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Calibration of typhoon engineering model based on field observation and its application for typical sites

*Genshen Fang[1)], Lin Zhao[2)] and Yaojun Ge[3)]

[1), 2), 3)] *State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China*
[1)] *2222tjfgs@tongji.edu.cn*

ABSTRACT

With the help of observation of typhoon pressure fields and geometric fields during typhoons occurred in Northwest Pacific, the presented typhoon engineering model was calibrated. A detailed description of the model and interrelationships among parameters were carried out. Some more validations have been conducted on typhoon Muifa (1109) considering the dependence among typhoon field parameters in four field observation sites with totally different terrain characteristics. The variation of several key parameters and time interval of the presented model was investigated. On the basis of typhoon tracks database and presented typhoon wind field model, MC algorithm is adopted for predicting wind parameters in a certain engineering sites. And the influence of two key parameters, R_{max} and β, on the variation of predicted wind speed are discussed. Finally, the design wind parameters for a typical site was predicted and the verification of the simulated results was performed.

1. INTRODUCTION

In the past few decades, long-span bridges and high-rise buildings have sprung up along coastal regions of China where are severely affected by typhoons. And longer and higher structures will probably be put forward and brought into being in the future. These structures are susceptible to wind load, particularly in the typhoon climate. It is essential to establish a practical typhoon field model and predict the design wind speeds for different engineering demand. To meet the demand of wind resistant design, at least several decades of observed wind speeds would be needed. However, the typhoon observation data bases are relatively insufficient. Monte Carlo simulation provides a feasible and reasonable method.

On the basis of the motion equilibrium equation of control air volume, a great deal of attempts and researches are conducted on modeling and solving typhoon

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[1)] PhD. Candidate
[2)] Professor
[3)] Professor

field(Batts 1980, Shapiro 1983, Vickery 1995, 2000, Meng 1995). Meng (1995) provided an analytical solution through simplifying the Navier-Stokes momentum equation and considering the effect of friction on the boundary layer. The tangential and radial boundary layer velocity is obtained by perturbation analysis. Ge (2003) made a comparison and discussion of different numerical models based on extreme wind speed predication. It was shown that the analytical typhoon model proposed by Meng (1995) performed good precision and uncomplicated computation which was applicable for describing typhoon boundary layer. Prior research and analyses based on Meng's model demonstrated its practicability for engineering demand (Zhao 2009).

All of these models mainly depend on several key parameters, central pressure deficit ΔP, radius to maximum wind speed R_{max}, radial pressure distribution coefficient β, translation speed c, center location of typhoon (latitude L_a, longitude L_o) and equivalent roughness length z_0. z_0 and center location are two most important parameters on determining the design wind speed for engineering structure based on sensitivity analysis, R_{max} and β come second (Zhao 2004). A prominent progress has been carried out for estimating R_{max} (Yasui 2002) and β (Holland 2008, Zhao 2013), especially in the Pacific Northwest region of the United States with the help of hurricane reconnaissance flights and H*Wind snapshots(Vickery 2008). However, it is found that the regional difference of parameters is remarkable which means the function relationship among these parameters and constant coefficients are totally different in different regions. In southeast coast of China and northwest Pacific Ocean, Lu (2012) proposed function relationships among parameters ΔP, R_{max} and β through WRF-ARW (Advanced Weather Research and Forecasting) mode provided by National Meteorological Center on simulating typhoon Saomai0608 and field measurement data of more than 1000 meteorological stations on four typhoons, Khanun0515, Wipha0713, Krosa0716 and Morakot0908. Validation and calibration for these parameters are the premise and foundation for engineering application.

In this paper, Interrelationships among ΔP, R_{max} and β (Lu 2012) are adopted, a typhoon engineering model is established based on the analytical model proposed by Meng (1995). The field observation and numerical simulation in four sites about typhoon Muifa (201109) are carried out. By the means of Monte Carlo algorithm, the variation of all parameters are considered to predict the extreme wind speed at a certain return period. In particular, the variation of R_{max} and β are emphatically discussed. In addition, the resolution of the simulated results is analyzed since the presented model is mesoscale and heavily reliant on the effect of terrain.

2. TYPHOON ENGINEERING MODEL

As mentioned before, the analytical typhoon model proposed by Meng (1995) performed good precision and uncomplicated computation which was applicable for describing typhoon boundary layer, especially for engineering demand. As a result, Meng's typhoon model is employed in this paper. And several key parameters are determined by on site measurements.

2.1 Wind field model

On the strength of previous research achievements (Holland 1980), the analytical model of radial pressure profile of typhoon field can be expressed as

$$P_r = P_c + (P_a - P_c)\cdot \exp\left[-(\frac{R_{\max}}{r})^{\beta}\right] = P_c + \Delta P \cdot \exp\left[-(\frac{R_{\max}}{r})^{\beta}\right] \quad (1)$$

where P_r is the atmosphere pressure at radius r from typhoon center, P_c is the central pressure and P_a is the pressure at infinite radius theoretically which can be valued as standard atmospheric pressure, 1013.25hPa. R_{max} indicats the radius of maximum wind speeds. And β is the radial pressure distribution coefficient, as so-called Holland parameter.

