TYPHOOM WIND FIELD IN ATMOSPHERIC BOUNDARY LAYER

Wen-Feng Huang¹, You-Lin Xu², Chi-Wai Li³ and Hong-Jun Liu⁴
¹Research Assistant, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong; PhD Candidate, Department of Urban and Civil Engineering, Harbin Institute of Technology Shenzhen Graduate School, Shenzhen, China, wfhuang@163.com.cn
²Chair Professor and ³Professor, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, ceylxu@polyu.edu.hk
⁴Professor, Department of Urban and Civil Engineering, Harbin Institute of Technology Shenzhen Graduate School, Shenzhen, China, liuhongjun@hit.edu.cn

ABSTRACT

For buildings and structures in typhoon regions, they must be designed to withstand typhoon winds. The modeling accuracy of typhoon wind field in the atmospheric boundary layer is therefore very important. The currently-used typhoon wind field models for buildings and structures assume that the pressure of a typhoon does not vary with height above the ground. However, the observations made from recent field measurements do not support this assumption, and this assumption may affect the prediction of typhoon wind field. This paper thus presents a refined typhoon wind field model including variation of pressure with height. The refined typhoon wind field model is then applied to Typhoon York. The wind speed and direction computed from the refined typhoon wind field model are compared with those measured at the Waglan Island and the Di Wang Tower, and those predicted by the Yan Meng model and the Shapiro model. The comparison demonstrates that the refined typhoon wind field model gives more accurate wind speed and direction than other models.

KEYWORDS: WIND FIELD MODEL, BOUNDARY LAYER, PRESSURE VARIATION, COMPARISON

Introduction

Buildings and structures in typhoon regions are inevitably affected by typhoon winds, and accordingly they must be designed to withstand typhoon winds during their design lives. The accuracy of modeling typhoon wind field in the atmospheric boundary layer is therefore very important. There are several typhoon wind field models, among which the models proposed by Vickery et al. (1995, 2000) and Meng et al. (1995, 1997) are most popular in the field of civil engineering for predicting design typhoon wind speeds for buildings and structures.

The model proposed by Vickery et al. (1995) is based on the Shapiro model (1983), which considered the equation of horizontal motion, vertically averaged over the height of the atmospheric boundary layer. A finite-difference scheme was used to solve the equation for the steady-state wind field over a set of nested rectangular grid. Meng et al. (1995) started from the Navier-Stokes equation and envisaged typhoon-induced mean wind velocity as the combination of a gradient wind in the free atmosphere and a surface wind caused by friction due to ground surface. The perturbation analysis was performed to find the solution. The above two models imply that the pressure of a typhoon is constant with height above the ground. The recent field observation using GPS dropsonde used by Kepert (2006), however, showed that the pressure of a typhoon actually decreases with increasing height above the
ground. The assumption that the pressure remains constant with height may affect the prediction of typhoon wind speed.

This paper thus presents a refined typhoon wind field model including variation of the pressure with height based on some simplifications of the three dimensional Navier-Stokes equations. Typhoon York, which is the strongest typhoon since 1983 and the typhoon of longest duration on record, hit Hong Kong on 16 September 1999. The refined typhoon wind field model is then applied to Typhoon York. The wind speed and direction computed from the refined model are finally compared with those measured at the Waglan Island and the Dih Wang Tower, and those predicted by the Yan Meng model and the Shapiro model.

Refined wind field model

The deduction of the refined typhoon wind field model is based on the three dimensional Navier-Stokes equations (Equation 1). Equation (1a) and (1b) is the momentum and continuity equation, respectively, whereas Equation (1c) and (1d) is the thermodynamic and state equation, respectively (Holton, 2004).

\[
\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho} \nabla p - gk - 2\Omega \times \mathbf{v} + \mathbf{F}
\]  
\[
\frac{dp}{dt} = -\rho \nabla \cdot \mathbf{v}
\]  
\[
p = \rho RT
\]  
\[
Jdt = c_v dT + pd\alpha
\]

where \( \mathbf{v} \) is the wind velocity with \( \rightarrow \) representing a vector; \( \rho \) is the air density; \( p \) is the atmospheric pressure; \( \nabla \) is the three-dimensional del operator; \( g \) is the gravitational acceleration; \( k \) is the unit vector; \( \Omega \) is the angular velocity of the earth; \( \mathbf{F} \) is the friction force; \( R \) is the ideal gas constant; \( T \) is the temperature; \( J \) is the adiabatic heat source; \( c_v \) is the heat capacity at constant volume; and \( \alpha = 1/\rho \).

