Collapse Analysis on 500kV Transmission Tower under Combined Action of Typhoon and Microtopography

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Abstract. This paper studies the stress state and collapse cause of transmission tower of 500kV Zhangquan II line under the combined action of wind speed, wind direction and wind speed up effect when Typhoon Meranti passes Xiamen. Based on the historical meteorological data and the destruction pattern of the tower, the input conditions of wind speed and direction which are most likely to cause the tower to collapse are determined. Based on CFD simulation analysis, the wind speed-up factor of 24 wind angles at the inverted tower position was determined, and the stress of the main member and inclined member under two wind angles conforming to the site failure pattern was analyzed, and the internal relationship between the failure pattern of transmission tower and wind speed, wind direction and wind speed up factor was clarified. The influence of wind speed, wind direction and wind speed up effect which widely existing in mountainous region should be considered comprehensively in the design of Fujian coastal high voltage transmission line to against typhoon.

Keywords: Collapse analysis; Wind speed-up ratio; CFD numerical simulation; Failure mode; Transmission tower.

1. Introduction
Along with the continuous improvement of China's national economy, the design safety margin of transmission towers has been upgraded to be hardly destructed by general strong wind over a short term in fine weather. However, in the events of extreme weather such as typhoons, there is still a risk of failure even for high-voltage transmission lines designed with 50 years of recurrence interval. The 1614# Typhoon Moranti that landed in Xiamen, Fujian province at around 2:00 am on September 15 inflicted heavy losses on the power grid of Xiamen by causing outage of 6 substations of 220kV, 21 lines of 220kV, 45 substations of 110kV, 52 lines of 110kV, 10,743 distribution transformers, and 713 lines of 10kV and power failure of up to 552,000 users. Unlike the previous typhoon induced disasters when 500kV transmission towers are rarely destructed [1], 5 towers collapsed when the typhoon swept. Field accident investigation and analysis find that all of these towers are located in mountains and close to peaks. Other adjacent 500kV transmission lines did not have fallen towers. Preliminary field disaster analysis shows that increasing the calculation wind speed only cannot explain why towers of the same
type are not destructed all, and the failure patterns are not in full accord. It indicates that some of the design parameters are not accurate enough and the calculation conditions are not comprehensive enough.

Structural failure can only be caused by two major reasons. One is that the resistance calculation method for the structure itself is improper and results in an overestimation of the true load-bearing capacity of the structure; the other is that the actual external load borne by the structure in use is more than the design load. In the two aspects of resistance calculation and wind load calculation for transmission line structures, extensive researches are carried out by scholars at home and abroad.

In terms of the structural resistance calculation methods for transmission lines, transmission lines are now designed mainly with the help of such design software as TTA [2] and Daoheng [3]. WANG Zhangqi [4] pointed out that such software is based on the full stress design theory, which should be based on the ultimate design theory and use the overall failure of the tower rather than the failure of individual poles as the design index. XIONG Tiehua [5] calculated the overall ultimate resistance of tower structures based on whether the overall structural stiffness matrix is singular to determine whether the structure fails. Towers that are designed based on the overall ultimate resistance are more economical, but it is widely believed by designers of the power industry at this stage that the full stress design can better meet the design safety requirements. Therefore, during the structural resistance analysis in this paper, stresses of tower poles are calculated in favor of safety based on the prevailing full stress design method.

In terms of the external load calculation for transmission lines, although comprehensive consideration [6] is taken for the design load of transmission tower structures at this stage, and dynamic properties of the structures and the coupling situations of power lines [7-8] are involved in the design process, some of the design parameters are not accurate enough, and the calculation conditions are not thorough enough [9-10]. The codes on loads of transmission lines in China are mainly derived from the codes on loads of building structures. However, the wind field characteristics in the mountainous areas where transmission lines are located greatly differ from those in plains and urban areas. A feasible way is to obtain the wind field characteristics under micro-topographic conditions such as mountainous areas by means of simulation analysis [11-14]. Extensive researches have been made by scholars at home and abroad [15-16] in this area, and the simulation analysis technology for wind field in mountainous areas is comparatively mature.