The differential equation of motion in the typhoon boundary layer is

$$\frac{D\mathbf{V_r}}{Dt} = \frac{\partial \mathbf{V_r}}{\partial t} + \mathbf{V_r}\cdot\nabla\mathbf{V_r} = -\frac{1}{\rho_a}\nabla P_r - f(\mathbf{k}\times\mathbf{V_r}) + \mathbf{F_r} \quad (2)$$

where ρ_a is the air density in kg/m^3. f is the Coriolis coefficient, f=2ΩsinΨ, in which Ω (radian/s) is the revolving speed of earth and Ψ is the latitude of selected point. $\mathbf{V_r}$ is the typhoon-induced wind velocity at radius r from typhoon center which can be divided into two components, $\mathbf{V_r}=\mathbf{V_g}+\mathbf{V_d}$, in which $\mathbf{V_g}$ is the gradient wind velocity in the free atmosphere and is the decay wind velocity caused by the friction of boundary layer. $\mathbf{k}$ is the unit vector in the vertical direction. $\mathbf{F_r}$ represents the frictional force on the boundary layer which can be neglected above the gradient level. It is assumed that the vertical advection of momentum is neglected since it is relatively small compared with the horizontal one.

The typhoon wind velocity field above the gradient level and on the boundary layer can be obtained by several approximate treatments. And in the free atmosphere, the tangential velocity $v_{\theta g}$ and radial velocity v_{rg} are expressed as

$$v_{\theta g} = \frac{1}{2}(c_\theta - fr) + \sqrt{(\frac{c_\theta - fr}{2})^2 + \frac{r}{\rho}\frac{\partial P_r}{\partial r}} \quad (3)$$

$$v_{rg} = -\frac{1}{r}\int_0^r \frac{\partial v_{\theta g}}{\partial \theta} dr \quad (4)$$

where c_θ is the tangential component of the translation velocity of typhoon. v_{rg} is approximately set at zero in general case.

On the boundary layer, the wind velocity components $v_{\theta d}$ and v_{rd} are obtained by the linear approximation.

$$v_{\theta d} = e^{-\lambda z_d}\left[D_1\cos(\lambda z_d) + D_2\sin(\lambda z_d)\right] \quad (5)$$

$$v_{rd} = \xi e^{-\lambda z_d}\left[D_1\sin(\lambda z_d) - D_2\cos(\lambda z_d)\right] \quad (6)$$

where

$$\lambda = \sqrt[4]{\left(\frac{\partial v_{\theta g}}{\partial r} + \frac{v_{\theta g}}{r} + f\right)\left(2\frac{v_{\theta g}}{r} + f\right)} \Big/ \sqrt{2k_m} \quad (7)$$

$$\xi = \sqrt{\left(\frac{\partial v_{\theta g}}{\partial r} + \frac{v_{\theta g}}{r} + f\right) \Big/ \left(\frac{2v_{\theta g}}{r} + f\right)} \quad (8)$$

$$D_1 = \frac{\chi v_{rg}/\xi - \chi(\chi+1)v_{\theta g}}{1 + (\chi+1)^2} \quad (9)$$

$$D_2 = \frac{\chi v_{\theta g} + \chi(\chi+1) v_{rg} / \xi}{1+(\chi+1)^2} \tag{10}$$

$$\chi = \frac{C_d}{k_m \lambda} |\boldsymbol{v}_s| = \frac{C_d}{k_m \lambda} \sqrt{v_{\theta s}^2 + v_{rs}^2} \tag{11}$$

$$C_d = \kappa^2 / \{\ln[(z_{10} + h - d) / z_0]\}^2 \tag{12}$$

Here k_m is the eddy viscosity, $100\mathrm{m}^2/\mathrm{s}$. C_d is the drag coefficient and the assumption that wind velocity profile on the boundary layer is logarithmic. κ=0.40 is the Karman constant. z_0, h, d, respectively, denote the equivalent roughness length, mean height of roughness elements and zero-plane displacement. Their interrelationship can be identified as d=0.75h=0.75×11.4×$z_0^{0.86}$ derived from the measurement data. z_{10} is the 10m height above the roughness elements. $\boldsymbol{v}_s$ indicates the wind velocity on the ground surface and the iterated computation is adopted in which $v_{\theta g}$ and v_{rg} are used for the initial value of $v_{\theta s}$ and $v_{\theta s}$.

2.2 Stochastic parameters of typhoon simulation model

In the process of typhoon field simulation, it is essential to determine several key and stochastic parameters, ΔP, R_{max} and β as defined in the Eq. (1), center location of typhoon (latitude L_a, longitude L_o), equivalent roughness length z_0 and translation velocity of typhoon c. As previously mentioned, the variability of typhoon field is high. And plentiful field measurement data are important for defining all of parameters and correlations with each other.

(1) Interrelationships among ΔP, R_{max} and β.

