EVALUATION OF TEMPORAL DESIGN WIND SPEEDS USING TYPHOON MODEL AND EMPIRICAL WIND CHARACTERISTICS

Masahiro Matsui¹, Takeshi Ohkuma² and Yukio Tamura¹

¹ Professor, Department of Architecture, Tokyo Polytechnic University
1583, Atsugi, Kanagawa, 243-0297, Japan,
matsui@arch.t-kougei.ac.jp, yukio@arch.t-kougei.ac.jp

² Professor Emeritus, Kanagawa University
3-27-1, Rokkakubashi, Kanagawa-ku, Yokohama, 221-8686, Japan,
Ohkuma@kanagawa.ac.jp

ABSTRACT

Based on the concept of scenario-based design wind speed, a method is proposed for calculating the temporal variation of wind speeds during a typhoon to estimate wind load effects on energy-consuming structural devices and cumulative fatigue damage under an extreme typhoon event. This method is based on parameter scaling, and consists of selecting a seed typhoon that had affected the target site, identifying its parameters, modifying its parameters and calculating the temporal change of wind speeds of a virtual typhoon. Some calculation examples are shown. The calculated temporal wind speeds give the same wind speeds as the design wind speeds and realistic temporal variations based on meteorological considerations.

KEYWORDS: SCENARIO-BASED DESIGN WIND, TYPHOON MODEL, EMPIRICAL WIND CHARACTERISTICS

Introduction

Conventional wind resistant design consists of setting the design wind speed, calculating the maximum response under the design wind speed, evaluating the wind load effects, and checking that they are within required criteria or allowable limits. The design wind speeds are prescribed in regulations or recommendations, and have been estimated from extreme value statistics using historical observed records and special considerations of local wind climates. For example, in Japan, the recommendations for loadings on buildings take typhoon effects into account (AIJ, 2004). The estimated design wind speeds are annual maximum wind speeds under standard observed conditions. The standard conditions are 10-minute mean at 10m above flat and open terrain.

Maximum load effects, e.g. maximum stresses, maximum deformations and maximum accelerations, can be evaluated from maximum wind speeds only. However, some structural devices need to be evaluated from the viewpoint of energy consumption or cumulative damage. To evaluate these types of devices, the total wind application time or temporal variation of one extreme wind event is required. Existing references, recommendations and regulations do not provide this kind of information.

This paper discusses the problem of how to estimate temporal variations of wind speeds whose maximum values are the same as the design wind speeds under extreme wind events, especially typhoons, the most predominant events in the north-west Pacific area, by applying a typhoon model and scaling parameters.
The proposed method is based on the concept of a scenario-based design wind speed, so to speak.

Evaluation of Methodology

Outline of Procedure

The proposed method follows a set procedure: selecting a seed typhoon that affected the target site, identifying its parameters, modifying its parameters, and calculating the temporal change of wind speeds of a virtual typhoon. The calculation is based on parameter scaling.

Source Typhoon Records and Identification of Pressure Parameters

The first step of the procedure is to select a remarkable typhoon that affected the site and to collect its observed records as a seed. The typhoon and its observed wind speeds are referred to as a seed typhoon (or an original typhoon) and seed wind records (or original records) hereafter.

The second step is to identify the typhoon’s parameters: central pressure depth \(D_P\), radius of maximum wind \(R_M\), translation speed \(C\), etc. These parameters are identified using observed atmospheric pressures around the typhoon’s path and applying Schloemer's empirical formula (Schloemer, 1954),

\[
P(r) = P_c + D_P \exp\left(-\frac{R_M}{r}\right)
\]  

(1)

to fit the distributed atmospheric pressure records.

Calculating Temporal Variation of Virtual Typhoon Wind Speeds

The virtual typhoon is assumed to move along the same path as the seed typhoon. The typhoon parameters of the virtual typhoon, however, are changed from their original values to values that show the same maximum wind speeds as the design wind speed.

Let \(U_{s-obs}\) and \(U_{syn}\) be the wind speeds under the seed and virtual typhoons. These wind speeds are assumed to be those under concentric circle typhoon pressure fields (for seed and virtual typhoon winds, \(U_{s-typ}\) and \(U_{typ}\), respectively), large scale geometrical effects and aerodynamic roughness effects of the ground surfaces. The large scale geometrical effects and aerodynamic roughness effects of the ground surfaces are assumed to be linear effects on the wind speeds, and are indicated by \(E_{env}\). These conditions are expressed as

\[
U_{s-obs} = U_{s-typ} \cdot E_{env},
\]  

(2)

\[
U_{syn} = U_{typ} \cdot E_{env}.
\]  

(3)

The wind speeds under concentric circle typhoon pressure fields are calculated from the typhoon model.