In addition, as the measured wind speed data of typhoons is accumulating, new research results on near-ground boundary layer characteristics of typhoons have been emerging, and scholars have proposed extreme wind speeds for typhoons with different recurrence periods [17] and analyzed wind profile characteristics [18] and fluctuating wind speed characteristics [19-21] of typhoons. An et al. used an improved genetic algorithm to solve the typhoon wind field model and analyzed the reason for the collapse of two 95m high river-crossing towers during the super typhoon Rammasun in 2014 [22]. However, due to the strong variability of typhoons and the high cost to follow the design idea of upgrading typhoon resistance for complete lines, these research results have not yet been able to develop a cost-effective typhoon resistant design approach. Currently, a feasible approach is to carry out the load calculation and analysis of transmission lines under specific typhoon conditions and make targeted reinforcement based on the stress characteristics of transmission towers under specific load conditions [23].

In this paper, the most reasonable failure conditions are determined by carrying out detailed meteorological data collection, data analysis, simulation and mechanical analysis, and comparing the results of mechanical analysis with the field failure conditions. Meanwhile, it is indicated that there are still some pending improvements for the current transmission lines in response to extreme wind-induced disasters, and many scientific research results are yet to be introduced into the design and calculation verification of transmission lines.
2. Brief Introduction to Project Background

2.1. Design Overview of 500kV Zhangquan Line II of Impaired Line

500kV Zhangquan Line II that starts from 500kV Zhangzhou Substation and ends at 500kV Quanzhou Substation covers a total length of 111.306km and uses 236 towers throughout the line, which are erected by single and double circuits. The line was put into operation on February 4, 2010. The towers are designed in line with the standards Technical Code for the Design of Tower and Pole Structures of Overhead Transmission Line (DL/T 5154-2002), and Technical Code for the Design of 110-500kV Overhead Transmission Line (DL/T 5092-1999). The section of the line subjected to the collapse accident is 120#-128# section of 500kV Zhangquan Line II, falling into the typical meteorological zone I-1 in Fujian Province. The key design meteorological conditions are that the design wind speed is 35m/s (once in 30 years, with an average height of 20m off the ground), the minimum temperature is -5℃, and the ice thickness is 0mm. The line is northward and 47°by east.

According to the original design drawings, 500kV Zhangquan Line II applies 4 × LGJ-400/35 aluminum conductor steel reinforced with a safety factor of 2.5. The average operating stress is 59.1MPa, 25% of its breaking force; the two ground wires both use GJ-80 galvanized strand wires with the safety factor of 4.65.

2.2. Field Failure Conditions of Impaired Line

The typhoon caused 126# (tower type ZMV522-36) and 127# (tower type ZMV522-33) towers of Zhangquan Line II to collapse. The field failure conditions of 126# and 127# towers are shown in Figure 1 and Figure 2, respectively. Field investigation shows that 126# tower of Zhangquan Line II was destroyed at the position above the tower head bottleneck and the tower head collapsed along the direction of the line (collapsed to the small number side). The four legs of the slab foundation were not destroyed, and the foundation bolts were not damaged. 127# tower of Zhangquan Line II suffered from overall buckling failure at the tower body part above the foundation. The tower collapsed in the direction perpendicular to the line, the angle steel at the joint between tower leg and foundation was completely bent, while the slab foundations of 4 tower legs were not destroyed, and the foundation bolts were not damaged. A great number of surrounding trees fell down, and the direction of the fall was roughly from a high place to a low place, i.e., from north to south (as shown in Figure 3).

![Figure 1. Failure Conditions of 126# Tower of 500kV Zhangquan Line II.](image-url)
2.3. Reflections Based on Field Failure Conditions

In connection with the field failure conditions, the design department took the wind speed for calculation of 42.9 m/s, and the angle between the strong wind and the line between 0 and 45°. Calculation shows that the stresses borne by cross diagonal members at the side of the bent arm are up to 140% when the angle of wind deflection is 0° and up to 110%-120% when the angle of wind deflection is 45°. It is speculated that the cross diagonal members at the side of tower head bent arm lost stability and caused the tower head to fail under the action of 0-45° wind. It is presumed that at the moment the 127# tower failed, the stresses borne by components of tower body main members and tower foot diagonal members were out of limit under the action of 90° wind deflection, and caused the tower to collapse. The above mechanical analysis seems to explain the cause of failure of the two towers very well. However, in the same tension section, other transmission towers of the same type and the same batch and designed with the same standard within a range of less than 1 km away were not destroyed all, which indicates that the cause for collapse of the towers is to be studied in depth.

