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A study of topographic multiplier considering the effect of complex terrains and tropical cyclones

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ABSTRACT

A topographic multiplier is widely used to evaluate the effect of topography on the design wind speed. The maximum value of directional topographic multipliers has been used as the topographic multiplier in many design codes. However, this simplified method is conservative and overestimates the speedup effect in some cases. In this paper a topographic multiplier considering wind directionality is proposed by using Monte Carlo simulation, and investigated at two typical meteorological stations. Then a reduction factor is proposed as the ratio of the topographic multiplier estimated by Monte Carlo simulation to that obtained by the simplified method. A topographic variation coefficient is proposed as the deviation of directional topographic multipliers and investigated systematically by using terrain models. As a result, the reduction factor decreased as the topographic variation increased. An empirical formula is proposed to improve the simplified method.

1. Introduction

The prediction of extreme wind speeds is essential for structural design. For practical purposes, basic wind speed maps are proposed in many countries. The map shows certain-year-recurrence wind speeds on flat terrains. For example, in the Architecture Institute of Japan (AIJ, 2004), the map illustrates 100-year-recurrence wind speeds on subcategory II at 10 m height above the ground. Designers use this map to determine the design wind speed at the construction site.

In complex terrains like escarpments and small hills, the speedup effect by topography has to be considered. Conventionally, a topographic multiplier is defined as the maximum value of directional topographic multipliers. It is widely used in design codes, although it sometimes overestimates the speedup effect since it does not consider the wind directionality of tropical cyclones. On the other hand, Monte Carlo simulation has been widely used to evaluate extreme wind speeds over complex terrains for tropical and subtropical regions, where the design wind speed is mainly determined by tropical cyclones. In this method, directional topographic multipliers are multiplied to individual storms considering their wind directions. The method was first suggested by Russell (1971) and developed by Tryggvason et al. (1976), Batts et al. (1980), Georgiou et al. (1983), Vickery and Twisdale (1995), Yasui et al. (2002), and Ishihara et al. (2005).

This paper aims to propose a topographic multiplier considering wind directionality by using Monte Carlo simulation for tropical cyclones and to evaluate the effect of terrain complexity and wind directions on topographic multipliers. In the following section, surface wind field models of tropical cyclones are described and a numerical simulation is verified with observations at a wind tunnel test. Monte Carlo simulation of tropical cyclones is stated and its accuracy is verified with measurements at two meteorological stations in Section 3. In the final section, a topographic multiplier considering the effect of complex terrains and tropical cyclones is defined and compared to the conventional one. A reduction factor is proposed as the ratio of the new topographic multiplier to the conventional one and investigated by using typical terrain models.

2. Wind field model of tropical cyclones

In this section, wind field models of tropical cyclones are explained. First, a gradient wind speed is estimated from a pressure field of tropical cyclones. Then, the surface wind speed is obtained with directional topographic multipliers and deviations of wind directions.

2.1. Wind field of tropical cyclones

The gradient wind field model expresses the balance that exists between the forces by horizontal pressure gradient, Coriolis acceleration and centrifugal acceleration, in the presence of general storm translations. The gradient wind speed $u_g(\vec{x})$ at

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the site $\vec{x}$ is evaluated by

$$u_g(\vec{x}) = \frac{-C\sin(\phi-\theta)-fr}{2} + \sqrt{\left(\frac{-C\sin(\phi-\theta)-fr}{2}\right)^2 + \frac{r}{\rho}\frac{\partial p}{\partial r}} \tag{1}$$

where C is the translation velocity; θ and ϕ are the approach angle and gradient wind direction measured counterclockwise positive from East, respectively; f is the Coriolis parameter; r is the distance from the tropical cyclone center; ρ is the air density; and p is the tropical cyclone pressure. The wind direction θ_g corresponding to this gradient velocity is given by

$$\theta_g(\vec{x}) = \pi - \phi \tag{2}$$

The tropical cyclone pressure model used here was proposed by Schloemer (1954), which was expressed as a function of r:

$$\frac{p(r)-p_c}{p_\infty - p_c} = \exp\left(-\frac{R_m}{r}\right) \tag{3}$$

where p_c is the center pressure, p_∞ is the surrounding pressure and R_m is the radius at maximum wind speed, which can be identified by the least squares method using the measured sea surface pressure at the meteorological stations; p_∞ can be assumed to be 1013 hPa or identified simultaneously.

