Typhoon Risk Analysis of Offshore Wind Farms

Takayuki Hayashi
Unit Leader, Property Risk Engineering Dept., Tokio Marine dR Co., Ltd., Tokyo, Japan

Masahiko Kaneko
Unit Leader, Property Risk Engineering Dept., Tokio Marine dR Co., Ltd., Tokyo, Japan

Mizuki Shinohara
Senior Consultant, Property Risk Engineering Dept., Tokio Marine dR Co., Ltd., Tokyo, Japan

Seiichiro Fukushima
CEO, RKK Consulting Co., Ltd, Tokyo, Japan

ABSTRACT: This paper examines the risk evaluation method for offshore wind farms. At first, damage function of wind generator was established by the event tree analysis whose branch probabilities are calculated by the fragility functions of components forming the generator. Then the risk curve of model offshore wind farms located in some sites are calculated, followed by the insight for the effect of risk diversification that is achieved by multi-location.

1. INTRODUCTION

Recently in Japan, offshore wind power generation has drawn attention in realizing decarbonized society, followed by the many projects of the offshore wind power generation are promoted throughout the country reflecting the commitment of the government that Japan will introduce the wind power of 10 million kW by the year of 2030.

To construct the offshore wind farm around Japan islands it is important to cope with the Japan-specific environmental problems and natural disasters, though many experience in construction has been accumulated in European countries. It is therefore necessary to establish proactive countermeasure against disasters by conducting risk evaluation and by appropriate risk control and risk financing, in the planning phase of the project. Since Japan is surrounded by various natural disasters, nevertheless no detailed risk evaluation procedure for natural disasters including typhoon disasters has been established so far for offshore wind farm.

Okazaki (2005) proposed a probabilistic typhoon hazard assessment method for Japan. Also, Okazaki (2006) employed the nonlinear wind prediction model MASCOT to account for the effects of terrain and surface roughness in their method. MASCOT is a wind prediction model developed by Ishihara (2003) and is often used in wind power studies in Japan. By taking vulnerability assessment into account in such probabilistic typhoon hazard assessments, some studies have been conducted to probabilistically assess the economic damage to structures (i.e., Watabe et al. (2006,2022)). Such a method is very important for the business planning of wind power generators in Japan, but has not yet been established.

This paper examines the probabilistic risk evaluation method for offshore wind farms that generate stable power and possessing the environmental advantages such as less noise and less vibration comparing with onshore wind farms.

2. CONSTRUCTION OF DAMAGE FUNCTION OF OFFSHORE WING FARM

2.1. Outline

Figure 1 shows the typical offshore wind farm consisting of some components. Also, it is noted the wind generator itself consists of some elements such as tower, nacelle, blades, and so on.

Although offshore wind farms are assumed to include both onshore and offshore facilities, this paper will focus on offshore wind turbines. Table 1 summarizes the components whose fragility functions are established.

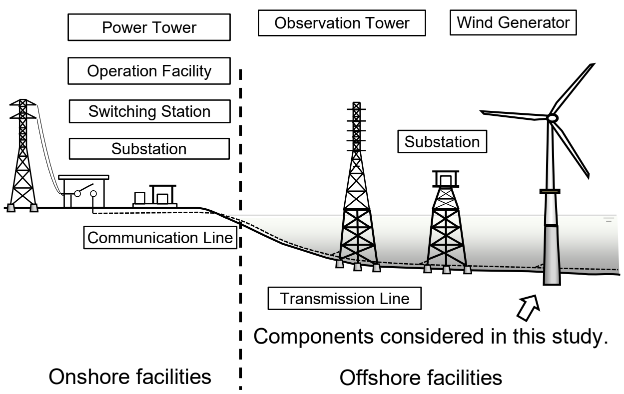

Figure 1: Configuration of offshore wind farm.

Table 1: Components whose damage functions are established.

Category of Component		
Offshore	Wind Generator	Blade
		Hub
		Nacelle Cover
		NRA Assy
		Tower
		Connection
		Pitch Control
	Foundation	Gravity
		Mono-pile
		Jacket
	Substation	
	Observation Tower	
	Transmission Line	
	Communication Line	
Onshore	Substation	
	Battery Facility	
	Operation Facility	

2.2. Fragility Analysis of Components

2.2.1. Method for offshore components

There are 2 ways to obtain fragility function, the empirical way and analytic way. Since very little typhoon damage data is obtained, this paper employs the latter way.

