Technique of Evaluating Surface Wind Speed Using Nonlinear Simulation Model for Catastrophe Bonds

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ABSTRACT: Several catastrophe bonds for typhoon risks, which enable the conversion of a natural disaster risk from insurance markets to capital markets, were issued in Japan. Originators and investors require less basis risk, which is the difference between actual losses and amount of collection from catastrophe bonds, for trigger type of catastrophe bond. Since the estimated losses are mainly calculated by surface wind speed, it is important to evaluate surface wind speed accurately. In order to improve the accuracy for evaluating surface wind speed, we propose a technique that combines a nonlinear simulation model with a typhoon simulation model. This method enables the evaluation of the effects of surface roughness and terrain. The accuracy of this method was verified by simulating significantly past typhoon.

KEYWORDS: Surface roughness and terrain, Catastrophe bond, Nonlinear simulation model, Typhoon simulation model, Basis risk

1 INTRODUCTION

The market for catastrophe bonds, which enable the conversion of a natural disaster risk from insurance markets to capital markets, has experienced continual annual growth. Catastrophe bonds are insurance-linked securities that pay the issuer a part or all of the proceeds of the issue after the occurrence of specific natural hazard events.

In Japan, several catastrophe bonds for typhoon risks were issued. Some catastrophe bonds use surface wind speed as the trigger condition since the damage due to a typhoon occurs in all the areas through which it passes. In the case of selecting surface wind speed as a trigger condition, it is important to improve the accuracy of surface wind speed prediction. In order to reduce the basis risk, which is the difference between actual losses and amount of collection from catastrophe bonds, it is essential that the wind speeds in urban areas be calculated accurately. Further, there are many mountains and valleys in Japan; therefore, the effect of terrain cannot be neglected.

Convective activity such as typhoons is governed by fluid dynamics, and a nonlinear simulation model expressed by the Navier-Stokes and continuity equations is able to determinately simulate the characteristics of a typhoon. However, a nonlinear simulation model need a large amount of calculation time and it is necessary to execute thousands of various cases of typhoon simulation for setting probabilities of attachment and exhaustion point of catastrophe bond.

In this study, we propose a technique that combines a nonlinear simulation model with a typhoon simulation model. This technique is able to predict surface wind speed under the considerations of surface roughness and terrain. In addition, as it need not to spend a large amount of time, it is suitable for typhoon simulation. We describe the incorporation of this method into a typhoon simulation model and the result of validating this technique is also reported.

2 TECHNIQUE OF EVALUATING SURFACE WIND SPEED

2.1 *Procedure*

In order to evaluate surface wind speed by numerical analysis, it is necessary to perform a three-dimensional numerical simulation discriminates Navier-Stokes equation. However, this numerical simulation requires a significant amount of calculation time. Therefore, we propose a technique for predicting surface wind speed that combines a typhoon simulation model with a nonlinear wind prediction model-MASCOT (Microclimate Analysis System for COmplex Terrain). This technique reduces the calculation time and predicts surface wind speed under the considerations of surface roughness and terrain. This procedure is described below:

(1) After dividing the entire landmass in Japan into 16 areas, the surface roughness and terrain data of each area are fed as inputs to MASCOT. The distributions of surface wind speed and wind direction are calculated for heights of 10 m, 20 m, 50 m, and 100 m. The surface wind speed under this condition is referred to as V_2 (Figure 1-2).

(2) In the same area, the flat terrain data and category Ⅱ roughness data defined by the Building Standards Act in Japan are fed as inputs to MASCOT. The distributions of surface wind speed and wind direction are calculated for heights of 10 m, 20 m, 50 m, and 100 m. The surface wind speed under this condition is referred to as V_1 (Figure 3-4).

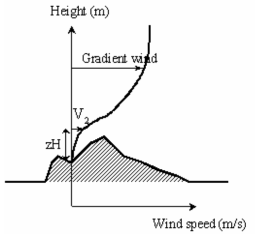

Figure 1. Distribution of wind speed under the condition of surface roughness and terrain of each area.

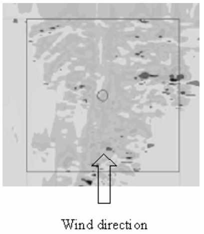

Figure 2. Example of wind speed calculated by MASCOT for height of 20 m under the condition of surface roughness and terrain.

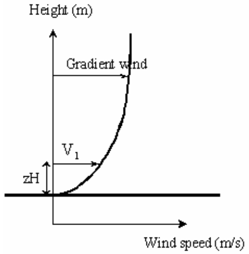

Figure 3. Distribution of wind speed under the condition of the flat terrain data and category Ⅱ roughness.

