Study on Full-scale Measurements of Wind Field Characteristics of Coastal Complex Mountainous Terrains

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Abstract. Based on full-scale wind field measurements of coastal complex mountainous terrains, data of fluctuating wind velocities at the height of 30m for four sites, including mountaintop and hillsides, are obtained. The wind load characteristics of mean wind velocities, wind directions, turbulence intensities and speed-up ratios of wind velocities are comprehensively examined. Results show that the maximum mean wind velocity at the mountaintop site is 12.4 m/s. The probability density distributions of mean wind velocities for the four measurement sites can be well represented by the Weibull probability model. The predominant wind directions are around the northeast and southwest. The longitudinal, lateral and vertical turbulence intensities decrease with the increase of mean wind velocities. The turbulence intensities for the mountaintop site are as many as 0.13, 0.12 and 0.089 under maximum wind velocities, respectively for the previously mentioned three directions. The speed-up ratios of wind velocities between mountaintop and hillside sites are reduced, as the wind velocities increase. However, in cases of intensive wind with mean wind velocities larger than 8 m/s, the speed-up effects of wind velocities can also appear. The maximum speed-up ratio can reach 1.17.

Key words: Complex mountainous region; Wind field measurement; Mean wind velocity; Turbulence intensity; Wind speed-up ratio

1. Introduction

China is a country dominated by mountains, with the area of mountains accounting for about 70% of its land area [1]. In the mountainous environment where the transmission lines pass by, there are widespread acceleration and redirection effects of the terrain on the airflow. Due to heat exchange and terrain induced reasons, the wind field characteristics of the mountainous terrain greatly differ from those of the flat ground. That is, when the wind flows through mountains, hills and other areas with a complex terrain, the wind characteristics (such as wind pressure and turbulence structure) flowing in the atmosphere near the ground will change significantly, and the local wind velocity and wind direction will change drastically.

Wind tunnel tests and CFD simulations that are time-consuming, inexpensive, highly expandable in working conditions are the common means used to study wind fields of mountainous terrains. Bowen et
al. [2] studied the effect of different slope angles on wind profile characteristics based on the wind tunnel test; Ishihara et al. [3] studied the effect of wind velocity increase of several typical hills; Li et al. [4] carried out wind tunnel tests on hill models with different shelter distances, slopes and other parameters; Sun et al. [5] carried out wind tunnel tests on three-dimensional axisymmetric hill models with different slopes and heights; Shen et al. [6] studied the wind fields of an isolated hill and two adjacent hills using wind tunnel tests. Shen et al. [7] used the wind tunnel test method based on cobra probe to analyze the distribution characteristics of horizontal and vertical wind speed-up ratios in each wind angle, compared the horizontal wind speed-up ratio in typical wind directions with the codes of different countries, and finally proposed the design suggestions for three-dimensional wind field of complex mountains. Lun, et al. [8] simulated the terrain speed-up effect of wind field in typical two-dimensional mountainous terrains with different slopes by numerical simulations and defined the turbulence boundary conditions applicable to numerical simulations of two-dimensional terrains; Tamura, et al. [11] and Liu, et al. [12] studied the average and fluctuating wind field characteristics of two-dimensional and three-dimensional terrains by large-eddy simulations; Zheng Deqian, et al. [13] used a simplified steep hill with a slope angle of 45° as the research object, carried out the flow field analysis with CFD numerical simulation method, and analyzed in detail the effects of grid resolution, turbulence model, and local smooth treatment of slope crest on the accuracy of wind field under numerical simulation by comparing with wind tunnel tests and codes of different countries.

Although measuring wind fields of mountainous terrains is tedious and expensive, it is still the most realistic and effective way to obtain wind field parameters compared with the abovementioned tests or simulation methods. Miller et al. [14-15] proposed a speed-up ratio model for wind fields of mountainous terrains based on the measurement results; Song et al. [16] studied wind profile characteristics of complex terrains using observation data of near-ground layers in mountainous areas of Guizhou and Xinjiang. Currently, the finite study on the wind field measurement of mountainous terrains is mainly for inland mountainous terrains, and there is still a lack of studies on wind field measurement and wind field parameters in coastal complex mountainous terrains. The geomorphic type of mountainous coastal terrains is often distinct from the inland and susceptible to typhoons. The accurate identification of their wind field parameters has a significant effect on defining the design parameters for wind loads of transmission lines in coastal typhoon-prone areas.