In southeast coast of China and northwest Pacific Ocean, Lu (2012) proposed function relationships among parameters ΔP, R_{max} and β through WRF-ARW (Advanced Weather Research and Forecasting) mode provided by National Meteorological Center on simulating typhoon Saomai0608 and field measurement data of more than 1000 meteorological stations on four typhoons, Khanun0515, Wipha0713, Krosa0716 and Morakot0908. The function relationships among ΔP, R_{max} and β are defined as

$$E\left[\ln(R_{max})\right] = -38.36 \times (\Delta P)^{0.02479} + 46.75 \tag{13}$$

$$\sigma(R_{max}) = 10549.2 \times (\Delta P)^{-1.5178} \tag{14}$$

$$\beta = 4.1025 \times 10^{-5} \times (\Delta P)^2 + 0.0293 \times \Delta P + 0.7959 \times \ln(R_{max}) - 4.6010 \tag{15}$$

$$\sigma(\beta) = -0.0027 \times \Delta P - 0.1311 \times \ln(R_{max}) + 0.8815 \tag{16}$$

where $E()$ and $\sigma()$ represent the mean value and standard deviation. And the coefficient of variation of R_{max} and β can be obtained

$$C \cdot V(R_{max}) = \sigma(R_{max}) / E(R_{max}) = \frac{10549.2 \times (\Delta P)^{-1.5178}}{\exp\left[-38.36 \times (\Delta P)^{0.02479} + 46.75\right]} \tag{17}$$

$$C \cdot V(\beta) = \sigma(\beta) / E(\beta) = \frac{-0.0027 \times \Delta P + 5.0290 \times (\Delta P)^{0.02479} - 5.2474}{4.1025 \times 10^{-5} \times \Delta P^2 + 0.0293 \times \Delta P - 30.5307 \times (\Delta P)^{0.02479} + 32.6073} \tag{18}$$

In general, the variation of ΔP ranges from 10hPa to 90hPa according to the field measurement data. As shown in Fig. 1, the change trend of coefficient of variation for R_{max} and β with the change of ΔP is plotted. With the increase of ΔP, $C \cdot V(R_{max})$ slowly

decreases from 0.69 to 0.24 and the mean value is 0.35. $C{\cdot}V(\beta)$ increases firstly and then get a gradual reduction. The maximum is 0.47 when ΔP is equal to 30 hPa. And the mean value is 0.26.

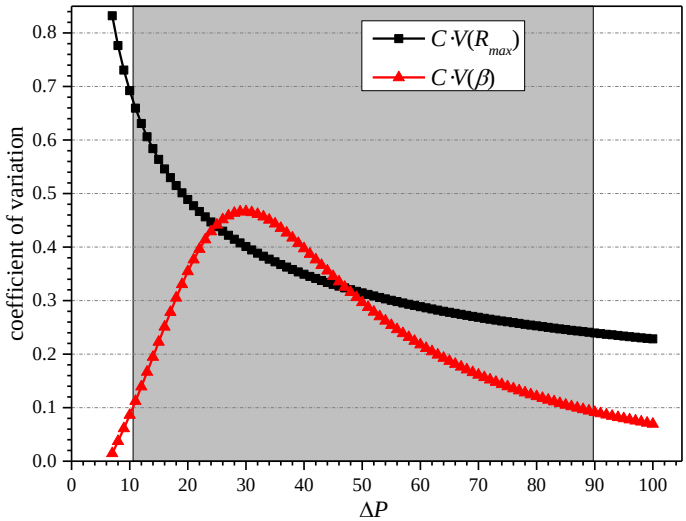


Fig. 1 The change trend of coefficient of variation for R_{max} and β with the change of ΔP

(2) Center location of typhoon (L_a, L_o) and equivalent roughness length z_0

According to the Tropical Cyclone Yearbooks of China, the identification of typhoon center location usually suffers error with 20 to 200 km. The latitude and longitude are range from 18° to 31° and 105° to 123° in southeast coast of China, respectively. As a result, the coefficients of variation are approximately defined as 0.0335 and 0.0077. And Gaussian distribution assumption is adopted. The value of z_0 mainly refers to the Chinese specification JTG/T D60-01-2004, "Wind-resistant Design Specification for Highway Bridges" (2004), in which four terrain types are defined and values of z_0 are 0.01, 0.05, 0.3, 1.0, respectively. The coefficient of variation is approximately defined as 0.05.

(3) Center pressure difference ΔP and translation velocity of typhoon c

Since no specific researches are found on ΔP and c, the Gaussian distribution assumption is adopted and the mean is set as measured value. The coefficient of variation can be set as 0.1 and 0.25, respectively.

3. CALIBRATION AND APPLICATION

3.1 Comparison with typhoon Muifa

As sketched in Fig. 2, the field observation data of typhoon Muifa (201109) was collected in four sites, Liangmaoshan Island (122.03°E, 29.92°N), mid-span of Xihoumen suspension (121.92°E, 30.06°N) and Shanghai Yangtze River bridge (121.74°E, 31.43°N), Houjiazhen meteorological station in Chongming Island (121.46°E, 31.62°N). The observation periods are from 10:35 to 21:29 in August 6th, from 5:00 in August 6th to 5:00 in August 7th, from 6:00 in August 6th to 5:00 in August 7th and from 9:00 in August 6th to 20:00 in August 7th, respectively. The observation heights are approximately 32m, 67.6m, 69.7m and 10m. Owing to the typhoon center is over the