It is common to replace temperature with potential temperature \( \theta \), which is defined as

\[
\theta = \frac{T(p_0)}{p}\exp\left(\frac{c_p R}{p} \right)
\]

where \( p_0 \) is the atmospheric pressure at zero-plane; \( c_p \) is the heat capacity at constant pressure and equals \( c_v + R \).

Equation (1a) can be decomposed into the horizontal momentum and the vertical momentum. It is known from scale analysis that Coriolis force in the vertical direction is small compared with Coriolis force in the horizontal direction (Holton, 2004). Therefore, Coriolis force in the vertical direction can be neglected. As a result, Equation (1) can be written as

\[
\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho} \nabla p - f k \times \mathbf{v} + \mathbf{F}_h
\]  
\[
\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g + \mathbf{F}_v
\]  
\[
\frac{dp}{dt} = -\rho \nabla \cdot \mathbf{v}
\]  
\[
p = \rho RT
\]  
\[
Jdt = c_v dT + pd\alpha
\]
where the subscript $h$ means the horizontal; $v_h$ is the wind velocity in the horizontal plane; $w$ is the vertical wind velocity; $f$ is the Coriolis parameter; $F_h$ and $F_v$ are the friction forces in the horizontal and vertical direction, respectively.

To obtain a typhoon wind field model for predicting design typhoon wind speeds for buildings and structures, some simplifications have to be made to Equation (3). First, the hydrostatic approximation is adopted in this study because the vertical scale of a typhoon is much less than its horizontal scale. As a result, Equation (3b) can be simplified as:

$$-\frac{1}{\rho} \frac{\partial p}{\partial z} - g = 0$$

Combining Equation (2) with Equation (3d) yields

$$T \frac{d\theta}{dt} = \theta \left( \frac{dT}{dt} - \frac{\alpha}{c_p} \frac{dp}{dt} \right)$$

Combining Equation (3d) with Equation (3e) produces

$$Jdt = c_p dT - \alpha dp$$

Substituting Equation (6) to Equation (5) and combining it with Equation (2) result in

$$\frac{d\theta}{dt} = \frac{J}{\Pi}$$

$$\Pi = c_p \left( \frac{p}{p_0} \right)^{R/c},$$

where $\Pi$ is the Exner function.

By taking the derivative of Equation (7b) with respect to $z$, and then substituting Equations (2), (3d) and (4) into it, one may have

$$\frac{\partial \Pi}{\partial z} = -\frac{g}{\theta}$$

Furthermore, topographic effects are considered in the model. A geometric height based terrain-following coordinate transformation is used to deal with the difficulties at lower boundary that arises from using the conventional $z$-coordinate (Galchen and Somerville, 1975).

$$z^* = \frac{z_t(z - z_s)}{z_t - z_s}$$

where $z^*$ is the terrain-following vertical coordinate; $z_t$ is the height of the wind model top; and $z_s$ is the height of the lower boundary.

The terrain-following coordinate transformation can be done by substituting Equation (9) into Equation (8). As a result, Equation (8) becomes

$$\frac{\partial \Pi}{\partial z} = -\left( 1 - \frac{z_s}{z_t} \right) \frac{g}{\theta} z^*$$

By integrating Equation (10) by part, one may have

$$\Pi = \Pi_0 - \left( 1 - \frac{z_s}{z_t} \right) \frac{g}{\theta} z^*$$

where $\Pi_0$ is a constant to be determined by the boundary condition.

The initial boundary condition is $p = p_0$ at $z = 0$. By substituting the initial boundary condition into Equation (9), the value of $z^*$ under this initial condition is

$$z^* = \frac{-z_t z_s}{z_t - z_s}$$

By substituting the initial boundary condition into Equation (7b), the value of $\Pi$ under this initial condition is
\[ \Pi = c_p \]  
(13)

Substitution of Equations (12) and (13) into Equation (11) yields

\[ \Pi_0 = c_p - \frac{g z}{\theta} \]  
(14)

Then, substituting Equations (14) and (11) into Equation (7b) leads to the expression of atmospheric pressure \( p \) varying with height as

\[ p = p_0 (1 - g z / \alpha c_p) / R \]  
(15)

Furthermore, by assuming that the air density is constant, Equation (3c) can be neglected. Equation (1) can be finally reduced to Equation (16) as

\[ \frac{d\bar{v}_h}{dt} = -\frac{1}{\rho} \nabla_h p - f \bar{v}_h \times \bar{v}_h + \bar{F}_h \]  
(16a)

\[ p = p_0 (1 - g z / \alpha c_p) / R \]  
(16b)

