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Calibration of Expressions of Radius of Maximum Winds and Radial Pressure Profile Constant in Typhoon-Induced Wind Velocity Prediction based on Field Data

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ABSTRACT

Wind characteristics of typhoon are different from monsoon. In prone-typhoon areas, how to determine wind velocity is very important for wind-sensitive structures. In this paper, Yan Meng analytical model was adopted to predict wind velocities of typhoon. In the simulation, radius of maximum wind velocity $R_{\max}$ and radial pressure profile constant β are two critical parameters and have greatly influence to prediction results. Using data provided by Tropical Cyclone Yearbook and new expressions of $R_{\max}$ and β which based on field data of southeast coastal areas of China, typhoon-induced wind velocities of Xiamen were simulated. Finally, simulated wind velocities compared with on-site measured data. Through comparison, the validity and applicability of the new expressions of $R_{\max}$ and β were calibrated.

1. INTRODUCTION

The southeast coastal area of China is usually seriously hit by typhoon and is one of the most serious typhoon disaster regions in the world. The wind sensitive structures such as long-span bridges, high-rise buildings and large span roofs located this region should consider typhoon-induced wind velocity. At present, the Chinese loading codes are based on monsoon and typhoon is not involved. Many researches have indicated (Ministry of Transport of the People's Republic of China, 2004; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2012) that wind field characteristics of typhoon are greatly different from monsoon's (Ge, *et al*. 2014). In most cases, typhoon-induced wind velocities are significantly higher than monsoon. In

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order to make sure the structural safety, it is necessary to study the typhoon-induced wind velocities of southeast coastal cities of China.

In this paper, Yan Meng analytical model (Meng, *et al.* 1995, 1997) is adopted to predict typhoon-induced wind velocity. In the numerical simulation, a new radius of maximum wind velocity $R_{\max}$ expression and radial pressure profile constant β estimation method which proposed by Zhao *et al* in 2012 (Lu, 2012) and 2013 (Zhao *et al*. 2013) respectively are used to predict 20 typhoon-induced wind velocities in Xiamen during 1990 to 2010. All of the typhoon simulation data are obtained from "Tropical Cyclone Yearbook" released by Shanghai Typhoon institute, China Meteorological Administration. Finally, the simulation results compared with the measured wind speed data of the observation station provided by Xiamen meteorological station. Through comparison, the accuracy of the model and the proposed parameters' expressions were calibrated. Meanwhile the applicability of the expressions of $R_{\max}$ and β were also checked.

2. YAN MENG ANALYTICAL TYPHOON MODEL

In this part, the Yan Meng analytical typhoon model (Meng, *et al.* 1995) was firstly reviewed. The pressure at radius r in a typhoon can be obtained by following equation which proposed by Holland (Holland, 1980)

$$P = P_c + \Delta P \exp\left[-\left(R_{\max}/r\right)^{\beta}\right] \tag{1}$$

Where, P is the pressure at radius r, P_c is the central pressure, $\Delta P = P_n - P_c$ is central pressure difference, P_n is ambient pressure, $R_{\max}$ is radius of maximum winds, β is radial pressure profile constant.

According to Navier-Stokes equation, the equation of motion in a typhoon wind field can be written as

$$\frac{d\mathbf{v}}{dt} = \frac{\partial \mathbf{v}}{\partial t} + \left(\mathbf{v}\cdot\nabla\right)\mathbf{v} = -\frac{1}{\rho}\nabla\mathbf{P} - f\vec{k}\times\mathbf{v} + \mathbf{F} \tag{2}$$

Where, $\mathbf{v}$ is the wind velocity, f is Coriolis parameter, $\vec{k}$ is unit vector, ∇ is Hamilton operator, $\mathbf{F}$ is frictional force.