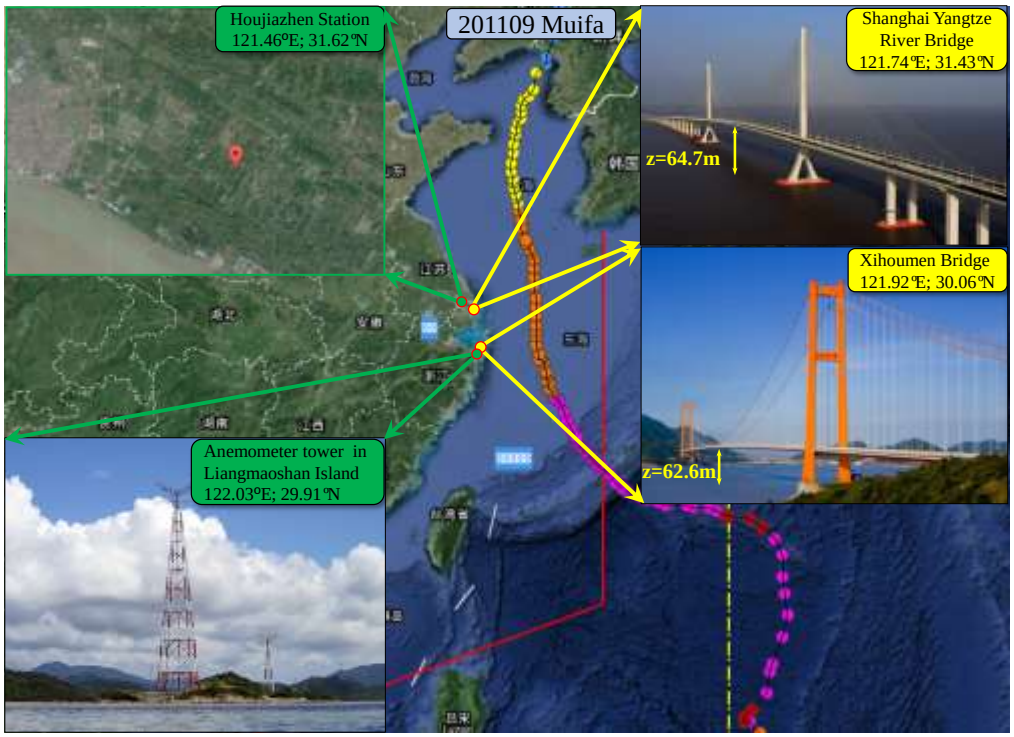


Fig. 2 Observation sites of typhoon Muifa (201109)

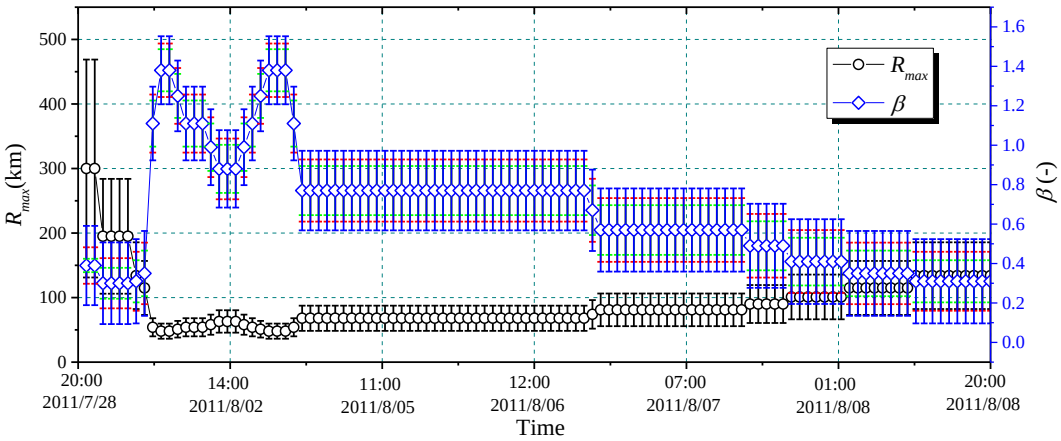
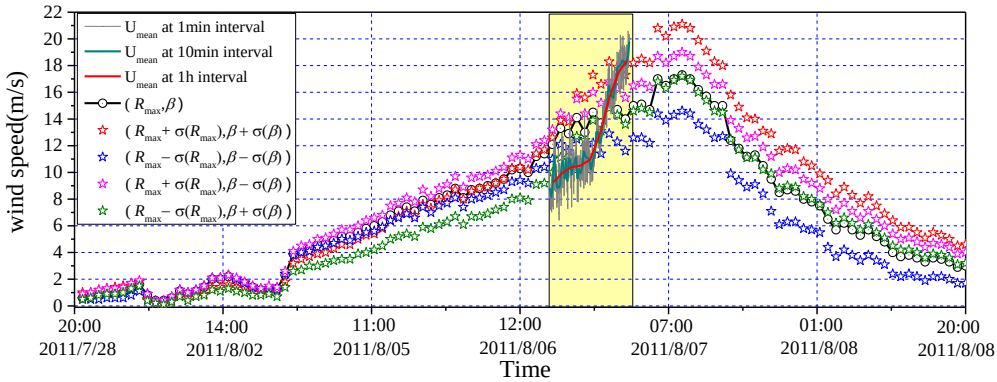