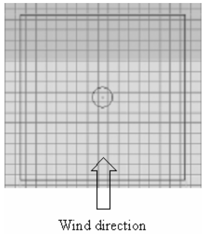

Figure 4. Example of wind speed calculated by MASCOT for height of 20 m under the condition of flat terrain data and category Ⅱ roughness.

Figure 5. 10-min mean surface wind speed distribution of typhoon Songda, in 2004. The conditions correspond to flat surface and category Ⅱ roughness in each area. This wind speed corresponds to V_1.

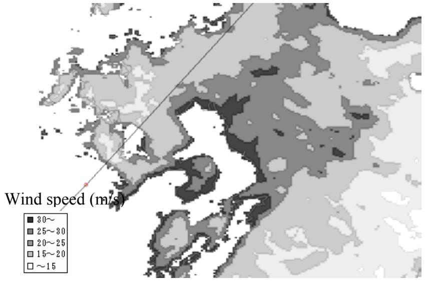

Figure 6. 10-min mean surface wind speed distribution of typhoon Songda, which occurred in 2004. The conditions correspond to terrain and surface roughness in each area. This wind speed corresponds to V_1.

(3) A database containing the ratios of surface wind speeds V_2/V_1 and deflections in surface wind speeds at heights of 10 m, 20 m, 50 m, and 100 m is prepared. Further, this database also includes the data corresponding to the 16 wind directions, which correspond to the inflow in MASCOT.

(4) On executing a typhoon simulation model under the conditions of flat terrain and category Ⅱ roughness, the surface wind speed and wind direction corresponding to V_1 for heights of 10 m, 20 m, 50 m, and 100 m are obtained. Figure 5 shows an example of the distribution of the surface wind speed of typhoon Songda, which occurred in 2004; it corresponds to V_1 at a height of 20 m. Then, the surface wind speed corresponding to V_1 is multiplied by V_2/V_1 at the same height in order to calculate the surface wind speed corresponding to V_2, and the wind direction is subtracted by the deflection of surface wind speed. Figure 6 shows an example of the distribution of the surface wind speed of typhoon Songda, which occurred in 2004; it corresponds to V_2 at a height of 20 m.

This technique is called the “Combined model” in this study, and the typhoon simulation model and MASCOT are explained in the subsequent sections.

2.2 *Typhoon simulation model*

A typhoon simulation model can predict the surface wind speed in each area under the conditions of flat terrain and category Ⅱ roughness.

2.2.1 *Pressure distribution model*

It is well known that pressure isobars in the domain of a typhoon are distributed approximately in concentric circles with respect to the center of the typhoon. This relationship is given as follows [1]:

$$P(r) = P_C + D_P \exp\left\{ -\left(\frac{R_M}{r} \right)^B \right\} \qquad (1)$$

where P(r) = pressure as a function of the distance r from the center of the typhoon; P_c = central pressure; D_p = central pressure difference; R_M = maximum radius of the winds; and B = profile coefficient. B assumes an appropriate value between 1.0 and 2.5. A study reported that pressure isobars in Japan are distributed approximately in a concentric circle when the central pressure is 985 hPa or less. Moreover, the profile coefficient of the model is set as B=1 [2].

2.2.2 *Georgiou’s gradient-level wind field*

A gradient wind speed is expressed by the following formula derived from the motion equation, which balances the pressure gradient force and the sum of the centrifugal and Coriolis forces:

$$v_{rg} = 0$$

(2)

$$v_{\theta g} = \frac{c \cdot \sin\theta - fr}{2} + \sqrt{\left(\frac{c \cdot \sin\theta - fr}{2} \right)^2 + \frac{r}{\rho} \frac{\partial P(r)}{\partial r}} \qquad (3)$$

where v_{rg} = gradient wind speed in the direction of r in cylindrical coordinates; $v_{\theta g}$ = gradient wind speed in the direction of θ; θ = angle (anticlockwise indicates positive); c = translation velocity of a typhoon; f = Coriolis parameter; and ρ = air density.

2.2.3 *Ishihara’s wind-field model*

The average wind speed v(z) can be calculated as the sum of the gradient wind speed in free atmosphere and the component v’(x). The component v’(x) at a height of z is caused by friction on the ground surface:

$$v(z) = v_{\theta g} + v'(z) \qquad (4)$$

where the expression for $v_{\theta g}$ is given by Equation 3 in cylindrical coordinates. The component $v'(z)=\{v_r', v_\theta'\}$ can be linearized as

$$-\xi \cdot f_\lambda v'_\theta = \frac{\partial}{\partial z}\left(K_m \frac{\partial v'_r}{\partial z} \right) \qquad (5)$$

$$\frac{1}{\xi} \cdot f_\lambda v'_r = \frac{\partial}{\partial z}\left(K_m \frac{\partial v'_\theta}{\partial z} \right) \qquad (6)$$

