IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 28, 2021, accepted January 21, 2022, date of publication February 23, 2022, date of current version March 1, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3153344

The Effect of Soil-Structure Interaction on Vibration Reliability of Transmission Line

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This work was supported in part by the China Southern Power Grid Corporation Science and Technology Project under Grant GDKJXM20200710.

ABSTRACT Since the main material of the plug-in foundation transmission tower legs is directly connected to the foundation, the traditional reliability calculation method is no longer accurate. For this reason, this paper considers the soil-structure interaction between the foundation soil and the tower legs, replaces the upper limit of the natural circular frequency and frequency ratio of the original iron tower with the corresponding value after considering the SSI (Soil-Structure Interaction), and proposes a SSI-based insertion Analysis method of vibration reliability of type foundation iron tower. First, perform modal analysis to obtain the natural circular frequency of the tower considering SSI; then, according to the external load of the tower under the icing of the wire and the vibration displacement equation of the tower considering SSI, the expression of the comprehensive amplitude amplification factor of the tower is derived, and then the consideration is obtained. The upper limit value of the frequency ratio of SSI and the functional function; finally combined with the normal distribution to solve the problem, the vibration reliability of the plug-in foundation tower considering SSI is obtained. The proposed method has been applied in the analysis of a galloping accident on a line in Guangdong Province. The maximum reliability of the damaged 6-base plug-in foundation tower obtained by this method is 0.9713, which is less than the target reliability of 0.9993.

INDEX TERMS Ice-coated dancing, SSI effect, vibration reliability, natural circular frequency.

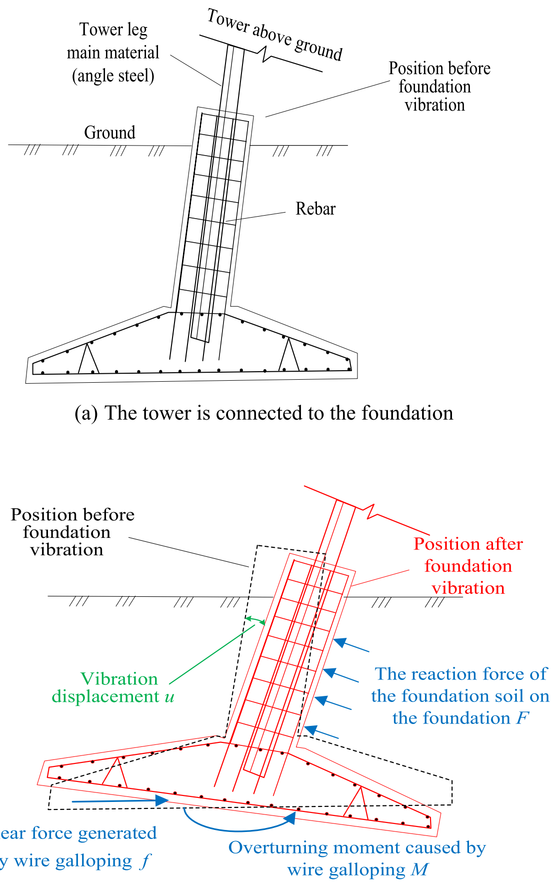
I. INTRODUCTION

The plug-in basic transmission tower has the advantages of wide applicable geological conditions, saving steel, and good economy [1]. However, due to the direct insertion of the main material into the foundation of this kind of iron tower, the iron tower and the foundation form a unified whole, which makes it easier to produce collapsed tower accidents than other iron towers under ice-coated galloping conditions [2]. Therefore, it is of great significance to clarify the vibration mechanism of the plug-in foundation iron tower under the ice-coated galloping condition and accurately evaluate its vibration reliability performance, which is of great significance to ensure the operation safety of the plug-in foundation iron tower transmission line.

Considering that the existing statics and dynamics methods are difficult to solve the problem of transmission line tower damage under ice galloping, reference [3] was the first to introduce reliability theory into the safety assessment of transmission towers to study the failure probability of towers under different ice thicknesses. However, the icing galloping of transmission lines is not only affected by the icing load, but also other influencing factors such as wind [4], tower-line system [5], and so on. Therefore, in the subsequent safety research on the reliability of transmission towers, wind load [6] and vibration effects [7] are successively introduced, and finally a reliability evaluation method for conventional towers under icing galloping has been formed [8]. However, these studies are limited to conventional anchor bolt foundation transmission towers, and only the load above the ground is considered in the reliability calculation, and the force of the foundation soil on the tower is ignored. Indeed, for the plug-in foundation iron tower, due to its unique structural characteristics of the connection between the main material of the iron tower and the soil, it is necessary to explore the force of the foundation soil on the iron tower in the reliability calculation.