In summary, wind field measurement is carried out on representative measuring points of coastal complex mountainous terrains. The mean wind velocity, wind direction, turbulence intensity, wind speed-up ratio and other wind load parameters in the coastal complex mountainous areas are explored in depth in this paper to provide data and theoretical support for improving the lean design of wind resistance of transmission lines in coastal complex mountainous terrains.

2. Overview of Wind Field Measurement

In this paper, a total of four measuring points are set up in a mountainous coastal terrain for the wind field measurement. Among them, the measuring point 4 is the hilltop measuring point, and the rest measuring points are distributed around the measuring point 4 in a triangle shape and located on open slopes at similar elevations with 80-200m distance from each other. At each of the measuring point, a triangle truss guyed tower is erected with a three-dimensional fluctuating wind meter and a data acquisition system installed at the height of 30m above ground, which collect data including three-dimensional wind velocity and wind direction at the sampling frequency of 10Hz. Locations of the said measuring points and wind measuring equipment are shown in Figure 1. The data was collected from January 13, 2021. A total of 132 days of complete data were collected by the end of May 2021 (some days of data were missing due to equipment debugging in the period of measurement). The subsequent research and analysis in this paper will be based on the data obtained.
3. Processing of Measured Data

3.1. Data Pre-processing

As the typhoon landing process is often accompanied by heavy rainfall, it easily leads to data anomalies. To ensure the validity of the measured data, the 4-time truncated variance method is used to eliminate outliers [17] and obtain reliable measured data that can be used for subsequent research and analysis. The specific calculation process is as follows.

For the wind velocity-time series \( v(t) \) \( (i=1,2,\ldots,n) \), the time series \( d v(t) \) is built,
\[
dv(t) = v(t + 2) - x(t), \quad (t = 1, 2, \ldots, n - 2)
\]

Calculate the mean value of time series \( dv(t) \) and \( dv(t)^2 \),
\[
\overline{dv} = \frac{1}{n-2} \sum_{i=1}^{n-2} dv(t)
\]
\[
\overline{dv^2} = \frac{1}{n-2} \sum_{i=1}^{n-2} dv(t)^2
\]

Calculate the truncated variance according to equation (4),
\[
\sigma = \overline{dv^2} - \left(\overline{dv}\right)^2
\]

Then the criterion for data outliers is,
\[
\Delta = a \times \sqrt{\sigma}
\]

in which, \( a \) is taken as 4. When \( |dv(i)| > \Delta \) or \( |dv(i+2)| > \Delta \), \( v(i+2) \) is regarded as a data outlier and directly eliminated.

3.2. Wind Speed and Wind Direction

The three directional axes, x-direction, y-direction and z-direction of the three-dimensional ultrasonic anemometer correspond to due north, due west and vertical directions respectively, the wind velocities-time courses obtained are denoted as \( u_x(t) \), \( u_y(t) \) and \( u_z(t) \) separately, and the mean wind velocities corresponding to the \( T=10\min \) time distance (basic time distance) are denoted as \( U_x \), \( U_y \) and \( U_z \).