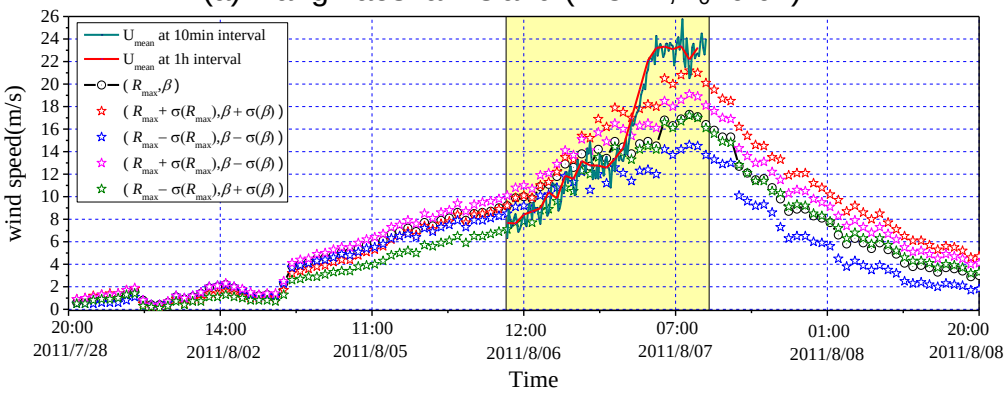
Fig. 3 Variation of R_{max} and β of typhoon Muifa (201109)

sea all the time, the wind direction is from offshore. The equivalent roughness length z_0 can be valued as 0.01 in first three sites according to the Chinese specification JTG/T D60-01-2004, "Wind-resistant Design Specification for Highway Bridges" (2004). Lu (2012) optimized the value of z_0 in Houjiazhen meteorological station based on the field measurement data of 47 typhoons from 1971 to 2007. The suggested value is 0.104~0.156 and 0.13 is chose here.

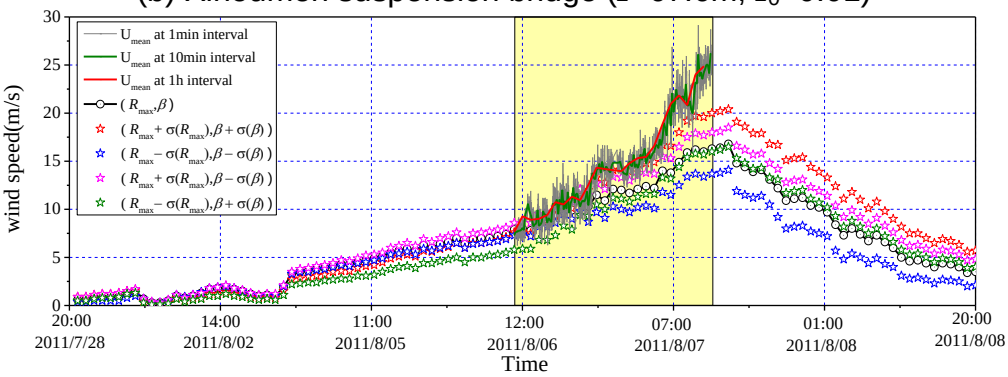
On the basis of Eq. (13)~(16), the mean value and standard deviation of R_{max} and β can be computed at different moments, as shown in Fig. 3. Therefore, the real-time wind speed is achieved at designated location. Fig. 4 describes the simulated results and observed wind velocities about typhoon Muifa in four sites. It can be seen



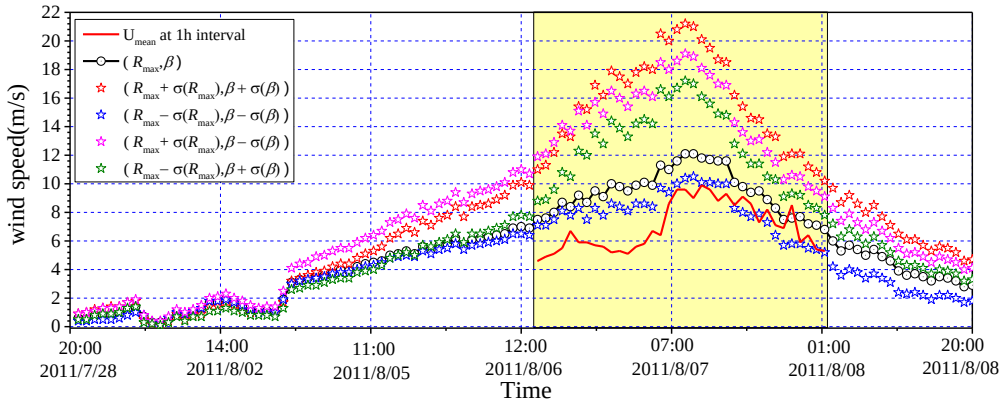
(a) Liangmaoshan Island (z=32m, z_0=0.01)



(b) Xihoumen suspension bridge (z=67.6m, z_0=0.01)



(c) Shanghai Yangtze River bridge (z=69.7m, z_0=0.01)



(d) Houjiazhen meteorological station (z=10m, z_0=0.13)

Fig. 4 Simulated and observed wind velocities about typhoon Muifa (1109) in four sites

that the simulated results can envelope the observed ones in general and the overall trends are fundamentally the same. In other words, the proposed typhoon engineering model, with acceptable accuracy, is practical for determining the basic wind speed on typhoon climate. It is worth mentioning that the uncertainties and errors on the simulated results are non-negligible, but to a certain extent unavoidable, such as the time interval and the equivalent roughness length z_0 are uncertain as a matter of fact.

