ESTIMATION OF DIRECTIONAL EXTREME WIND SPEED IN MIXED CLIMATES COMBINED WITH TYphoon SIMULATION

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ABSTRACT

To date, no method that can provide directional extreme wind speed estimates in mixed climates has been established. A new definition for design wind speeds that considers wind direction is proposed in this paper. Samples of extreme wind speeds in two types of climates are obtained separately through the Monte Carlo method. Results are presented and discussed with Shanghai as the example.

Keywords: Mixed climate, Wind direction, Extreme wind speed, Typhoon simulation, Correlation

Introduction

Davenport (1964; 1977; 1961, 1983) pointed out that researchers must consider wind direction to accurately estimate wind load on a structure.

Only annual maximum wind speeds in normal-wind climate zones are utilized in the traditional wind extremum estimation method. This process leads to significant wastage of relevant wind speed data, and consequently, the lack of information for estimating directional extreme wind speeds. Cook (1982) developed a stable estimation method based on independent storm records to improve data utilization rate, thus making it possible to analyze wind speed in each wind direction. Cook (1983; 1999) proposed a practical method to estimate directional design wind speeds based on a previous technique.

However, in typhoon-prone coastal areas, sampling and analyzing wind speed in mixed climates lead to false results because of the difference between the distributions of extreme wind speed of typhoons and normal wind. Gomes and Vichery (1978) presented an extreme wind speed estimation method based on mixed climates, which was later improved by Cook, Harris, and Whiting (2003). The confidence intervals of the improved method were provided by Cook (2004). However, no method can provide directional extreme wind speed estimates in mixed climates because of the lack of extreme wind speed records for cyclones. By contrast, methods for typhoon simulation have been sufficiently developed. For example, the typhoon wind field model established by Yan Meng (1995, 1997) can provide complete analytical solutions.

A new definition for design wind speed that considers wind direction is proposed in this paper. Samples of extreme wind speed in two types of climates are obtained separately through the Monte Carlo method. The results are presented and discussed with Shanghai as an example.
Definition of Directional Design Wind Speed

The definition of directional design wind speed $v_{R,dir}$ for $dir = 1, 2, \ldots, M$ under return period $R$ is as follows. (1) The probability that annual maximum wind speed $V_{dir,max}$ is smaller than design wind speed $v_{R,dir}$ in all directions is $1 - 1/R$. That is, the probability of exceedance for any one year is $1/R$ as shown in the following equation.

$$\Pr\{ V_{dir,max} < v_{R,dir}, dir = 1, 2, \ldots, M \} = 1 - \frac{1}{R}. \tag{1}$$

(2) The probability of exceedance in each wind direction is constant in one year. Such probability can be expressed as follows:

$$\Pr\{ V_{dir,max} < v_{R,dir} \} = \text{const}, \quad dir = 1, 2, \ldots, M. \tag{2}$$

In this study, $dir$ represents wind directions and $M$ is the number of wind directions. The wind direction in China is often divided into 16 sectors. We let 1 identify the sector in the north, 2 identify the sector in the north by east, and so on. This manner of dividing and numbering was implemented in this study.

The following two extreme cases were considered.

Case 1: Wind speeds in different wind directions are entirely positively correlated, which means that wind speeds in all the directions always reach their maximum once in $R$ years at the same moment. Hence,

$$\Pr\{ V_{dir,max} < v_{R,dir}, dir = 1, 2, \ldots, M \} = \Pr\{ V_{dir,max} < v_{R,dir} \} = 1 - \frac{1}{R}. \tag{3}$$

Case 2: Wind speeds in different wind directions are entirely independent. In this case,

$$\Pr\{ V_{dir,max} < v_{R,dir}, dir = 1, 2, \ldots, M \} = \prod_{dir} \Pr\{ V_{dir,max} < v_{R,dir} \}. \tag{4}$$

Combining Eqs. (1) and (2) provides

$$\Pr\{ V_{dir,max} < v_{R,dir} \} = \left(1 - \frac{1}{R}\right)^{\frac{1}{M}}. \tag{5}$$

