Research on a Non-destructive Testing Technology for the Foundation of Transmission Tower Based on Rayleigh Wave Method

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Abstract. There are more and more accidents of transmission tower collapse caused by the defects of foundation. The safety of the foundation of transmission tower has gradually attracted the attention of relevant departments. However, for the existing concrete foundations of transmission towers, the conventional detection methods will not only cause structural secondary damage, but also have extremely low efficiency, which is not conducive to actual large-scale detection. Therefore, this paper aims to propose a non-destructive testing technology for the foundation of transmission tower based on Rayleigh wave method. The non-destructive testing theory for the foundation of transmission tower based on Rayleigh wave method was firstly introduced. And then the non-destructive testing procedure of the foundation size of transmission tower based on Rayleigh wave method was described in details. The proposed non-destructive testing technology for the foundation of transmission tower based on Rayleigh wave method was verified through an actual foundation model of transmission tower. The experimental results prove that the proposed method in this paper is feasible.

1. Introduction
Transmission towers are an important part of the long-distance transmission systems. The stronger foundation of transmission tower is one of the key factors affecting and ensuring the safe operation of transmission systems [1]. It was found that the main cause of most existing accidents of transmission tower collapse is attributed to the damage of the foundation of transmission tower [2]. In general, there is usually less problem in the design bearing capacity of the foundation, while the main reason is due to the defects of the foundation itself, one of which is that the foundation size of transmission tower does not meet the design requirements. For example, some foundations with a spherical shape at the bottom due to unqualified constructions would greatly reduce the bearing capacity of the foundation of transmission tower, which lays a hidden danger for accidents of transmission tower collapse. Therefore, the detection of the foundation of transmission tower has gradually attracted more and more attention of relevant departments [3]. Because the foundations are usually buried underground, the detection of the foundation are often performed after manual excavation. However, this traditional detection method has some obvious shortcomings, such as the structural secondary damage, high cost, low efficiency and so on. At the same time, it would be difficult to carry out the detection for some foundations with large buried depths and meet the requirements of actual large-scale detection. In order to solve the above...
shortcomings of the existing detection methods for the foundation of transmission tower, a more efficient and practical detection method is urgently needed now.

Rayleigh wave method is a new non-destructive testing method, which has the advantages of convenient operation, fast speed, low cost, accurate testing results, and high reliability [4]. This Rayleigh wave method has been widely used in non-destructive testing of foundations in road and bridge engineering, and there is less related research and applications in the power industry and engineering yet. It is necessary to further explore the applicability of this non-destructive testing method of foundations of transmission tower. Thus, the studies on a non-destructive testing technology for the foundation of transmission tower based on Rayleigh wave method were carried out in this paper. The non-destructive testing principle for the foundation of transmission tower based on Rayleigh wave method was described in details. An actual foundation model of transmission tower was adopted to verify the feasibility of the proposed non-destructive testing technology for the foundation of transmission tower based on Rayleigh wave method.

2. Non-destructive Testing Theory for the Foundation of Transmission Tower Based on Rayleigh Wave Method

Rayleigh waves are a type of surface acoustic wave that travel along the surface of solids and are frequently used in non-destructive testing for detecting defects, which have the following characteristics [5]:

Due to the changing properties of the material, the elastic constants of a Rayleigh wave often change with depth, which referred to as Rayleigh wave dispersion.

The velocity of a Rayleigh wave in practice becomes dependent on the wavelength and the velocity is closely related to the physical properties of the materials.

The above characteristics could provide a sufficient theoretical basis for Rayleigh waves applied in non-destructive testing, Rayleigh wave equation is given by the following equations:

\[
\frac{\partial^2 \varphi}{\partial t^2} - \frac{\lambda + 2\mu}{\rho} \nabla^2 \varphi = 0
\]

(1)

\[
\frac{\partial^2 \psi}{\partial t^2} - \frac{\mu}{\rho} \nabla^2 \psi = 0
\]

(2)

In which \(\varphi\) is scalar potential of displacement field, \(\psi\) is vector potential of displacement field, \(\lambda\) represents Lame constants, \(\mu\) is Poisson ratio of the material, \(\rho\) is density of the material, \(\nabla\) is Laplace operator.