The typhoon-induced wind velocity $\mathbf{v}$ can be divided into gradient wind $\mathbf{v}_g$ in the free atmosphere and friction caused component $\mathbf{v}'$ in the boundary layer.

$$\mathbf{v} = \mathbf{v_g} + \mathbf{v}' \tag{3}$$

Based on characteristics of the free atmosphere and boundary layer, equation (2) is divided into the following two formulas,

$$\frac{\partial \mathbf{v}_g}{\partial t} + \left(\mathbf{v}_g\cdot\nabla\right)\mathbf{v}_g = -\frac{1}{\rho}\nabla\mathbf{P} - f\vec{k}\times\mathbf{v}_g \tag{4}$$

$$\frac{\partial \mathbf{v}'}{\partial t} + \left(\mathbf{v}'\cdot\nabla\right)\mathbf{v}' + \left(\mathbf{v}'\cdot\nabla\right)\mathbf{v_g} + \left(\mathbf{v_g}\cdot\nabla\right)\mathbf{v}' = -f\vec{k}\times\mathbf{v}' + \mathbf{F} \tag{5}$$

In the free atmosphere, the gradient wind velocity moves at the translation velocity of typhoon $\mathbf{c}$. Then the first part of the right-hand side of equation (4) becomes

$$\frac{\partial \mathbf{v}_{\mathrm{g}}}{\partial t} = -(\mathbf{c}\cdot\nabla)\mathbf{v}_{\mathrm{g}} \tag{6}$$

In the boundary layer of typhoon, the unsteady term in equation (5) is smaller than the viscosity term and the inertia term. So the unsteady term is ignored as

$$\frac{\partial \mathbf{v}'}{\partial t} = 0 \tag{7}$$

Submit equation (6) and (7) into equation (4) and (5) respectively, then following formulas can be obtained

$$\left((\mathbf{v}_{\mathrm{g}} - \mathbf{c})\cdot\nabla\right)\mathbf{v}_{\mathrm{g}} = -\frac{1}{\rho}\nabla\mathbf{P} - f\vec{k}\times\mathbf{v}_{\mathrm{g}} \tag{8}$$

$$(\mathbf{v}'\cdot\nabla)\mathbf{v}' + (\mathbf{v}'\cdot\nabla)\mathbf{v}_{\mathrm{g}} + (\mathbf{v}_{\mathrm{g}}\cdot\nabla)\mathbf{v}' = -f\vec{k}\times\mathbf{v}' + \mathbf{F} \tag{9}$$

The boundary condition at the upper atmosphere is

$$\mathbf{v}'\big|_{z'\to\infty} = 0 \tag{10}$$

Above the ground surface, the boundary condition can be obtained by the balances between shearing stress and drag force

$$\rho k_m \frac{\partial \mathbf{v}'}{\partial z}\bigg|_{z'\to 0} = \rho C_d \left|\mathbf{v}_s\right| \mathbf{v}_s \tag{11}$$

Where, ρ is air density, $\mathbf{v}_s$ is wind velocity on the ground surface, k_m eddy viscosity, C_d drag coefficient and can be expressed as

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

Where, $\kappa = 0.4$ is Karman constant, $d = 0.75h$ is zero-plane displacement, $h = 11.4 z_0^{0.86}$ is height of the roughness elements, z_0 is equivalent roughness length, z_{10} is 10 m above the mean height of roughness elements.

In the free atmosphere, $\mathbf{v}_{\mathrm{g}}$ can be divided into component in the tangential direction $\mathbf{v}_{\theta\mathrm{g}}$ and component in the radial direction $\mathbf{v}_{\mathrm{rg}}$. Therefore equation (8) is written as

$$(\mathbf{v}_{\mathrm{rg}} - \mathbf{c}_r)\frac{\partial \mathbf{v}_{\mathrm{rg}}}{\partial r} + \frac{\mathbf{v}_{\theta\mathrm{g}} - \mathbf{c}_\theta}{r}\frac{\partial \mathbf{v}_{\theta\mathrm{g}}}{\partial \theta} - \frac{\mathbf{v}_{\theta\mathrm{g}}^2}{r} + \frac{\mathbf{v}_{\theta\mathrm{g}}\mathbf{c}_\theta}{r} = -\frac{1}{\rho}\frac{\partial \mathbf{P}}{\partial r} + f\mathbf{v}_{\theta\mathrm{g}} \tag{13}$$

$$(\mathbf{v}_{\mathrm{rg}} - \mathbf{c}_r)\frac{\partial \mathbf{v}_{\theta\mathrm{g}}}{\partial r} + \frac{\mathbf{v}_{\theta\mathrm{g}} - \mathbf{c}_\theta}{r}\frac{\partial \mathbf{v}_{\theta\mathrm{g}}}{\partial \theta} + \frac{\mathbf{v}_{\theta\mathrm{g}}\mathbf{v}_{\mathrm{rg}}}{r} - \frac{\mathbf{v}_{\mathrm{rg}}\mathbf{c}_\theta}{r} = -f\mathbf{v}_{\mathrm{rg}} \tag{14}$$