Equation (16) can not be directly solved because the continuity equation 3(b) is not included so that the number of unknown quantities is greater than the number of equations. Nevertheless, Holland (1980) proposed the following analytical model for the radial profiles of sea level pressure in a typhoon based on field measurement data.

\[ p_b = p_{c_o} + \Delta p \exp\left[-\left(\frac{r_m}{r}\right)^B\right] \]  
(17)

where \( p_{c_o} \) is the central pressure of a typhoon at zero-plane; \( \Delta p \) is the central pressure difference \( p_m - p_{c_o} \); \( p_m \) is the ambient pressure (theoretically at infinite radius) at zero-plane; \( r_m \) is the radius to maximum wind speed; \( r \) is the radial distance from the center of the typhoon; and \( B \) is Holland’s radial pressure profile parameter, taking on values between 0.5 and 2.5.

Equation (16) and Equation (17) are the basic equations of the refined typhoon wind field model. The basic equations can be solved by using the same way as proposed by Yan Meng (1995), in which typhoon-induced mean wind velocity is regarded as the combination of a friction-free wind and a surface wind caused by friction due to ground surface. The perturbation analysis was performed to find the solution.

**Validation**

On 12 September 1999, the tropical depression York developed at about 430km northeast of Manila and intensified into a tropical storm on the next day over South China Sea. The movement of York was erratic, heading north at first on 14 September. After moving north-westly for almost two days, Typhoon York passed Hong Kong and Shenzhen in the early morning of 16 September. The signal No.10 was forced to hoist for 11h, the longest on record in Hong Kong. Typhoon York finally make landfall near Zhuhai, a city of Guangdong province of China and then weakened gradually over further inland on 17 September (Hong Kong Observatory, 1999). The central pressure difference at sea level, the position of typhoon center, and the translation direction and speed of Typhoon York was given by Hong Kong Observatory (HRO) for an interval of 6 hours. The radius to maximum wind speed is obtained by using the method proposed by Anthes (1982). The best overall fit for Typhoon York by using a non-linear least-squares fit gives the optimal parameter value \( B=1.3 \) and the terrain roughness length along the typhoon track is estimated by using the formula proposed by Pande et al. (2002).

To simulate the typhoon wind field at an hourly interval, all the track parameters of Typhoon York are linearly interpolated from the available 6-hourly track information. The minimum sea-level pressure difference is calculated using a periphery pressure of 1010mb,
which is a typical value for the Northwest Pacific region (Georgiou, 1985). Then, all the parameters including the position of typhoon center, the translation direction and speed, the central pressure difference at sea level, the radius to maximum wind speed, and the representative roughness length are put into the typhoon wind field model. The hourly mean wind speed and direction at any given site can be finally simulated and presented.

**Wind velocity simulation at Waglan Island**

The weather station at the Waglan Island, which is situated over the southeastern tip of Hong Kong, is the major outpost of the HKO in weather monitoring. It provides measurement data critical for the early alert of inclement weather associated with typhoons and rainbands approaching Hong Kong from the northern part of the South China Sea. The data recorded at the Waglan Island is interested because that the site is exposed to the predominant winds and can provide information on the characteristics of typhoons over sea if corrected for the topographic error. During Typhoon York, the hourly mean wind speed and direction were recorded by the anemometers installed on the Waglan Island of Hong Kong at the measurement level of 90m.

The measured hourly mean wind speed and direction at the Waglan Island measurement level are compared with those predicted by the refined wind field model. The comparison results are plotted in Figure 1. In Figure 1, the x-coordinate is the local time (HKT) and the duration of observed data starts from 6:00 HKT, 15 September 1999 and ends at 6:00 HKT, 16 September 1999. It can be seen that the refined wind field model can predict the wind speed satisfactorily within the time duration of 24 hours. The refined model underestimates the maximum wind speed by about 7%. The tendency of wind direction predicted by the refined wind field model agrees well with the measured one. The error between the predicted wind direction and measured wind direction is about 30 degree in the first 22 hours and a relatively larger error in the next three hours. Prediction errors in the maximum wind speed and the last 3 hours’ wind directions may be due to simplifications used in the development of refined wind field model, but the errors are considered to be acceptable.