Laplace operator \((\nabla)\) could be described as:

\[
\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}
\]

(3)

According to the above wave equations, it can be seen that the velocity of a Rayleigh wave is closely related to the density and Poisson ratio of the materials. Based on the characteristics of travelling and dispersion of Rayleigh waves in the material, the dispersion curve of a Rayleigh wave around the foundation of transmission tower could be measured, and then the velocity distribution of a Rayleigh wave can be obtained by using the inversion calculation. In general, the foundation of transmission tower is a reinforced concrete structure and it is usually surrounded by rocks or soil. Due to the significant differences between the characteristics of these two materials, there will be an obviously sudden change in the velocity of a Rayleigh wave between these two materials. In addition, the size of the foundation of transmission tower could be determined through the velocity distribution of a Rayleigh wave.
The basic principle of a Rayleigh wave in the determination of the foundation size is mainly attributed to the difference between the foundation and surrounding rocks or soil. By applying a transient excitation force near the experimental foundation, there will be different Rayleigh waves of different frequencies generated. Then the velocity of a Rayleigh wave could be determined from the signal positions and reception time based on the pre-arranged sensors surrounding the foundation. Assume that \((n + 1)\) sensors are arranged at an equal interval \(\Delta x\) around the foundation in order to receive Rayleigh waves with a wavelength of \(n\Delta x\), the interval of Rayleigh waves received by adjacent sensors is \(\Delta t\) and the phase difference is \(\Delta \phi\), then the velocity of the wave in any \(\Delta x\) is:

\[
V_R = \frac{2\pi f \Delta \phi}{\Delta t} \quad \text{or} \quad V_R = \frac{2\pi f \Delta \phi}{\Delta t} \quad \text{(4)}
\]

The average velocity of Rayleigh waves in the range \(n\Delta x\) is

\[
\bar{V}_R = \frac{n\Delta x}{\sum_{i=1}^{n} \Delta t_i} \quad \text{or} \quad \bar{V}_R = \frac{2\pi fn \Delta \phi}{\sum_{i=1}^{n} \Delta \phi_i} \quad \text{(5)}
\]

Then the velocity of Rayleigh waves with different frequencies can be calculated by using the Equations (4) and (5), that is a dispersion curve. Therefore, the velocity of Rayleigh waves at different locations could be further obtained by the inversion calculation of dispersion curve based on the relationship between wave velocity and geological conditions.

While testing by using a transient excitation force, it needs to satisfy that there is a sufficient phase difference between adjacent sensors locations, which meets the following equations:

\[
\Delta x \leq \frac{\lambda_R}{2} = \frac{V_R \cdot \lambda_R}{2f} < \Delta x < \lambda_R \quad \text{(6)}
\]

Then the phase difference \((\Delta \phi)\) satisfies the Equation (7).

\[
\frac{2\pi}{3} < \Delta \phi < \pi \quad \text{(7)}
\]

Through the received signal of different frequencies by pre-arranged sensors, Rayleigh waves generated during transient excitations are used in geophysics and geotechnical engineering. Rayleigh waves also make a major contribution to traffic-induced ground vibrations and structure noise in buildings. Based on the geometric dispersion of Rayleigh waves and the collected signal data could solve the inverse problem and obtain the desired results.

3. Determination of the Foundation Size of Transmission Tower Based on Rayleigh Wave Method

3.1. Determination of Applied Working Frequency Range
Before non-destructive testing of the foundation of transmission tower by using Rayleigh waves method, the working frequency range need to be determined firstly. Generally, Rayleigh waves of different frequency ranges are used to characterize different geologic structures at different depths. In Rayleigh waves method, the relationship between the effective detection depth \((H)\) and wavelength \((\lambda_R)\) can be expressed by an improved equivalent half-space method, which is expressed as follows:

\[
H = \beta \lambda_R \quad \text{(8)}
\]

It can be seen from the Equation (8) that Rayleigh waves with shorter wavelength are used to detect the shallow layer and those with longer wavelength are used to detect the deep layer. With respect to the foundation of transmission tower, the foundation is not generally required to be buried at too deep layer.
Thus, Rayleigh waves with shorter wavelength are selected as the applied working wavelength for detection. Table 1 shows the relationship between conversion factor ($\beta$) of wavelength and depth in the Equation (8) and Poisson ratio ($\mu$) of the measured materials [7].