The effect of topography can be separated from that of tropical cyclones' pressure fields since the scale of topography is smaller (Ishihara et al., 2005). Surface wind speeds u_T and directions θ_T on real terrains of tropical cyclones are obtained as follows:

$$u_T(\vec{x},\theta_f) = u_f(\vec{x})S_t(\vec{x},\theta_f), \tag{4}$$

$$\theta_T(\vec{x},\theta_f) = \theta_f(\vec{x}) + D_t(\vec{x},\theta_f) \tag{5}$$

where u_f, and θ_f are wind speeds and directions on flat terrains, respectively, calculated using the following surface wind field models:

$$u_f(\vec{x}) = u_g(\vec{x})(z/z_g)^{\alpha_u}, \tag{6}$$

$$\theta_f(\vec{x}) = \theta_g(\vec{x}) + \theta_s(1.0-0.4(z/z_g))^{1.1} \tag{7}$$

where the exponent index α_u and the gradient height z_g are expressed as functions of the absolute vorticity and the surface Rosby number. Inflow angle θ_s is a function of the homogeneity of vorticity and the surface Rosby number (Ishihara et al., 1997). S_t and D_t are the directional topographic multiplier and deviation of wind direction, respectively, which are calculated by Computational Fluid Dynamics (CFD).

2.2. Evaluation of directional topographic multipliers and deviation of wind directions

A CFD program, MASCOT (Microclimate Analysis System for Complex Terrain) is employed to evaluate the directional topographic multiplier S_t and the deviation of wind direction D_t.

MASCOT is a nonlinear flow simulation model for the prediction of microscale wind climates on complex and steep terrains (Ishihara and Hibi, 2002). The Reynolds averaged Navier–Stokes equations and turbulence models expressed by the following Equations are used, providing information on the mean velocity components along the directions, the static pressure, turbulence kinetic energy and its dissipation:

$$\frac{\partial \rho \bar{u}_j}{\partial x_j} = 0, \tag{8}$$

$$\frac{\partial \rho \bar{u}_j \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right), \tag{9}$$

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho \bar{u}_j k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] - \rho\overline{u_i' u_j'}\frac{\partial \bar{u}_i}{\partial x_j} - \rho\varepsilon, \tag{10}$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial \rho \bar{u}_j \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - C_{\varepsilon 1}\frac{\varepsilon}{k}\rho\overline{u_i' u_j'}\frac{\partial \bar{u}_i}{\partial x_j} - C_{\varepsilon 2}\frac{\rho \varepsilon^2}{k}. \tag{11}$$

In these equations, ρ is the fluid density and μ is the laminar viscosity. The constants (C_μ, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, and σ_k) are assigned to standard values (1.44, 1.92, 1.0, and 1.3; Jones and Lauder, 1972). The turbulent viscosity μ_t is defined as a function of turbulence kinetic energy and dissipation:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$

The fluctuating velocity components are identified by the turbulent Reynolds stress tensor. In this study, the standard k–ε model is used to approximate the Reynolds stress:

$$\rho\overline{u_i' u_j'} = \frac{2}{3}\rho k \delta_{ij} - \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{12}$$

To suit the computation of complex flow, an arbitrary non-orthogonal collocated grid system is used. The governing equations are rewritten in the curvilinear coordinate system and solved using a common discrete method. In this program, the finite volume method and the SIMPLE algorithm are adopted. The QUICK scheme is employed for convection terms in the equation of k and ε and the second order central difference for the order terms. Rhie and Chow's PWIM (pressure weighted interpolation method) is used to avoid pressure–velocity decoupling. For detailed information, refer to Ishihara and Hibi (2002).

Using this model, wind speeds and directions on flat and real terrains are calculated with regard to the wind sector i:

$$S_{ti}(\vec{x}) = \frac{u_{ti}(\vec{x})}{u_{fi}(\vec{x})}, \tag{13}$$

$$D_{ti}(\vec{x}) = \theta_{ti}(\vec{x}) - \theta_{fi}(\vec{x}). \tag{14}$$

S_t and D_t are obtained by a linear interpolation. S_t values computed by MASCOT are compared with wind tunnel test data (Ishihara et al., 1999). In the experiment, the turbulent flow over a circular hill, having a cosine-squared cross section, was investigated using split-fiber probes designed for measuring flows with high turbulence and separation. Profiles of the mean and variance for the three velocity components were presented and compared with those in the undisturbed boundary layer. In this study, one-thousandth of a mountain model of the wind tunnel test is prepared for CFD. The analytical domain in horizontal and vertical planes are set to 3500 m and 900 m, respectively, the minimum intervals of mesh in horizontal and vertical are fixed at 10 m and 3 m, and the surface roughness is given as 0.3 m as the wind tunnel test. The topographic multipliers predicted by CFD agree favorably with observations at the top of the mountain (Fig. 1).