where f_λ = absolute vorticity; ξ = parameter of the axial nonuniformity of vorticity; and K_m = vortex viscous coefficient. Ishihara applied the closure model to K_m and estimated the velocity component in the atmospheric boundary layer as follows [3,4]:

$$Z_g = 0.06 \frac{v_{\theta g}}{f_\lambda} \left(\log R_{0\lambda} \right)^{-1.45} \qquad (7)$$

$$\gamma_s = (69 + 100\xi)(\log R_{0\lambda})^{-1.13} \tag{8}$$

$$U(z) = v_{\theta g}\left(\frac{z}{Z_g}\right)^{\alpha_u} \tag{9}$$

$$\gamma(z) = \gamma_s\left(1 - 0.4\frac{z}{Z_g}\right)^{1.1} \tag{10}$$

$$\alpha_u = 0.27 + 0.09\log_{10} z_0 + 0.018(\log_{10} z_0)^2 + 0.0016(\log_{10} z_0)^3 \tag{11}$$

where U(z) = the wind velocity at the height z; γ (z) = angle deviation at the height z; α_u = index parameter; z_0 = roughness length; Z_g = height of gradient wind speed; $R_{o\lambda}$ = modified surface Rossby number; and γ_s = surface shearing stress angle. Using Equation 7-11, we can evaluate the wind velocity and wind direction for heights of 10 m, 20 m, 50 m, and 100 m. This equation can evaluate the effect of surface roughness but not that of the terrain. The roughness length is set to category Ⅱ roughness for all regions.

2.3 *Nonlinear wind prediction model MASCOT*

MASCOT [5,6] is a numerical simulation model that is expressed by the Navier-Stokes and continuity equations. MASCOT can evaluate the effects of surface roughness, terrain, and canopy. The resolutions of elevation and roughness length are 50 m and 100m, respectively. These two data are to be averaged according to the mesh size.

3 VERIFICATION OF THE TECHNIQUE

3.1 *Simulation of past typhoons*

The surface wind speeds calculated by the proposed technique was compared with the observed wind speeds of a significantly past typhoon—typhoon Songda; it occurred in 2004 and resulted in maximum insurance loss in the past five years in Japan.

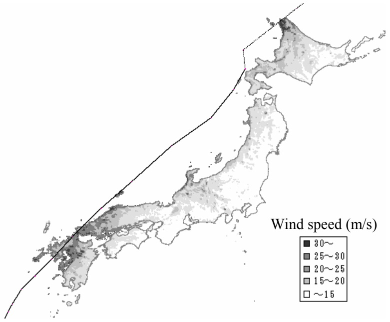

Figure 7. Distribution of the calculated surface wind speed of typhoon Songda, which occurred in 2004.

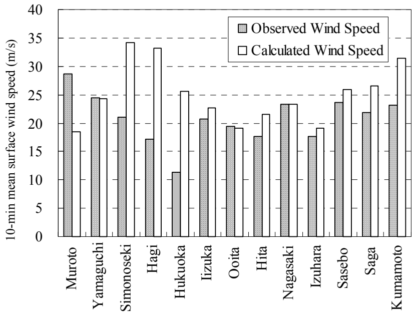

Figure 8. Calculated and observed wind speeds for each observation.

Figure 7 shows the distribution of the surface wind speed obtained by using the proposed technique, and Figure 8 shows the comparison of the observed and calculated wind speeds at the height of each anemometer. As a result, it was verified that the calculated wind speed is consistent with the observed wind speed, except near the coastal areas.

3.2 *Comparison of basis risk*

Basis risk between the proposed technique and empirical technique was validated. Basis risk, which means a difference between actual loss and predicted loss estimated by typhoon simulation model, needs to be minimum for applying catastrophe bonds. Reduction percentage is mainly determined by typhoon index value that is calculated by typhoon simulation model. In this study, the following equation is selected for calculating typhoon index value.

$$\text{Typhoon Index Value} = \sum_{i=1}^{n}\left\{w_i \cdot (V_i - V_0)^b\right\} \tag{12}$$

$$w_i = \frac{H_i}{\sum_{i=1}^{n} H_i} \tag{13}$$

where w_i = weight of location i; V_i = calculated wind speed; V_o = threshold of wind speed; a = coefficient; H_i = household set for all regions in Japan with a 1-km mesh; and n = number of location with a 1-km mesh.

