Determination of Ultimate Load and Stability Evaluation of Transmission Tower Foundation during Operation Period

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Abstract: 500kV transmission tower foundation on the Yanzi landslide is taken as the research object this article. The extreme working conditions of the transmission tower foundation under different operating conditions, including maximum wind speed, icing and disconnection, are determined. Based on this, the stability of the tower foundation, including foundation uplift stability, foundation overturning stability, foundation bearing capacity, is initially evaluated according to the "Code for Design of 110kV ~ 750kV Overhead Transmission Line" (GB 50545-2010). The results show that when the wind speed is greater than 20m/s, the maximum wind speed is determined as the extreme load condition of the tower foundation. Preliminary evaluation of the stability of the tower foundation shows that its stability is related to the wind speed and the buried depth of the tower foundation. Therefore, the research results can provide technical reference for related power departments.

1. Introduction

In order to meet the rapid development of the national economy and the continuous increase in power demand, and to achieve a wider range of resource optimization and the construction of a modern smart grid, in recent years, with the construction of the "West-to-East Power Transmission" and national networking projects, the realization of cross-border The mutual assistance of hydro-thermal power in large regions and across river basins, and the optimization of power resources on a larger scale, is of great significance to improving energy utilization. As the carrier of high-load electric energy transmission, the safe operation ability of transmission lines has always been highly concerned by all sectors of society. As an important infrastructure of the country, the safe and stable operation of the power system is related to the country’s economy and people’s lives. Once a failure or damage occurs, it will cause huge economic losses and trigger various secondary disasters [1].

Under complex geological conditions, in addition to its own self-weight load, the tower often bears the instantaneous or cyclic effects of large wind loads and snow loads. The complex load bearing characteristics of the tower foundation, the size, distribution and eccentricity of the load determine the force state and working characteristics of the foundation. When the load design is unreasonable or under the action of alternating loads, the foundation will have different degrees of cracks, which will affect the stability of the tower foundation [2]. Therefore, this paper takes the 500kV transmission tower foundation on the Yanzi landslide as the research object, studies the ultimate load of the transmission tower during the operation period, and evaluates the stability of the tower foundation on this basis.
2 The load of tower foundation

The 500kV Panlong Yihui 200# tower is a large cross-river pole tower in Badong, and the 200# pole tower is located in the Yanzi landslide in the Xirangpo community of Xinling Town, Badong County. Taking the 200# transmission tower on the Yanzi landslide as the object, according to the local meteorological conditions, the load on the foundation of the transmission tower under normal operating conditions (including maximum wind speed, icing) and disconnection is analyzed [2]. The schematic diagram of the force is shown in Figure 1. a and b are the root openings of the tower legs, and $\theta$ is the angle between the main side material and the ground. The remaining symbols are all load symbols, including gravity, wind pressure, wire break tension, calculated under normal operating conditions (including maximum wind speed, icing) and wire breakage. The results show that when the wind speed is greater than 20m/s, the maximum wind speed is determined as the maximum load condition of the tower foundation, and the relationship between the tower foundation load and the wind speed is also calculated, as shown in Figure 2. It can be seen that the vertical load (including the downward pressure N and the pull-up force N') and the horizontal load ($H_x$ and $H_y$) of the tower foundation are basically linear with the wind speed. The y direction is the main sliding direction of the landslide, and the x direction is perpendicular to the main sliding direction of the landslide.