Directional topographic multipliers S_t and deviations of wind directions D_t are evaluated at two meteorological stations located with typical complex terrains: Murotomisaki and Nagasaki. Fig. 2 illustrates elevation maps around the stations. The Murotomisaki station is on a cliff at the tip of the peninsula, which leads to increased wind speed. In contrast, the Nagasaki station is surrounded by mountains and forests, which leads to decrease in wind speeds. Fig. 3 shows S_t and D_t computed with meshes and boundary conditions in Table 1. The number of wind direction sectors is set at 16 and the terrain subcategory is fixed to II as specified in AIJ in which z_0 is 0.01. Wind directions are expressed in degrees progressing clockwise from North. At the Murotomisaki station, directional topographic multipliers are almost constant, except those around 0° corresponding to wind from the land. Meanwhile, at the Nagasaki station, directional topographic multipliers have a clear peak due to wind from the bay. The result indicates that topographic effect on wind speed is significant on complex terrains.

3. Monte Carlo simulation of tropical cyclones

In Monte Carlo simulation of tropical cyclones, tropical cyclone parameters are evaluated from a historical track record of past tropical cyclones. Then synthetic tropical cyclones are generated for a long period to satisfy probability distributions and their correlations using a modified orthogonal decomposition method. Finally, surface wind speeds are predicted and extreme wind distributions of tropical cyclones are estimated.

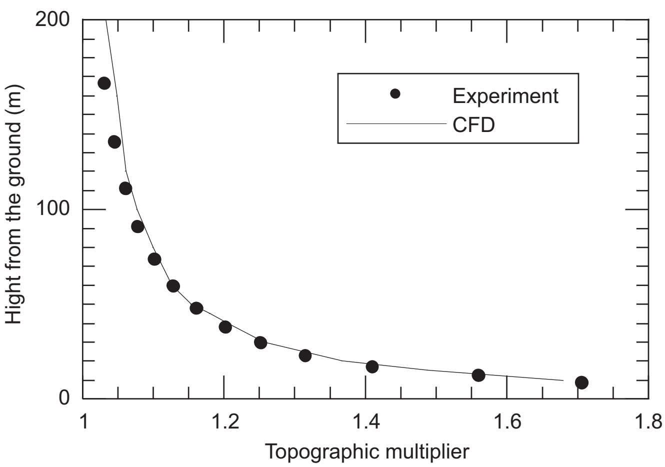

Fig. 1. Comparison of predicted and measured directional topographic multipliers.

3.1. Evaluation of tropical cyclone parameters

Tropical cyclones can be generated by Monte Carlo simulation (MCS) based on six tropical cyclone parameters. For each tropical cyclone, four parameters, namely the central pressure p_c, the translation velocity C, the approach angle θ taken counterclockwise positive from East and the minimum approach distance d_{min} when the cyclone approaches the site of interest most closely, are obtained from the historical track record of tropical cyclones. Another parameter is the radius at maximum wind speed R_m, which can be identified by the pressure field model in Eq. (3).

Table 1
Mesh and boundary conditions.

	Murotomisaki	Nagasaki
Location	N33°15′06″ E129°52′00″	N32°44′00″ E134°10′36″
Area	5 km × 5 km × 10 km	5 km × 5 km × 10 km
Minimum mesh size (m)		
Horizontal	50	50
Vertical	5	5
Resolution terrain	50	50
Resolution roughness	100	100
Inflow	z_0=0.01	z_0=0.01
Wind direction sector	16	16

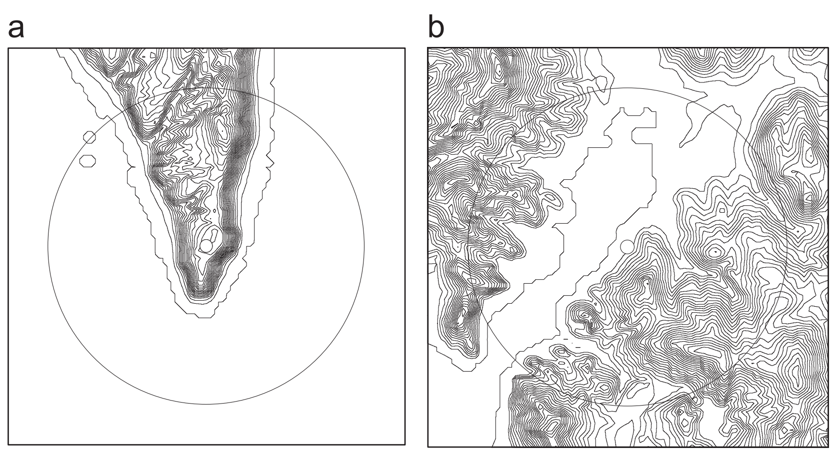

Fig. 2. Elevation maps around two stations: (a) Murotomisaki and (b) Nagasaki.

