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Estimation of Extreme Wind Speeds with Consideration of Wind Directionality for Typhoon-prone Areas

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Abstract

Considering wind directionality effect in estimating extreme wind speeds is important for evaluating design wind loads on structures. A estimate method of directional extreme wind speeds is established for typhoon-prone areas using the Copula theory and the Monte Carlo simulation. At first, an approach of estimating extreme wind speeds for a given return period is established for typhoon-prone areas with consideration of directionality based on the Sklar theorem and the empirical Copula function. Next, the annual maximum wind speeds of typhoon and monsoon are generated by Monte Carlo simulations respectively. Then, the samples in mixed climates are obtained by taking the larger annual maximum wind speeds of typhoon and monsoon. Finally, taking Shenzhen as an example, the directional extreme wind speeds for 10-year, 50-year and 100-year return periods are estimated and the influence of wind directionality on the estimated results in mixed climates are discussed.

Introduction

The estimates of extreme wind speed are both affected by the sample size and sample quality. The quantity and quality of observed wind-speed data in monsoon areas are often reliable. So the extreme wind speeds in monsoon areas are generally estimated with observed wind-speed records from meteorological stations. However, the recurrence rate of typhoon is much lower than monsoon and the anemometers are vulnerable to damage from typhoon, typhoon wind-speed records are often too short to statistically determine the wind climate of a given area [15]. Therefore mature prediction of extreme typhoon speed using numerical modeling is commonly used at the international level [17]. The predecessors [7,1,9,6,11,8,12] have successively established the typhoon numerical models for wind engineering to simulate the typhoon wind speeds. The typhoon model is often parameterized by a set of key typhoon parameters [15]. The series of typhoon wind speeds can be generated by Monte Carlo simulation based on the typhoon numerical models with the set of key typhoon parameters. The extreme wind speeds for a given return period are estimated by statistic method with the annual maximum of the generated wind-speed samples.

The importance of considering wind directionality effect in estimating probabilistic wind load effects of structures has been well recognized [16]. However, the dependence among directional extreme wind speeds have not been fully considered in previous analysis of extreme wind speeds based on the typhoon simulation. In addition, since both of the typhoon and monsoon are main climates in middle and low latitude coastal areas, these two main climates are both need to be considered for these areas. To solve the above problem, a new estimate method of directional extreme wind speeds is established for typhoon-prone areas in present study.

The Proposed Approach

distribution of directional extreme wind speed for typhoon-prone areas can be divided into two aspects:

1) The estimation of one-dimensional marginal distribution functions in each sector with the simulated annual maximum wind speeds in mixed climates.

2) The estimation of Copula model to consider the correlation of extreme wind speeds among different sectors.

The one-dimensional empirical distribution [3] and the empirical Copula function [4] are adopted to describe the probabilistic information of the directional extreme wind speeds in mixed climates. The expression of the estimated joint distribution in present study is

$$F\left(v_1, v_2, \cdots, v_N\right) \approx C_{emp}\left(F_{emp,1}\left(v_1\right), F_{emp,2}\left(v_2\right), \cdots, F_{emp,N}\left(v_N\right)\right) \tag{1}$$

where $F_{emp,n}(v_n)$ (n=1,2,···,N) is the one-dimensional empirical distribution [3] in the n^{th} sector. $C_{emp}(\cdot)$ denotes the empirical Copula function [4].

The relationship between the return period R and the directional extreme wind speeds v_1 , v_2 , ···, v_N is

$$1-\frac{1}{R} \approx C_{emp}\left(F_{emp,1}\left(v_1\right), F_{emp,2}\left(v_2\right), \cdots, F_{emp,N}\left(v_N\right)\right) \tag{2}$$

where the non-exceedance probability $F_{emp,n}(v_n)$ of each sector is assumed to be the same value to ensure the same degree of safety in each sector and to avoid the infinitely many solutions of equation (2). Then, the directional extreme wind speeds for a given return period R can be solved based on equation (2).

When the directional extreme wind speed of each sector is assumed to be the same value, the all-directional extreme wind speeds for a given return period R can be solved based on equation (2).

Production of the Annual Maximum Wind-Speed Samples

The annual maximum of 10-min average typhoon wind speeds at 10-m level in countryside (the roughness length z_0 is 0.05 [14] are simulated with the typhoon wind field model proposed by [8] and the probabilistic distributions of the key typhoon parameters proposed by [15]. The tracks of the virtual typhoon are assumed to be a straight line in its evolution [15]. The expression of the pressure profile constant B proposed by [5] is adopted since the data of radial profile of air pressure is unavailable in the southeast China coastal regions [17].