![Figure 1 Schematic diagram of loads of tower foundations](image1)

![Figure 2 Relationship between loads of tower foundation and wind speed](image2)

3. Stability evaluation of tower Foundation

The stability of the tower foundation mainly includes the uplift stability, the foundation overturning stability, and the foundation bearing capacity. The foundation overturning stability is divided into upturning overturning and down overturning stability. Based on the site topography and geological factors, it is assumed that the tower foundation is a concrete step foundation, and the main pillars and bottom plates of the foundation are circular, as shown in Figure 3. According to the "110KV~750KV Overhead Transmission Line Design Code" (GB 50545-2010), for foundations that are subject to relatively small lateral loads, the buried depth is generally not less than 0.6m. For iron tower foundations that withstand large uplift forces, they should be buried as deep as possible, but should not exceed the critical depth of uplift soil. According to a large number of geotechnical tests and the soil weight method,
it can be known that for the circular base plate, the critical depth is twice the diameter of the circular base plate under the hard-cohesive soil. Therefore, in order to analyze the stability of the tower foundation under extreme conditions, three working conditions with buried depths of 1m, 2m and 3m are set up to analyze the stability of the tower foundation under different buried depths and different loads.

3.1 Uplift stability of tower foundation

According to the calculation formula of the soil weight method, the uplift stability of the tower foundation needs to meet the following:

$$\gamma_f T_E \leq \gamma_E \gamma_{\delta} (V_t - \Delta V_t - V_b) + Q_f$$  \hspace{1cm} (1)

Where $\gamma_f$ is the additional sub-factor of the foundation, and $T_E$ is the pull-up force of the foundation. $\gamma_E$ is the horizontal force influence coefficient, and $\gamma_{\delta}$ is the weighted average weight of the soil above the bottom of the foundation. $\gamma_{\delta}$ is the influence coefficient of the plane slope angle on the foundation slab, and $V_t$ is the volume of soil and foundation buried deep in the foundation. $\Delta V_t$ is the volume affected by the adjacent foundation, and $Q_f$ is the foundation gravity. For the convenience of analysis, the left side of the above range is called the pullout force, and the right side of the range is the pullout resistance. Figure 4 shows the pullout force and pullout resistance of the tower foundation at different depths under different wind speeds. It can be seen that the pullout resistance of the foundation is only related to the shape of the tower foundation and the soil. The greater the buried depth of the tower foundation, the greater the pullout resistance of the foundation is, while the pullout force on the foundation is approximately in a positive linear relationship with the wind speed and has nothing to do with the depth of the buried. For the tower foundation with a buried depth of more than 2m, the foundation meets the uplift stability, and for the foundation with a buried depth of 1m, the foundation meets the uplift stability when the wind speed is less than 26m/s.

![Figure 4](image1.png)  
Figure 4 Relationship between pullout force and pullout resistance on the tower foundation and wind speed

![Figure 5](image2.png)  
Figure 5 Relationship between overturning moment and anti-upturning overturning moment on the tower foundation and wind speed

3.2 Overturning stability of tower foundation

3.2.1 Upturning overturning stability

When the horizontal force and the pullout force of the foundation act on the top surface of the foundation at the same time, it can be seen from the balance equation of moment that the upturn and overturn stability of the tower foundation needs to meet:

$$\gamma_f (T_E L + H_E (h_1 + h_2)) \leq Q_b L$$  \hspace{1cm} (2)

Where $h_1$ is the height of the foundation column exposed to the designed ground, and $h_2$ is the buried depth of the foundation. $L$ is the moment arm, and $Q_b$ is the sum of the foundation gravity and the soil
3.2.2 Down overturning stability

Similarly, under the action of horizontal thrust and foundation downforce, the foundation will also have the possibility of overturning. Therefore, in order to meet the down overturning stability of foundation, it is necessary to meet:

\[ \gamma_f H_E (h_1 + h_2) \leq (Q_y + N_E) L \]  

Where \( Q_y \) is the sum of the weight of the soil directly above the foundation and the weight of the foundation, and \( N_E \) is the downforce of the foundation. Similarly, for the convenience of analysis, the left side of the above inequality is referred to as the down overturning moment, and the right side of the unequal value is the downward anti-overturning moment. Figure 6 is a diagram of the relationship between the down overturning moment and downward anti-overturning moment of the tower foundation and wind speed. It can be seen from the figure that the down anti-overturning moment of the foundation is not only related to the shape of the tower foundation and soil, but also approximately linearly with the wind speed. The greater the buried depth of the tower foundation, the greater the down anti-overturning moment of the foundation is. The growth rate of the down anti-overturning moment of the foundation under the buried depth is basically the same with the wind speed. The down overturning moment of the foundation is also approximately in a positive linear relationship with the wind speed. The greater the buried depth, the greater the down overturning moment is, and the greater the slope of the down overturning moment and wind speed is. It can be found that foundations under different buried depths meet the requirements for down overturning stability.