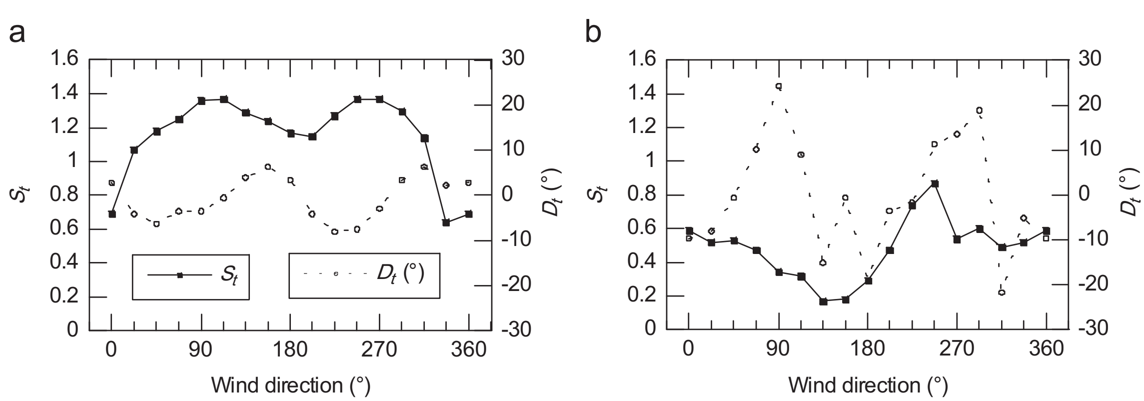

Fig. 3. Directional topographic multipliers S_{ti} and deviations of wind directions D_{ti} at the two stations: (a) Murotomisaki and (b) Nagasaki.

The other parameter is an occurrence rate of the tropical cyclones at the specific site, λ, which can be defined as the number of tropical cyclones that pass, and is obtained from the track records of past tropical cyclones. These six parameters are approximated by analytical functions. Table 2 shows an example of the probability distribution for these parameters estimated at the Murotomisaki meteorological station. Here, μ is the averaged value, σ is the deviation of each parameter, k is the shape factor, c is the scale factor and a is the mixed paramater, z is the coefficient of quadratic function, and λ_m is the averaged number of tropical cyclones hit Japan per year.

3.2. Generation of synthetic tropical cyclones

Synthetic tropical cyclones are generated for N years to satisfy the modeled probability distributions and the correlations of tropical cyclone parameters. The change in pressure field of tropical cyclones can be neglected since wind speeds and directions are estimated only when tropical cyclones are located inside a simulation cycle with a diameter of 500 km. A modified orthogonal decomposition (MOD) method should be used to satisfy the statistical distribution functions of tropical cyclone parameters and the correlations between them at the same time, as proposed by Ishihara et al. (2005). The detailed procedure of the MOD method is described below.

Five parameters describing a tropical cyclone are normalized and written in vector form as follows:

$$x^T = \{\ln(\Delta p), \ln(R_m), \ln(C), \theta, d_{min}\} \tag{15}$$

The covariance matrix of x is defined as S. The eigenvalues $\lambda^{(k)}$ and the eigenvectors $\Phi^{(k)}$ are calculated by solving the following equation:

$$[S - \lambda^{(k)} E]\Phi^{(k)} = 0 \tag{16}$$

The independent parameters z_i with five components are then generated following the approximated distributions to the intended ones for specified years and the number of the generated vectors following the estimated annual occurrence rate. The correlated parameters x_i can be obtained by the following equation:

$$x_i = [\Phi^{(1)}\Phi^{(2)}\cdots\Phi^{(5)}]^{-1} z_i \tag{17}$$

These vectors x_i should be considered as a set of parameters for tropical cyclones. Although the correlation between each component of x_i satisfies the target correlations, their probability distributions do not follow the target ones. The x_i should be rearranged in ascending order and modified so that its probability distribution follows the target probability distributions. This operation hardly affects the correlations because it does not change the set of parameters.