Reference [9] considered the dynamic effect of the foundation soil on the tower during the icing of the transmission tower when calculating the wind-induced vibration response

The associate editor coordinating the review of this manuscript and approving it for publication was Luca Cassano.



(a) The tower is connected to the foundation

(b) Interaction between foundation and foundation soil

FIGURE 1. Schematic diagram of plug-in foundation connection and interaction between foundation and foundation soil.

of the transmission tower. The study found that considering soil-structure dynamic interaction, that is, considering the SSI (Soil-Structure Interaction). The wind-induced vibration response after solving is more accurate. Reference [10] also found that after considering SSI, the error between the calculated and measured results of the natural frequency response of the transmission tower under icing galloping conditions does not exceed 6%. Therefore, the above research provides a reference for the introduction of SSI in the reliability calculation of the plug-in basic transmission tower, and it can be considered that the reliability solution result after considering the SSI is more accurate.

For this reason, based on the traditional reliability analysis method of transmission towers, this paper considers the influence of SSI and proposes a SSI-based vibration reliability analysis method of plug-in foundation transmission towers under icing galloping. The research results have been applied in the analysis of a galloping accident on a certain line in Guangdong Province. This provides better technical guidance for solving the problem of vibration damage to the plug-in foundation transmission tower under ice galloping.

II. VIBRATION DAMAGE AND RELIABILITY OF THE PLUG-IN FOUNDATION IRON TOWER

A. THE CHARACTERISTICS OF THE PLUG-IN BASE IRON TOWER

The plug-in foundation iron tower is a type of iron tower commonly used in power transmission projects [2]; it means that when the foundation is poured, the main material of the tower leg is directly inserted into the foundation, and the foundation is poured into one body, and then the diagonal material of the tower leg is connected with the main material of the tower leg through bolts and bolt plates, and the connection between the plug-in foundation iron tower and the foundation is finally completed. The connection between the plug-in foundation and the transmission tower is shown in Figure 1(a).

Compared with other basic types of transmission towers, the plug-in type foundation tower has the advantages of eliminating the need for anchor bolts and the connection structure between the tower legs during construction, and saving steel; and because the main material of the tower legs is directly poured into the foundation as a whole, the tower will not fall due to the loosening of the anchor bolts, and the mechanical performance under the action of static force is better. However, its disadvantages are: the main material of the tower legs and the foundation are poured together, which requires higher construction accuracy; when subjected to external loads, the foundation receives greater force, which causes the foundation to overturn or slip, resulting in changes in the force of the tower, eventually leading to tower collapse accident under uneven force.

B. VIBRATION FAILURE MECHANISM OF PLUG-IN FOUNDATION IRON TOWER UNDER ICING AND GALLOPING

Under certain meteorological conditions, the surface of the transmission line conductors will form an uneven ice coating. At this time, under certain wind excitation, the unevenly iced conductors will vibrate greatly. This phenomenon is the conductor ice galloping [11]. The periodic force of the wire due to the icing galloping is transmitted to the tower through the line fittings [12]. When the frequency of the periodic force is close to the natural frequency of the plug-in foundation iron tower, the system composed of the wire and the plug-in foundation iron tower resonates. At this time, the frequency of the system vibration is called the resonance frequency. At the resonance frequency, the vibration amplitude of the entire system will reach the maximum. At this time, the plug-in foundation iron tower is most vulnerable to damage [13], and even a tower downfall may be caused by a power outage in severe cases.

When the system resonates, the overturning moment and horizontal shear force generated by the wire galloping on the foundation will cause the foundation to vibrate, and the foundation vibration will drive the soil around the foundation to vibrate; the soil vibration around the foundation will further consolidate the tower legs and the foundation into a unified whole reaction force (which is soil-structure dynamic interaction) is generated. In this process, the reaction force of the foundation soil on the tower legs and the foundation as a whole is shown in Figure 1(b). Finally, this reaction force will cause the transmission tower to produce secondary vibrations and damage the transmission tower again, thereby further increasing the risk of tower collapse.

