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Directional Characteristics of Probability Distribution of Extreme Wind Speeds by means of Typhoon Simulation

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1 Introduction

In wind engineering practice, reasonable structure design is available, if directional characteristics of design wind are considered. In this paper, using Monte-Carlo technique, a formulation of directional variation of design wind speeds are shown.

2 Typhoon model

2.1 Outline

For Monte-Carlo simulations, calculation will amount to be very huge. So an easy-to-calculate method is required for typhoon models as well as accuracy. The model used here is similar to what researchers[1)2)3)4)] have used, while some modification were made on the boundary layer model and calibration based on meteorological data. The typhoon model consists of some models described below (i.e. pressure and gradient wind field, boundary layer and calibration).

2.2 Pressure and gradient wind field

The typhoon model employed here is a forward model that calculates a wind field from a given pressure field. Pressure field $P(r)$ is expressed as Schloemer's empirical formula[5)] in the cylindrical coordinate (r, θ, z).

$$P(r) = P_C + D_P e^{-(R_M/r)}, \qquad (1)$$

where P_C is the central pressure of typhoon, D_P is the pressure difference between the central and ambient pressure and R_M is the radius of maximum wind speed. Including the function of $P(r)$, gradient wind speed U_G is evaluated by Meyers and Markin's formula[6)], expressed as

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

where C, θ_r are translation speed and direction, ρ is the air density and f is the Coriolis parameter.

2.3 Typhoon boundary layer

In the boundary layer of the typhoon, vertical wind speed profile (wind speed and direction, $u(z), \theta(z)$) is affected by absolute vorticity that is given as a sum of vorticity of a flow field and the planetary vorticity(i.e. Coriolis parameter). The absolute vorticity is considered in boundary layer model was proposed by Meng, et. al[7)].

$$u(z) = u_G(z/z_G)^{\alpha_u}, \qquad (3)$$

$$\theta(z) = \theta_G + \theta_S(1.0 - 0.4\frac{z}{z_G})^{1.1}, \qquad (4)$$

where u_G, θ_G are gradient wind speed and direction, α_u is the exponent index, z_G is the gradient height that is affected by absolute vorticity. The power law index α_u is given as a function of directional roughness length z_0[7)].

2.4 Calibration

The models described above are assumed with uniform roughness and plane topography. In the practice, however, there are variations of roughness and topography. Considering the variation of roughness, directional roughness length is decided according to the directional surface appearance.

Wind directions and speeds are also affected by topography. For the effect of topography, a modified calibration technique is used, that was originally used by Gumley and Wood[8)] for evaluation of wind speed and direction considering the relation between records of target and reference. In the modified procedure, gradient wind speeds and directions from the typhoon model are regarded as reference.

3 Maximum wind speed and Monte-Carlo simulation

Design wind speeds are decided based on their return period. The return period T_R is defined as a simple relation with non-exceeding probability $F_Y(v)$ of annual maximum wind speed v as,

$$T_R = \{1 - F_Y(v)\}^{-1} \quad (5)$$

So, evaluation of annual maximum wind speed and its probability distribution is the main subject of this study.

3.1 The maximum wind speeds during typhoons

To evaluate the maximum wind speed during typhoons, a procedure was proposed by Mataui et.al[9]. In the procedure the maximum wind speed is evaluated as not a value but a probability distribution function (PDF) F_T, which expressed as

$$F_T = \prod F_j, \quad (6)$$

where F_j is a probability distribution function where each observed wind speed in time series would be expected. Equation (6) is a strict form of the extreme distribution in case wind speeds fluctuations are expressed with probability distributions. The mean of the distribution is given by equation (3) and the standard deviation is decided considering fluctuations existing in a full-scale observation according to its averaging time.

Unless using the probabilistic evaluation, underestimation will occur, while the model would evaluate blunt characteristics of wind speed time series. This is because the wind speed evaluated by macroscopic models (equation (1)-(4)) does not include fluctuations existing in a full-scale observation.

3.2 A formulation for directional characteristics of wind speed

The following assumes the independence of fluctuations between wind speeds and directions.