3.3. Evaluation of extreme wind distributions

Wind speeds on flat and real terrains are calculated with wind field models expressed by Eqs. (1)–(7). Annual maximum wind speed u_i can be extracted and ranked in ascending order from u_1 to u_N (Gumbel, 1958; IEC61400-1, 2005):

$$F(u_i) = 1 - \frac{i}{N+1} \quad (i = 1,\ldots,N) \tag{18}$$

u_i is plotted against a reduced variate y_i as follows:

$$y_i = -\ln(-\ln(F(u_i))) \tag{19}$$

The extreme wind distributions predicted by MCS for 10,000 years are compared to those by observations at Murotomisaki and Nagasaki meteorological stations. 10 minutes mean wind speed data is acquired from Automated Meteorological Data Acquisition System (AMeDAS) developed by Japanese Meteorological Agency. The data is available from 1995 to 2009. With regard to the Murotomisaki

Table 2
Examples of the probability distributions of tropical cyclones parameters.

Parameter	PDF	Model parameters
Central pressure depth	$F_M(x) = a \times \frac{1}{\sqrt{2\pi}\sigma_{\ln x}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu_{\ln x}}{\sigma_{\ln x}}\right)^2\right] + (1-a) \times \frac{k}{C}\left(\frac{x}{C}\right)^{k-1} \exp\left[-\left(\frac{x}{C}\right)^k\right]$	$\mu = 1.64$, $\sigma = 0.12$, $k = 4.01$, $c = 49.7$, $a = 0.99$
Radius of maximum wind speed		$\mu = 1.98$, $\sigma = 0.22$, $k = 2.16$, $c = 122.7$, $a = 0.57$
Translation speed		$\mu = 1.54$, $\sigma = 0.21$, $k = 2.43$, $c = 43.07$, $a = 0.40$
Translation direction	$F_S(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right]$	$\mu = 161.02$, $\sigma = 36.29$
Minimum distance	$d_{min}(x) = z(x^2 - x) + 1000x - 500$	$z = -166.11$
Number of typhoons per year	$\lambda(x) = \frac{\lambda_m^x \exp(-\lambda_m)}{x!}$	$\lambda_m = 3.30$

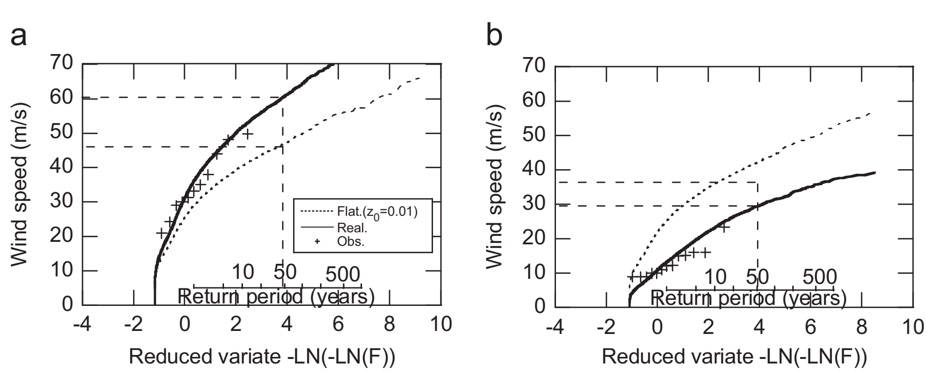

Fig. 4. Extreme wind distributions at the two stations: (a) Murotomisaki and (b) Nagasaki.

station, data until 2005 are used since the station was relocated in 2006. Tropical cyclone data is collected from cyclones passing within 500 km from the site with the center pressure less than 985 hPa.

In Fig. 4, the predicted distributions considering topographical effect (lines) show a good agreement with those by observations (plots), whereas the distributions without consideration of topographic effect (dot lines) underestimate wind speeds at Murotomisaki and overestimate it at Nagasaki. This indicates the importance of considering speedup effect by complex terrains to evaluate extreme wind speeds and proves the accuracy of MCS.

4. Study of topographic multiplier

In this section, a topographic multiplier considering wind directions with Monte Carlo simulation is proposed. A reduction factor is proposed as the ratio of the new multiplier to the conventional one and investigated using typical terrain models.

