Research on Characteristics of Field Measured Near-earth Turbulence of Typhoon “Soulik” by Transmission Tower

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Abstract. To explore the variation of mean wind speed, turbulence intensity and gust factor along the height, a 500kV transmission tower located in Ningde Fujian was chosen and the wind data during typhoon “Soulik” were collected from five anemometers arranged at 15m, 27m, 53m, 67m and 82m height. The results show that the rough factor decreases with wind speed when it is less than 12m/s, And little variation when wind speed over 12m/s. The friction velocity is increase with wind speed. The variation of the near-earth boundary calculated by the formula is not obvious with time, The average height of neutral ABL is 2,007.89m, which is much higher than the 350m of gradient height. Recommended by Chinese National Load Code for open terrain. The profile of mean wind speed of typhoon “Soulik” agrees well with the power law and the log law. In this paper, the expressions of longitudinal, lateral and vertical turbulence profiles are obtained by exponential fitting. Finally, the actual gust factor is fitted as the shape of \( G_i = \alpha \left( \frac{z}{10} \right)^\beta \), and obtained the empirical expression of gust factor.

1. Introduction

Typhoon is a kind of natural disaster frequently occurs in coastal area. Each year, the typhoon will cause a lot of casualties and house collapse in coastal area, especially that a large number of large-span iron towers have been constructed in coastal area in recent years, and the wind load becomes control load of such high structure. This thesis is crucial for guaranteeing safety of power transmission iron tower, enhancing wind resistance of structure and getting to know wind distribution and intensity of typhoon better.

Through researching the variation law of near-earth wind along with height, we can obtain wind characteristic parameters required by design wind load precisely, and this is very important for wind resistance design of high iron tower which is greatly influenced by wind load. In the past tens of years, various countries all over the world have conducted many actual field measurement to strong wind. For example, through analyzing a lot of actually measured data, Tieleman¹ obtained the conclusion that “the height of atmospheric surface layer is increased along with increasing of roughness and mean wind speed, and the value is 150m at least”, and he believed that the “gradient wind height” of Davenport was not the function of wind speed, and approximately equaled to twice as large as the height of atmospheric surface layer. Li Xiaoli et al. [2] researched the characteristics of wind profile of typhoon “Hagupit” boundary layer, and obtained the conclusion that “the relationship between friction velocity and mean wind speed is approximate to linear increasing”. Wang Xu et al. [3] researched the wind profile characteristics of near-earth wind in Pudong, Shanghai based on the actually measured data of typhoon “Muifa” at the height of 10m, 20m, 30m and 40m in Pudong, Shanghai, and obtained...
the variation law of mean wind speed, turbulence intensity and gust factor along with height. Zhao Lin et al. [4] utilized three typhoons (Haitang, Matsa and Khanun) actually measured at the Donghaitang observation station along with coast of Zhejiang Province, and through statistics, they obtained the conclusion that “the power exponent of wind profile decreases along with increasing of distance between typhoon center and observation tower, and is greater than the value 0.12 which is suggested in the code of our country under Category A terrain”. Li Bo et al. [5] analyzed the near-earth wind field characteristics in Fujian Province of our country based on the data actually measured with 5 sets of 3D ultrasonic anemographs at different heights on some power transmission tower, and fit the wind profile power exponent and turbulence intensity profile according to the power law model. Shu et al. [6] obtained the wind profile shapes of monsoon, thunderstorm and gale based on the data actually measured by cup-type anemograph and Doppler radar at the coastal meteorological observation station in Hong Kong in a synchronous way, and deduced the power law and fitting parameters included in the power law model. However, due to long field monitoring period and high equipment maintenance cost, the real-time typhoon data cannot be collected easily, which makes our country lack research on near-earth wind field characteristics when the typhoon “Soulik” transits, so as to provide reference for wind resistance design of high structures such as power transmission iron tower in the areas impacted by typhoon.

2. Observation Location and Measurement Procedures

2.1. Characteristics of Average Wind Speed
No. 07 tropical storm “Soulik” in 2013 formed above northwest Pacific Ocean, upgraded to super typhoon in 42 hours, with the maximum wind force of 16, moving at the speed of 20km/h, landing the coastal area of Huangqi peninsula in Lianjiang County, Fujian Province, China at 16:00 on July 13, 2013; and at 17:00, it was weakened to tropical storm again. The typhoon is featured by high intensity, stable route and wide impact scope.