3. Determination of Wind Speed and Wind Direction When Typhoon Induced Collapse of Towers Occur

A typhoon is a wind field that changes dramatically with time and space. As the typhoon moves, wind speed and wind direction inflicted on transmission lines change all the time. How to determine the exact wind speed and wind direction at the moment of tower collapses is key to grasping the true wind load borne by transmission lines under the action of the typhoon. In this paper, the maximum average wind speed in 10 min (with sample time interval of 1 h), wind direction data, as well as corresponding wind directions and longitude and latitude data of meteorological stations within the 72h from typhoon generation to landing (0:00 on September 14, 2016 to 23:00 on September 16, 2016) were collected from 1,111 meteorological stations in Fujian, and the spatial position relationship among typhoon center, force-7 wind ring, force-10 wind ring, and 127# tower in the vector field of wind speed and wind direction were plotted. Based on this, how wind speed and wind direction change while the typhoon is moving, and in which time period the tower is most likely to fail were judged. Figure 4 shows the
changes in the vector field of wind speed and wind direction in the course of the typhoon center approaching the collapsed tower.

Figure 4. Vector Field of Wind Speed and Wind Direction in the Process of the Typhoon Approaching the Collapsed Tower (600km×680km).

According to Figure 4, as the typhoon center is getting closer, the wind speed at the site of the collapsed tower is increasing, and the wind direction gradually turns from the initially disordered to be consistent with the tangential line from the typhoon center to the tower; when the tower enters the force-10 wind ring, the surrounding wind directions tend to be multiple tangential wind directions under counterclockwise rotation. This is in line with the general distribution rules for wind speed and wind direction fields of the typhoon. In order to clarify the vector field of wind speed and wind direction near the tower site close to tower collapse, the spatial scale is further reduced (as shown in Figure 5) to determine wind speed and wind direction data of which meteorological station can be used to analyze the collapsed tower.

Figure 5. Vector Field of Wind Speed and Wind Direction of the Tower Site Close to Tower Collapse (200km×680km)
Further fine analysis is carried out to the vector wind fields of meteorological stations in the area near the 127# tower (as shown in Figure 6). According to Figure 6, judging from the wind speed and the wind direction corresponding to the direction of tower collapse, the airflow that is most likely to cause the tower to collapse should be recorded by station F2188 and station F2185, where the coordinate of station F2188 is (E118.0445, N24.3331) and of station F2185 is (E118.0424, N24.2951) with a straight-line distance of 4.061km between them. The maximum average wind speed in 10min collected at station F2188 is 32.1m/s in the wind direction of 344°, and the maximum average wind speed in 10min collected at station F2185 is 41.7m/s in the wind direction of 320°. Within a spatial distance of 4km, both wind speed and wind direction change significantly and indicate an obvious microtopography effect. How to use wind speed and wind direction data of the two stations to accurately reflect the effect of microtopography on the tower stress will be discussed and determined in connection with the results of subsequent tower stress analysis and tower failure pattern.

![Figure 6. Vector Field of Wind Speed and Wind Direction of the Tower Site When Tower Collapses (100km×100km)](image)

### 4. Parameters for Analysis of Tower Stress under Combined Action of Typhoon and Microtopography

#### 4.1. Parameters for Calculation and Verification

Based on the above analysis and in connection with existing research conclusions on characteristics of the typhoon wind field, the relevant parameters used for the analysis of collapsed towers are as follows:

1. Design wind speed. The working conditions to be verified are that the maximum average wind speed in 10min collected at station F2188 is 32.1m/s; the maximum average wind speed in 10min collected at station F2185 is 41.7m/s.

2. The angle of angular wind. The wind speed of 32.1m/s collected at station F2188 corresponds to the wind direction of 344° and its angle with the line heading in the geographic coordinate system is 62°. The angle of the angular wind is taken 60°. The wind speed of 41.7m/s collected at F2185 station corresponds to the wind direction of 320° and its angle with the line heading in the geographic coordinate system is 87°. The angle of angular wind is taken as 90°. The schematic diagram of the angle of angular wind is as shown in Figure 7.
(3) Wind profile factor. As the wind speed profile data of Typhoon Moranti are not collected in the relevant data collection work, it is suggested to take a conservative value of 0.12 according to the research results of reference [18].

(4) Turbulence intensity at 10m height. As the turbulence intensity at 10m height of Typhoon Moranti is not collected in the relevant data collection work, 1.6 times of the turbulence intensity in the non-typhoon area is taken according to the corrections proposed in references [19] and [20].