The wind velocity by which the component of concern reaches to the given limit state is hereafter called the capacity wind velocity in this paper. It is noted that the capacity wind velocity is defined by 10min averaged velocity at 20m above ground. Let the capacity wind velocity be V_0, and V_0 is given by the eqn. (1),

$$V_0 = V_{hub} \times f_1 \times f_2 \times f_3 \quad (1)$$

where, V_{hub} is wind velocity at the hub height, f_1 is design load factor, f_2 is wind velocity conversion factor, and f_3 is strength tolerance, respectively.

f_1 is defined by IEC61400-3-1, and the deference of wind loads in feathering state and fine state is given by the factor. f_2 is the factor by which wind velocity is converted to one at 20m above ground. f_3 is determined by existing study and engineering knowledge.

It is also noted the above factors possess the uncertainties, β_1, β_2 and β_3 which correspond to f_1, f_2 and f_3, respectively. β_1 is the c.o.v of wind speed described in IEC61400-1, β_2 is the uncertainty of wind speed conversion, and β_3 is the uncertainty arising from judgement and material properties in design. These uncertainties are modelled as log-normally distributed. The total uncertainty β is given by the eqn. (2),

$$\beta^2 = {\beta_1}^2 + {\beta_2}^2 + {\beta_3}^2 \quad (2)$$

2.2.2. Trial calculation for offshore components

Three model wind generators are employed to examine of the size of component. The outline of the model generator is shown in Table 2.

Table 2: Outline of model wind generator.

Items	Model Generator		
	G1	G2	G3
Ourput (MW)	15	10	3
Dia. of Rotor (m)	240	175	110
Hub Hight (m)	145	110	75
Tower Hight (m)	125	90	60
V_{hub} (m/s)	57	57	57
Turbulence category	0.16	0.16	0.16
Exponent	0.11	0.11	0.11

As an example of estimation, the factors described in the previous paragraph, Table 3 summarizes them. It is noted that the factors are for blades. It is noted the difference in factors appears in wind velocity conversion factor.

Table 3: Summary of factors to obtain capacity wind velocity for blades.

Parameters	Model Generator		
	G1	G2	G3
f_1 (in feathering state)	1.35	1.35	1.35
f_1 (in fine state)	1.10	1.10	1.10
f_2	0.804	0.829	0.865
f_3	1.25	1.25	1.25
β_1	0.11	0.11	0.11
β_2	0.10	0.10	0.10
β_3	0.05	0.05	0.05

The same procedure is conducted for other component, so that the median and log-normal standard deviation of the capacity wind velocity are other components are obtained. An example of results is summarized in Table 4, in which m_1 is the median in feathering state and m_2 is one in fine state.

Table 4: Example of results of fragility analysis of Components.

Items		Model Generator		
		G1	G2	G3
Blade	m_1	77.4	79.7	83.2
	m_2	63.0	65.0	67.8
	β	0.157	0.157	0.157

Since transmission and communication lines have enough strength against typhoon, large median values are assigned for median.

Some samples of fragility functions are shown in Fig.2, from which it can be seen that components are more fragile in fine state and the differences by the size of wind generator are relatively small.

