support frame and incoming and outgoing line casing in substations and can also be applied to the early warning evaluation of the tilt degree of other towering objects, so as to avoid unnecessary dangerous accidents.

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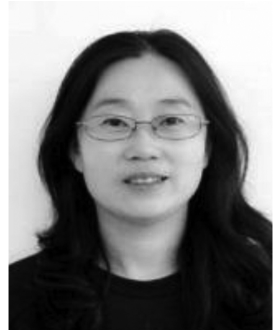

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