(5) Wind speed-up at the tower site. In order to reflect the effect of microtopography on typhoon wind speed, the wind field of microtopography surrounding the 127# tower of Zhangquan Line II was simulated in this paper by means of CFD simulation (as shown in Figure 8). The wind speed-up of 127# tower in each wind angle is shown in Figure 9. For the reliability of the results, another unit was entrusted to carry out synchronous comparative simulation analysis at the tower site. The two groups of simulation results are basically the same in all wind angles, and the results are very close, especially in the two angles of 330° and 345°.
Figure 9. Radar Chart of Wind Speed-up at 10m Height of 127 # Tower

Table 1 lists the wind speed-ups with incoming wind directions of 344° and 320°. Analysis of Table 1 shows that, due to the influence of local topography, the wind speed-up factor in the height range of the tower is more than 1 in the wind direction of 344°, reflecting the acceleration effect of the mountainous area on the wind speed. While in the wind direction of 320°, the wind speed-up factor in the height range of the tower is less than 1, reflecting the shelter effect of the mountainous area on wind speed.

Table 1. Wind Speed-ups in Wind Directions of 344° and 320°

| Height (m) | Wind Direction (°) | 10 | 30 | 50 | 70 | 90 | 120 |
|------------|--------------------|----|----|----|----|----|-----|
| 344        | 344                | 1.112 | 1.236 | 1.239 | 1.237 | 1.235 | 1.231 |
| 320        | 320                | 0.465 | 0.513 | 0.517 | 0.502 | 0.626 | 0.473 |

4.2. Calculation of Tower Ground Wires under the Action of Typhoon

(1) The variation factor of wind pressure height $\mu_z$ is calculated with the following equation:

$$\mu_z = \alpha \frac{10^{0.30} \cdot \left( \frac{350}{10} \right)^{0.30} \cdot \left( \frac{z}{10} \right)^{2\alpha}}{H_{G}}$$

(1)

$H_{G}$ is the gradient wind height corresponding to the actual geomorphic type, in which $\alpha$ is the wind profile factor.

(2) Wind load adjustment factor $\beta_z$ is calculated with the following equation

$$\beta_z = 1 + 2l_{10} I_z \sqrt{1 + R^2}$$

(2)

In the calculation of wind load inflicted on towers by conventional wind, the values of $\alpha$ and $l_{10}$ are defined according to the geomorphic type assumed in the design document, in which $\alpha$ is taken as 0.15 and the turbulence $I_{10}$ at 10m height is taken as 0.14; in the calculation of wind load of towers vulnerable to typhoons, $\alpha$ and $I_{10}$ are taken as 0.12 and 0.192 separately.

(3) Calculation of wind load inflicted on tower body
The standard values of wind load inflicted on front and side of the tower $W_{saW}$ and $W_{sbW}$ are calculated with equation (3). The wind load inflicted on the tower body is generally calculated by the tower analysis program based on the wind pressure sections (as shown in Figure 10). Refer to Section 10.1.18 in reference [6] for the parameters involved in the equation.

$$
W_{sa} = W_0 \cdot \mu_z \cdot \mu_{a,z} \cdot B_z \cdot A_{a,z} \cdot \beta_z \\
W_{sb} = W_0 \cdot \mu_z \cdot \mu_{b,z} \cdot B_z \cdot A_{b,z} \cdot \beta_z
$$

(3)

(4) Calculation of wind load inflicted on ground wires

The standard value of wind load inflicted on ground wires is calculated with equation (4), and generally calculated by referring to the electrical load computation sheet.

$$
W_z = \alpha_z \cdot W_0 \cdot \mu_z \cdot \mu_{a,z} \cdot \beta_z \cdot B_z \cdot d \cdot L_z \cdot \sin^2 \theta
$$

(4)

(5) Distribution of angular wind

Considering the action of angular wind between the transmission line and the actual wind direction, the wind load inflicted on the tower body and ground wires under the effect of each angular wind calculated separately according to the regulations on angular wind given in reference [6].

Figure 10. Wind Pressure Sections of 127# Tower
5. Stress Analysis of 127# Tower under the Combined Action of Typhoon and Microtopography

In order to explain the reasons for the difference among towers of varying types within the spatial distance of less than 1km, where one tower collapsed, one tower failed and two towers remained undamaged, the stresses under four working conditions were calculated in this paper with the use of Daoheng analysis software. The distribution of calculated stress ratios of tower poles is shown in Figure 11. The stress ratio of a tower pole is the ratio between the actual stress of the pole under load and its yield stress.

Case 1: Stress analysis of 127# tower under the originally designed strong wind conditions
Case 2: Stress analysis of the tower with the wind angle of 345° not considering the effect of microtopography (corresponding to wind with 60° angle).
Case 3: Stress analysis of the tower with the wind angle of 345° considering the effect of microtopography (corresponding to wind with 60° angle).
Case 4: Stress analysis of the tower with the wind angle of 320° not considering the effect of microtopography (corresponding to wind with 90° angle).