Table 1. The relationship between conversion factor ($\beta$) and Poisson ratio ($\mu$)

| $\mu$ | 0.1  | 0.15 | 0.2  | 0.25 | 0.3  | 0.35 | 0.4  | 0.45 | 0.5  |
|-------|------|------|------|------|------|------|------|------|------|
| $\beta$ | 0.55 | 0.575| 0.625| 0.65 | 0.7  | 0.75 | 0.79 | 0.84 | 0.88 |

According to Table 1, the mathematical expression of the relationship between $\beta$ and $\mu$ can be obtained by using exponential function fitting, which is shown in the Equation (9):

$$\beta = 0.486 e^{1.2 \mu}$$

The correlation coefficient of the fitting exponential function in the Equation (9) is 0.996, and then the conversion factor ($\beta$) of wavelength and depth can be calculated for any Poisson ratio ($\mu$) through the Equation (9). Figure 1 shows the relationship curve between conversion factor ($\beta$) and Poisson ratio ($\mu$).

According to the dispersion characteristics of Rayleigh waves, the relationship of wavelength ($\lambda_R$), frequency ($f$) and velocity ($V_R$) of Rayleigh waves is written as the following equation:

$$\lambda_R = \frac{V_R}{f}$$

Then the frequency ($f$) of Rayleigh waves can be expressed as:

$$f = \frac{0.486 e^{1.2 \mu V_R}}{H}$$

By using the Equation (11), an appropriate working frequency will be calculated and set for the non-destructive testing of the foundation size.

3.2. Non-destructive Testing Procedure of the Foundation Size of Transmission Tower

There are generally five main steps in determining the foundation size of a transmission tower based on Rayleigh wave method, and the corresponding procedure is presented as follows:

Step 1: Determination of Applied Working Frequency Range

Due to the general buried depth of 3–8 m for the foundation of transmission tower, the effective detection depth (H) can be selected as the range from 0.5 m to 10 m. The Poisson ratio of the concrete is set as 0.2. As for the soil, the Poisson ratio needs to be determined according to the actual situation.
on site, whose upper limit is usually 0.4. With respect to the velocity of Rayleigh waves, the lower velocity for the soil is taken as 100 m/s and the upper velocity for the concrete is taken as 3000 m/s. The working frequency range directly affects the accuracy of the non-destructive testing results, and it is appropriate to select an appropriate range considering specific conditions. Therefore, the working frequency range of Rayleigh waves applied for the non-destructive testing could be calculated as 6~4700 Hz by using the Equation (11).

In fact, the different compositions of soil and concrete will have a certain effect on the Poisson ratio, which will affect the frequency of Rayleigh waves. However, it will have no effect on the non-destructive testing results as long as the actual frequency is included in the working frequency range. For the detection depth \( H \), the irregular shape of foundation has no effect on the non-destructive testing results, while there is small shape change. And it may not be detected when the measuring point arrangement interval is too large.

Step 2: Arrangement of measuring points for the foundation of transmission tower

According to the design diagram, the outline of the foundation of transmission tower is firstly determined. Generally, the non-destructive testing scope could be set by extending for about 2 m from the outline of the foundation of transmission tower. The measuring points arrangement method is as follows:

The x-y plane coordinate system is established firstly according to the non-destructive range.

Several measuring lines are arranged at a certain distance and parallel to the x-axis, and then the measuring lines are numbered.

Several measuring points are arranged for each measuring line at a certain distance equal to that of measuring lines, and the measuring points are also numbered according to the measuring line and measuring point. For example, the measuring point (2-1) represents the first measuring point of the second measuring line.