C. VIBRATION FAILURE MECHANISM OF PLUG-IN FOUNDATION IRON TOWER UNDER ICING AND GALLOPING

When this method solves the reliability, it first needs to obtain the reliability functional function Z. To effectively assess whether the transmission tower is damaged under icing and galloping conditions [14], the existing engineering usually adopts the analysis method based on the reliability of the transmission tower [15]. When the method solves the reliability, firstly, the functional function Z of the reliability needs to be obtained. According to the reference [8], the functional function Z of the vibration reliability of the transmission tower is:

$$Z = \omega_n - \omega/\chi_M \tag{1}$$

In the equation: ω is the wire galloping circular frequency; ω_n is the natural circular frequency of the transmission tower; χ_M is the upper limit of the ratio of the wire galloping circular frequency ω to the natural circular frequency of the iron tower ω_n.

In equation (1), the functional function Z is related to ω_n, ω and χ_M. Traditional analysis methods based on the reliability of transmission towers believe that both ω_n and ω are random variables and obey normal distribution. The statistical parameters can be obtained from the statistical data of the line. To solve χ_M, more complicated calculations are required. First, it is necessary to substitute the periodic force generated by the wire galloping on the transmission tower into the vibration displacement equation of the tower to obtain the maximum vibration displacement response of the tower under the ice-coated galloping condition; then according to the design that the maximum vibration displacement response does not exceed the allowable value criterion [7] constructs an inequality to solve the value range of frequency ratio χ, and its upper limit is χ_M.

After obtaining the three parameters of ω_n, ω and χ_M, by calculating the probability of Z >0, the reliability R of the transmission tower can be obtained [7]:

$$R = P(Z > 0) = \Phi(\frac{\mu_Z}{\sigma_Z}) = \Phi\left(\frac{\mu_{\omega n} - \mu_\omega/\chi_M}{\sqrt{V_{\omega n}^2\mu_{\omega n}^2 + V_\omega^2\mu_\omega^2/\chi_M^2}}\right) \tag{2}$$

In the equation: $P(Z > 0)$ is the probability of $Z > 0$; $\Phi(\cdot)$ is the distribution function of the standard normal distribution; μ_Z and σ_Z are the mean and standard deviation of the functional function Z, respectively; $\mu_{\omega n}$ and $V_{\omega n}$ are random variables, respectively the mean and coefficient of variation of ω_n (the ratio of standard deviation to the mean); μ_ω and V_ω are the mean and coefficient of variation of random variables ω, respectively. The above parameters can be obtained from the statistical data of normal distribution.

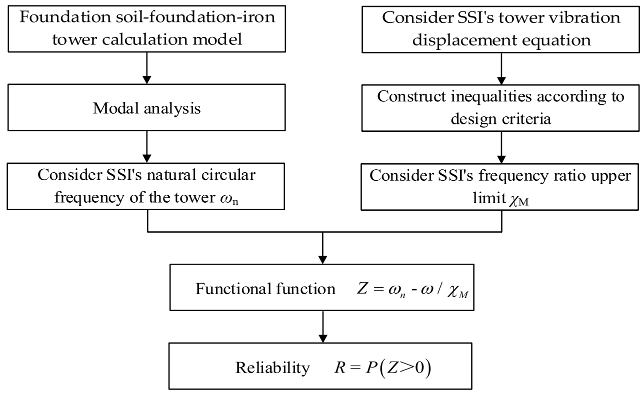


FIGURE 2. Flow chart for solving vibration reliability based on SSI.

From the above solution process, to accurately solve the reliability R, the values of the three parameters ω_n, ω and χ_M must be clarified. Among them, ω represents the frequency of the wire dancing under the action of the wind load, which is directly related to the wind element [16]. Considering that wind speed and wind direction are changing, parameters, ω can only be obtained through statistical methods. However, ω_n represents the natural circular frequency of the transmission tower and is determined by the characteristics of the tower itself. Therefore, ω_n is only related to the inherent characteristics of the tower's shape and material [17]. When the tower model is determined, ω_n is also a fixed value. If ω_n is regarded as a random variable, according to the traditional method, the number of random variables in the functional function Z will increase at this time, which will lead to changes in the values of μ_Z and σ_Z in equation (2) [18], which deviates from the given tower the accurate value of eventually causes the reliability R obtained by equation (2) to be inaccurate.

In addition, it can be seen from the solution process of equation (1) χ_M that when solving the maximum vibration displacement response of the iron tower, the traditional method only considers the periodic force generated by the wire galloping on the iron tower. However, it can be seen from the analysis in Section 2.2 that due to the unique characteristics of the basic structure of the plug-in basic transmission tower, the vibration excitation source of the tower under the icing galloping condition includes not only the system resonance caused by the periodic force of the wire galloping on the tower, but also the secondary vibration caused by the soil-structure dynamic interaction of the foundation soil, that is, the maximum vibration displacement response of the plug-in foundation transmission tower actually comes from the superposition of the effects of these two forces. Therefore, the traditional method ignores the soil-structure dynamic interaction, which causes the calculation error of χ_M, and finally leads to the inaccurate solution of the reliability R, which is not suitable for the reliability analysis of the plug-in foundation transmission tower.