Because radial velocity $\mathbf{v}_{\mathrm{rg}}$ is smaller than tangential velocity $\mathbf{v}_{\theta\mathrm{g}}$ and the first and second convection terms on the left-hand side of equation (13) are disregarded. The tangential velocity $\mathbf{v}_{\theta\mathrm{g}}$ is expressed as

$$\mathbf{v}_{\theta g} = \frac{1}{2}\left(\mathbf{c}_\theta - fr\right) + \left[\left(\frac{\mathbf{c}_\theta - fr}{2}\right)^2 + \frac{r}{\rho}\frac{\partial \mathbf{P}}{\partial r}\right]^{1/2} \tag{15}$$

The radial velocity $\mathbf{v}_{rg}$ can be obtained from continuity equation as

$$\mathbf{v}_{rg} = -\frac{1}{r}\int_0^r \frac{\partial \mathbf{v}_{\theta g}}{\partial \theta} dr \tag{16}$$

In the study, $\mathbf{v}_{rg}$ is set at 0.

In the analysis, $\mathbf{v}'$ is assumed much smaller than $\mathbf{v}_g$, and the first derivative of the velocity components $\mathbf{v}'_\theta$, $\mathbf{v}'_g$ with respect to θ are much smaller compared with the velocity components. Then, equation (9) can be linearized as follows,

$$-\left(2\frac{\mathbf{v}_{\theta g}}{r} + f\right)\mathbf{v}'_\theta = k_m \frac{\partial^2 \mathbf{v}'_r}{\partial z^2} \tag{17}$$

$$\left(\frac{\partial \mathbf{v}_{\theta g}}{\partial r} + \frac{\mathbf{v}_{\theta g}}{r} + f\right)\mathbf{v}'_r = k_m \frac{\partial^2 \mathbf{v}'_\theta}{\partial z^2} \tag{18}$$

Introducing the following two abbreviations,

$$\xi = \left(\frac{\partial \mathbf{v}_{\theta g}}{\partial r} + \frac{\mathbf{v}_{\theta g}}{r} + f\right)^{1/2} \Big/ \left(2\mathbf{v}_{\theta g}/r + f\right)^{1/2} \tag{19}$$

$$\lambda = \left(\frac{\partial \mathbf{v}_{\theta g}}{\partial r} + \frac{\mathbf{v}_{\theta g}}{r} + f\right)^{1/4} \left(2\frac{\mathbf{v}_{\theta g}}{r} + f\right)^{1/4} \Big/ \left(2k_m\right)^{1/2} \tag{20}$$

And equations (17) and (18) becomes

$$2\lambda^2 \mathbf{v}''_\theta = \frac{\partial^2 \mathbf{v}''_r}{\partial z^2} \tag{21}$$

$$-2\lambda^2 \mathbf{v}''_r = \frac{\partial^2 \mathbf{v}''_\theta}{\partial z^2} \tag{22}$$

Where $\mathbf{v}''_\theta = \mathbf{v}'_\theta$ and $\mathbf{v}''_r = -\mathbf{v}'_r/\xi$. Equation (21) times i and adds equation (22) then got the following equation

$$\frac{\partial^2 \mathbf{v}''}{\partial z^2} - \left[\left(1+\mathrm{i}\right)\lambda\right]^2 \mathbf{v}'' = 0 \tag{23}$$

Considering boundary condition of equation (10), solution can be obtained as

$$\mathbf{v}'' = \mathbf{D}\exp\left[-\left(1+\mathrm{i}\right)\lambda z'\right] \tag{24}$$

Where $\mathbf{D} = \mathrm{D}_1 + \mathrm{i}\mathrm{D}_2$ is a complex constant. The velocity components in the boundary layer are obtained as

$$\mathbf{v}'_\theta = \mathrm{e}^{-\lambda z'}\left[\mathrm{D}_1 \cos\left(\lambda z'\right) + \mathrm{D}_2 \sin\left(\lambda z'\right)\right] \tag{25}$$

$$\mathbf{v}'_r = -\xi \mathrm{e}^{-\lambda z'}\left[\mathrm{D}_2 \cos\left(\lambda z'\right) - \mathrm{D}_1 \sin\left(\lambda z'\right)\right] \tag{26}$$