In order to improve the accuracy of linear interpolation, the distance between two adjacent measuring lines should be controlled as 0.1 m ~ 0.3 m. The schematic diagram of the measuring point arrangement for the foundation is shown in Figure 2.

Step 3: Data collection for the foundation of transmission tower

An excitation point is firstly selected outside the non-destructive range and an excitation signal is generated at the excitation point. Then the signal of Rayleigh waves at each measurement point is collected by the acquisition system. The excitation point is set at 5 m distance from the nearest measuring point. According to the characteristics of Rayleigh waves, the excitation point should be as far away from the observation point as possible, and the maximum buried depth of the foundation of transmission tower is small, generally less than 10 m. Therefore, the excitation point is selected to be 5 m distance away from the nearest observation point. Due to the limitation of the instrument channel, each measuring point can be tested in batches. Therefore, it needs to excite at the same point for several times. There are multiple collectors and detectors that match the number of measuring points. According to the collected signals of Rayleigh wave at each measuring point, the velocity of Rayleigh waves at different depths at each measuring point would be obtained.
Fig. 2 Schematic diagram of measuring point arrangement for the foundation

Step 4: Calculation and analysis for collected data

Based on the curve between velocity and detection depth obtained from the measured velocity of Rayleigh waves at each measuring point, the coordinate values of each measuring point are obtained by using the established x-y plane coordinate system in the non-destructive testing range. Through the velocity of the same depth at two adjacent measuring points on the same measuring lines, the velocity distribution along the x-axis direction between two adjacent measuring points on the same measuring line could be obtained by linear interpolation.

Assume that the coordinates of two adjacent measuring points on the same measuring line are \((x_1, y_1, z)\), \((x_1, y_1, z)\), respectively, the corresponding velocities of Rayleigh wave are \(v_1\) and \(v_2\), respectively, then the wave velocity at any point between the two measuring points on the measuring line is:

\[
v(x, y_1, z) = v_1 + \frac{x-x_1}{x_2-x_1} (v_2 - v_1)
\]  

(12)

From the Equation (12), the two-dimensional \((x-z)\) velocity distribution cloud diagram of Rayleigh waves along the direction of each line can be obtained. Then, according to the two-dimensional distribution cloud diagram of Rayleigh wave velocity of adjacent measuring lines, the positions of each measuring line at the x- and z-axis directions can be determined for the same Rayleigh wave. The velocity distribution of Rayleigh waves along the y-axis direction between two measuring lines is obtained by linear interpolation. Given that the y-coordinates of the two measuring lines be \(y_1\) and \(y_2\), respectively, the wave velocity at any point \((x, y, z)\) between the two measuring lines is \(v(x, y, z)\), which can be calculated by the following equation:

\[
v(x, y, z) = v(x, y_1, z) + \frac{y-y_1}{y_2-y_1} [v(x, y_1, z) - v(x, y_2, z)]
\]  

(13)

The velocity distribution of Rayleigh waves along the y-axis direction can be obtained by the Equation (13). Then the three-dimensional velocity distribution cloud diagram of Rayleigh waves in the non-destructive testing range would be obtained by using the two-dimensional \((x-z)\) velocity distribution cloud diagram of Rayleigh waves.

Step 5: Determination of the foundation size of transmission tower

According to the three-dimensional velocity distribution cloud diagram of Rayleigh waves, the velocity of Rayleigh waves for the foundation of transmission tower can be firstly determined. And then the velocity distribution cloud diagram is used to select the range that matches the Rayleigh wave
velocity of the foundation of transmission tower. The outline of the foundation of transmission tower is obtained through the velocity range so that its foundation size can be further determined.

The testing procedure of the foundation size of transmission tower based on Rayleigh wave method is shown in Figure 3.

