Journal of Wind Engineering & Industrial Aerodynamics 173 (2018) 227–240

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Revised power-law model to estimate the vertical variations of extreme wind speeds in China coastal regions

Y.C. Liu[a,b], D.Y. Chen[a,b], S.W. Li[a,*], P.W. Chan[c]

[a] Division of Ocean Science and Technology, Graduate School at Shenzhen, Tsinghua University, Shenzhen 518055, Guangdong, China
[b] School of Environment, Tsinghua University, Beijing 100084, China
[c] Hong Kong Observatory, 134A Nathan Road, Kowloon, Hong Kong

ARTICLE INFO

Keywords:
Power-law model
Extreme wind profile
Numerical simulation
China coastal regions

ABSTRACT

Typhoons originated from the Northwest Pacific pose severe threats on the coastal megacities of China. Hence, the typhoon-resistance capability should be given priority in the building designs along the coastline of China. The wind profile model, which has been widely used to estimate the vertical variation of wind loads, is of importance due to its value in evaluating the structural safety of the buildings under extreme wind conditions. In practice, the classical power-law model with four specific exponents has been recommended by the load code (GB 50009-2012) of China to calculate the vertical profile of extreme wind speeds. Based on the results of a series of artificial typhoon simulations, which have been verified by both the track data of historical typhoons and observations obtained from three land weather stations, the classical power-law model with the exponents recommended by the code is evaluated. It has been found from the evaluation that the classical power-law model is insufficient to estimate the vertical variation of design wind speeds in the coastal area of China. Consequently, an empirical correction ratio and a scale factor are introduced to provide more reliable estimates of extreme wind speeds with any desired return periods.

1. Introduction

The tropical cyclones, known as the typhoons (GB/T 19201 2006) in the Northwest Pacific, are in association with strong winds, heavy rains and storm surges. In each year, around 7–9 typhoons make landfall onto the East and South coasts of China (China Meteorological Administration, 2014). They pose threats to coastal megacities of China and cause damages to industrial facilities, urban structures and infrastructures. For instance, it was reported that the economic losses in China coastal regions resulted from the Typhoon Meranti were estimated to be 11.7 billion RMB (US $ 1.8 billion) and at least 44 causalities were recorded during the passage of the particular typhoon.[1] Therefore, the typhoon-resistant design is of great importance in the construction of buildings in typhoon-prone regions in China.

In the typhoon-resistant design of buildings (China Association for Engineering Construction Standardization, 2012), the vertical variation of mean wind speeds, known as the mean wind profile, is vital in the determination of static wind loads acting on the buildings. Although the mean wind profile is often the focus in the field measurement campaigns, the vertical profile of design wind speeds with desired return periods is employed to estimate wind loads. In other words, the extreme wind profile, not the mean wind profile, in the typhoon boundary layer is the key in the typhoon-resistant design of buildings (Kikumoto and Ooka, 2015).

The wind profile in the typhoon boundary layer attracts attentions from scholars as shown in a series of publications (He et al., 2016; Li et al., 2014; Tse et al., 2013). In practice, a power-law model has been recommended by the national load code in the design of buildings (GB 50009-2012) (China Association for Engineering Construction Standardization, 2012) to estimate the vertical variation of the design wind speeds with the 50 years return period, enveloping most (98%) mean wind profiles observed under extreme conditions. Considering that the design wind profile is not a realistic wind profile but an imaginary profile bounding long-term temporal variations in mean wind speeds at various heights, it should be independent from any meteorological events with a time scale less than the return period of the design wind speed. In other words, the design wind profile is only influenced by the factors that are temporally constant, such as the terrain roughness. Therefore, the

---

* Corresponding author.
E-mail address: li.sunwei@sz.tsinghua.edu.cn (S.W. Li).

[1] The Ministry of Civil Affairs of the People's Republic of China, 2016: http://www.mca.gov.cn/article/yw/jzjz/zqkb/zqhz/201609/20160900001798.shtml.

https://doi.org/10.1016/j.jweia.2017.12.002
Received 6 August 2017; Received in revised form 4 October 2017; Accepted 3 December 2017

power-law model suggested in the load code employs four exponents, i.e., 0.12, 0.15, 0.22 and 0.30, corresponding to the four surface roughness categorizations (classes A, B, C and D). In detail, the class A covers the regions of offshore areas, islands and bare areas; the class B includes the lands with croplands and sparse vegetation; classes C and D correspond to urban areas and city centers, respectively. Since the extreme wind speeds are most likely observed under typhoon conditions, it is reasonable to project that the design wind profile would reflect general features contained in the real mean wind profile observed in the typhoon boundary layer. It should be emphasized that the features associated with a single typhoon process are certainly eliminated in the estimation of the design wind speed, and what remains should be shared by all the typhoons occurred in the desired return period. Since the extreme wind speeds with 50 years return period at the 10m level show clear geographic variation, it is natural to postulate that the vertical variation in the extreme/design wind speeds should be site-dependent. The load, however, provides an universal power-law model with the fixed exponents, which are in association with only the surface roughness condition (China Association for Engineering Construction Standardization, 2012). Furthermore, the extreme probability distribution, such as the Gumbel, Fréchet and Reversed Weibull distribution, are commonly used to project the extreme wind speeds with the desired return periods (Soukissian and Tsalis, 2015). The parameters contained in various extreme probability distributions are, however, not included in the model calculating the design wind profile. Because the conventional power-law model does not reflect general features of the typhoon boundary layer, shows no geographic variations and exclude the parameters of extreme probability distributions, it is necessary to systematically investigate the validity of the power-law model to describe the vertical variations of design wind speeds in the coastal regions of China.