In reality, wind speeds in different wind directions are positively correlated although this correlation might be weak. Thus, the true value of $\Pr\{ V_{dir,max} < v_{R,dir} \}$ should be in the interval

$$1 - \frac{1}{R} < \Pr\{ V_{dir,max} < v_{R,dir} \} < \left(1 - \frac{1}{R}\right)^{\frac{1}{M}}. \tag{6}$$

If we introduce the value $\gamma$, the following equation can be obtained:

$$\Pr\{ V_{dir,max} < v_{R,dir} \} = \left(1 - \frac{1}{R}\right)^{\frac{1}{\gamma M}}. \tag{7}$$

$\gamma M$ can be considered the number of wind directions in which wind speeds are entirely independent. According to Eq. (3), $1 < \gamma M < M$.

If a huge set of annual maximum wind speed data is available for each wind direction, the value of $\gamma$ and the empirical distribution of $V_{dir,max}$ can be easily obtained. Therefore, $v_{R,dir}$ can be ascertained by Eq. (7). The Monte Carlo method was used in this study to obtain huge data sets.
Sampling Extreme Wind Speeds in Two Types of Climates through the Monte Carlo Method

Shanghai, a coastal city in China, was used as an example in this study. The sampling methods adopted to obtain extreme wind speeds from typhoons and normal wind were introduced separately.

Sampling Annual Maxima from Typhoons

The actual structure of typhoons is complex. However, all typhoons have a similar structure, which can be described by a set of key parameters. Wind speed processes can be simulated with the Monte Carlo method.

Xiao et al. (2011) summarized the statistic models of the key parameters for all the typhoons that once affected wind speed in Shanghai. Typhoon data were obtained from the Tropical Cyclone Yearbook (1949 to 2008) published by China Meteorological Administration. These data include the location and strength of typhoons every 6 h. The State Oceanic Administration also provides some useful information. The key parameters and their statistic models are reported as follows.

1. Annual incidence rate: A number of typhoons enter the range of 500 km distance around Shanghai. This parameter can be fit by Poisson distribution with the parameter 2.74.

2. Moving direction: This parameter is calculated based on two adjacent coordinate records of the typhoon center. North is represented by 0°, and clockwise is positive. This parameter can be fit by bivariate normal distribution with the probability density function

\[
f(x) = \frac{a_1}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{(x-\mu_1)^2}{2\sigma_1^2}\right) + \frac{1-a_1}{\sqrt{2\pi}\sigma_2} \exp\left(-\frac{(x-\mu_2)^2}{2\sigma_2^2}\right), \quad x \in (-180, 180],
\]

where \(a_1 = 0.63\), \(\mu_1 = -60.07\), \(\sigma_1 = 31.22\), \(\mu_2 = 59.22\), and \(\sigma_2 = 39.35\).

3. Traveling speed: This parameter is calculated based on two adjacent coordinate records of the typhoon center. Empirical distribution was used in this study because the use of fitting distribution would yield a large error.

4. Central pressure difference: The difference between the central pressure of the typhoon and atmospheric pressure. Empirical distribution was used because the use of fitting distribution would yield a large error.

5. Minimum distance between the typhoon track and Shanghai: This parameter is calculated based on the coordinate records of the typhoon center. Empirical distribution was used because the use of fitting distribution would yield a large error.

6. Maximum wind radius: The natural logarithm of this parameter and central pressure difference is assumed to have a linear relation, which can be represented as

\[
\ln R_{max} = c_0 + c_1\Delta p + \epsilon_1,
\]

where \(R_{max}\) is the maximum wind radius in km; \(\Delta p\) is the central pressure difference in hPa; \(c_0\) and \(c_1\) are the fitting coefficients with the values of 5.0705 and -0.0214, respectively; and \(\epsilon_1\) is a random error that follows a Gaussian distribution with a standard deviation of 0.4459.