The typhoon-affected wind-speed records are removed from the raw observed data of meteorological station before the Monte Carlo simulation of the annual maximum monsoon wind speeds. This process needs to refer to the historical meteorological data in the given site. Then the samples of directional monthly maximum wind speeds is generated by t-Copula model [13] with the rest of the observed data.

The simulated results of typhoon and monsoon are saved as two matrices. The matrix of the annual maximum wind-speed samples in mixed climates is obtained by taking the larger value of each elements of the two matrix.

Results and Discussion

Shenzhen (a typhoon-prone area in the southeast China coastal regions) is taken as an example for the extreme wind-speed analysis. At first, 1×10^6 annual maximum of 10-min average typhoon wind speeds at 10-m level in countryside are simulated for Shenzhen by the Monte Carlo method.

Then, The directional wind-speed samples of monsoon are generated based on the 10-min average wind-speed records from December 1st, 1996 to January 31th, 2016 at meteorological station 59493 in Shenzhen China. Since the wind above 6 beaufort scale (containing the 6 beaufort scale, about 10.8m/s) is considered in the typhoon wind hazard analysis for China coastal regions in [2], the wind speeds which are above 10.8m/s are removed to eliminate the impact of typhoon on monsoon simulation. 1×10^6 annual maximum of monsoon wind speeds are generated by t-Copula model [13] with the rest of the observed data. Finally, the annual maximum wind-speed samples in mixed climates is obtained based on the simulated typhoon and monsoon wind-speed samples.

The directional extreme wind speeds $v_{R,dir}$ (dir=1,2,···,N) and the all-directional extreme wind speed $v_{R,all}$ for 10-year, 50-year, 100-year return periods are estimated by the proposed approach. The directional extreme wind speeds $v_{R,dir,ind}$ (dir=1,2,···,N) in the independent case (in which the dependence among extreme wind speeds in different directions are ignored) are also estimated. For quantify the effect of wind directionality on the estimated results, the directional-dependence factor of the basic wind speed is defined as

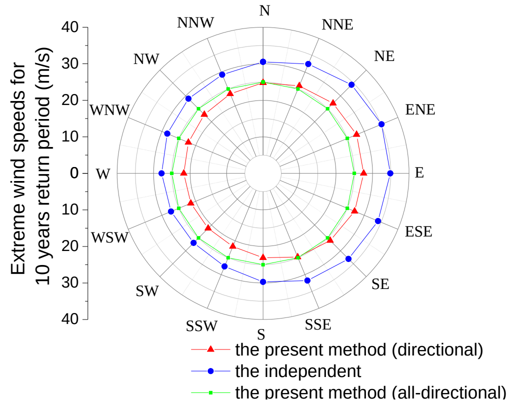
$$\gamma_{r,R,dir} = \frac{v_{R,dir}}{v_{R,dir,ind}} \tag{3}$$

and the direction factor of the basic wind speed is defined as

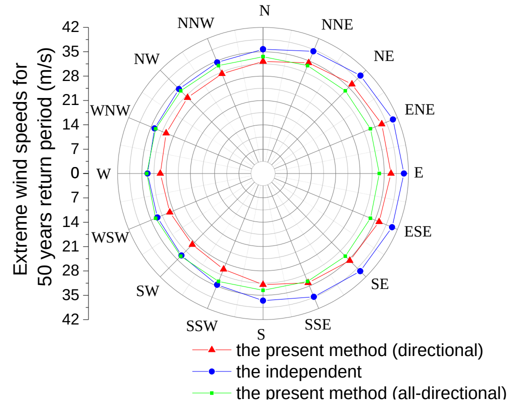
$$\gamma_{d,R,dir} = \frac{v_{R,dir}}{v_{R,all}} \tag{4}$$

$v_{R,dir}$, $v_{R,all}$ and $v_{R,dir,ind}$ are compared in figure 1. They are obviously different. The estimated results in independent case are too conservative. Using $v_{R,all}$ as the basic wind speed will be more conservative than using $v_{R,dir}$ in westerly wind-directions and will be less secure in easterly wind-directions.