4.1. Definition of topographic multiplier considering wind directions of tropical cyclones

In a conventional way, a topographic multiplier ($S_{t,max}$) is defined as the maximum value of directional topographical multipliers:

$$S_{t,max} = \max(S_t) \tag{20}$$

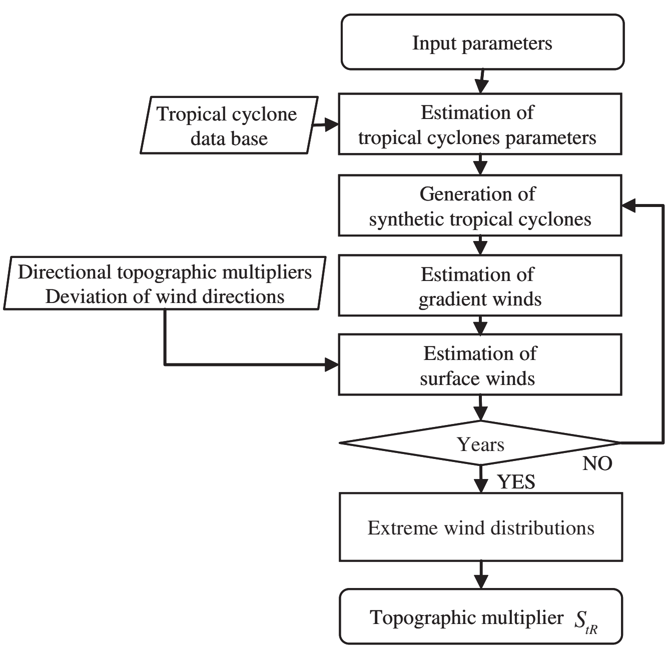

Fig. 5. Flowchart for evaluation of topographic multiplier by MCS, S_{tR}.

This simplified method is practical, but has a possibility of overestimation since wind directions are out of consideration. A topographic multiplier considering wind directions by MCS S_{tR} is proposed as

$$S_{tR} = U_{tR}/U_{fR} \tag{21}$$

where U_{tR} is R-year-recurrence wind speed on real terrains and U_{fR} is that on flat terrains evaluated by MCS. This index considers the probability of occurrence of wind direction. Fig. 5 summarizes a flow for obtaining S_{tR} with wind field models and MCS of tropical cyclones.

To evaluate the new topographic multiplier, a reduction factor r_R is proposed as the ratio of the topographic multiplier by MCS to that by the simplified method:

$$r_R = S_{tR}/S_{t,max} \tag{22}$$

Here, the smaller value of r_R means that the new topographic multiplier shows a lower value against the conventional one. It expresses the effect of taking wind directions into account.

The topographic multipliers are investigated at Murotomisaki and Nagasaki meteorological stations to see the effect of return period. Fig. 6 shows variations of topographic multipliers with return periods. For short return periods, S_{tR} shows a small value because the occurrence rate of wind directions with a large directional topographic multiplier is relatively low. For long return periods, S_{tR} increases, but does not reach $S_{t,max}$, since the probability of wind directions with $S_{t,max}$ is lower than 100%. In this study, 50-year-recurrence period is considered following the international standard for the design of wind turbine (IEC61400-1, 2005).

4.2. Relationship between reduction factors and complex terrains

Topographic multipliers and reduction factors at the two stations are summarized in Table 3. The reduction factor is larger at Murotomisaki than that at Nagasaki. This difference in reduction factor is probably related to the distribution of directional topographic multipliers (Fig. 3). If all directional topographic multipliers are the same, the proposed topographic multiplier

Table 3
Topographic multipliers by the simplified method $S_{t,max}$ and MCS S_{t50}, reduction factors r_{50}, and topographic variation coefficients σ_t, at the two stations.

	$S_{t,max}$	S_{t50}	r_{50}	σ_t
Murotomisak	1.37	1.29	0.94	0.21
Nagasaki	0.87	0.70	0.80	0.50

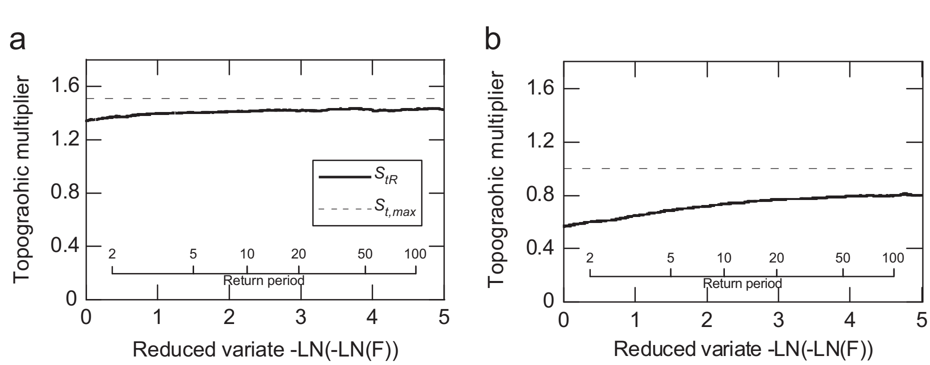

Fig. 6. Topographic multipliers with return period at (a) Murotomisak and (b) Nagasaki.

coincides with the simplified one. When the difference between directional topographic multipliers and their maximum value is large, the reduction factor will decrease. To quantitatively evaluate this difference, a topographic variation coefficient σ_t is introduced as follows:

$$\sigma_t = \sqrt{\left\{ \sum_{i=1}^{M} (1 - S_t/S_{t,\max})^2 \right\} / M} \tag{23}$$

where $S_t/S_{t,\max}$ is a normalized topographic multiplier and M is the number of wind direction sectors. This factor should be 0 when all topographic multipliers are the same as those of a symmetric hill, and become larger for complex terrains. σ_t becomes 0.21 in Murotomisaki and 0.50 in Nagasaki.