Non-exceeding probability of maximum wind speed during a typhoon in each directional sector $F_{T,k}$ is expressed as,

$$F_{T,k} = \prod F_j^{W_k}, \quad (7)$$

where k is index of the directional sectior (e.g. N, NNE,..) and

$$W_k = \begin{cases} 1, & \text{if calculated wind directions are in the interested directional sector } k \\ 0, & \text{otherwise} \end{cases} \quad . \quad (8)$$

Supposing full-scale record of wind direction, there exist random fluctuations (e.g. unstationality of wind direction). Taking this fluctuation into account, the expression of equation (8) will be modified as follows.

$$W_k(\theta_j) = \int_{-\pi}^{\pi} D(\theta - \theta_j) E_k(\theta) \mathrm{d}\theta \quad (9)$$

where $D(\theta)$ is the probability density function of wind direction whose mean value is given as the calculated wind direction. $E_k(\theta)$ is a window function that is 1 in the directional sector k. Standard deviation of the distribution will be discussed later. The treatment and effects of some errors on analysis will be also discussed there.

3.3 Evaluation of probability distribution in Monte-Carlo simulation

In order to evaluate of probability, Monte-Carlo technique is often used. In the post process of most hurricane simulation techniques a straight-forward plotting procedure was often used (e.g. Hazen plot, Gumbel plot, etc.) based on order statistics. In such ordinary plotting procedures, it is hard to incorporate the evaluated PDF F_T shown in the previous section. An evaluation, therefore, is proposed as shown below.

Theoretically the evaluated value in the Monte-Carlo simulation is

$$F_A(u) = \int_{\Omega} F(u > V|\Omega) f(\Omega) d\Omega, \quad (10)$$

where $\Omega = \{D_P, R_M, C, \theta_T, m, r_{min}, \theta_{min}\}$ are probabilistic typhoon parameters concerning its depth D_P, size R_M, translation(speed & direction) C, θ_T and occurrence (number & position) m, r_{min}, θ_{min}. $F(u > V|\Omega)$ is the conditional probability of maximum wind speed being less than u with Ω.

In the simulation, this equation is evaluated as discrete expression,

$$F_A(u) \simeq \frac{1}{N_T} \sum_{i=1}^{N_T} \left\{ \prod_{l=1}^{m_i} {}_{i,l}F_T(u) \right\}, \quad (11)$$

where N_T is the simulation year, ${}_{i,l}F_T(u)$ is the cumulate distribution function of the l-th typhoon maximum wind speed in the i-th year. ${}_{i,l}F_T(u)$ is given by equation (7).

4 Numerical results

4.1 Configurations of the site and calculation

Chiba meteorological station is chosen to analysis. Location of the station is shown in Figure 1. Surface condition around the station is varied from seacoast (in the south) to urban(in the north).

Table 1 shows roughness length parameter z_0 in each of 16 directional sectors. These values were optimized so that wind speed had been evaluated fairly well while wind direction had systematic errors. The directional error was corrected by means of the calibration method mentioned above. Comparing the observed record and calculation of the typhoon model, on the wind speeds, the residue of them are 2.6m/s in root mean square. On wind directions, differences are almost within two directional sectors. Figure 2 shows wind speed and direction of typhoon No.9019. In the figures observed and calculated values are indicated for comparison. Wind speeds and directions of macroscopic models do not include random fluctuations existing in full-scale observation, while these values of macro models have good agreement in the sense of longer time scales. Kurihara[10] who had studied wind field of a hurricane numerically concluded that spatial variation of wind speed field due to hurricane is 2-3 m/s.

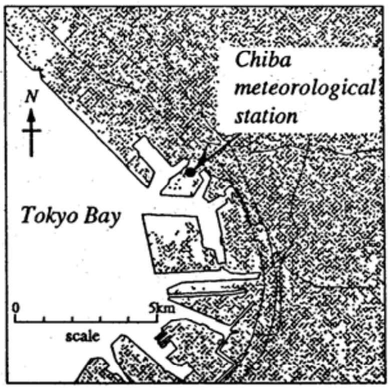


Figure 1: Chiba meteorological station

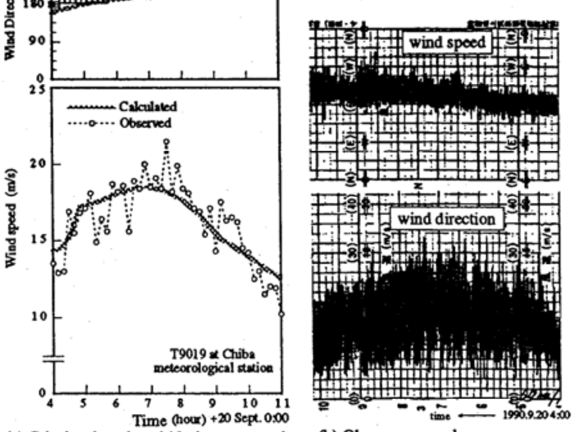
Table 1: Directional roughness length around Chiba station

