Prediction of Wind Speedup Ratio Considering Wind Direction of Tropical Cyclones

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1 INTRODUCTION

Speedup ratio is widely used to evaluate the effect of topography on the design wind speed. The maximum value of topographic multipliers has been used as the speedup ratio in the design codes like AIJ (AIJ, 2004.), although the effect of topography depends on wind direction.

This study proposes speedup ratio considering wind direction of tropical cyclones. The extreme wind speed is predicted by Monte Carlo simulation and verified at typical two metrological stations in the section 2. The wind speedup ratio based on Monte Carlo simulation is proposed and compared with the conventional one. A reduction factor and a topographic variation are proposed and the relationship between them is investigated in the section 3.

2 PREDICTION OF EXTREME WIND SPEED INDUCED BY TROPICAL CYCLONES

This section shows the prediction method of extreme wind speeds of tropical cyclones by Monte Carlo simulation (MCS) and the performance of the method at two typical metrological stations.

First, the probability density functions of the parameters of tropical cyclones and the occurrence rate are estimated. For each tropical cyclone, four parameters, namely, the central pressure, the translation velocity, the approach angle, the minimum approach distance are obtained from the track records. The other parameter is the radius at maximum wind speed R_m, which can be identified by the pressure field model proposed by Schloemer. (Schloemer, 1954)

$$\frac{p(r)-p_c}{p_\infty - p_c} = \exp\left(-\frac{R_m}{r}\right) \tag{1}$$

where $p(r)$ is the sea surface pressure at the distance from the center of tropical cyclone, p_c is the center pressure and p_∞ is the surrounding pressure. Virtual tropical cyclones are generated for a long period to satisfy the modeled probability density functions and the correlations as proposed by Ishihara et al. (Ishihara et al., 2005)

Next, a tropical cyclone induced wind at the site of interest $\vec{x}$ is predicted. Wind speed $u_t(\vec{x})$ and direction $\theta_t(\vec{x})$ on complex terrains are obtained by multiplying topographical effect to wind speed $u_f(\vec{x})$ and direction $\theta_f(\vec{x})$ on flat terrains. Wind speed and direction at the height of interest can be written as:

$$u_t(\vec{x}) = S_{ti} u_f(\vec{x}) = S_{ti} E_q u_g(\vec{x}) \tag{2}$$

$$\theta_t(\vec{x}) = \theta_f(\vec{x}) + D_{ti} = \theta_g(\vec{x}) - \gamma_p + D_{ti} \tag{3}$$

where $u_g(\vec{x})$ and $\theta_g(\vec{x})$ are the gradient wind speed and direction, E_p and γ_p are the wind profile factors and the geographic angle, S_{ti} and D_{ti} are the topographic multiplier and the difference in wind direction due to local topography. The gradient wind speed and direction at the site $\vec{x}$ can be calculated from the pressure field of the tropical cyclone assuming the balance among pressure gradient force, centrifugal force and Corioli's force.

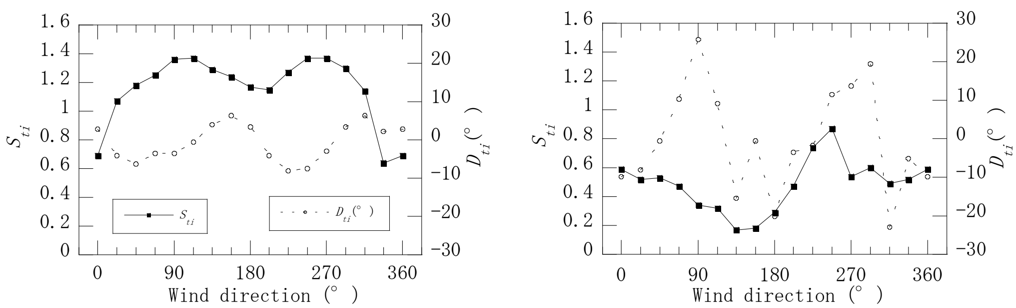
$$u_g\left(\vec{x}\right)=\frac{-C\sin\left(\phi-\theta\right)-fr}{2}+\sqrt{\left(\frac{-C\sin\left(\phi-\theta\right)-fr}{2}\right)^2+\frac{r}{\rho}\frac{\partial p}{\partial r}} \tag{4}$$

$$\theta_g\left(\vec{x}\right)=\pi-\phi \tag{5}$$

where ϕ is the angle measured counterclockwise positive from east, f is the Coriolis parameter. u_g and θ_g are functions of the time due to the motion of tropical cyclones. E_p and γ_p can be estimated by semi-theoretical formula (Ishihara and Hibi, 2005.) or CFD. S_{ti} and D_{ti} can be calculated by CFD. (Ishihara and Hibi, 2002.)