![Figure 1: Comparison of Predicted and Measured Wind Velocity at Waglan Island](image)

The Yan Meng model and the Shapiro model are also used in this study to predict wind speed and wind direction at the Waglan Island, and the results are compared with those predicted by the refined wind model as shown in Figure 2. It can be seen that the variation of wind speed and the maximum wind speed predicted by the Shapiro model show a significant overestimation from the measured data. The Shapiro model overestimates the maximum wind
speed by about 20%. The maximum wind speed predicted by the Yan Meng model has a relatively small difference from the measured data and the Yan Meng model slightly overestimates wind speed within the time duration of 24 hours. The wind direction predicted by the Yan Meng model can give a comparatively good estimation compared with the wind direction predicted by the Shapiro model especially in the last 3 hours.

![Wind velocity comparison](image)

**Fig. 2** Comparison of wind velocity among three models at Waglan Island

*Wind velocity simulation at Di Wang Tower*

Di Wang Tower, located in the downtown Shenzhen City of China, is one of the tallest steel and reinforced concrete buildings in the world. The tower has 69 stories and a total height of 384m at the top of its mast. The tower is completed in 1996. A wind and structural monitoring system was installed at 348m height of the tower above the ground in August 1999 and started the measurement immediately afterwards. The measurement program was jointly developed by the Hong Kong Polytechnic University and the China Academy of Building Research (Xu and Zhan, 2001). The measurement data at the Di Wang Tower are interested because the tower is about 350m high above the ground and hence the data could provide the strong evidence to the upper-level design wind speed in Hong Kong, including the effect of a complex topography. During Typhoon York, the maximum wind speed measured by the wind and structural monitoring system at local time about 6:00(HKT), 16 September 1999. The time histories of wind speed and direction of 38h duration starting from 17:20 HKT, 15 September 1999 to 8:20 HKT, 17 September 1999 were recorded.

The measured hourly mean wind speed and direction at the measurement level are compared with those predicted by the refined wind field model, and the comparison results are plotted in Figure 3. In Figure 3, the x-coordinate is the local time (HKT) and the duration of observed data starts from 6:00 HKT, 15 September 1999 and ends at 6:00 HKT, 16 September 1999. It can be seen that the refined wind field model can predict the wind speed and the maximum wind speed satisfactorily within the time duration of 24 hours. The wind direction predicted by the refined wind field model slightly underestimates the measured wind direction in the first 8 hours, overestimates the measured wind direction in the following 11 hours. In the last 6 hours, the wind direction predicted by the refined wind field model can match well with the measured wind direction. Errors between the predicted wind direction and measured wind direction are considered to be acceptable.

The Yan Meng model and the Shapiro model are also used in this study to predict wind speed and wind direction at the Di Wang Tower, and the results are compared with those predicted by the refined wind model as shown in Figure 4. It can be seen that the variation of
wind speed and the maximum wind speed predicted by the Shapiro model show a significant difference from the measured data within the time duration of 24 hours. The model overestimates the maximum wind speed by about 30%. The maximum wind speed predicted by the Yan Meng model has a relatively small difference from the measured data. The wind direction predicted by the Shapiro model overestimated the measured wind direction within the time duration of 24 hours. The wind direction predicted by Yan Meng model gives almost same value with the wind direction predicted by refined wind field model.

Figure 3: Comparison of Predicted and Measured Wind Velocity at Di Wang Tower

Fig.4 Comparison of Wind Velocity among Three Models at Di Wang Tower

Based on the above comparisons, it can be seen that the wind speed and direction predicted by the refined model match well with the measured wind speed and direction and are better than those predicted by the Yan Meng model and the Shapiro model no matter when Typhoon York is over sea (Waglan Island) or over land (Di Wang Tower).

Conclusions

A refined typhoon wind model has been proposed in this paper by taking into consideration the variation of pressure of a typhoon with height. The wind speed and direction
predicted from the refined model for Typhoon York have been compared with those measured at the Waglan Island and the Di Wang Tower, and those predicted by the Yan Meng model and the Shapiro model. The comparison demonstrates that the refined wind field model gives more accurate wind speed and direction than other models no matter when the typhoon is over sea or over land.

Acknowledgements
The work described in this paper was financially supported by the Research Grants Council of Hong Kong through a GRF grant (PolyU 5327/08E) and The Harbin Institute of Technology Shenzhen Graduate School through a PhD studentship to the first author. The support from the Hong Kong Observatory to allow the authors to access the measured data for academic purpose only is particularly appreciated. Any opinions and conclusions presented in this paper are entirely those of the authors.

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