For this reason, this article improves the traditional method. In the process of solving the reliability of the plug-in foundation transmission tower, ω_n is regarded as a fixed value, and when solving χ_M, the soil-structure dynamic interaction between the foundation soil and the transmission tower is also considered. Taking this into account, a SSI-based plug-in foundation transmission tower vibration reliability analysis method is proposed.

III. SOLVING THE VIBRATION RELIABILITY OF THE PLUG-IN FOUNDATION TOWER CONSIDERING SSI

A. OVERALL SOLUTION IDEAS

The key to solving the reliability of the plug-in foundation transmission tower considering SSI is to accurately calculate the two parameters ω_n and χ_M.

The natural circular frequency ω_n of the transmission tower is a function of the characteristics of the transmission tower itself, which can be obtained by the method of modal analysis. First, a finite element model of the plug-in foundation transmission tower needs to be established. Considering that the tower is affected by the dynamic interaction between the soil and the structure when it vibrates, in addition to establishing the conventional tower model, a calculation model for the dynamic interaction of the foundation soil-foundation-transmission tower directly connected to the main material of the tower leg must be established. Then modal analysis is performed on the model, and finally ω_n is obtained. Since the above solution process takes into account the influence of the SSI effect, the physical meaning of equation (1) ω_n is correspondingly changed to consider the natural circular frequency of the transmission tower in terms of SSI.

It can be seen from Section 2.3 that to accurately solve the upper limit χ_M of the frequency ratio of the plug-in foundation tower, it is necessary to consider the influence of the SSI effect when solving the maximum vibration displacement response of the tower. Therefore, it is necessary to improve the tower vibration displacement equation, replace the natural circular frequency of the transmission tower in the original equation with the natural circular frequency of the transmission tower considering SSI, and obtain a new vibration displacement equation of the tower considering SSI, to achieve an accurate solution of χ_M. At this time, the physical meaning of χ_M in equation (1) becomes the upper limit of the frequency ratio considering SSI accordingly.

Finally, the process of solving the vibration reliability of the plug-in foundation tower considering SSI under the icing galloping condition is shown in Figure 2.

B. THE NATURAL CIRCULAR FREQUENCY OF THE PLUG-IN FOUNDATION IRON TOWER

The calculation model of soil-foundation-iron tower dynamic interaction mainly includes three parts, namely, the soil-foundation interface model, the soil model of the calculation area, and the tower body model.

The commonly used modeling method of the soil-foundation interface model is to set a specific unit on the soil-foundation interface to simulate the slip and separation phenomenon of the soil-foundation interface. At present, Goodman unit is mostly used for simulation. The establishment of the soil model of the calculation area is divided into two steps. Firstly, a limited soil is intercepted with the semiinfinite earth medium as the calculation area; then a viscoelastic artificial boundary is set on the soil boundary to effectively simulate the continuous soil radiation damping. As for the tower body model, the key to its modeling lies in the effective treatment of the tower connection nodes and tower components, which should be treated as rigid nodes and beam elements, respectively.

After modeling, the model needs to be modal analysis to solve ω_n. The dynamic balance equation of the plug-in foundation iron tower during modal analysis is:

$$[\boldsymbol{M}]\{\ddot{\boldsymbol{u}}\} + [\boldsymbol{C}]\{\dot{\boldsymbol{u}}\} + [\boldsymbol{K}]\{\boldsymbol{u}\} = \boldsymbol{F}(t) \tag{3}$$

where: [M], [C], [K] are the system mass matrix, damping matrix and stiffness matrix respectively; $\{u\}$, $\{\dot{u}\}$, $\{\ddot{u}\}$ are the displacement, velocity and acceleration vectors of the transmission tower respectively; $F(t)$ is the load imposed on the system, t is the time.

Since the influence of damping on structural frequency can be ignored in engineering structures [19], the structural damping matrix in equation (3) can be ignored. Under the action of no external load, the dynamic equation of the free vibration of the plug-in foundation transmission tower is:

$$([\boldsymbol{K}] - [\boldsymbol{M}]\omega_n^2)\boldsymbol{X} = 0 \tag{4}$$

In the equation: X is the node amplitude matrix of the node displacement of the plug-in basic transmission tower.