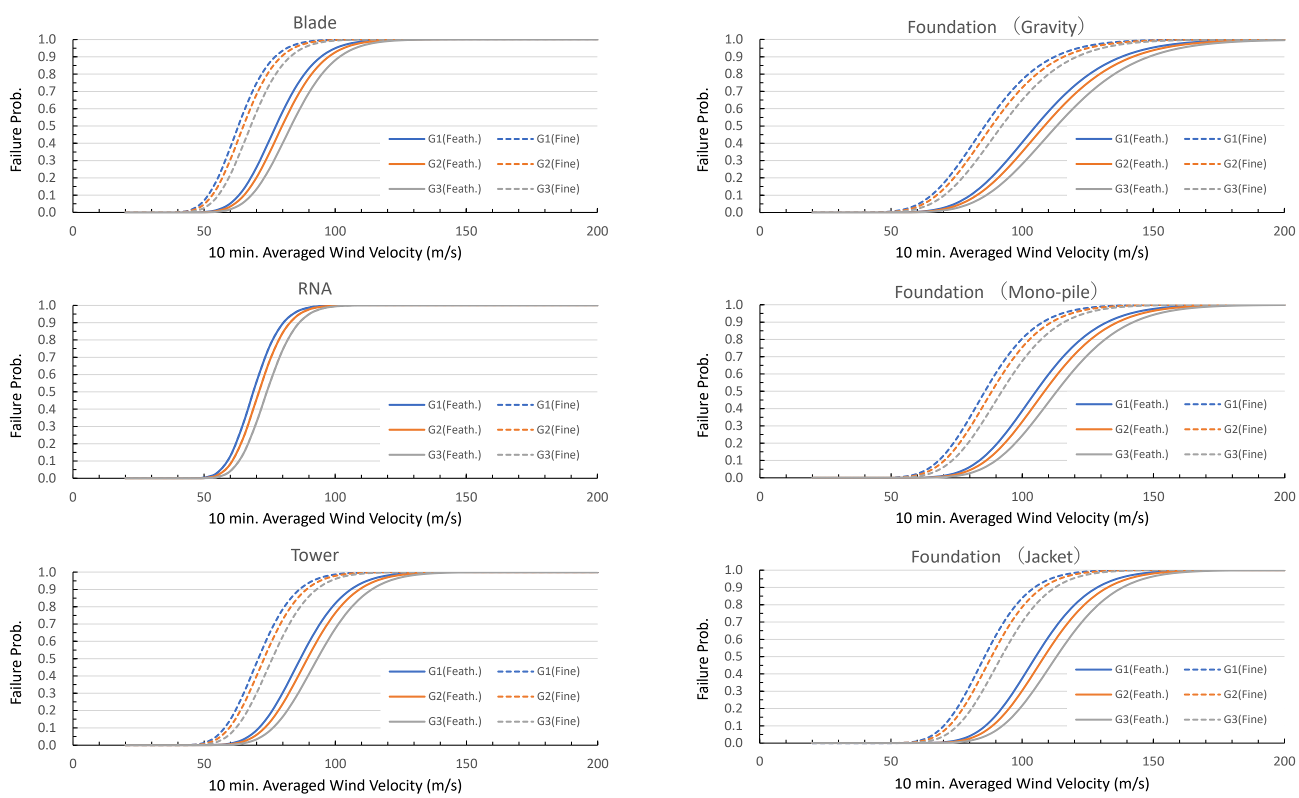

Figure 2: Example of fragility functions of offshore components.

2.2.3. Method for onshore components

For onshore components, the existing damage functions based on the past typhoon accidents are assigned as fragility functions

2.3. Evaluation of Damage Function

2.3.1. Method

As shown in Fig.1, the offshore wind farm is a system consisting of many components. So, this paper employes the event tree (hereafter called ET) to examine the system damage comprehensively as shown in Fig. 3.

The top branch is given to “Damage to Pitch Control”, since the damage causes the deference in receiving area so that almost the components are affected. In case that the damage does not occur, blades remain in feathering state. On the contrary, blades reach to fine state if damage occurs.

The supporting component consists of foundation, connection (transition pierce) and tower. The damage to the foundation and to connection is defined as the loss of capacity to withstand the banding moment from thew tower. Damage to the tower is defined by the bending buckling at the bottom as observed from past accidents.

RNA assembly consists of blade, hub and nacelle. The number of blades of RNA is three, and the probability of damage to the blades p_n is given by the eqn. (3),