wind direc.	NNE	NE	ENE	E
z_0 (m)	3	3	3	1
wind direc.	ESE	SE	SSE	S
z_0 (m)	0.3	0.3	0.3	1
wind direc.	SSW	SW	WSW	W
z_0 (m)	0.1	0.1	0.1	0.1
wind direc.	WNW	NW	NNW	N
z_0 (m)	1	3	5	3

These values were optimized to evaluate wind speeds well, but were almost the same as ones from site's directional surface appearance.

α_u in equation (3) is given as function of z_0 as[7],

$$\alpha_u = 0.27 + 0.09 \log z_0 + 0.018(\log z_0)^2 + 0.0016(\log z_0)^3.$$



(a) Calculated result and 10min.-avr. records (b) Observes records

Figure 2: Time history of wind (T9019, obs. and cal.)

To clarify the directional effects of wind speed, fluctuation and uncertainty, four cases in Table 2 are calculated. In every case fluctuation in wind speeds is considered. Wind directionality is not considered in the first case but considered in the second and third case. Fluctuation of wind direction is not considered in the second case but considered in the third case.

Table 2: Conditions of calculations

case	*directional windspeed*	*directional fluctuation*	*directional uncertainty*
1	ignore	ignore	ignore
2	consider	ignore	ignore
3	consider	consider	ignore
4	consider	consider	consider

From the comparison of observation and calculation from macro-model, the fluctuations are modeled as normal distributions whose standard deviations are 2.6 m/s and 10 degree for wind speed and wind direction, respectively. These values are for the present and should be studied farther for details in future.

4.2 Comparison of the results and discussion

Figure 3 shows 100 year wind speeds for the cases in Table 2.

4.2.1 Comparison between directional wind speed and non-directional wind speed

In the case 2, the wind speed is largest along the S direction while smallest along N. They are 0.89 and 0.47 of the non-directional wind speed(case-1). Directional wind speeds are varied in these directions, but never exceed non-directional wind speed.

4.2.2 Effects of the fluctuation on wind direction

Considering the fluctuation of wind direction, we expect some smoothing effect such that values of relatively small wind speed directions would be large and those of relatively large wind speed direction would be small. But as a result, comparing case 2 and 3, in most wind directions wind speeds are increased by considering the wind's directional fluctuation.

4.2.3 Considering uncertainties in the evaluation of directional wind speeds

Uncertainties including statistical uncertainty (e.g. sampling error), modeling uncertainty and measurement error should be considered in the design practice.

These uncertainties are modeled considering two general situations: the maximum uncertain situation, where wind speed is used regardless of its direction, and minimum uncertain (certain), where wind direction is evaluated definitely. Taking these situations into account, a directional wind speed evaluation is formulated as the width of the window function $E_k(\theta)$ in equation (9). Relations of $D(\theta), E_k(\theta)$ and $W_k(\theta)$ are illustrated schematically in figures 4 (a) and (b). In case 4 the width of the window function is set ± 30 degree, while that for the other cases is ± 11.25 degree. Comparing with case 3, wind speed of case 4 is increased in every wind direction.