3.2 Database and Monte Carlo simulation procedure

According to the Tropical Cyclone Yearbooks provided by National Meteorological Center, 1616 typhoons from 1949 to 2015 are recorded. It consists mainly of center location of typhoon (L_a, L_o) every other one, three or six hours, central pressure P_c (the minimum pressure on the central sea level), maximum wind speed in the center and the whole time course for each typhoon translation.

Based on all of these database and previously mentioned interrelation among stochastic parameters, Monte Carlo algorithm, which is practical for engineering application, is adopted. Then, the procedure to predict the extreme wind velocity on typhoon climate pattern are put forward, as shown in Fig. 5.

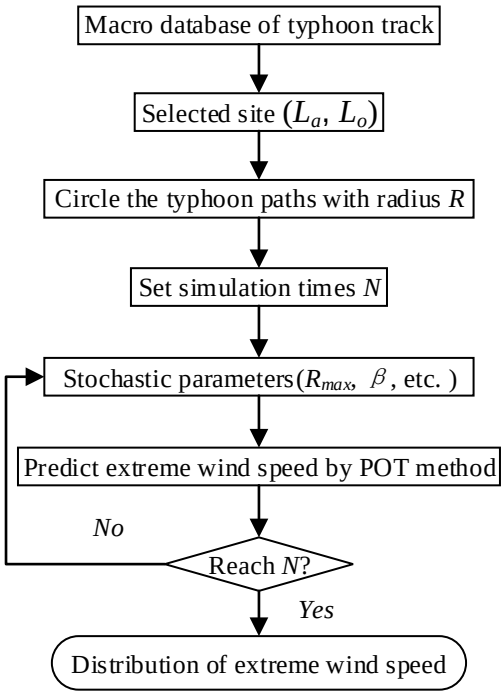


Fig. 5 The flow chart of Monte Carlo simulation

In Fig. 5, radius R is defined as 500km in this paper. And 5×10^3 times simulation are conducted. POT (Peak Over Threshold) method (Pickands 1975), which is based on generalized Pareto distribution, is practical for predicting extreme wind speed. Various discussions on this method have been made and its feasibility and accuracy on the prediction of extreme wind speeds have been verified (Heckert 1998).

3.3 Sensitivity analysis of R_{max} and β

It is worth noting that parameters R_{max}, β and z_0 play a remarkable role in typhoon risk assessment and extreme wind velocity prediction (Zhao 2004). However, the variation of R_{max} and β are considerable as described in Fig. 1. The sensitivity assessment is important. Meanwhile, z_0 is closely related to the terrain. Lu (2012) optimized the value of z_0 in Houjiazhen meteorological station of Chongming Island (31.62°N，121.46°E), Shanghai City, based on the field measurement data of 47 typhoons from 1971 to 2007. The value is 0.104~0.156 and uniform distribution is adopted.

Another crucial point is that the time interval in the presented model is indeterminate. As a mesoscale model, the translation velocity of typhoon and central pressure are obtained from the typhoon track database in which the record intervals are every other one, three or six hours. It can been verified from Fig. 4, the interval simulated results is one hour. Therefore, time interval of Monte Carlo simulated results is defined as two hours. And design basic wind speed for engineering application is set at 10 minutes interval in China. As a result, it is essential to establish a reasonable relationship among height z, turbulence intensity $I_u(\mathrm{TC})$ and converting coefficient $G_{2h,10min}$ from two hours to ten minutes. Combining the observation data (Lu 2012) and referring to the conversion relationships proposed by Sharma (1999), the rules are defined as

$$I_u(\mathrm{Non-TC})=a\times(z/10)^{-b} \tag{19}$$

$$I_u(\mathrm{TC})=c\times I_u(\mathrm{Non-TC}) \tag{20}$$

$$G_{2h,10min}=1+d\times I_u(\mathrm{TC}) \tag{21}$$

where TC is the typhoon climate condition. a and b are the constant coefficient of turbulence intensity, c indicates the conversion coefficient of turbulence intensity from non-TC to TC. The values of a and c are 0.194, 0.259, 0.323, 0.45 and 1.6, 1.48, 1.36, 1.24 for terrain categories A, B, C and D, respectively. b is valued as 0.3. And constant coefficient d is defined as 0.82 according to the field observation results.