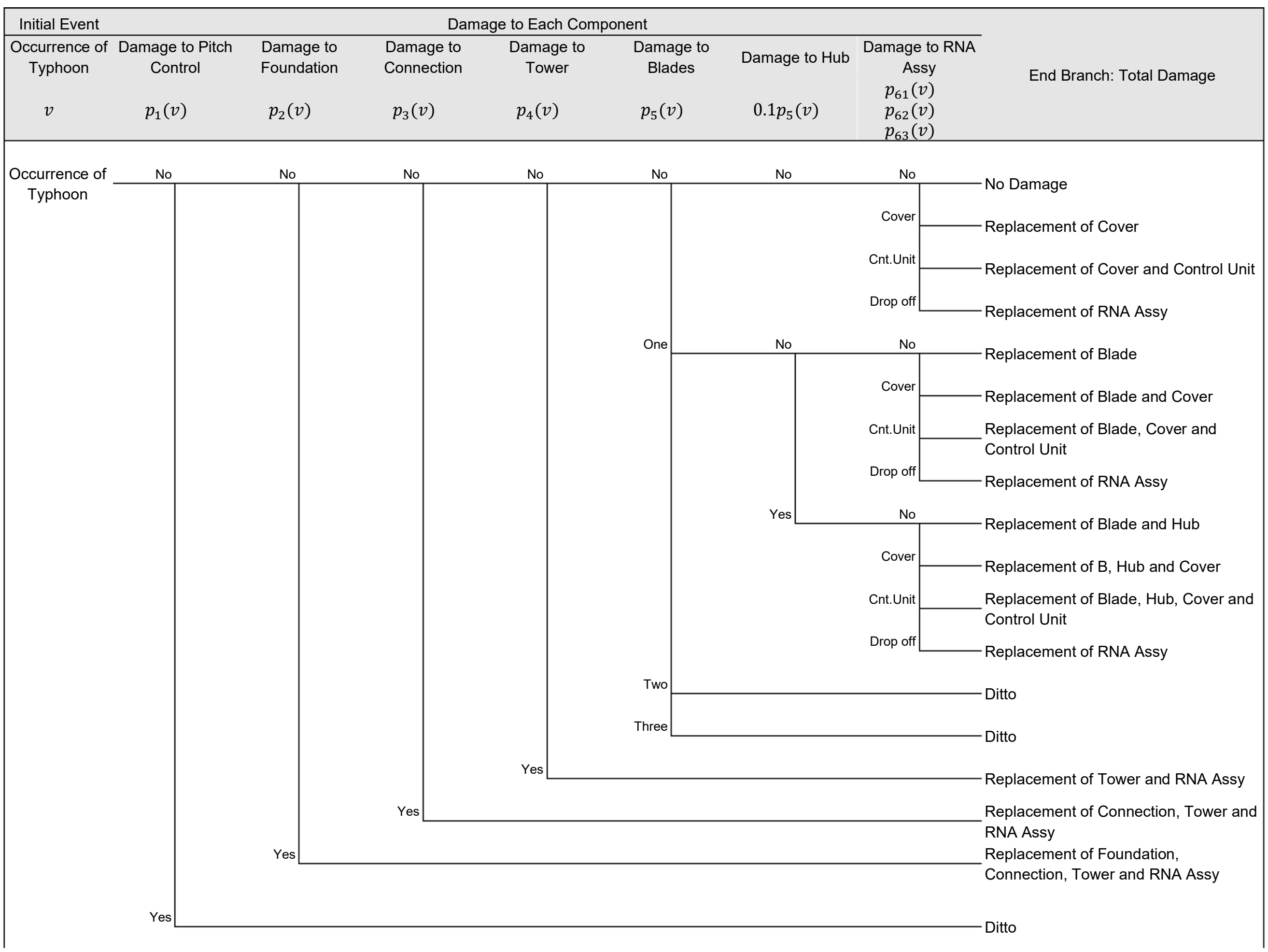

Figure 3: Event tree to obtain the damage function of offshore wind farm.

$$p_n = {}_3C_n \cdot (1-p)^{3-n} \cdot p^n \tag{3}$$

where, n is the number of damaged blades, and p is the damage probability of the single blade. Figure 4 shows the relationship between p and p_n.

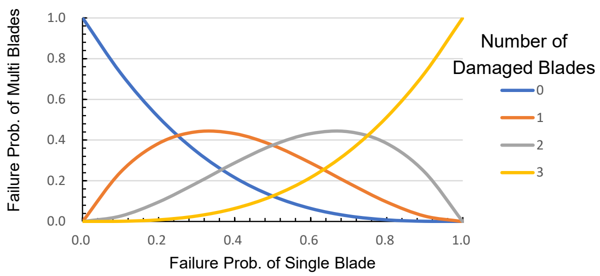

Figure 4: Relationship damage probability of blade and that of single blade.

It is assumed that the damage to the hub is caused by that to the blades, so that the constant ratio of 0.1 is multiplied to the damage probability of blades. For RNA assembly, three types of damages are considered, damage to cover, that to control unit and that to whole assembly.

Probability of each branch is obtained from the fragility function for the given wind velocity.

2.3.2. Setting of end branch

The value of the end branch is given as the damage ratio that is the ratio of rebuilding cost to the initial cost. In this study, two types of damage ratio are employed, one for manufacturing and the other for installation. These ratios are established based on the existing materials. Example of setting of each component cost is shown in Fig.5. The cost ratio of each component changes depending on the hub height.