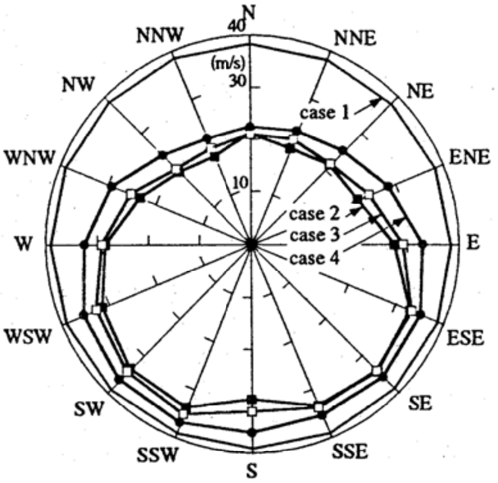
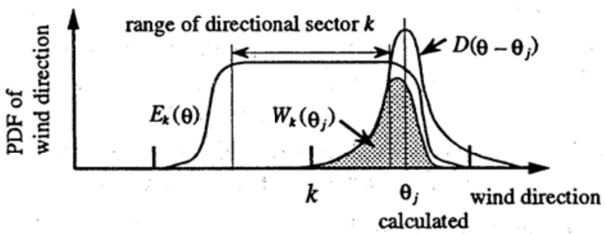
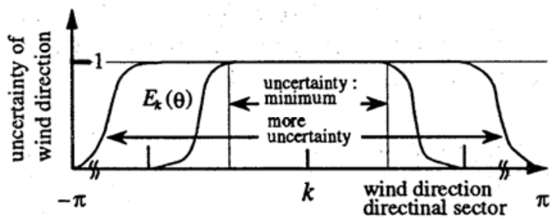


Figure 3: Directional wind speeds of 100-year period



(a) Probability density function of fluctuating wind direction



(b) Uncertainty of wind direction $E_k(\theta)$

Figure 4: Probability density function of fluctuating wind direction, $D(\theta)$, and window function of uncertainty, $E_k(\theta)$

5 Concluding remarks

In Monte-Carlo simulation of a typhoon model, wind direction fluctuation was considered as well as wind speed fluctuation.

- Assuming the independence of fluctuations between wind speed and direction, a formulation was shown.
- Effects of physical wind directional fluctuation and wind direction uncertainty were indicated as a little increase of wind speeds for long time (100-year) recurrence wind speeds.

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Reference

1) Russell,L.R.: Probability distributions for hurricane effects. J.of the Waterways, Harbor and Coastal Engineering Division, ASCE, Vol.97, No.WW1, proc.paper 7886,Feb, 1971,pp.139-154.
2) Tryggvason, B. V., Surry, D. and Davenport, A. G.: predicting wind induced response in hurricanezones, J. of the structural div., ASCE, Vol.102, No.ST12, proc.paper 12630,Dec.1976,pp.2333-2350.
3) Georgiou, P. N., Davenport, A. G. and Vickerry, B. J.: Design wind speeds in regions dominated by tropical cyclones, J. of Wind Engineering and Industrial Aerodynamics, Vol.13, 1983,pp.139-152.
4) Vickery, P. J. and Twisdale, L. A. : Wind-Field and Filling Models for Hurricane Wind-Speed Predictions, Journal of Structural Engineering, Vol.121, No.11, Nov. 1995,pp.1700-1709
5) Schloemer, R. W.: Analysis and Synthesis of Hurricane Wind Patterns over Lake Okeechobee, Florida, Hydrometeorological Report, No.31, 1954, pp1-49
6) Meyers, V. A. and Malkin, W.: Some properties of hurricane wind fields as deduced from trajectories, National Hurricane Research Project Report No.49, U.S. Department of Commerce, Weather Bureau, Washington, D.C., 1961
7) Meng, Y., Matsui, M. and, Hibi, K.: A numerical study of the wind field in a typhoon boundary layer, Journal of Wind Engineering and Industrial Aerodynamics 67&68, pp.437-448, 1997
8) Gumley, S.J. and Wood, C. J. : A Comparison of Winds at Two Sites on The Isle of Portland, Journal of Wind Engineering and Industrial Aerodynamics, Vol.10, 1982, pp.47-62
9) Matsui M., Meng, Y. and Hibi, K.: Extreme Typhoon Wind Speeds Considering the Random Variation in a Full-Scale Observation, Proceedings of ICOSSAR'97, pp.1343-1349, 1997
10) Kurihara, Y. and Tuleya, R. E. : Structure of a tropical cyclone developed in a three-dimensional numerical simulation model, Journal of the Atmospheric Sciences, Vol.31, pp.893-919, 1974

key words : *design wind, directional wind speed, typhoon model, Monte-Carlo simulation method*