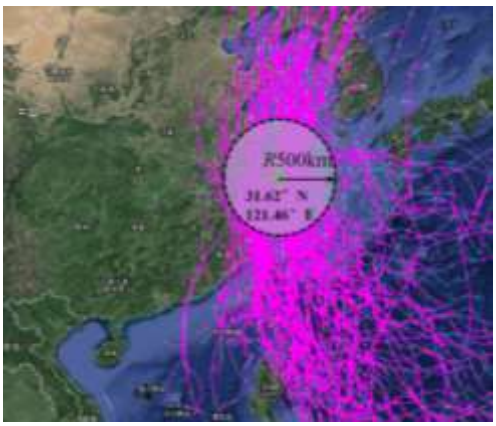


Fig. 6 144 typhoons affect Houjiazhen

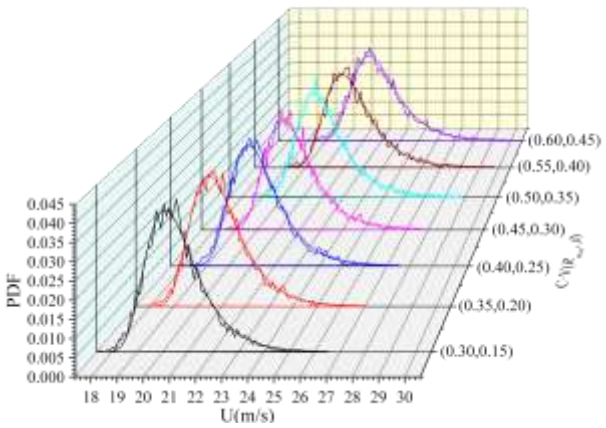


Fig. 7 Distribution of extreme wind speeds

As plotted in Fig. 6, 144 typhoons which affect Houjiazhen meteorological station from 1949 to 2015 are selected and radius R=500km is defined. The Gaussian distribution is applied to stochastic parameters, ΔP, R_{max}, β, c, L_a and L_o.

And the coefficients of variation are 0.1, 0.3 to 0.6, 0.15 to 0.45, 0.25, 0.0335 and 0.0077, respectively. 5×10^3 samples are conducted via Monte Carlo simulation. Fig. 7 illustrates the variation of extreme wind speed at the height of 10m with the effects of R_{max} and β. The polylines are the simulated results according to 5×10^3 samples while the smooth curves are fitted ones with least square method. The shapes of probability distribution functions (PDF) with different coefficients of variation of R_{max} and β are almost similar, and only the location parameters are different. The location parameter or mean value of extreme wind speed gets increase with the increase of $C\cdot V(R_{max})$ and $C\cdot V(\beta)$.

As two most important stochastic parameters for assessing the characteristics of typhoon, $C\cdot V(R_{max})$ and $C\cdot V(\beta)$ have nearly same effect trend on the extreme wind speed according to the results in Fig. 8. $U^*_{99\%}$ represents the extreme wind speed with 99% guaranteed rate at 100 years return period which obtained from the probability distribution functions as shown in Fig. 7. And the time interval converting coefficient from two hours to ten minutes is 1.314 (terrain category is between B and C). Obviously, the variations of R_{max} and β are higher, the wind speed $U^*_{99\%}$ is higher. And variation trend is approximately linear. In addition, the variation of R_{max} seems more considerable on the contribution for the change of $U^*_{99\%}$ which can be defined as basic wind speed on engineering site.

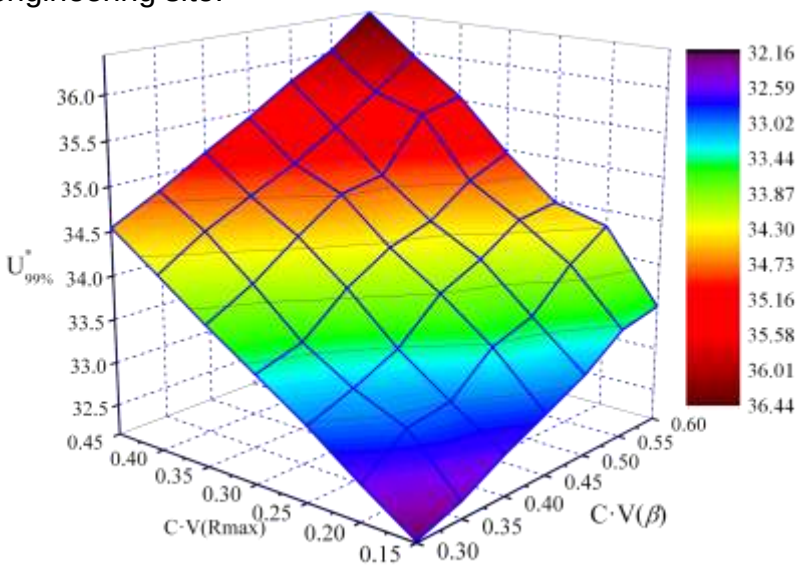


Fig. 8 Influence of variation of R_{max} and β on the extreme wind speed

3.4 Vertical wind profile and basic wind speed

Vertical profile of wind speed is of great concern for engineering design, especially for high-rise structures. And the profile in typhoon climate mode is totally different from usual one (Willoughby 2004, Vickery 2009). The same parameters are chose as described in part *3.3*. The coefficients of variation of R_{max} and β are defined as the mean value as plotted in Fig. 1, 0.35 and 0.26. The simulation height is up to 1500m with an interval of 50m. Besides, the time interval conversion refers to Eq. (19)~(20). Four constant coefficients, a, b, c and d, are set as 0.28, 0.3, 1.48 and 0.82. 5×10^3 samples are obtained at each heights. The simulated results of Houjiazhen meteorological station are illustrated in Fig. 8. The gradient wind height is about 1200m.