Where

$$\mathrm{D}_1 = -\frac{\chi(\chi+1)\mathbf{v}_{\theta \mathrm{g}} - \chi \mathbf{v}_{\mathrm{rg}}/\xi}{1+(\chi+1)^2}$$

$$\mathrm{D}_2 = \frac{\chi \mathbf{v}_{\theta \mathrm{g}} + \chi(\chi+1)\mathbf{v}_{\mathrm{rg}}/\xi}{1+(\chi+1)^2}$$

$$\chi = \frac{C_d}{k_m \lambda}|\mathbf{v}_{\mathrm{s}}| = \frac{C_d}{k_m \lambda}\sqrt{\mathbf{v}_{\theta \mathrm{s}}^2 + \mathbf{v}_{\theta r}^2}$$

3. RADIUS OF MAXIMUM WIND VELOCITY R_{max} AND RADIAL PRESSURE PROFILE CONSTANT β

In the prediction of wind velocity of typhoon, many parameters are involved. Among them, the radius of maximum wind velocity $R_{\max}$ and pressure profile β are two of the most critical parameters.

With the help of WRF-ARW (Advanced Research Weather Research and Forecasting) software which used in simulation of typhoon by Chinese National meteorological center, a new expression of the radius of maximum wind velocity $R_{\max}$ was proposed by Zhao et al (Lu, 2012) as follows

$$E(\ln R_{\max}) = -38.36\Delta \mathrm{P}^{0.02479} + 46.75 \tag{27}$$

$$\sigma(R_{\max}) = 10549.2\Delta \mathrm{P}^{-1.5178} \tag{28}$$

Where $E()$ denotes average value of $\ln R_{\max}$, $\sigma()$ denotes standard deviation of $R_{\max}$.

According to comparison research by Zhao et al, the typhoon pressure profile β has a great influence for the results of typhoon-induced wind velocity simulation. Utilizing a large number of on-site observed typhoon data along Chinese coastal regions, a new functional expression of the pressure profile β was proposed (Zhao, *et al*. 2013) as follows

$$\beta = -2.365 + 0.0573\Delta \mathrm{P} + 0.0035 R_{\max} \quad \text{(Before landfall)} \tag{29}$$

$$\beta = 0.4899 + 0.0178\Delta \mathrm{P} \quad \text{(After landfall)} \tag{30}$$

The above expression is based on the actual pressure data from hundreds of ground stations in Zhejiang province, whether this expression is suitable for other cities located in southeast China coastal areas, more on-site data are needed to verify.

4. COMPARISON OF SIMULATED RESULTS WITH ON-SITE MEASURED DATA

With the help of Xiamen Meteorological Station, 20 typhoon-induced wind velocity series records at the height of 10 m above the ground were obtained. The names, numbers and instantaneous wind velocities of the 20 typhoons are shown in Table1.

Based on Yan Meng typhoon analytical model, using the radius of maximum wind velocity and pressure profile constant expressions in Part 3, the instantaneous wind velocities on the observation site can be simulated. In the simulation, the main parameters involved are shown in Table 2. Comparison between simulated results and measured results are shown in Figure 1.

Table 1 Measured instantaneous wind velocities of different typhoons

No.	Typhoon Name	Typhoon Number	Instantaneous Wind Velocity
1	Yancy	199012	15.7 m/s
2	Dot	199018	14.7 m/s
3	Gladys	199418	6.3 m/s
4	Tim	199406	14.3 m/s
5	Gloria	199607	13.0 m/s
6	Herb	199608	16.3 m/s
7	Amber	199714	19.0 m/s
8	Dan	199914	5.0 m/s
9	Bilis	200010	14.0 m/s
10	Chebi	200102	7.7 m/s
11	Haitang	200505	10.7 m/s
12	Talim	200513	15.3 m/s
13	Longwang	200519	12.1 m/s
14	Kaemi	200605	12.9 m/s
15	Saomai	200608	5.4 m/s
16	Sepat	200709	13.3 m/s
17	Wipha	200713	8.1 m/s
18	Fung-wong	200808	11.7 m/s
19	Morakot	200908	12.9 m/s
20	Fanapi	201011	15.1 m/s