Converting the matrix solution to the eigenvalue solution can be obtained:

$$\left|[\boldsymbol{K}] - [\boldsymbol{M}]\omega_n^2\right| = 0 \tag{5}$$

Finally, substituting the specific parameters of the plug-in basic transmission tower into equation (5), you can get its natural circular frequency ω_n.

C. RELIABILITY SOLUTION OF PLUG-IN FOUNDATION IRON TOWER

Reference [20], the tension change Δf of the conductor on one side of the plug-in foundation transmission tower at time t under ice galloping conditions is:

$$\Delta f = \begin{cases} \dfrac{n^2\pi^2 k_c a_0^2}{4l}\sin^2\omega t & (n \text{ is even}) \\ \dfrac{n^2\pi^2 k_c a_0^2}{4l}\sin^2\omega t \\ -\dfrac{2Wlk_c a_0}{n\pi T_0\cos\gamma}\sin\omega t & (n \text{ is odd}) \end{cases} \tag{6}$$

In the equation: n is the galloping half-wave number; k_c is the elastic coefficient of the wire; a_0 is the wire dancing amplitude; ω is the wire dancing circle frequency; l is the pitch; ω is the wire dancing circle frequency; W is the load per unit length of the ice-coated wire; T_0 is the wire Horizontal tension; γ is the height difference angle.

Therefore, the external load $f(t)$ on the plug-in foundation iron tower at time t is:

$$f(t) = \Delta f_1 - \Delta f_2 = \begin{cases} -\frac{C}{2}\cos(2\omega t) + \frac{C}{2} \ (n \text{ is even}) \\ -\frac{C}{2}\cos(2\omega t) - D\sin\omega t + \frac{C}{2} \ (n \text{ is odd}) \end{cases} \tag{7}$$

In the equation: C is the difference in the tension amplitude of the dancing wires on both sides, N; D is the difference in the tension amplitude between the dancing wires on both sides and the odd half-wave number, N.

After that, substituting the ω_n obtained from equation (7) and Section 3.2 into the vibration displacement equation of the original iron tower, the vibration displacement equation of the transmission tower considering SSI can be obtained as:

$$m\frac{d^2u}{dt} + 2m\xi\omega_n\frac{du}{dt} + m\omega_n^2 u = f(t) \tag{8}$$

where: m is the equivalent mass of the iron tower, kg; u is the vibration displacement of the iron tower, m; ξ is the damping ratio of the transmission tower considering SSI; ω_n is the natural circular frequency of the transmission tower considering SSI, rad/s.

It can be known from vibration mechanics that when f(t) is the superposition of multiple excitations, the maximum vibration displacement response of the tower is the superposition of the effect of each force acting alone. It can be seen from equation (7) that when the conductor dances with an odd half-wave number, there is one more excitation than when it dances with an even half-wave number. Therefore, the maximum vibration displacement response of the plug-in foundation transmission tower solved at this time is larger. Therefore, this paper focuses on this situation.

In equation (7), f(t) is the superposition of 3 excitations when the wire dances with an odd half-wave number, which are $-C\cos(2\omega t)/2$, $-D\sin\omega t$ and $C/2$ respectively. When the simple harmonic excitation $-C\cos(2\omega t)/2$ acts alone, according to equation (8), the vibration displacement u_1 of the iron tower at this time can be solved as:

$$u_1 = -\frac{C}{2m\omega_n^2} \cdot \frac{\cos(2\omega t + \varphi_1)}{\sqrt{\left(1-4\chi^2\right)^2 + (4\chi\xi)^2}} \tag{9}$$

For equation (9), when $\cos(2\omega t + \varphi_1) = 1$, u_1 takes the maximum value u_{1m}. In practical applications, for the convenience of calculation, the actual value u_{1m} is often replaced by a dimensionless parameter u_{1m}/u_{10}. The dimensionless parameter u_{1m}/u_{10} is also called the amplitude amplification factor and can be expressed by β_1. Among them, $u_{10} = H_1/(m\omega_n^2)$, which represents the static displacement of the tower under the sole action of the maximum excitation amplitude H_1, H_1 of the simple harmonic excitation $-C\cos(2\omega t)/2$ is $-C/2$, and the corresponding u_{10} is $-C/(2m\omega_{n1}^2)$. It can be obtained that the amplitude amplification factor β_1 when $-C\cos(2\omega t)/2$ excitation acts alone:

$$\beta_1 = u_{1m}/u_{10} = \frac{1}{\sqrt{(4\chi\xi)^2 + \left(1-4\chi^2\right)^2}} \tag{10}$$