If the large scale geometrical effects and aerodynamic roughness effects of the ground surfaces are assumed to be identical in equations (2) and (3), equation (2) is expressed as

\[
U_{syn} = \left(U_{typ} / U_{s-typ}\right) \cdot U_{s-obs}.
\]  

(4)

Assuming that the temporal variation, whose period is longer than that of the spectral gap pointed out by Van der Hoven (1957), is organized according to the pressure field's movement, the time scale of the seed record is transferred into the value of the virtual typhoon through the non-dimensional time \(\tau\).

\[
\tau = T / (L / U),
\]  

(5)

where \(T, L\) and \(U\) are the reference values of time, length and velocity scales relevant to the typhoon pressure field.
Model of Typhoon Wind Field

The typhoon wind field model employed here is Meng's model (Meng et al., 1997).

In a typhoon's boundary layer, the vertical wind speed and directional profiles (wind speed and direction, $u(z)$, $\theta(z)$) are given as

$$u(z) = u_G(z / z_G)^{\alpha_u},$$

$$\theta(z) = \theta_G + \theta_S (1.0 - 0.4 \frac{z}{z_G})^{\alpha_u},$$

where $u_G$, $\theta_G$ are gradient wind speed and direction; $\alpha_u$ is the power law index; and $z_G$ is the gradient height. The power law index $\alpha_u$ and the gradient height $z_G$ are expressed as functions of the absolute vorticity $f_\lambda$ and the surface Rossby number $R_{0G} (= u_G / f \lambda z_0)$. Inflow angle $\theta_S$ is a function of the homogeneity of vorticity $\xi$ and the surface Rossby number.

$$\alpha_u = 0.27 + 0.09 \log z_0 + 0.018 \log^2 z_0 + 0.0016 \log^3 z_0,$$

$$z_G = 0.06 \frac{u_G}{f_\lambda} (\log R_{0G})^{-1.45},$$

$$\theta_S = (69 + 100 \xi) (\log R_{0G})^{-1.13},$$

$$f_\lambda = \left( \frac{\partial u_G}{\partial r} + \frac{u_G}{r} + f \right)^{1/2} \left( \frac{2 u_G}{r} + f \right)^{1/2},$$

$$\xi = \left( \frac{2 u_G}{r} + f \right)^{1/2} \left( \frac{\partial u_G}{\partial r} + \frac{u_G}{r} + f \right)^{1/2},$$

The gradient wind direction $\theta_G$ is assumed to be parallel to the isobar. The gradient wind speed $u_G$ is evaluated by Meyers and Markin's formula (1961) as

$$u_G = \frac{C \sin \theta_t - fr}{2} + \sqrt{\left( \frac{C \sin \theta_t - fr}{2} \right)^2 + \frac{r \partial P}{\rho \partial r}},$$

where $C$ and $\theta_t$ are translation speed and direction of a typhoon. $f$ is the Coriolis parameter.

Examples of Calculation

Calculation of Temporal Variation of Design Wind Speeds due to Virtual Typhoon at Kagoshima Local Meteorological Observatory Site

Typhoon KIRK (T9612) was selected as a seed typhoon, during which the second maximum wind speed was recorded at the Kagoshima Local Meteorological Observatory. The typhoon's path is shown in Figure-1. The historical records of maximum wind speeds at the site are listed in Table-1.

The target design speed at the site is 45m/s under standard observation conditions. The value was converted to 45.1m/s according to the actual observation conditions, i.e., observation height 45m and suburban terrain exposure (category III in the AIJ recommendations).

After repeated trial and error, two cases were found in which the maximum wind speeds corresponding to the design wind speed were reproduced.

Case a: The central pressure depth was 1.6 times the original typhoon's value.

Case b: The central pressure depth was 1.5 times and the translation speed was 2 times the original typhoon's values.

The time histories of wind speeds under these conditions are shown in Figure-2 a) and b). The original records are also shown so that both maximum wind speeds appeared at the same position. The calculation was done using the identified typhoon parameters. For the parameter interpolation, linear interpolation was applied. For the parameter extrapolation, the nearest time value was applied.
In case-a, the central pressure depth was estimated as 85hPa. The corresponding central pressure was 928hPa (=1013-85hPa). In case-b, the central pressure was 79.8hPa (the corresponding central pressure was 933.2hPa) and the translation speed was 18.4m/s. As shown here, the temporal wind speed variations whose maximum wind speeds were the same as the design speed were reproduced under the virtual typhoon conditions.