![Figure 6 Relationship between down overturning moment and anti-overturning moment of tower foundation and wind speed](image)

3.3 Bearing capacity of tower foundation

The transmission tower belongs to the bidirectional eccentric force foundation, and the following formula must be satisfied at the same time when it is pressed down:

When axial compression:  \[ \gamma_o P \leq f_a \]  

 gravity within the uplift soil. For the convenience of analysis, the left side of the above unequal is called the overturning moment, and the right side of the unequal is the base anti-upturning overturning moment. Figure 5 shows the relationship between the overturning and anti-upturning overturning moments on the tower foundation and the wind speed. It can be seen from the figure that the anti-upturning overturning moment of the foundation is only related to the shape of the tower foundation and the soil. The greater the buried depth of the tower foundation, the greater the anti-upturning overturning moment of the foundation is. While, the overturning moment is also approximately in a positive linear relationship with the wind speed. When the foundation uplift depth is more than 3m, the foundation uplift stability meets the requirements, and when it is less than 3m, the foundation uplift stability needs to be determined by wind speed. When the buried depth of the foundation is 2m, and the wind speed is less than 27m/s, the foundation satisfies the uplift and overturning stability. However, when the buried depth of the foundation is 1m and when the wind speed is greater than 22m/s, the foundation cannot reach the uplift and overturning stability.
When eccentric compression: \[ \gamma_{rf} P_{\text{max}} \leq 1.2 f_u \] (5)

Where \( \gamma_{rf} \) is the adjustment coefficient of the foundation bearing capacity, taking 0.75, and \( f_u \) is the average pressure at the ground of the foundation. \( P_{\text{max}} \) is the maximum pressure on the edge of the bottom surface of the foundation, and \( f_u \) is the characteristic value of the corrected foundation bearing capacity. Figure 7 is a diagram showing the relationship between the maximum pressure on the edge of the bottom of the foundation and the bearing capacity of the foundation and the wind speed when the tower foundation is eccentrically compressed and axially compressed. It can be seen from the figure that with the increase of wind speed, the maximum pressure on the edge of the bottom of the foundation will also increase approximately linearly when eccentric compression is applied. The greater the depth of the foundation, the greater the maximum pressure is, and the same is true for axial compression. In general, the bearing capacity of the tower foundation meets the requirements.

![Diagram showing relationship between bearing capacity and wind speed](image)

(a) axial compression  (b) eccentric compression

Figure 7 Relationship between the bearing capacity of the tower foundation and the wind speed

4. Conclusion
The extreme load of the tower foundation during the operation period is determined, and the stability of the tower foundation under this extreme load condition is then analyzed, and the following conclusions are obtained:

1. According to the local meteorological conditions, the load on the foundation of the transmission tower under normal operating conditions (including maximum wind speed and icing) and disconnection is analyzed, and the results show that when the wind speed is greater than 20m/s, the normal operating condition of the maximum wind speed is determined as the ultimate load condition for the tower foundation.

2. For the tower foundation with a buried depth of more than 2m, the foundation meets the uplift stability, while for the foundation with a buried depth of 1m, when the wind speed is greater than 26m/s, it is not satisfied. When the foundation uplift depth is more than 3m, the foundation uplift and overturning stability meets the requirements, and when it is less than 3m, the foundation uplift and overturning stability needs to be determined by wind speed. Foundations under different buried depths all meet the down overturning stability requirements and foundation bearing capacity requirements.

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