In the same way, the amplitude amplification factor β_2 when the simple harmonic excitation-$D\sin\omega t$ acts alone:

$$\beta_2 = u_{2m}/u_{20} = \frac{1}{\sqrt{(2\chi\xi)^2 + \left(1-\chi^2\right)^2}} \tag{11}$$

In the equation: u_{2m} is the maximum vibration displacement of the tower under the simple harmonic excitation -$D\sin\omega t$ alone, m; u_{20} is the maximum amplitude of the simple harmonic excitation $-D\sin\omega t$ static displacement of the tower under the single action of $-D$.

And the amplitude amplification factor $\beta_3 = 2$ when the constant force $C/2$ acts alone.

Then, superimpose the amplitude amplification factors of the individual excitations, and finally get the comprehensive amplitude amplification factor of the plug-in base iron tower (considering that the steel structure damping ratio ξ is very small, its value is about 0.02, so it can be ignored):

$$\beta = \beta_1 + \beta_2 + \beta_3 = 2 + \frac{1}{1-4\chi^2} + \frac{1}{1-\chi^2} \tag{12}$$

Since the dimensionless parameter β is used in the calculation process to replace the actual value u_m, the design criterion is correspondingly changed to β but not allowed to exceed the allowable value $[\beta]$. According to the new design criteria, construct the inequality and carry out the transformation to obtain the inequality χ:

$$\frac{1}{1-\chi^2} + \frac{1}{1-4\chi^2} \leq [\beta] - 2 \tag{13}$$

Solving equation (13), we can get $0 \leq \chi \leq \chi_M$, where χ_M is:

$$\chi_M = \left[\frac{5([\beta]-2) + \sqrt{9([\beta]-2)^2 + 16}}{8([\beta]-1)}\right]^{\frac{1}{2}} \tag{14}$$

According to the reference [7], the value of $[\beta]$ can be determined, so that χ_M can be solved using equation (14). After the values of the 2 parameters χ_M and ω_n are determined, the mean value μ_Z and the standard deviation σ_Z of the functional function Z can be obtained according to equation (1) as:

$$\begin{aligned} \mu_Z &= \omega_n - \mu_\omega/\chi_M \\ \sigma_Z &= \sigma_\omega/\chi_M \end{aligned} \tag{15}$$

Finally, substituting μ_Z and σ_Z into equation (2), the reliability R of the plug-in basic transmission tower based on SSI can be obtained.

FIGURE 3. 141# iron tower inverted tower.

TABLE 1. Damaged tower parameter table.

Tower number	Tower model	Bottom width/m	Top width/m	Tower height/m
139	ZM1-30	8.34	8.98	42.55
140	ZM1-30	8.34	8.98	42.55
141	ZM2-39	10.36	9.00	50.30
142	ZM1-36	9.54	8.98	48.55
143	ZM1-30	8.34	8.98	42.55
150	ZM2-39	10.36	9.00	50.30

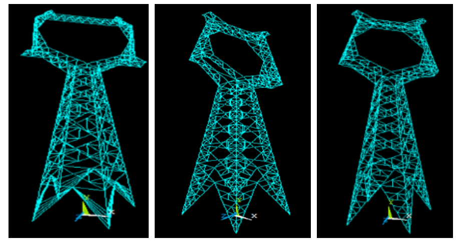
IV. APPLICATION OF SSI IN A GALLOPING ACCIDENT OF A LINE IN GUANGDONG PROVINCE

A. OVERVIEW OF A GALLOPING ACCIDENT ON A LINE IN GUANGDONG PROVINCE

From the night of January 23 to 25, 2018, a large-scale severe temperature drop and snowy weather occurred in a certain area of Guangdong Province, and the temperature continued to be below 0°C. Continuous freezing rain occurred in some areas. The freezing rain quickly formed ice on the transmission lines and caused 29 EHV and UHV lines in the province to dance under the action of wind. In this galloping accident, the line's six-base straight line tower fell, accounting for 60% of the tower collapse accidents, and the damaged iron towers were all plug-in basic transmission towers, of which the 141# iron tower was the most damaged, as shown in Figure 3. According to the engineering data, the parameters of the damaged iron tower in this area are shown in Table 1.