2.3.3. Trial calculation of damage function

The damage functions for manufacturing and those for installation are shown in Figs. 6 and 7, respectively. The upper figure shows the median of damage ratio and the lower figure shows the lognormal standard deviation.

From the comparison it can be seen that the higher the wing generator is, the bigger the damage cost is. In the range of low wind velocity, the standard deviation is small since the damage occurrence ratio and damage itself are small. In the middle velocity range, the standard deviation gets larger since various damage scenarios can appear the range. In the extreme high wind velocity range, the standard deviation reduces to null due to the fact that only one scenario appears, that is the total collapse of the generator.

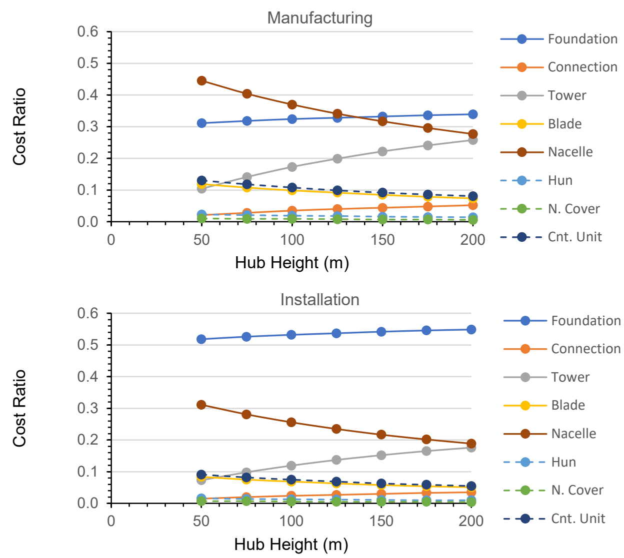

Figure 5: Example of setting cost ratio (Mono-pile foundation).

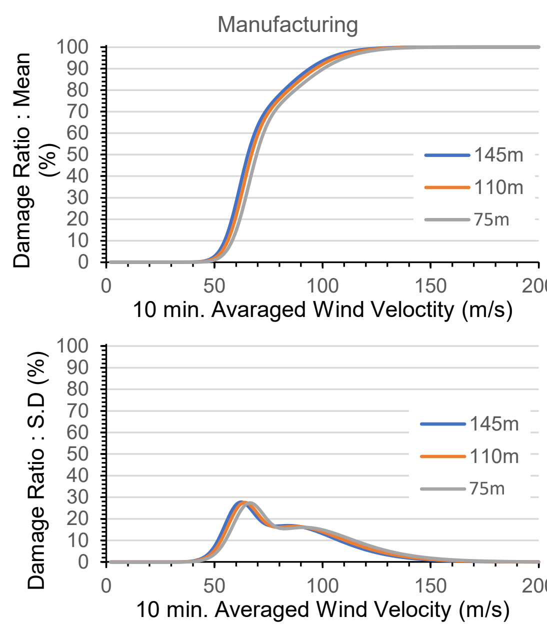

Figure 6: Damage Function for manufacturing (Mono-pile foundation).

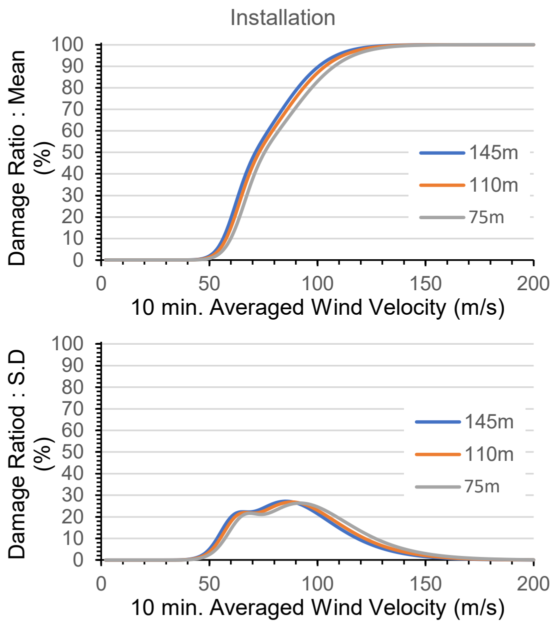

Figure 7: Damage Function for installation (Mono-pile foundation).