Following the philosophy of the design wind profile as articulated above, the vertical variations in extreme wind speeds are estimated in the present work to verify the reliability of the power-law model with the fixed exponents relating only to the surface roughness condition. In detail, a series of full-set three-dimensional meteorology simulations of artificial typhoons are conducted to provide a large number of typhoon wind fields for the evaluation of the classical power-law model. Based on the evaluation, an empirical correction ratio and a scale factor are suggested to revise the classical power-law model to estimate extreme wind speeds with any desired return periods. The formulae calculating the correction ratio and the scale factor for several coastal cities in China are then presented and discussed based on the comparisons to the recommendations in the load code and the results from previous studies.

After the introduction, section 2 reviews the classical power-law model and the probability models for projecting extreme values, as the basis for the calculation of the extreme wind profile. From a theoretical perspective, section 2 presents the formulae calculating the correction ratio and the scale factor, which revise the power-law model to calculate a more reliable design wind profile. Section 3 briefly summarizes the configurations employed to run the full-set three-dimensional meteorology simulation of artificial typhoons. Based on the simulation results, the applicability of the power-law model to describe the vertical profile of extreme wind speeds with the desired return period is evaluated in section 4. Furthermore, the correction ratio and the scale factor introduced in section 2 are investigated based on the numerical simulation results in section 4. The conclusions are given in section 5.

2. Extreme wind profile model

2.1. Power-law model

The power-law model, as recommended by the load code, is widely used to characterize the vertical variations of design wind speeds (China Association for Engineering Construction Standardization, 2012), and then used to estimate wind loads acting on structures (Davenport, 1960). The design wind speed, which is essentially the extreme wind speed with a specific return period, is assumed to be a power function of heights in the power-law model. In most cases, the extreme wind speed with 50 years return period x_{e50} is employed in the design of general buildings, and the power-law model shows,

$$x_{e50}(h) = x_{e50,10}\cdot(h/10)^{\alpha} \tag{1}$$

In equation (1), $x_{e50,\,10}$ is the extreme wind speed with 50 years return period at 10m level and α is the exponent of the power-law model, which is stipulated as $0.12,\ 0.15,\ 0.22$ and 0.30 according to the surface roughness categorization (classes A, B, C and D) in the load code of China.

2.2. Extreme value distribution model

The probability distribution of extreme values, or the extreme value distribution, is widely employed to project the extreme wind speed with a desired return period based on a series of "samples" of extreme wind speeds. According to the extreme value theory (EVT) developed by Fisher and Tippett (1928), the extreme value distributions can be categorized into three types, namely the Fisher-Tippett I type (FT-I or Gumbel distribution), the Fisher-Tippett II type (FT-II or Fréchet distribution) and the Fisher-Tippett III type (FT-III or Reversed Weibull distribution). The load code of China specifies that the Gumbel distribution should be adopted for the projection of the extreme wind speed.

In practice, all three types could be generalized into a single model with a set of universal parameters, namely the generalized extreme value (GEV) distribution, as,

$$F(x|\mu,\sigma,k) = exp\left\{-\left[1+k\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/k}\right\} \tag{2.a}$$

In equation (2.a), k is the shape parameter, μ is the location parameter and σ is the scale parameter. When $k > 0$, the GEV distribution transforms into the Fréchet distribution. When $k < 0$, it converts into the Reversed Weibull distribution. When $k = 0$, the GEV distribution reduces to the Gumbel distribution shown as,

$$F(x|\mu,\sigma) = exp\left[-exp\left(-\frac{x-\mu}{\sigma}\right)\right] \tag{2.b}$$

Given the typhoon occurrence rate λ, the extreme wind speed exceeding probability F_T corresponding to the desired return period T is calculated as (Vickery et al., 2000),

$$F_T = 1 + (1/\lambda)\cdot ln(1 - 1/T) \tag{3}$$

Provided the desired return period T, the corresponding extreme wind speed is derived from combing equations (2) and (3). More specifically, the extreme wind speed x_{eT} with the return period of T can be calculated as,

$$x_{eT}(h) = \mu(h) - [\sigma(h)/k(h)]\cdot\left\{1 - [-ln(F_T)]^{-k(h)}\right\} \tag{4}$$

According to the extreme value theory (EVT) (Fisher and Tippett, 1928), the parameters of k, σ and μ are related to the mean ($\bar{x}$) and the standard deviation (s) of the given extreme value series as

$$\bar{x} = \mu + \sigma\frac{g_1 - 1}{k}, \quad s = \left|\frac{\sigma\cdot\sqrt{g_2 - g_1^2}}{k}\right| \tag{5.a}$$

In equation (5.a) g_n represents the Gamma function shown as,

$$g_n = \Gamma(1 - n\cdot k(h)) \tag{5.b}$$

When substituting equation (5) into (4), the extreme wind speed x_{eT} is obtained from the mean of the extreme value series ($\bar{x}$) as,