According to the vector decomposition method [18], the mean wind velocity \( U \) in the incoming wind direction and the horizontal wind angle \( \alpha \) (with north wind as 0°, increasing clockwise when looked down) within the basic time distance are
\[
U = \sqrt{U_x^2 + U_y^2}
\]

\[\text{Figure 1. Locations of Wind Field Measuring Points and Test Equipment}\]
\[ \alpha = \arccos \left( \frac{U_x}{U} \right)^{\text{sep}(-U_x)} \times 180^\circ \]  

(7)

in which, \( \text{sep}(\cdot) \) is the step function. Within the basic time distance, the longitudinal fluctuating wind \( u(t) \), the lateral fluctuating wind \( v(t) \) and the vertical fluctuating wind \( w(t) \) can be calculated according to equations (8)-(10), respectively.

\[
\begin{align*}
    u(t) &= u_x(t)\cos \alpha + u_y(t)\sin \alpha - U \\
    v(t) &= -u_y(t)\sin \alpha + u_x(t)\cos \alpha \\
    w(t) &= u_z(t) - U_z
\end{align*}
\]

(8)-(10)

3.3. Turbulence Intensity

The turbulence is defined as the ratio of the root mean square of the fluctuating wind to the mean wind velocity, which can be calculated according to equation (11),

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

(11)

in which, \( \sigma_i \) represents for the root mean square of fluctuating wind in longitudinal (incoming wind direction), lateral (horizontal direction perpendicular to the incoming wind direction) and vertical directions.

3.4. Wind Speed-up Ratio

The horizontal wind speed-up ratio is,

\[ S_u(z) = \frac{U_i(z)}{U_0(z)} \]

(12)

where, \( U(z) \) is the mean wind velocity at a measuring point \( z \) high from the mountain surface; \( U_0(z) \) is the mean wind velocity of the incoming airflow at the corresponding height; the height \( z \) of wind velocity above ground is 30m in the study on measurement of this paper.

4. Analysis of Measured Data

4.1. Mean Wind Velocity and Wind Direction

Figure 2 gives the scatter plot of mean wind velocities in 10min at four measuring points in the horizontal direction, and the results show that the mean wind velocities at each measuring point basically range between 0 and 15m/s, and the wind velocities at the hilltop measuring point (measuring point 4) have a large range of variations with the maximum wind velocity up to 12.4m/s. For the hillside measuring points, the mean wind velocities at measuring point 1 are low and basically less than 10m/s. To further study the pattern of mean wind velocities at each measuring point, the histograms of the probability density distribution of mean wind velocities at measuring points 1-4 are given in Figures 3-6. According to the figures, the probability density distribution of mean wind velocities at each measuring point is left-skewed compared with the mean value, and the mean values for each measuring point are 3.9m/s, 5.5m/s, 5m/s, and 6.2m/s, respectively. The Weibull distribution model is used for probability distribution fitting of mean wind velocities at each measuring point, and the results show that it has a good fitting effect and can reflect the probability distribution shapes and values of the mean wind velocities at each measuring point.
Figure 2. Horizontal Mean Wind Velocity in 10min of Each Measuring Point

Figure 7 shows the distribution diagram of wind directions corresponding to mean wind velocities at each measuring point. For measuring point 1, the dominant wind directions are broad and mostly in the northeast by east and southwest by south, and the wind direction with the maximum wind velocity is in the northwest by north; for measuring points 2-3, the dominant wind directions are roughly northeast and southwest, and the maximum wind velocities all occur in the southwest wind range; for the hilltop measuring point (measuring point 4), the dominant wind direction is similar to that of measuring points 2-3, but the maximum wind velocity occurs in the range corresponding to northeast wind velocities. In general, the measured periods in this paper are mostly in winter and spring. By considering the effects of local monsoon wind direction and mountain body, the mean wind velocities of the said four measuring points are mainly in northeast and southwest directions, and the maximum wind velocity at each measuring point basically occurs under the said dominant wind direction conditions.

Figure 3. Probability Density Distribution and Fitting Curve of Mean Wind Velocity at Measuring Point 1
Figure 4. Probability Density Distribution and Fitting Curve of Mean Wind Velocity at Measuring Point 2

Figure 5. Probability Density Distribution and Fitting Curve of Mean Wind Velocity at Measuring Point 3

Figure 6. Probability Density Distribution and Fitting Curve of Mean Wind Velocity at Measuring Point 4
4.2. Turbulence Intensity