3. RISK ANAMYSIS

3.1. Typhoon Hazard Analysis

The typhoon hazard is evaluated by Monte-Carlo simulation of generating sample typhoons. For each sample typhoon, estimated is the distribution of barometric pressure, by which gradient wind is calculated using Ishihara's formula (1995). Then, the 10-minute averaged wind speed at the height of 20m above sea level is estimated using nonlinear wind condition anticipating model MASCOTT. For the detailed information, refer the Hayashi *et al*. (2022).

3.2. Method of Typhoon risk Analysis

3.2.1. Single component case

Let Y and y be the loss by typhoon and threshold, respectively. The annual probability that Y exceeds y is given by eqn. (4),

$$P(Y > y) = 1 - \prod_{k}\left(1 - P_k(Y > y)\right) \tag{4}$$

where, suffix k shows the number of virtual typhoons in the given year. For the given k^{th} typhoon, the annual probability that Y exceeds y is given by eqn. (5),

$$P_k(Y > y) = P(T_k)P(Y_m + Y_i > y) \tag{5}$$

where, Y_m is the manufacturing cost and Y_i is the installation cost. $P(T_k)$ is the occurrence probability of typhoon T_k.

It is noted that the relationship between y and $P(Y > y)$ is often referred as risk curve.

3.2.2. Single-site case

Offshore wind farms usually consist of plural offshore wind generators and related facilities. For this case, eqn. (4) is available to calculate risk curve. It is necessary to assume the constant correlation among the losses of facilities.

3.2.3. Multi-site case

In addition to the constant correlation among the facilities, correlation among the sites will be considers in case that the offshore wind farm consists of some sites. The correlation among the sites is site-to-site distance dependent.

3.3. Trial Calculation

3.3.1. Condition Setting

As shown in Fig.8, two sites, one is in offshore of Akita Pref. (hereafter called Site-A) end the other is in offshore of Fukushima Pref. (hereafter called Site-F). Three sizes of generators called G1, G2 and G3 in the previous section are employed.

Regardless of size of offshore wind farm, identical amount of property is set 1,000,000, in which 80% is for manufacturing and 20% is for installation.

3.3.2. Results

Results of calculation are shown in Table 5 and Figs. 9 and 10. It is noted that single wind generator is installed in each site. Loss at 50-year return period is quite small, since the return period corresponds to design return period. By comparing the risks of Site-A and Site-F, it can be seen that the risk of Site-F is quite large since many typhoon pass the Kyushu island where Site-F is located. It can also be seen that the larger generator size is, the larger risk is. This tendency is given by the difference in damage functions given in the previous section.

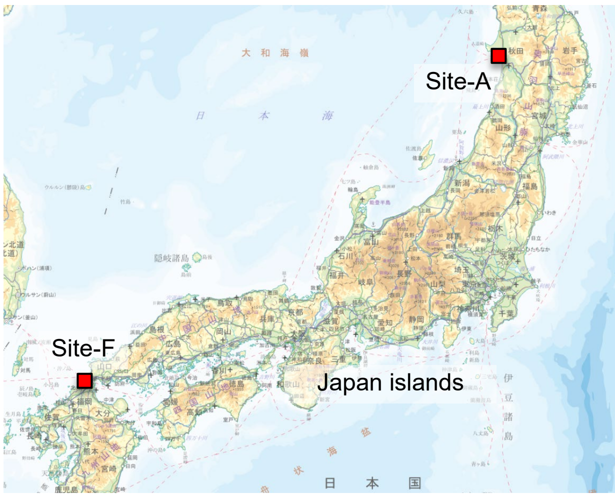

Figure 8: Locations of model site.

Table 5: Typhoon loss at some return periods by size of wind generator.

R.P. (Yr.)	Site-A			Site-F		
	G1	G2	G3	G1	G2	G3
50	3	1	0	1,589	913	508
70	11	5	2	3,138	1,896	1,107
100	41	18	8	5,831	3,681	2,248
200	299	156	78	15,688	10,516	6,900
500	2,009	1,192	675	42,564	30,035	20,965