Table-1 Historical daily maximum wind speed at Kagoshima Local Meteorological Observatory

<table>
<thead>
<tr>
<th>order</th>
<th>daily maximum wind speed (m/s)</th>
<th>wind direction</th>
<th>date</th>
<th>affecting typhoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39.3</td>
<td>SSE</td>
<td>Aug. 27, 1942</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>36.6</td>
<td>SSE</td>
<td>Aug. 14, 1996</td>
<td>T9612</td>
</tr>
<tr>
<td>3</td>
<td>35.1</td>
<td>SSE</td>
<td>Oct. 14, 1951</td>
<td>T5115</td>
</tr>
<tr>
<td>4</td>
<td>35.0</td>
<td>SNS</td>
<td>Sept. 17, 1945</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>31.7</td>
<td>E</td>
<td>Sept. 29, 1955</td>
<td>T5522</td>
</tr>
<tr>
<td>6</td>
<td>31.5</td>
<td>SE</td>
<td>Sept. 29, 2004</td>
<td>T0421</td>
</tr>
<tr>
<td>7</td>
<td>31.0</td>
<td>ESE</td>
<td>Aug. 22, 1969</td>
<td>T6909</td>
</tr>
<tr>
<td>8</td>
<td>30.8</td>
<td>S</td>
<td>Sept. 24, 1999</td>
<td>T9918</td>
</tr>
<tr>
<td>9</td>
<td>28.2</td>
<td>SSE</td>
<td>Sept. 06, 2005</td>
<td>T0514</td>
</tr>
<tr>
<td>10</td>
<td>28.0</td>
<td>NE</td>
<td>Sept. 24, 1964</td>
<td>T6420</td>
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</table>

Figure-1 Path of Typhoon KIRK (T9612) (best track, RSMC Tokyo)
Calculation of Temporal Variation of Design Wind Speeds due to Virtual Typhoon at Haneda AMeDAS (Automated Meteorological Data Acquisition System) Site

Typhoon MA-ON(T0422) was selected as a seed typhoon, during which the highest wind speed was recorded at the Haneda AMeDAS (Automated Meteorological Data Acquisition System). The typhoon’s path is shown in Figure-3. The historical records of maximum wind speeds at the site are listed in Table-2.

Since the observation conditions at Haneda AMeDAS were the same as the standard conditions, i.e. observation height 10m and open terrain exposure (terrain category II in the AIJ recommendations), the target wind speed was the right value of design wind speed 38m/s.

After repeated trial and error, two cases were found in which the maximum wind speeds at the site are listed in Table-2.

Case a: The central pressure depth was 1.7 times the original typhoon's value.
Case b: The central pressure depth was 1.6 times and translation speed was 0.5 times the original typhoon's values.

The time histories of wind speeds under these conditions are shown in Figure-4 a) and b). They were plotted in the same manner as Figure-2 a) and b).

In case-a, the central pressure depth was estimated as 71.2hPa. The corresponding central pressure was 941.8hPa (=1013-71.2hPa). In case-b, the central pressure was 67hPa.
(the corresponding central pressure was 946hPa) and the translation speed was 9.8m/s. As shown here, the temporal wind speed variations whose maximum wind speeds were the same as the design speed were reproduced under the virtual typhoon conditions.

In case-b, the reduction of translation speed increased the maximum wind speed. This was opposite to the effect of the Kagoshima Local Observatory record. This was because the original typhoon, T0422, passed the eastern side of the Haneda site to the north. This result shows that not only the typhoon pressure parameters, but also the path of the original typhoon affects the resultant wind speeds of virtual typhoons.

Table-2 Historical daily maximum wind speed at Haneda AMeDAS (Automated Meteorological Data Acquisition System)

<table>
<thead>
<tr>
<th>order</th>
<th>daily maximum wind speed (m/s)</th>
<th>wind direction</th>
<th>date</th>
<th>affecting typhoon</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
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<td>SSE</td>
<td>Sept. 07, 2007</td>
<td>T0709</td>
</tr>
<tr>
<td>3</td>
<td>24.0</td>
<td>SW</td>
<td>Dec. 05, 2004</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>24.0</td>
<td>W</td>
<td>Oct. 01, 2002</td>
<td>T0221</td>
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<td>5</td>
<td>23.0</td>
<td>NE</td>
<td>April 18, 2008</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>23.0</td>
<td>SSW</td>
<td>June 20, 1997</td>
<td>T9707</td>
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<tr>
<td>7</td>
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<td>S</td>
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<td></td>
</tr>
<tr>
<td>8</td>
<td>23.0</td>
<td>NNW</td>
<td>Sept. 22, 1996</td>
<td>T9617</td>
</tr>
<tr>
<td>9</td>
<td>22.0</td>
<td>SSW</td>
<td>March 31, 2007</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>22.0</td>
<td>SSW</td>
<td>March 30, 1996</td>
<td></td>
</tr>
</tbody>
</table>

Figure-3 Path of Typhoon MA-ON(T0422) (best track, RSMC Tokyo)
Figure 4: Temporal variations of virtual typhoon and original record (T0422)

Conclusions

Based on the concept of scenario-based design wind speed, a method has been proposed for estimating the temporal variation of design wind speed under typhoon conditions. The method is based on parameter scaling, and consists of selecting a seed typhoon that had affected the target site, identifying its parameters, modifying its parameters and calculating the temporal change of wind speeds of a virtual typhoon. Some calculation examples were shown and the effects of modifying the typhoon’s pressure parameters and their paths were studied. The calculated temporal wind speeds gave the same wind speeds as the design wind speeds and realistic temporal variations based on meteorological considerations.

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References