7. Attenuation model: When a typhoon lands, its energy and strength are reduced. An exponential model was used in this study to describe the attenuation pattern of the typhoon after landing. The model is represented as follows:

\[
\Delta p(t) = \Delta p_0 \exp\left(-at - b\right),
\]

where \(t\) is the time of typhoon landing with the unit of hour and \(b\) follows a Gaussian distribution with a mean value of 0.0458 and standard deviation of 0.1522. The expression is

\[
a = a_0 + a_1\Delta p_0 + \epsilon_2,
\]
where \( c_0 \) and \( c_1 \) are 0.0083 and 0.0005, respectively; \( \varepsilon_i \) is a random error that follows a Gaussian distribution with a standard deviation of 0.0171.

(8) Pressure profile constant \( B \): This parameter is difficult to determine because meteorological institutions in China have no information on this parameter. Applying empirical formulas provided by researchers in other countries is not suitable because these formulas were not established to describe typhoons in the northwest Pacific Ocean. In this study, the formula provided by Jakobsen and Madsen (2004) was adopted. The formula is as follows:

\[
B = \frac{e \rho_d}{1.05 \Delta p} (V_{\text{max}})^2, \tag{12}
\]

where \( \rho_d \) is air density and \( V_{\text{max}} \) is maximum wind speed. All the values in Eq. (12) use SI units. Eq. (12) is derived with the typhoon momentum equation combined with typical values. The value of \( B \) must be obtained from iterated computation after the other key parameters are determined because wind speed is included in the formula.

Average wind speed at the height of 10 m with standard ground roughness (exponential wind speed profile with the parameter of 0.15 according to the wind load code of China) is the focus of this study. The typhoon wind field model established by Yan Meng (1995, 1997) was employed to calculate wind speeds in Shanghai. The annual maxima wind speed for each direction was generated as follows:

Step 1: We assumed that a random number of typhoons occurred in this virtual year according to the distribution of annual incidence rate. Key parameters were assigned to each typhoon.

Step 2: We assumed that each typhoon passed through the area of 500 km distance around Shanghai. The wind speed in Shanghai per hour was then calculated. The time history of wind speed and wind direction was also recorded.

Step 3: We determined the maximum wind speed in each direction in this virtual year.

**Sampling Annual Maximum from Normal Wind**

Extreme wind speeds were sampled from normal wind through the Monte Carlo method to combine samples of extreme wind speeds from normal wind with those from typhoons.

The daily wind data utilized in this paper were obtained from the meteorological station in Shanghai Longhua. The data include 12,784 daily maximum wind speed records with an average of 10 min from January 1, 1956 to December 31, 1990. The records after 1990 were not used because of the huge environmental change around the meteorological station after this period.

![Fig. 1. Comparison of the proposed MIS and Cook’s MIS.](image-url)
The method of independent storm (MIS) was utilized to process daily wind data. The MIS used in this study is different from Cook’s MIS. As shown in Fig. 1, each maximum wind direction in the independent storm should be selected. Samples from the same wind direction should be entirely independent of one another because they were obtained from different independent storms. The figure also shows that strong wind speed samples in several directions are disregarded in Cook’s MIS because only one value is selected from an independent storm. This problem can be avoided in the proposed method.

A total of 2350 wind speed samples with a threshold of 6.7 m/s were obtained after omitting wind speeds influenced by typhoons. The cumulative distribution function of annual maximum wind speeds in each direction was fitted with XIMIS (Harris, 2009).

The annual maxima wind speeds of normal wind in each direction were simulated based on these pieces of information; their values were also recorded.

Blending Annual Maximum Samples of Two Climates

The larger value of annual maximum wind speed of the two types of climates in each direction was selected. This process was repeated \(1 \times 10^6\) times. A data set for annual maximum wind speeds in mixed climates was then obtained.

The following two points were duly noted in the Monte Carlo simulation.

1. The correlation among extreme wind speeds in different wind directions is disregarded in the Monte Carlo simulation on normal wind because asymptotic independence character (Coles, 2001) is observed among wind speeds in different wind directions in normal wind climates. The tail dependence coefficients of wind speeds in different wind directions in most Chinese inland cities can be calculated to affirm this characteristic.