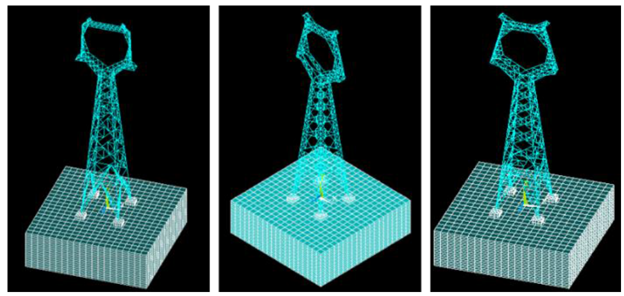
B. APPLICATION PROCESS OF SSI IN RELIABILITY SOLVING

Equations should be provided in a text format, rather than as an image. It can be seen from Section 4.1 that the 141# iron tower was the most severely damaged in this accident, so this article focuses on the analysis of this iron tower. The 141# iron tower is a 500kV transmission line plug-in basic cattou tower, and the iron tower model is ZM2-39. According to the actual size of the ZM2-39 iron tower and using the modeling method in Section 3.2, 141# plug-in foundation iron tower model is established with ANSYS software, as shown in



(a) ZM2-39 (b) ZM1-36 (c) ZM2-39

FIGURE 4. Three types of plug-in foundation iron tower.



(a) ZM2-39 (b) ZM1-36 (c) ZM2-39

FIGURE 5. Three types of plug-in foundation iron tower considering foundation soil and foundation.

Figure 4(a). Then, the foundation, soil and foundation are also taken into consideration, and the foundation soil-foundation-iron tower dynamic interaction calculation model of 141# iron tower as shown in Figure 5 (a) is further established. Finally, by modal analysis of the model, it can be found that the natural frequency f_n of the 141# iron tower considering SSI is 1.6238Hz, and further the natural circular frequency of the iron tower considering SSI $\omega_n = 2\pi f_n = 10.203$ rad/s.

According to the data in Table 1, in addition to ZM2-39, the damaged plug-in foundation tower models include ZM1-30 and ZM1-36. The iron tower model established in Figure 4(a) only corresponds to the ZM2-39 iron tower. For this reason, it is also necessary to model the other two types of damaged iron towers. Combining the data in Table 1, the established iron tower models are shown in Figure 4 (b) and (c), respectively. Among them, ZM2-39 corresponds to 150# iron tower in addition to 141# iron tower; ZM1-36 type iron tower corresponds to 142# iron tower; ZM1-30 corresponds to 139# iron tower, 140# iron tower and 143# iron tower. Then, the foundation soil-foundation-tower dynamic interaction calculation model of each tower is further established, as shown in Figure 5(b) and (c) respectively. Finally, through modal analysis, the natural circular frequency ω_n of each tower considering SSI is obtained.

According to the reference [7], for transmission lines, $[\beta]$ is taken as 3.0. Substituting $[\beta] = 3.0$ into equation (14), the upper limit χ_M of the frequency ratio considering SSI is 0.791.

According to Section 2.3, ω is a random variable that obeys a normal distribution. From this, the value range of the coefficient of variation V_ω of ω is 0.10~0.15. Since V_ω

TABLE 2. Traditional method calculation results.

Tower number	Tower model	Reliability index	Reliability R	Target R value
139	ZM1-30	5.2	1.0000	0.9993
140	ZM1-30	5.2	1.0000	0.9993
141	ZM2-39	3.4	0.9997	0.9993
142	ZM1-36	4.9	1.0000	0.9993
143	ZM1-30	5.2	1.0000	0.9993
150	ZM2-39	3.4	0.9997	0.9993

characterizes the magnitude of the change in ω, considering that the reason for the transmission tower from normal operation to vibration failure is the abrupt increase of ω, the maximum value of V_ω is 0.15 in this article. At this time, the standard deviation of ω is $\sigma_\omega = V_\omega \mu_\omega = 0.15\mu_\omega$. To solve μ_ω, we can get $\mu_\omega = 2\pi\mu_f$ according to $\omega = 2\pi f$ (f is the wire dancing frequency), where μ_f is the average wire dancing frequency in the area where the line is located. According to the statistical data of the line in this area, μ_f is 1.0Hz, so $\mu_\omega = 6.283$rad/s, and then $\sigma_\omega = 0.942$.

Finally, substituting the solved values of ω_n, χ_M, μ_ω, and σ_ω into equation (15) can obtain the values of μ_Z and σ_Z, to obtain the reliability R of different types of plug-in foundation iron towers.