Based on the analysis of turbulence intensity data at four measuring points in this paper, the representative cases with great (measuring point 4) and small (measuring point 1) maximum mean wind velocities are selected for analysis in this paper, as shown in Figure 8. For measuring point 1, as shown in Figure 8(a), its mean wind velocities are low in magnitude, not more than 8 m/s. The longitudinal, lateral and vertical turbulence intensities decrease gradually as the mean wind velocity increases, and the decay rate is high under gentle wind conditions (when the mean wind velocity is less than 2 m/s). The decay rate tends to level off as the mean wind velocity increases further, and when the mean wind velocity reaches its maximum, the relevant turbulence intensities in three directions are 0.034, 0.043, and 0.041, respectively. For measuring point 4 [Figure 8(b)], its mean wind velocities have greater magnitude, and the overall variation trend of its turbulence intensities with the mean wind velocity is in line with situations of measuring point 1. The variation in turbulence intensities in three directions with the wind velocities is almost stable for the high wind velocity samples, especially when the wind velocity is greater than 8 m/s. The turbulence intensities corresponding to the maximum wind velocity are 0.13, 0.12, and 0.089, respectively. The longitudinal turbulence intensity is more than 2.8 times larger than the results of measuring point 1.
Figure 8. Turbulence Intensity Variations with Mean Wind Velocity for Measuring Points 1 and 4

4.3. Wind Speed-up and Sheltering Effect

Figure 9 gives a scatter plot of horizontal wind speed-up ratio varying with the mean wind velocity at the hilltop measuring point (measuring point 4) in comparison with the hillside measuring points. To reduce the negative effect of small wind velocity samples on the result analysis, only the cases with mean wind velocity higher than 5m/s are shown in Figure 9. Compared with measuring point 1, the horizontal wind speed-up ratio ($U_4/U_1$) at measuring point 4 is more than 1 for most of the time, and the maximum wind speed-up ratio is 1.46, which corresponds to a wind velocity of 5.03 m/s. The wind speed-up ratio ($U_4/U_1$) at measuring point 1 is close to 1 for the maximum wind velocity. Compared with measuring point 2, the maximum value of $U_4/U_2$ is less than 1.3; when $U_2$ is above 10m/s, $U_4/U_2$ drops to below 1, with a mean value of 0.93. In comparison with measuring point 3, $U_4/U_3$ is up to 1.54, corresponding to a wind velocity of 5.37m/s; the wind speed-up effect is still significant when the wind velocity is high ($U_3$ over 8m/s), and the wind speed-up ratio is between 1.04 and 1.17.
5. Conclusion

Based on wind field measurement of representative measuring points in coastal complex mountainous terrains, data of fluctuating wind 30m above ground are obtained at four measuring points, including hilltop and hillside. The characteristics of wind load parameters such as mean wind velocity, wind direction, turbulence intensity and wind speed-up ratio in the coastal complex mountainous terrains are explored. Conclusions are drawn as follows:

(1) Based on the existing measured data, the mean wind velocities at each measuring point, including hilltop and hillside basically range between 0 and 15m/s, and the maximum wind velocity at the hilltop measuring point is 12.4m/s. The probability distribution model of mean wind velocities at each measuring point can be represented by the Weibull distribution model that has a good imitative effect.

(2) Considering the effects of local monsoon wind direction and mountain, the mean wind velocities at the four measuring points in this paper are mainly in northeast and southwest directions, and the maximum wind velocities at each measuring point basically occur in the said dominant wind directions.

(3) Longitudinal, lateral and vertical turbulence intensities at each measuring point gradually decrease as the mean wind velocity increases, and the decay rate is high under the gentle wind conditions. The decay rate tends to level off as the mean wind velocity increases further. When the mean wind velocity at the hilltop measuring point reaches its maximum, the relevant turbulence intensity ratios in the said three directions are 0.013, 0.012, and 0.089, respectively.

(4) In comparison with the hillside measuring points, the horizontal wind speed-up ratio at the hilltop measuring point gradually decreases as the mean wind velocity increases. The wind speed-up effect may still be significant in the case of strong winds with a mean velocity greater than 8m/s, and the speed-up ratio can be 1.17 at most.

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