Table 2 Main parameters in the simulation

Height	longitude	Latitude	Roughness length	Radius of influence	Air density
10 m	118.08°	24.48°	0.05 m(0.01-0.1)	500 km	1.2 kg/m^3

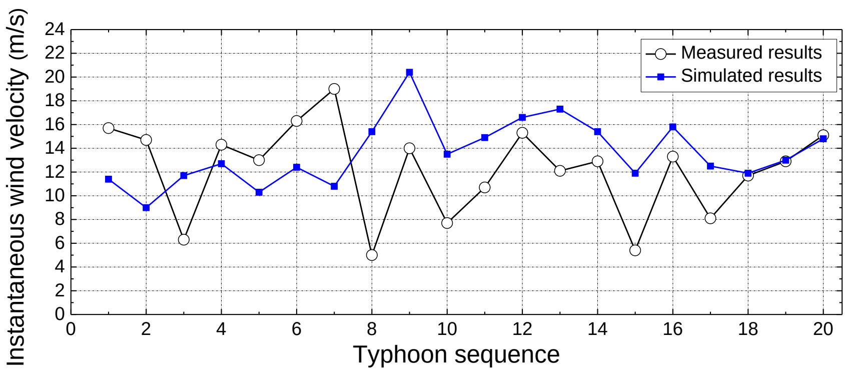

Fig. 1 Comparison between measured and simulated wind velocity

In order to check the validity of the parameters, the error D_{error} is defined to evaluate the simulated results and measured data in Xiamen Meteorological Station.

$$D_{error} = \left(v_s - v_m\right) / v_m \tag{31}$$

Where, v_s and v_m are the simulated and measured instantaneous wind velocities respectively. The errors for the 20 typhoon sequences are shown in Figure 2.

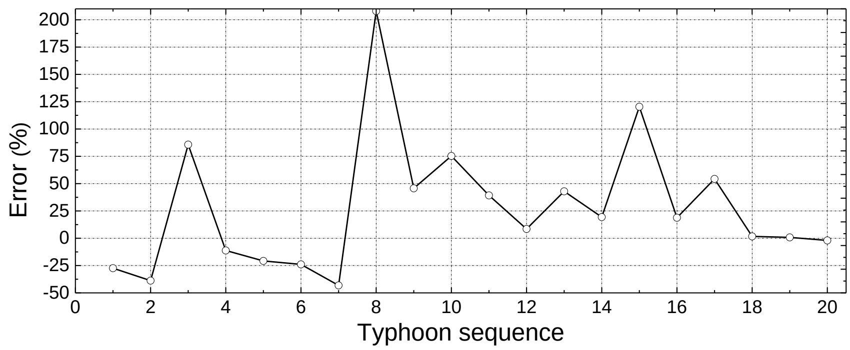

Fig. 2 Comparison between measured and simulated wind velocity

The wind field characteristic difference between different typhoons is very large, which can be obtained from Figure 1 and 2. For typhoon Gladys, Dan, Chebi, Saomai and Wipha, the simulation errors are larger than 50%. On the contrary, in typhoon Tim, Talim, Fung-wong, Morakot and Fanapi, the simulation results are precise and all of the errors are smaller than 11.2%. Especially for typhoon Fung-wong, Morakot and Fanapi, the largest error is just -2%. The mean error of the 20 typhoons is 27.7%. On the whole, in most cases, the simulation method can get a safety typhoon-induced instantaneous wind velocity.

5. CONCLUSIONS

From analysis and comparison of simulated and measured results at Xiamen observation site, 3 conclusions can be obtained as follows,

(1) The characteristics of wind velocities in typhoon have a great difference between different typhoons.
(2) Comparison results showed that the expressions of $R_{\max}$ and β and the Yan Meng analytical model have great calculation accuracy in the prediction of instantaneous wind velocities of some typhoons in Xiamen, but in some other typhoons the estimation errors are large and the simulated results should be modified.
(3) More measured wind velocity data of typhoon are needed to check the validity the expressions of $R_{\max}$ and β.

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