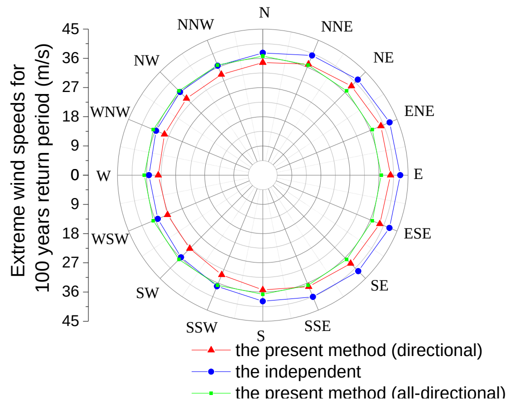
The directional-dependence factors of the basic wind speed for 10-year, 50-year and 100-year return periods in Shenzhen are shown in figure 2. The estimated results are obviously overestimate, if the dependence among extreme wind speeds in different directions are ignored. The directional-dependence factors of the basic wind speed for 10-year return periods are close to 0.8. The directional-dependence factors of the basic wind speed for 50-year and 100-year return periods are close to 0.9. The overestimations for a low return period (10-year) are higher than the overestimations for a long return period (50-year or 100-year). These may lead to the more conservative wind loads on structures. So the dependence among directional extreme wind speeds are not negligible in typhoon-prone areas. Using $v_{R,dir,ind}$ (dir=1,2,···,N) as the basic wind speeds is too conservative.



a 10-year return period



a 50-year return period



a 100-year return period

Figure 1. The estimated directional extreme wind speeds (by the proposed method or the independent case) and the estimated all-directional extreme wind speed

The direction factor of the basic wind speed for 10-year, 50-year and 100-year return periods in Shenzhen are shown in figure 3. The direction factors of the basic wind speed in several sectors are less than 1.0. Some of them are less than 0.9, Using $v_{R,all}$ as the basic wind speed is too conservative in these sectors. The direction factors of the basic wind speed in several sectors are larger than 1.0 in figure 3. Some of them are close to 1.1. Since the winds in different sectors may have different characteristics, setting a same value $v_{R,all}$ to represent the extreme wind speeds in different sectors will lead to unreasonable design.

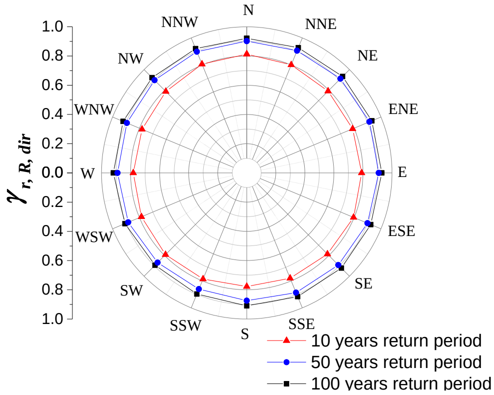


Figure 2. The directional-dependence factor of the basic wind speed in Shenzhen

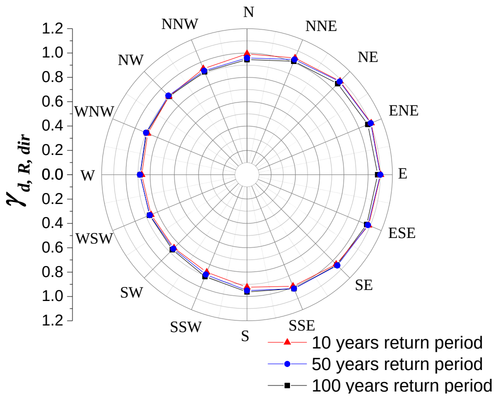


Figure 3. The direction factor of the basic wind speed in Shenzhen

Conclusions

A new extreme wind analysis method which can fully consider the dependence among extreme wind speeds in different directions is established for typhoon-prone areas in present study. In addition, the influence of wind directionality on the estimated results in mixed climates are discussed. Several conclusions are obtained:

1) The dependence among extreme wind speeds in different directions are not negligible in typhoon-prone areas. If they are ignored, The results are obviously overestimate. The overestimations for a low return period (10-year) are higher than the overestimations for a long return period (50-year or 100-year).

2) Using the all-directional extreme wind speed as the basic wind speed will be more conservative than using directional extreme wind speed in some sectors and will be less secure in other sectors. Setting an all-directional extreme wind speed to represent the extreme wind speeds in different sectors will lead to unreasonable design.

Acknowledgments

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