Fig. 3 Testing procedure of the foundation size of transmission tower based on Rayleigh wave method

4. Experimental Verification of Non-destructive Testing for the Foundation Size of Transmission Tower

The sizes of the foundation model of a reinforced concrete transmission tower are as follows: the length and width are 0.4 m, the height is 1.75 m, and the C25 concrete is adopted for the foundation prefabrication (as shown in Figure 4). The formwork is used to prefabricate the foundation and then hoisting, and then the final foundation of transmission tower will be formed by landfill.

Fig. 4 Foundation model of transmission tower (before landfill)
The square center of the foundation of transmission tower is set as the coordinate origin, with the x-axis horizontally to the right, the y-axis downward, and the z-axis along the foundation depth. The measuring lines numbered 1~5 are arranged at equal intervals around the foundation with lime and a measuring tape, in which the measuring line numbered 3 coincides with the x-axis, the distance between two adjacent measuring lines is 0.3 m. And there are five measuring points arranged at equal intervals on each measuring line, the distance between two adjacent measuring points on the same measuring line is 0.3 m. The measuring points are marked with lime, whose number is expressed by measuring line number-measuring point number. For example, “1-2” represents the second measuring point on the first measuring line, and the coordinate of measuring point is (-0.3, 0.6, 0). The excitation point is located 5 m away from the “5-1” measuring point. The measuring points distribution is shown in Figure 5.

Data collection for the foundation of transmission tower
(a) Prepare the acquisition system and turn on the data collector and wireless transmission system DTU. The working frequency range of Rayleigh waves is set as 6 ~ 4700 Hz.
(b) Four geophones are placed at the measuring points “1-1” to “1-4”, and an exciter is adopted to generate an excitation signal at the excitation point.
(c) The data collection is carried out by the collector for 10 s, and the data will be automatically transferred to the cloud for storage.
(d) After the acquisition, the geophone is moved to the next measuring point in sequence, and repeat the above steps (b) and (c) until all the measuring points are collected.

Data analysis for the foundation of transmission tower
(a) After the data collection, the wave velocity distribution at each measuring point along the z-axis direction can be retrieved from the cloud storage, as shown in Figure 6, which lists wave velocity distribution at the measuring points of “1-1”, “3-2”, “3-3” and “5-3”.
Fig. 6 The velocity distribution along the depth direction at measuring points “1-1”, “3-2”, “3-3” and “5-3”

Fig. 7 The cloud distribution of the measuring line numbered 3

(b) Through the Equation (12), the two-dimensional (x-z) distribution cloud diagrams of the measuring lines numbered 1~5 can be obtained and the wave velocity distribution of the measuring line numbered 3 is shown in Figure 7. Based on different velocities of Rayleigh waves in different materials, there are differences in the properties between the foundation and the soil around the foundation of transmission tower, resulting in different velocities of Rayleigh waves. From the velocity cloud distribution in Figure 7, it can be seen that there is a large difference between the velocities in the areas “1” and “2”, and the velocity distribution in the area “1” gradually spreads from the center to both sides. Therefore, it can be inferred that the area “1” is the velocity distribution area of the foundation of transmission tower, and the area “2” describes the velocity distribution of the soil around the foundation of transmission tower. Finally, the foundation size of transmission tower from the area “1” can be determined as: the length is 0.38 m and the buried depth (height) is 1.73 m.

Similarly, the two-dimensional (y-z) distribution cloud diagrams of Rayleigh wave velocity from the cloud storage can be extracted, therefore, the width of transmission tower is identified as 0.38 m.

Through the comparison of experimental and design results, it can be known that the errors of the non-destructive testing results are as follows: the errors for the length, width and height are 5%, 5% and 1.1%, respectively. The errors are small enough to meet the non-destructive testing requirements.

5. Conclusion
In this paper, the non-destructive testing technology of the foundation size of transmission tower based on Rayleigh wave method has been carried out. The experimental results show that the model size by using the non-destructive testing technology based on Rayleigh wave method agree well with the actual size in this paper. The errors are controlled within the acceptable range by the actual project, which
proves that the non-destructive testing technology of the foundation size of transmission tower based on Rayleigh wave method proposed in this paper is feasible and has better accuracy.

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