2. Wind speed records influenced by typhoons are omitted in the simulation on normal wind. These data are useless in directional extremum estimation because a typhoon can have extreme-level wind speed in more than one direction in one day. Several daily maxima wind speed cannot used to represent the maxima wind speed of a typhoon in all directions. However, these omitted data can still be used to check whether the result of the simulation is reasonable.

Checking Reasonableness

The correctness of the samples was checked by comparing the simulated results with the measured data before using the results of simulation. The daily maxima wind speed records from the meteorological station in Shanghai Longhua were used as the measured data. Eight-day maxima or storm maxima (Cook, 1982) were plotted on Gumbel probability paper together with the simulated results as shown in Fig. 2. Wind direction need not be considered in this case. Hence, only the maxima of the wind speeds from all directions, i.e., the annual maxima wind speeds, were plotted. The bootstrap procedure described by Cook (2004) was applied to derive the mean plotting positions that represent the empirical distribution. The difference between the empirical distributions of the simulated results and the measured data are not obvious as can be seen in Fig. 2.

Hypothesis testing was performed to quantify the reasonableness of the simulated results. The hypotheses are as follows:

\(H_0\): The empirical distribution of the simulated results can be regarded as the actual distribution of annual maxima wind speed in mixed climates.

\(H_1\): The empirical distribution of the simulated results has an extremely large error that it should not be trusted.

The significance level was set as \(\alpha = 0.05\). We let \(v_1 < v_2 < \ldots < v_m < \ldots < v_n\) be the sorted measured data (i.e., eight-day maxima or storm maxima) and \(N_s\) be the data size.
According to Harris (1996), the real non-exceedance probability of \( v_m \) should be a random variable in which the probability density function is

\[
\phi_m(p_m) = \frac{\Gamma(N_s+1)}{\Gamma(N_s-m+1)\Gamma(m)} p_m^{m-1}(1-p_m)^{N_s-m},
\]

where \( p_m \) is the real non-exceedance probability of \( v_m \) and \( \Gamma(*) \) is the famous Gamma function. The upper and lower limits of the 95% confidence interval of \( p_m \) are ascertained by

\[
1 - \frac{\alpha}{2} = \int_0^{\phi_m(p)} dp = I_{p_{\text{up}}}(m, N_s-m+1),
\]

\[
\frac{\alpha}{2} = \int_0^{\phi_m(p)} dp = I_{p_{\text{low}}}(m, N_s-m+1),
\]

where \( P_{\text{up}} \) and \( P_{\text{low}} \) are the upper and lower limits. \( I_x(z, w) \) is the incomplete Beta function, which can be represented as follows:

\[
I_x(z, w) = \frac{\Gamma(z+w)}{\Gamma(z)\Gamma(w)} \int_0^x t^{z-1}(1-t)^{w-1} dt.
\]

The inverse function of \( I_x(z, w) \) is included in Matlab (R2013a) to determine the value of \( x \) when \( z, w \), and the function value are known. The value of \( P_{\text{up}} \) and \( P_{\text{low}} \) can be conveniently calculated by a computer program written in Matlab language. Hence, the upper and lower limits of the 95% confidence interval of yearly non-exceedance probability are \( (P_{\text{up}}) \) and \( (P_{\text{low}}) \), where \( r \) is the average number of the measured samples in one year. With the empirical distribution of annual maxima wind speeds in mixed climates, the upper and lower limits of the 95% confidence interval of \( v_m \) were obtained and then plotted in Fig. 2. This interval means that if \( H_0 \) is true, every measured sample \( v_m \) has a 95% probability of being within this interval. Fig. 2 shows that all the measured samples are within this interval. Therefore, the null hypothesis, i.e., the results of the simulation in this study are reasonable, is accepted.

Fig. 2. Comparison of the empirical distributions of the simulated results and the measured data (left: eight-day maxima, right: storm maxima).

**Estimating Directional Extreme Wind Speeds in Mixed Climates**

A huge data set for annual maximum wind speeds in mixed climates was obtained in the previous section. Prior to using Eq. (7) to estimate directional design wind speeds \( v_{R, \text{dir}} \), the value of \( \gamma \) must be ascertained.