Finally, the probability distribution of annual maximum wind speed, (i.e. the extreme wind distribution,), is estimated from the N years of the MCS. Annual maximum wind speed is extracted and ranked in the ascending order against the reduced variate.

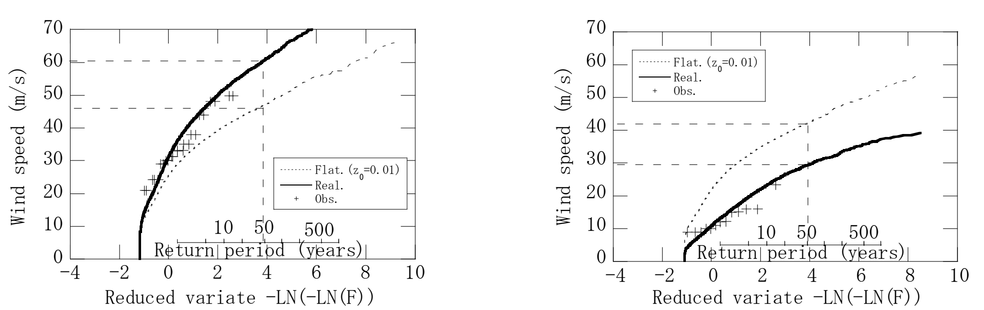
In order to verify the MCS method, extreme wind speeds are predicted at two typical meteorological stations, Murotomisaki and Nagasaki. Figure 1 shows topographic multipliers S_{ti} and the difference in wind direction D_{ti} calculated by CFD. The terrain sub category is set to II as shown in AIJ (AIJ, 2004.), which means that z_0 is 0.01. At Murotomisaki station, the wind speed increased for almost all wind direction because the station locates on the cliff at the tip of the peninsula. The significant increase is observed at 90 and 270 degree from the north. In contrast, Nagasaki station shows low topographic multipliers because the station is surrounded by mountains. Maximum topographic multiplier of each station is summarized in Table 1.



(a) Murotomisaki. (b) Nagasaki.

Figure 1. Topographic multipliers at the two metrological stations.

Figure 2 illustrates the extreme wind distributions obtained by tropical cyclones estimated by MCS method and observations. The estimated distributions considering topographical effect (lines) show a good agreement with observations (plots), while the wind speed distributions without consideration of the topographic effect (dot lines) underestimates to wind speeds at Murotomisaki and overestimates wind speeds at Nagasaki. This indicates that topographical effect is important.



(a) Murotomisaki. (b) Nagasaki.

Figure 2. The extreme wind distributions at the two metrological stations.

3 SPEEDUP RATIO CONSIDERING WIND DIRECTION OF TROPICAL CYCLONES

In this section, a method for the estimation of the speedup ratio considering wind direction of tropical cyclones is proposed. The speedup ratio for N-year-recurrence wind speed is defined as:

$$S_{tN} = U_{tN} / U_{fN} \tag{6}$$

where U_{tN} is N-year-recurrence wind speed on real terrains and U_{fN} is that on flat terrains.

In the conventional method, speedup ratio is defined as the maximum value of topographical multipliers.

$$S_{t,\max} = \max\left(S_{ti}\right) \tag{7}$$

Table 1 shows the proposed and conventional speedup ratios at 50-year-recurrence period estimated at the two metrological stations. The proposed speedup ratio is smaller than the conventional one.

In order to evaluate the reduction of the proposed speedup ratio, the reduction factor is defined as the ratio of the proposed speedup ratio to the conventional one.

$$r_{fN} = S_{tN} / S_{t,\max} \tag{8}$$

The reduction factor should be less than 1.0 from the definition. The reduction factor is 0.94 at Murotomisaki and 0.80 at Nagasaki.

To explain the difference of reduction factors at the two metrological stations, the topographic variation is introduced as:

$$\sigma_t = \sqrt{\left\{\sum_{i=1}^{M}\left(S_{ti} / \max(S_{ti}) - 1\right)^2\right\} / M} \tag{9}$$

where $S_{ti} / \max(S_{ti})$ is a normalized topographic multiplier and M is the number of sectors. This factor should be 0 when all topographic multipliers are same. This is a case of a symmetric hill. As expected from the Figure 1, the topographic variation at Nagasaki is larger than that at Murotomisaki as shown in Table 1.