In order to investigate the relationship between reduction factors and topographic variation coefficients, topographic multipliers are systematically examined for terrains modeled using square cosine on an x–y plane.

$$z = H\cos^2(\pi/2\sqrt{(x/L_x)^2 + (y/L_y)^2}) \tag{24}$$

where H is the hill height; L_x and L_y are the radius of short and long axis of the hill, respectively. The y axis corresponds with the southerly wind. Fig. 7 illustrates a cross-section of the model at $y=0$. The four models have aspect ratios varying from 1 to 8 as shown in Table 4s. Case 1 is an isolated hill and Case 4 expresses a ridge.

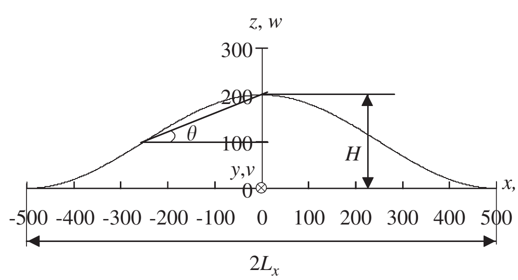

Fig. 7. Cross-section of model at $y=0$.

Table 4
Size for each hill model.

	θ (°C)	$2L_x$ (m)	$2L_y$ (m)	H (m)	L_y/L_x
Case 1	21.8	1000	1000	200	1
Case 2	11.3	1000	2000	200	2
Case 3	5.7	1000	4000	200	4
Case 4	2.9	1000	8000	200	8

Fig. 8(a) and (b) depicts directional topographic multipliers and normalized ones calculated by CFD. For larger aspect ratios, directional topographic multipliers vary significantly and speedup effects become smaller at 0° and 180° because model slopes get gradual.

In order to investigate the sensitivity of the effect of terrain orientations on reduction factors, the axes of models are rotated clockwise from the north at 45°, 90°, and 135° as shown in Fig. 9.

For 12 cases, the proposed topographic multipliers are computed by conducting MCS for 10,000 years. Terrain models are assumed to be located at the same longitude and latitude as those of the Murotomisaki station for MCS. Topographic variation coefficients, topographic multipliers by the simplified method and MCS and reduction factors for each model are summarized in Table 5. The reduction factor decreases as topographic variation coefficient increases, and variations in reduction factors are slight compared with the reduction effect by terrain complexity. The result indicates that the reduction effect by considering wind directionality works in combination with terrain complexity. For practical purposes, it is found that when topographic variation coefficient is large, the MCS method is recommended since the effect of considering wind direction of tropical cyclones is greater.

Fig. 10 plots all data including models and real terrains. The relationship between reduction factors and topographic variation coefficients are expressed as follows:

$$r_{50} = 2 - \exp(\sigma_t/3) \tag{25}$$

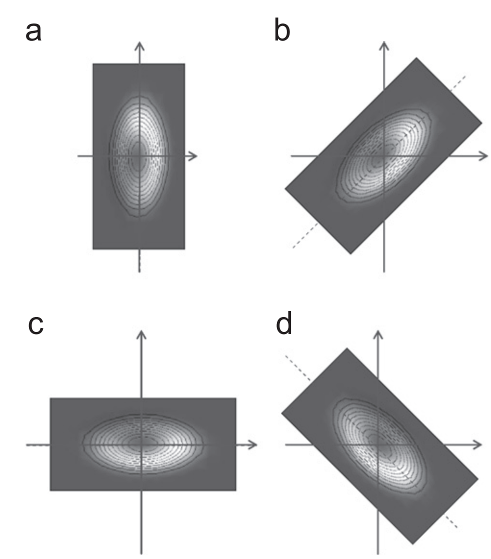

Fig. 9. Terrain model rotated by (a) 0°, (b) 45°, (c) 90° and (d) 135°.