2.2. Characteristics of Average Wind Speed
The actual measurement site is located in Hongshan Village, Yacheng Town, Xiapu County, Ningde City, Fujian Province. The 52# pole tower on the route of 550kV Lili nuclear power transmission line in Ningde is adopted as research object. The site refers to river valley terrain surrounded by hills in south and north directions, within northern latitude 26°25′-27°9′ and eastern longitude 119°46′-120°26′, 160km away from Wenzhou to the north and 160km away from Fuzhou to the south. There are five 3D ultrasonic anemographs on the tower body, which are 15m, 27m, 53m, 67m and 82m above the ground; 5 anemographs are adopted to measure wind speed synchronously, with sampling frequency of 10Hz. The sampling time period is from 0:00 to 22:00 on July 13, 2013. In addition, the subsample segmentation is conducted according to 10min average time interval.

3. Data Processing Method

3.1. Wind Speed Profile
In the atmospheric boundary layer, research the variation law of mean wind speed along with height with the wind speed profile theory. The wind speed profile theory which is used frequently includes power law model [7], logarithmic law model [7] and Deaves-Harries model [8-10].

(1) Power Law Model
Through a large number of actual measurement researches, Davenport proposed that “the mean wind speed shows exponential distribution along with height”. For the power law model is simple, it has been incorporated into the code for structural load of buildings in our country [11], and the empirical expression is shown as below:
\[
\frac{U(z)}{U(z_{\text{ref}})} = \left( \frac{z}{z_{\text{ref}}} \right)^\alpha
\]

Wherein: \(z_{\text{ref}}\) means standard height; \(U(z_{\text{ref}})\) means wind speed at the standard height; and \(\alpha\) means roughness index of ground.

(2) Deaves-Harries Model

Deaves improved the logarithmic law model, and the improved one was completely applicable to the full boundary layer, and the obtained Deaves-Harries model expression is shown as below:

\[
U(z) = \frac{1}{k} \ln \left( \frac{z}{z_g} \right) + 5.75 \left( \frac{z}{z_g} \right)^{1.33} - 1.88 \left( \frac{z}{z_g} \right)^2 + 0.25 \left( \frac{z}{z_g} \right)^3
\]

In the formula, \(z_g\) means boundary layer height, and the calculation expression is shown as below:

\[
z_g = \frac{U'_g}{B f}
\]

In the formula, \(B\) refers to empirical parameter, which takes the value 6 generally; \(f\) refers to Coriolis parameter, taking the value of \(7.554 \times 10^{-5}\) s\(^{-1}\) in this thesis.

3.2. Turbulence Intensity

The turbulence intensity is a relative index for balancing turbulence strength, and it is an important characteristic quantity for describing atmospheric turbulence movement. It is defined as the specific value of standard deviation of fluctuation wind speed within average time interval to the longitudinal wind speed in corresponding time interval, and the expression is shown as below:

\[
I_i = \frac{\sigma_i}{U} (i = u, v, w)
\]

Wherein, \(\sigma_i\) refers to root mean square of fluctuation wind speeds \(u(t)\) and \(v(t)\); \(u, v, w\) refer to components of longitudinal, horizontal and vertical fluctuation wind speeds respectively.

The 3D ultrasonic anemograph will output the wind speed components in three directions, i.e. \(u_x(t), u_y(t)\) and \(u_z(t)\). In this thesis, the vector decomposition method is adopted to work out the mean wind speed \(U\) and wind direction angle \(\phi\), and the calculation expression is shown as below:

\[
U = \sqrt{u_x(t)^2 + u_y(t)^2 + u_z(t)^2}
\]

\[
\cos \phi = \frac{u_x(t)}{U}
\]

Wherein, \(u_x(t), u_y(t)\) and \(u_z(t)\) are used to represent the mean value of wind speeds of \(u_x(t), u_y(t)\) and \(u_z(t)\) at the time of 10min.