It has high consistency of the simulated variation trend and the observed results (Vickery 2009). The fitted result of profile with exponential law is gained and the exponent is about 0.089. However, it appears that the exponential law cannot fit the wind speed profile well. The linearity seems more suitable to describe the function of the profile. Certainly, a further study and more simulations are necessary for accurately describing its variation rule.

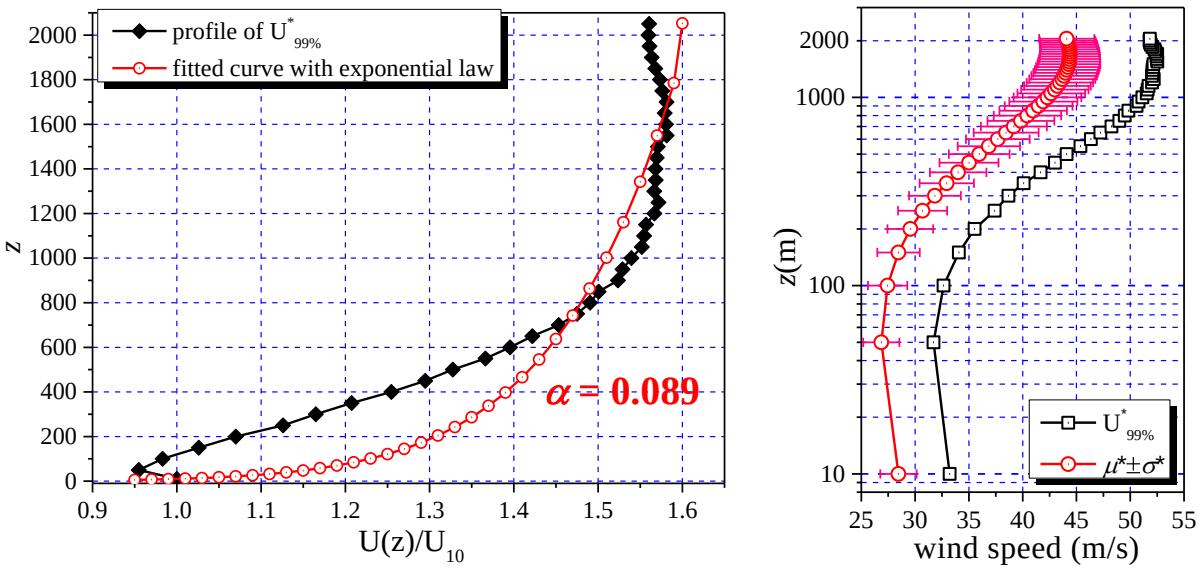


Fig. 8 Vertical profile of wind speed in Houjiazhen meteorological station (μ^* and σ^* denote the average wind speed and standard deviation of 5×10^3 samples)

On the other hand, the most immediate wind resistant parameter is the basic wind speed which represents the average wind speed of 10min at the height of 10m and 100 years return period. It also a significant criterion for assessing a typhoon numerical model whether it suitable for engineering application or not. As displayed in Table 1, the basic wind speed in Houjiazhen meteorological station or Shanghai through three approaches is listed. The first result is based on long-term field observation (Zhao 2003) and second result in Shanghai is also predicted from large amounts of observation data, not only from Houjiazhen meteorological station. It can be seen that the simulated wind speed with 99% guarantee rate is quite close to other two results, with the errors of 1.6% and -1.7%.

Table 1 Comparison of basic wind speed at the height of 10m (m/s)

Location	Zhao (2003)	Chinese specification (2004)	Simulation results z_0=U(0.104,0.156)	
			($\mu^*\pm\sigma^*$)	$U^*_{99\%}$
HMS	32.7	-	28.45±1.69	33.21
Shanghai	-	33.8	-	-

Note: HMS denotes the Houjiazhen meteorological station. U(0.104,0.156) means the uniform distribution is applied for z_0 with the value from 0.104 to 0.156.

4. CONCLUSIONS

This paper described a typhoon engineering model based on an analytical model and interrelationships among several key parameters. The calibration with the help of field observation data are conducted. And more applications on determining the design wind parameters in a certain sites by the MC algorithm are carried out. Several conclusions can be drawn as follows:

- The presented typhoon engineering model is a mesoscale numerical model. It can basically reproduce the variation of wind speed at a certain sites during the translation of typhoon. The simulation precision is acceptable. The uncertainties and errors on the simulated results are non-negligible, but to a certain extent unavoidable.
- The variations of two key parameters, R_{max} and β, are remarkable. Their influences on the extreme wind speed are approximately linear. The higher variation of R_{max} and β, the higher extreme wind speed. In addition, the variation of R_{max} on the contribution for the change of wind speed seems more considerable
- With the modification of time interval, the simulation results of vertical wind profile at a certain sites is dramatically similar with the observation results. The exponent of wind profile is much smaller than the usual one. And the design wind speed of the simulated one is quite close to the long-term observation results.
- With the help of MC algorithm, the proposed typhoon engineering model provides an effective approach for determining the design wind parameters. It is practical for engineering demand with sufficient accuracy.

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