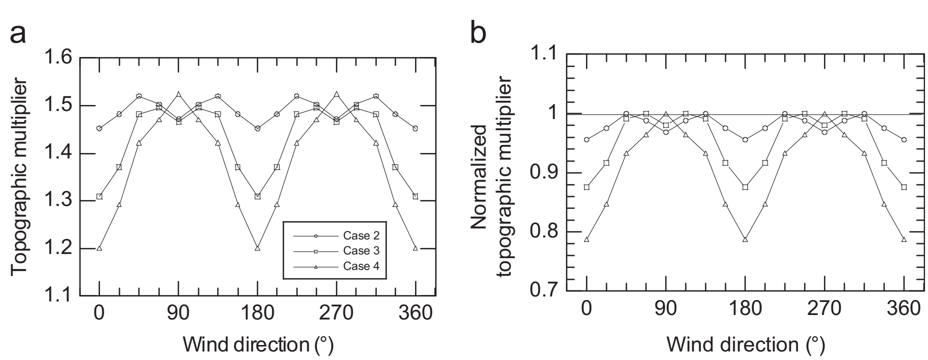

Fig. 8. Variation of (a) directional topographic multipliers and (b) normalized ones with wind directions.

Table 5
Topographic variation coefficients σ_t, topographic multipliers by the simplified method $S_{t,\max}$ and MCS S_{t50} and reduction factors r_{50} for each model.

	σ_t	$S_{t,\max}$	S_{t50}	r_{50}
Case 1	0	–	–	1
Case 2-0	0.04	1.520	1.490	0.980
Case 2-45			1.494	0.983
Case 2-90			1.498	0.986
Case 2-135			1.490	0.980
Case 3-0	0.09	1.496	1.443	0.965
Case 3-45			1.454	0.972
Case 3-90			1.443	0.965
Case 3-135			1.447	0.967
Case 4-0	0.17	1.525	1.419	0.930
Case 4-45			1.432	0.939
Case 4-90			1.442	0.946
Case 4-135			1.417	0.929

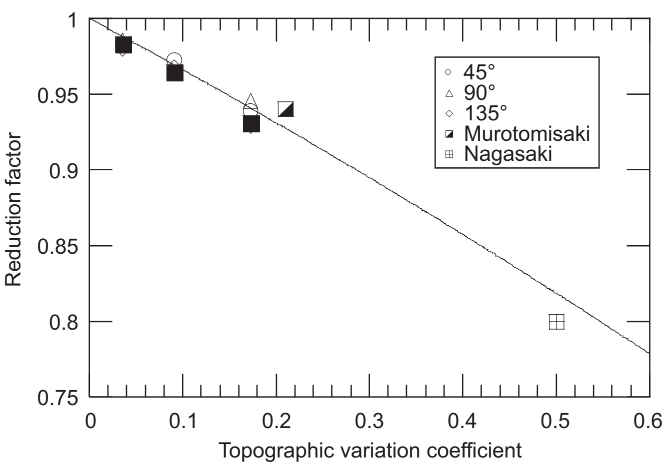

Fig. 10. Variation of reduction factors with topographic variation coefficients.

In order to improve the accuracy of simplified method, Eq. (26) is proposed to predict the topographic multiplier of 50-year-recurrence wind speed by the product of the maximum of directional topographic multipliers $S_{t,\max}$ and the reduction factor r_{50}. The lower limit is set to 1.0 because the wind speed decrease should not be adopted in the design of wind turbines (Ishihara, 2010).

$$S_{50} = \max(S_{t,\max} r_{50}, 1) \tag{26}$$

5. Conclusions

The topographic multiplier considering the effect of complex terrains and tropical cyclones is proposed and investigated. The following conclusions are obtained:

1) The accuracies of the CFD simulation and Monte Carlo simulation are verified with the wind tunnel test data and the observations at two typical meteorological stations. Considering a speedup effect by complex terrains was important to evaluate extreme wind speeds.
2) A topographic multiplier considering wind directionality is defined as the ratio of certain-year-recurrence wind speed on real terrains to that on flat terrains. A reduction factor is introduced as the ratio of the topographic multiplier by Monte Carlo simulation to that by the simplified method. The reduction factors are investigated at the two meteorological stations. The reduction factor at the Murotomisaki station is less than that at the Nagasaki station.
3) A topographic variation coefficient is proposed as the deviation of directional topographic multipliers and is investigated systematically by using terrain models. The reduction factor decreases as the topographic variation coefficient increases. The speedup ratio of 50-year-recurrence wind speed is evaluated as the product of the maximum of directional topographic multipliers and the reduction factor to improve the simplified method.
4) The proposed topographic multiplier considering the wind directionality for strong winds is the general framework and can be used for strong winds induced by extratropical cyclones.

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