The fluctuation wind speed can be calculated according to the formula below:

\[
u(t) = u_x(t) \cos \phi + u_y(t) \sin \phi - U
\]

\[
v(t) = -u_x(t) \sin \phi + u_y(t) \cos \phi
\]

\[
w(t) = u_z - u_z(t)
\]

3.3. Gust Factor

The fluctuation strength of natural wind also can be represented with gust factor. The definition of gust factor is specific value of the peak value of mean wind speed within the gust lasting period \(t_g\) at the height \(z\) to the mean wind speed within average time interval, and its general expression is shown as below:
\[ G_x(t_g) = 1 + \frac{\text{max}(\bar{u}(t_g))}{U} \]  
\[ G_y(t_g) = 1 + \frac{\text{max}(\bar{v}(t_g))}{U} \]  
\[ G_z(t_g) = 1 + \frac{\text{max}(\bar{w}(t_g))}{U} \]

Wherein, \(\text{max}(\bar{u}(t_g))\), \(\text{max}(\bar{v}(t_g))\) and \(\text{max}(\bar{w}(t_g))\) means the peak value of mean wind speeds of longitudinal, horizontal and vertical fluctuation winds within the gust lasting period.

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**4. Processing of Actually Measured Data**

**4.1. Analysis on Wind Speed Profile Theory and Relevant Parameters**

**4.1.1 Mean Wind Speed and Wind Direction Angle**

It is ruled that the wind direction angle of actual measurement takes true north direction as 0°, and the clockwise rotation direction refers to positive direction. Figure 1 is the variation curve of mean wind speed \(U\) and wind direction angle \(\phi\) at the time of 10min at different heights \(z\) as time goes by from 0:00 to 21:00 on July 13. From Figure 3, it can be known that the mean wind speed is in direct proportion to the wind speed collection height. The variation trends of mean wind speeds and wind direction angles at different heights are basically consistent. The mean wind speeds at various heights reach the peak from 13:00:00 to 13:10:00 on July 13, 2013, and the maximum mean wind speeds corresponding to 15m, 27m, 53m, 67m and 82m are 15.24m/s, 16.67 m/s, 17.22m/s, 17.72m/s and 18.24m/s respectively. The corresponding wind direction angles are 73.58°, 83.23°, 80.39°, 74.21° and 76.40°, and then the mean wind speed starts to decrease, and the wind direction angles tend to stable at 07:00:00 on July 13, 2013.
4.1.2 Mean Wind Speed and Wind Direction Angle

The theoretical model mentions relative parameters such as roughness index, friction velocity and boundary layer height, and this thesis will implement analysis on them one by one.

(1) Roughness Index $\alpha$

The roughness index $\alpha$ is related to the ground roughness. It is an important parameter of wind resistance design of structure. Figure 4 gives the variation situation of roughness index along with mean wind speed at the time of 10min at the height of 10m. The roughness index is obtained through fitting of exponential distribution of men wind speed at the time of 10min at the heights of 15m, 27m, 53m, 67m and 82m. The result in the Figure shows that when the mean wind speed is less than 12m/s, the roughness index $\alpha$ will decrease along with increasing of mean wind speed, and the data is relatively dispersed, with the maximum value of 0.58 and the minimum value of 0.026; when the mean wind speed is greater than 12m/s, the roughness index will not variation along with mean wind speed; which is basically consistent with the conclusion in the reference [6].

(2) Boundary Layer Height $z_g$

The boundary layer height is the critical height that the free atmosphere isn’t influenced by ground friction force, and the boundary layer height is impacted by mean wind speed. Figure 3(a) shows the variation situation of boundary layer height $z_g$ calculated through formula along with mean wind speed. From the Figure, it can be known that the boundary layer height increases along with increasing
of mean wind speed, thus obtaining the mean value of boundary layer height $z_g$ as 2,007.89m, much higher than the boundary layer height 350m under Category B terrain ruled in the code of our country[11]. The conclusion of this thesis is similar to conclusions of the reference [3] and reference [18]. The variation of boundary layer height along with height is as shown in the box plot in Figure 3(b), and it can be known that there is obvious difference in distribution of boundary layer height at different heights, the mean value of boundary layer height increases along with increasing of height, and along with the increasing of height, the difference between the median and the mean value is greater and greater.