In order to investigate how reduction factors change with topographic variations, the speedup ratios are systematically analyzed on several typical terrains modeled by the square cosine.

$$z = \cos^2(\pi / 2 * \sqrt{\left(x / L_x\right)^2 + \left(y / L_y\right)^2}) \tag{10}$$

where L_y / L_x is the aspect ratio varying from 1 to 8 as shown in Table 2. Figure 4 illustrates the cross-section of a model at y = 0. Wind direction is defined clockwise.

Table 1. Factors at the two stations.

	S_{t50}	$\max(S_{ti})$	r_{f50}	σ_t
Murotomisaki	1.29	1.37	0.94	0.21
Nagasaki	0.70	0.87	0.80	0.50

Table 2. Size of models and aspect ratios.

	θ (°)	$2L_x(m)$	$2L_y(m)$	$H(m)$	L_y/L_x	σ_t	r_{f50}
Case 1	21.8	1000	1000	200	1	0	1
Case 2	11.3	1000	2000	200	2	0.04	0.98
Case 3	5.7	1000	4000	200	4	0.09	0.96
Case 4	2.9	1000	8000	200	8	0.17	0.93

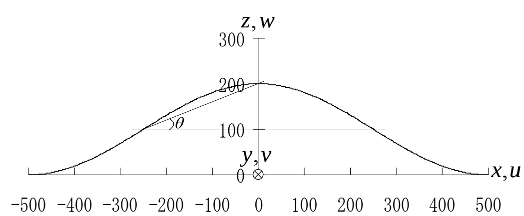


Figure 4. The cross-section of a model at y=0.

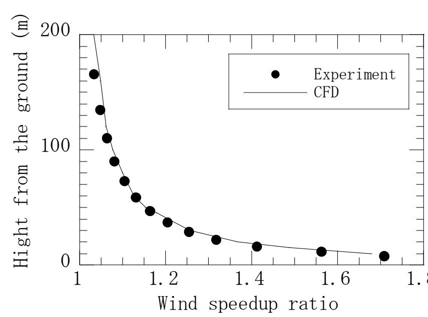


Figure5. The comparison of predicted wind speedup ratio by CFD and experiment.

Figure 5 demonstrates the comparison of the predicted wind speedup ratio by CFD and a wind tunnel test (Ishihara et al., 1999). The profile by CFD agrees favor with the experiment. Figure 6 shows the normalized topographic multipliers for typical model terrains. The multipliers vary a lot as the aspect ratio becomes larger. Topographic variation for each model terrain is evaluated in Table 2.

These virtual terrains are assumed to locate at the same longitude and latitude as Murotomisaki station. The speedup ratios at the 50-year-recurrence period are calculated and reduction factors for each terrain are computed as Table 2 shows.

The Variation of reduction factors with topographic variations is summarized in Figure 7. The reduction factors decrease as topographic variations become higher.

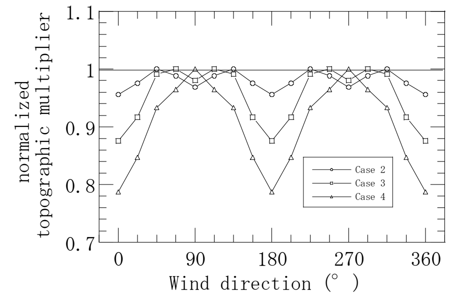


Figure 6. Variation of normalized topographic multipliers with wind direction for the typical model terrains.

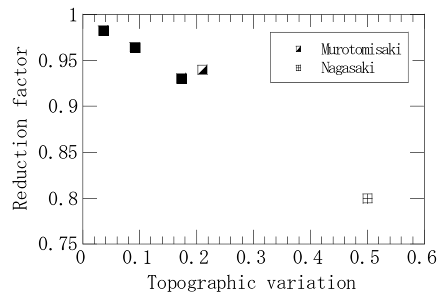


Figure 7. Variation of reduction factors with topographic variations.

4 CONCLUSION

In this study, the speedup ratio considering the wind direction of tropical cyclones was proposed as the ratio of 50-year-recurrence wind speed on real terrains to that on flat terrains. The following conclusions were obtained.

1) The extreme wind speeds predicted by Monte Carlo simulation are verified at two typical metrological stations.

2) The proposed speedup ratio is compared with the conventional speedup ratio. The proposed speedup ratio is smaller than the conventional speedup ratio.

3) The reduction factor and the topographic variation are proposed in order to estimate the reduction by the proposed speedup ratio. The reduction factor decreases as the topographic variation becomes larger.

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