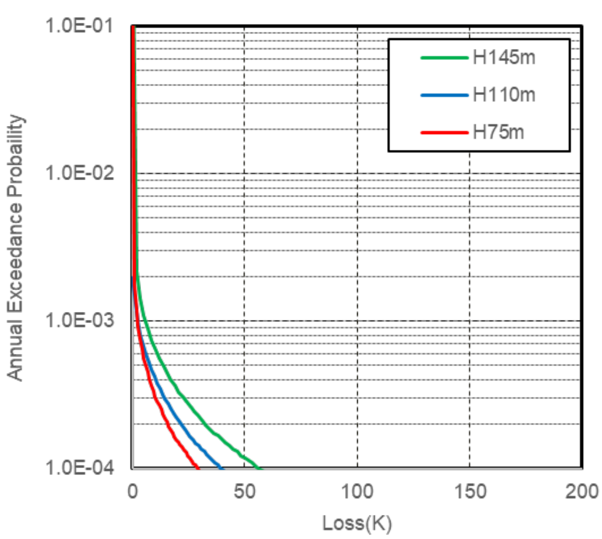

Figure 9: Typhoon risk curves of Site-A by size of wind generators.

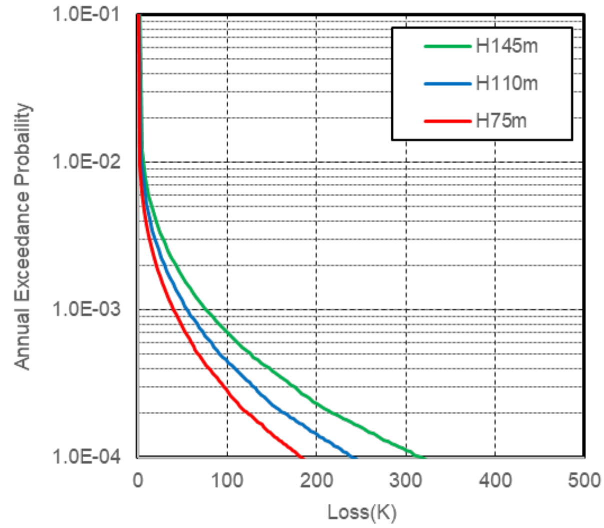

Figure 10: Typhoon risk curves of Site-F by size of wind generators.

As a trial, three types arrangement of installation of generators are examined. Type-1 is the case that 6 generators are in Site-A, Type-2 is the case that 6 generators are in Site-F, and Type-3 is the case that 3 generators in Site-A and 3 in Site-F. The size of the generator is set 145m.

The results of calculation are shown in Table 6 and Fig. 11.

From the Table 6, it is seen that the losses of Type-3 are average of those of Type-1 and Type-2. This shows that the occurrences of loss at Site-A and at Site-F are independent to each other. From the viewpoint of loss mitigation only, Type-1 is the best. However, Type-3 can be the alternative from the viewpoint of avoidance of total damage of offshore wind farm.

Table 6: Typhoon loss at some return periods by arrangement type of wind generator.

R.P. (Yr.)	Type-1	Type-2	Type-3
50	15	8,877	5,438
70	63	17,196	10,141
100	232	31,461	18,010
200	1,666	81,839	44,962
500	10,970	216,248	115,066

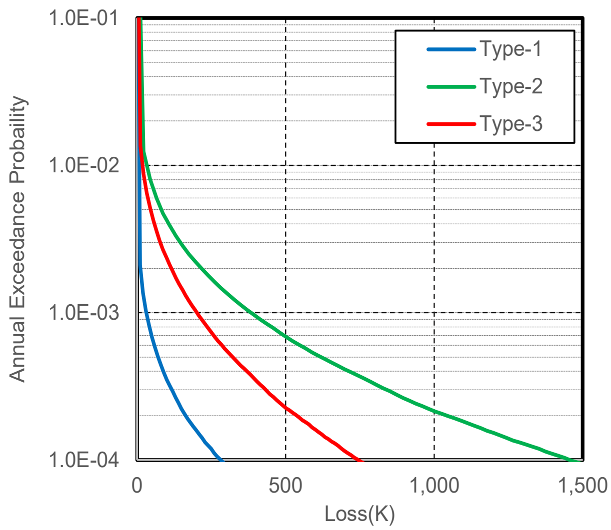

Figure 11: Typhoon risk curves of Site-F by size of wind generators.

4. CONCLUSIONS

Authors proposed the method to evaluate the damage function of offshore wind farms subjected to the typhoons, based on the ET analysis. Some fragility curves of components in the wind farm and some damage functions of the offshore wind generators were calculated as the result of application.

Using the developed damage functions, conducted the typhoon risk analysis of virtual offshore wind farms at two sites. The applicability of the risk analysis method is examined by the trial calculation, followed by the insight of effects of risk diversification.

5. ACKNOWLEDGEMENTS

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