Suppose that \( v_{\text{dir},	ext{i}} \) is the \( i \)th sample of annual maximum wind speeds in direction \( \text{dir} \). In this case, \( \text{dir} = 1, 2, \ldots, M ; \ i = 1, 2, \ldots, N ; \) and \( N \) is the data size, which is \( 1 \times 10^6 \) in this study. In each direction \( \text{dir} \), \( v_{\text{dir},	ext{i}} \) must be replaced with probability \( P_{\text{dir},	ext{i}} \), which can be represented as follows:
where $m_{\text{dir},d}$ is the rank of $v_{\text{dir},d}$ in direction $\text{dir}$. $m_{\text{dir},d}=1$ if $v_{\text{dir},d}$ is the smallest sample in direction $\text{dir}$, $m_{\text{dir},d}=2$ if $v_{\text{dir},d}$ is the second smallest sample in direction $\text{dir}$, and so on. We let

$$p_i = \max_{m_{\text{dir},d}} \left( p_{\text{dir},d} \right).$$

This $p_i$ array is arranged from smallest to largest. The $\text{round}\left(\left(\frac{N+1}{1-1/R}\right)\right)$th value was obtained from this sorted array, and the value of $(1-1/R)^{\frac{1}{\gamma M}}$ was derived. $\text{round}(\cdot)$ means that the number in the parenthesis is rounded off to the nearest integer. After a simple algebraic operation, the value of $\gamma$ was obtained.

The directional design wind speeds can then be ascertained by combining Eq. (7) with the empirical distribution of wind speed in each direction. After calculation, the design wind speeds at a return period of 50 years were determined to be 26.70 m/s (disregarding wind directions), 29.53 m/s in direction ESE (which is the maximum), and 22.86 m/s in direction WNW (which is the minimum). The design wind speeds are shown in Fig. 3. The result is in accordance with the geographic feature of Shanghai, which is a southeast coastal city.

**Discussion**

**Advantage of Separate Sampling from Two Climates**

The comparison between the outcomes of the present method and those of fitting by stage-maxima method is shown in Fig. 4. Sampling wind speeds in typhoon-prone coastal areas without discriminating between typhoons and normal wind leads to false results. The empirical distribution of the 8 d maxima exhibits an increasing trend in the upper tail. The stage-maxima method fails to achieve such increase and leads to the wrong conclusion that the design wind speed increases with the observation interval. The method proposed in this paper solves the aforementioned problem by separately sampling extreme wind speeds from typhoons and normal wind. The results are appropriate for demonstrating the distribution of extreme wind speeds in two types of climates and the reasonable transition between them. Therefore, the results of the proposed method are closer to the actual results.
Correlation Parameter $\gamma$

The calculation of $\gamma$ indicates that this value changes with return period $R$. The value of $\gamma$ is plotted versus return period $R$ in Fig. 5. $\gamma$ is mainly controlled by typhoons and indicates a strong correlation among the extreme wind speeds in different directions.

![Fig. 5. Change in the value of $\gamma$ with return period $R$.](image)

The correlation among extreme wind speeds in different wind directions is disregarded in Monte Carlo simulation on normal wind. That is, the value of $\gamma$ for normal wind should always be 1. However, the line for normal wind in Fig. 5 fluctuates when $R > 1000$ because the number of extreme data is gradually reduced with the increase in $R$. This condition can cause an error in the estimation of directional wind speeds. Hence, we suggest that the number of simulated samples in every direction be more than $1000R$ if directional design wind speeds at a return period of $R$ years are the goal.

Conclusion

A new definition for design wind speeds that considers wind direction is proposed in this paper. Samples of extreme wind speeds in two types of climates were obtained separately.
through the Monte Carlo method. The results of design wind speeds were presented and discussed with Shanghai as an example. The following conclusions were obtained.

1. The proposed new definition of directional design wind speed considers the correlation among the extreme wind speeds in different directions.

2. Separate sampling from two climates optimizes the estimation of extreme wind speeds. The proposed method reveals the distribution of extreme wind speeds in two types of climates and the reasonable transition between them. Therefore, the results of the proposed method are closer to the actual results.

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