The accuracy of technique is compared with that of the empirical equation, which has been employed in previous techniques. The empirical equation relates the gradient wind speed to the surface wind speed was proposed [7]. The expression is as following and this expression called the “Gradient model” in this study:

$$V_{so} = V_{gr} \times G(\infty) \times \left[1 + \left(\left(10^{0.0231\times\Delta p - 1.96}\right)\right) \times \left(\frac{x}{x_p}\right)^{k-1} \exp\left[\left(1 - \frac{1}{k}\right)\left\{1 - \left(\frac{x}{x_p}\right)^{k}\right\}\right]\right] \tag{14}$$

where V_{gr} = gradient wind speed; V_{so} = surface wind speed; and G(∞) = parameter corresponding to the land condition. In the case of plains, G(∞)=1/2, and in the case of seas, G(∞)=2/3. This expression does not evaluate the roughness and terrain effects for each region.

Seven typhoons, which are seven most expensive insurance losses from 1970 to 2004 in Japan, are Mireille in 1991, Songda in 2004, Bart in 1999, Vicki in 1998, Tokage in 2004, Shanshan in 2006, and Chaba in 2004. Figure 9 shows paths of seven typhoons.

The typhoon index value is calculated using Equations 12-13. Table 1 shows the result of seven typhoon index value in case of a = 2 and b = 26. Table 2 shows the result in case of a = 3 and b = 26. In this study, the amount of basis risk is estimated by the correlation between typhoon index value and paid loss reported by the General Insurance Association of Japan [8]. In case of a = 2 and b = 26, a relation of paid loss and typhoon index value is presented in Figure 10, and the correlation coefficient of Combined model is 0.956 and that of Gradient model is 0.943. In case of a

= 3 and b = 26, a relation of paid loss and typhoon index value is presented in Figure 11, and a correlation coefficient of Combined model is 0.938 and that of Gradient model is 0.919. It was confirmed that Combined model is more correlated than Gradient model.

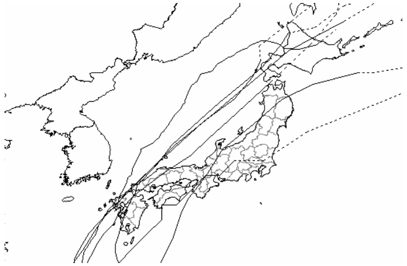

Figure 9. Paths of typhoons

Table 1. Typhoon index values of Combined model and Gradient model in case of a = 2 and b = 26

Typhoon name	Typhoon Index Value		Paid loss (billion yen)
	Combined model	Gradient model	
Mireille	107	112	523
Songda	69	73	356
Bart	42	36	285
Vicki	32	20	151
Tokage	12	3	111
Shanshan	37	36	111
Chaba	23	14	104

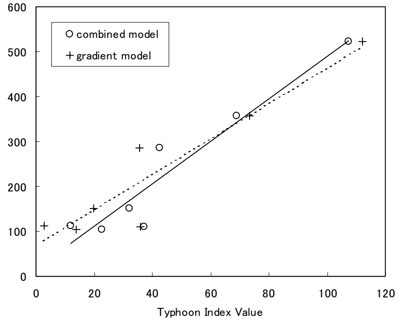

Figure 10. A relation of paid loss and Combined model, and that of Gradient model in case of a = 2 and b = 26

Table 2. Typhoon index values of Combined model and Gradient model in case of a =3 and b = 26

Typhoon name	Typhoon Index Value		Paid loss (billion yen)
	Combined model	Gradient model	
Mireille	2,655	2,625	523
Songda	1,490	1,196	356
Bart	791	578	285
Vicki	429	171	151
Tokage	149	24	111
Shanshan	841	725	111
Chaba	298	133	104

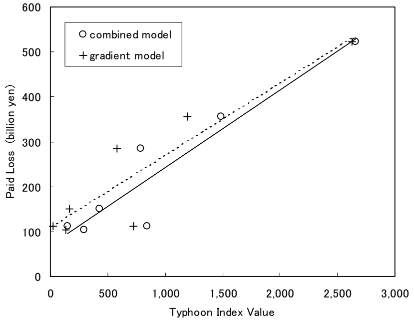

Figure 11. A relation of paid loss and Combined model, and that of Gradient model in case of a = 3 and b = 26

4 SUMMARY

Originators and investors require less basis risk that is the difference between actual losses and amount of collection from bonds. In order to reduce the basis risk, it is essential that the wind speeds in urban areas be calculated accurately. The following conclusions were derived from this study:

(1) In order to calculate the surface wind speed for a typhoon simulation model, a technique combining a typhoon simulation model and a nonlinear numerical simulation model was proposed.
(2) A typhoon simulation model, which was incorporated in this technique, was developed.
(3) Typhoon Songda, which occurred in 2004, was simulated, and it was verified that the simulated wind speed was consistent with the observed wind speed, except near the coastal areas. A decrease of basis risk was confirmed by the correlation coefficient between typhoon index value and paid loss.

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