C. ANALYSIS OF THE CALCULATION RESULTS OF THE RELIABILITY ALGORITHM

To verify the accuracy of the vibration reliability analysis method considering the SSI, the traditional transmission tower reliability calculation method and the method in this paper were used to analyze the reliability of the 6-base plug-in foundation tower damaged in the galloping accident of a line in Guangdong Province. And compare the analysis results with the damage of the tower in the actual project.

1) RELIABILITY CALCULATION METHOD OF TRADITIONAL TRANSMISSION TOWER

According to the specification "Uniform Standard for Reliability Design of Building Structures" (GB 50068-2001), the target reliability index μ_Z/σ_Z of 500kV transmission towers is 3.2, that is, when μ_Z/σ_Z is greater than or equal to 3.2, it is considered safe and reliable. Substituting $\mu_Z/\sigma_Z = 3.2$ into equation (2), the corresponding target reliability $R = 0.9993$ can be obtained.

Combined with the transmission tower parameters given in Table 1, the traditional transmission tower reliability calculation method in reference [6] is used to calculate the minimum reliability index of the members of the damaged 6-based plug-in foundation tower, and then the minimum value is substituted into equation (2) to obtain the reliability of each tower. The calculation results are shown in Table 2.

It can be seen from the data in Table 2 that under the calculation of the traditional transmission tower reliability calculation method, the minimum reliability index of the 6-base damaged iron tower is 3.4, and the corresponding reliability is 0.9997, which is greater than the target value of 0.9993, so it can be considered that the 6-base iron tower all are reliable, and are inconsistent with the damage to the iron tower in the actual project. This shows that the traditional reliability analysis methods of transmission towers are not suitable for the reliability calculation of plug-in foundation towers under icing galloping.

TABLE 3. Calculation results of the method in this paper.

Tower number	Tower model	μ_Z/σ_Z	Reliability R	Target R value
139	ZM1-30	2.9	0.9981	0.9993
140	ZM1-30	2.9	0.9981	0.9993
141	ZM2-39	1.9	0.9713	0.9993
142	ZM1-36	2.8	0.9974	0.9993
143	ZM1-30	2.9	0.9981	0.9993
150	ZM2-39	1.9	0.9713	0.9993

2) VIBRATION RELIABILITY ANALYSIS METHOD BASED ON SSI

The analysis in Section 3.2 shows that the natural circular frequency ω_n of 141# tower considering SSI is 10.203rad/s, the upper limit of frequency ratio χ_M is 0.791, and the statistical parameters μ_ω and σ_ω of the wire galloping circular frequency ω are 6.283rad/s respectively and 0.942, substituting the above parameters into equation (15), we can get μ_Z and σ_Z to be 1.191rad/s and 2.260, respectively, and we can get $\mu_Z/\sigma_Z = 1.9$. Finally, substituting $\mu_Z/\sigma_Z = 1.9$ into equation (2), the reliability R of the plug-in basic transmission tower considering SSI is obtained as 0.9713. Use the same method to calculate the reliability of other damaged 5-base plug-in foundation transmission towers. The calculation results are shown in Table 3.

It can be seen from the data in Table 3 that the maximum value of the reliability index of the 6-base damaged iron tower calculated according to the method in this paper is 2.9, and the corresponding reliability is 0.9981, which is less than the target reliability of 0.9993. Therefore, it can be considered that all 6-base iron towers are unreliable. It is consistent with the damage to the iron tower in the actual project. This shows that the SSI-based vibration reliability analysis method is suitable for the reliability calculation of the plug-in foundation iron tower under ice galloping.

V. CONCLUSION

The conclusions are drawn as follows.

1) The plug-in foundation iron tower is directly inserted into the foundation by the main material of the tower legs. When the tower vibrates, it is inevitably subjected to strong soil-structure dynamic interactions. If this effect is ignored, it will directly affect the safety evaluation of the tower. Therefore, based on the traditional tower reliability analysis method, this paper replaces the original tower natural circular frequency and the upper limit of the frequency ratio with the corresponding value after considering SSI, and then proposes an SSI-based vibration reliability analysis method, which is suitable for inserting analysis of the reliability of the foundation iron tower.

2) The analysis and application of a galloping accident on a line in Guangdong Province showed that the maximum reliability of the damaged 6-base plug-in foundation tower solved by the SSI-based vibration reliability analysis method was 0.9713, which is less than the target reliability of 0.9993. It is found that the iron tower used in the original project is actually unreliable, which is consistent with the actual project. Therefore, it is recommended that the SSI effect must be considered in the reliability analysis of the plug-in foundation tower in the future.

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