![Boxplot of Distribution of Boundary Layer Height along with Height](image)

**Figure 3.** Variation of Boundary Layer Height along with Mean Wind Speed

### 4.1.3 Mean Wind Speed and Wind Direction Angle

Figure 4 gives variation curve of mean wind speed profile as time goes by. Due to limitation of terrain and instrument installation conditions, no 3D anemograph is set at the height of 10m, and the wind speeds at the heights of 53m, 67m and 83m are adopted to work out the wind speed at the height of 10m as per power law. Take the specific value of $U(z)$ to mean wind speed at the height of 10m as horizontal coordinate, the result shows that the mean profile variations as time goes by, and at 6:00, due to increasing of wind speed, the wind profile variations obviously, and there is obvious difference among various profiles. At the beginning, the specific values of mean wind speeds at various measuring point heights to mean wind speed at the height of 10m are similar to each other. As time
goes by, the specific value starts to increase, and the specific value of \( U(82) \) to \( U(10) \) is increased to 1.37 from 1.06. Figure 5 gives wind profiles corresponding to 5 groups of different time periods at the mean wind speed. The result in the Figure shows that 5 groups of wind profiles show different variation trends. When the wind speed is less than 12m/s, the variation curve of mean wind speed along with height is relatively gentle, while when the wind speed is greater than 12m/s, the variation of mean wind speed along with height is relatively violent.

Figure 4. Variation of Wind Profile as Time Goes by

Figure 5. Comparison between measured results and theoretical results of wind profiles at different wind

4.2. Turbulence Intensity Profile

Figure 6 gives the relationship between longitudinal turbulence intensity and height and the turbulence profiles ruled in the American [12], Japanese [19] and European [20] Codes. From the Figure, it can be known that the longitudinal turbulence intensity decreases along with increasing of height; when the wind speed is relatively low, the turbulence intensity at the wind speed greater than 12m/s can reflect the turbulence characteristics of typhoon in neutral atmosphere better. After being compared with codes of various countries, it is found that the variation trend of turbulence intensity along with height is consistent with that of normative empirical variation curve. However, the actually measured values of longitudinal turbulence intensity at different heights are all less than normative empirical value, which means that it is not suitable to adopt three normative empirical expressions to describe the turbulence profile of the typhoon “Soulik”. Therefore, we conduct exponential fitting to longitudinal turbulence intensity with mean wind speed greater than 12m/s, and the expression after fitting is \( I_u = 0.01(0.7 / z)^{0.97} \).
4.3. Gust Factor Profile

Figure 7 gives the variation law of actually measured gust factor along with height, and the result shows that the gust factors in various directions decrease along with increasing of height. For there is no definite rule about expression of gust factor profile, this thesis conducts the fitting like $G_i = \alpha \left( \frac{z}{10} \right)^\beta$ to gust factors in various directions. From the Figure, it can be known that the variation of actually measured gust factors in various directions along with height can be consistent with fitting results well, which means that the fitting expression can be used to describe the gust factor profile in the location of typhoon this time.

5. Conclusions

This thesis takes the 500kV power transmission pole tower in Ningde City, Fujian Province as observation point, and through the typhoon “Soulik” data actually measured at the heights of 15m, 27m, 53m, 67m and 82m, we have conducted research on near-earth wind profile and relevant parameters, and obtained the following conclusions:

(1) When the mean wind speed is less than 12m/s, the roughness index $\alpha$ will decrease along with increasing of mean wind speed, and the data is relatively dispersed, with the maximum value of 0.58 and the minimum value of 0.026; when the mean wind speed is greater than 12m/s, the roughness
index will not change along with mean wind speed; which is basically consistent with the conclusion in the reference [6].

(2) The variation of boundary layer height calculated according to formula along with mean wind speed is not obvious; the actually measured mean value is 2,007.89m, much higher than the 350m of boundary layer height under Category B terrain ruled in our country’s code. The conclusion obtained in this thesis is similar to the conclusions in reference [3] and reference [8].

(3) The variation law of the mean wind speed of typhoon “Soulik” along with height can be described with power law. The empirical expressions of longitudinal profiles in the USA, Japan and European Codes cannot be consistent with longitudinal turbulence profiles of typhoon this time, and this thesis obtains the expressions of longitudinal, horizontal and vertical turbulence profiles respectively through exponential type fitting.

(4) For there is no definite rule about expression of gust factor profile, this thesis conducts the fitting like to $G_i = \alpha \left( \frac{Z}{10} \right)^\beta$ actually measured gust factors. The actually measured gust factors can be consistent with fitting results well along with variation of height, and we also obtain the empirical expression of gust factor.

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