![Stress Ratio of Tower Poles](image1)

The following rules can be obtained through comprehensive comparison and analysis of the distribution of tower stress ratios under the above 4 working conditions:

(1) Comparison between typhoon load and originally designed strong wind conditions

The wind speed of the typhoon is 32.1m/s that is slightly higher than the originally designed strong wind speed of 31.3m/s and makes the maximum stress ratio of tower poles up to 94.6%, but the poles are still in the safety range. It indicates that the design safety margin of transmission towers even in the typhoon force-10 wind ring is still sufficient in most cases, and most of the towers will not suffer from failure.
(2) Superimposed action of typhoon load and microtopography acceleration effect

① In addition to considering the effect of increased typhoon wind speed and intensified wind shear, it is necessary to further superimpose the effect of microtopography surrounding the collapsed tower on the wind speed as there is a certain spatial distance between the meteorological station and the collapsed tower and the microtopography conditions may have changed. After comprehensive consideration of the above factors, both diagonal members and main members at the tower leg part suffered from the situation that their stress ratios exceed the limit. With the maximum stress ratio up to 112.5%, the tower leg part was destroyed. ② In terms of the tensile and compressive states of poles, the tower leg diagonal members at one side suffered from tensile failure, while the tower leg main members at the opposite side suffered from compressive failure at the time of collapse, which is consistent with failure pattern of 127# tower observed in field. ③ In terms of the wind direction leading to the collapse of the tower, the tower and its surrounding tress under the action of 345° incoming wind all fell from north to south and formed the failure pattern of collapsed tower from the top of the hillside to the bottom of the hillside. ④ After the collapse of 127# tower, the directly adjacent 126# tower was destroyed at the upper bent arm position on the tower head under the action of unbalanced tension and action force caused by break of the line, which is consistent with the failure pattern of 126# tower observed in field.

(3) Superimposed action of typhoon load and microtopography shelter effect

Although the typhoon wind speed in the 320° wind angle was as high as 41.7m/s, the 127# tower just facing the wind was located in the shelter area at the downstream of the mountain, where wind speed-up was less than 1, and the stress borne by tower poles was smaller than the designed strong wind conditions. It shows that it is not reasonable to judge whether the tower is risky based on the wind speed provided by the meteorological station while ignoring the microtopography effect.

6. Conclusion

The purpose of this paper is to analyze the cause for the collapse of 127# tower when Typhoon Moranti swept and raise the degree of recognition for the combined action of typhoon wind field characteristics and microtopography acceleration in the design of high-voltage transmission lines in coastal typhoon-prone areas. In this paper, the wind speed and wind direction information that may cause towers to collapse was determined by collecting and analyzing the wind speed and wind direction data from coastal meteorological stations in Fujian at the time of Moranti. The wind speed-up of the 127# tower site was obtained by means of CFD simulation analysis of the micro-topographic wind field at the site of tower collapse and the stress analysis and failure pattern analysis of towers under the influence of typhoon and microtopography were carried out. The conclusions obtained mainly include:

(1) In terms of the meteorological factor, the wind environment of the tower site is under constant changes while typhoon is moving. The data recorded by ground meteorological stations indicate that the maximum average wind speed in 10min collected at station F2188 is 32.1m/s in the wind direction of 344°, and the maximum average wind speed in 10min collected at station F2185 is 41.7m/s in the wind direction of 320°, which are the meteorological conditions most likely to cause 127# tower to collapse.

(2) In terms of topographic factor, as there is a certain spatial distance between the meteorological station and the collapsed tower, the meteorological conditions provided by the meteorological station cannot be directly used for collapse analysis, but instead, the difference in topography between the two sites must be considered by means of CFD simulation analysis.

(3) The simulation analysis shows that the wind speed-up of 127# tower is less than 1 in most cases when the tower is under the action of wind coming from the north. Only in the 345° wind angle, the wind speed-up at 10m height is 1.112 and that at 30m height is 1.236 as it lies in the gap between two small peaks. The acceleration effect in this very wind angle is superimposed with the effect of typhoon and causes the stresses of tower leg main members to exceed the limit and finally fall northward.

Acknowledgments

This work has been funded by the State Grid Corporation of China (Project name: Research on Digital Wind Field of Complex Mountain Based on Composite Sensing Technology), and the financial aid.
number is GCB17202000122. The authors would like to thank the sponsor of State Grid Corporation of China.

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