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Development of Probabilistic High Wind Risk Assessment Methodology for Korea Nuclear Power Plants

Junhee Park[1*], Young-Sun Choun[1] and Min Kyu Kim[1]

[1]Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong, Daejeon, 305-353, Republic of Korea

*Corresponding author:jhpark78@kaeri.re.kr

Abstract

A typhoon with high wind affects a structure and equipment. The important buildings such as nuclear power plants (NPPs) should be designed to ensure the safety of structure against external event (seismic, typhoon etc.). Because the NPPs in Korea were located in coastal region the structural/functional damage by high wind caused by typhoon can occur. In this study, the high wind risk assessment using a probabilistic method was systematically developed.

Introduction

After Fukushima accident, the USA continuously focused on the external event (e.g. seismic, flooding, high wind etc.) of NPPs. The wind-born missile assessment using probabilistic method was developed by Electric Power Research Institute (EPRI) [1]. In 2015, EPRI was published the high wind risk guideline which includes high wind and wind-born missile hazard assessment, fragility assessment and risk model of NPPs by high wind [2]. According to the RIS-2015-06 [3], USNRC has accepted the license amendment request (LAR) using Probabilistic Risk Assessment (PRA) methodologies to assess compliance with tornado missile requirements, including the NRC accepted EPRI TORMIS computer code. Licensees may decide to use other PRA computer models, and those new methodologies should be submitted for approval.

According to the previous meteorological data, the annual occurrence frequency of typhoon of Korea was to 2~3 per year. Many buildings and people of Korea have suffered the damage by the typhoon per year.

Because the important structures in nuclear power plants (NPPs) (i.e. containment building and auxiliary building) are generally designed to resist earthquake load it was concluded that the buildings have a sufficient margin for a wind load generated by typhoon. Thus, there have been no studies on a probabilistic high wind risk assessment in Korea.

However, it has been predicted by many researchers that a super typhoon (maximum sustained surface winds of at least 65m/s) will occur in Korea because the intensity and frequency of typhoons have been increasing as a result of global warming [4]. Studies on high wind induced by typhoon for the Korea NPPs located in coastal regions have received little attention compared with other external events, despite recent strong typhoon landfalls near NPPs. Therefore, a development of high wind risk assessment is needed to establish a response system and predict the damage of NPPs from a typhoon.

High wind hazard analyses include a method to select the appropriate wind field model and to consider the uncertainty related to the typhoon wind profile, the probability distribution of the central pressure, and the maximum wind radius.

The important SSCs were selected to perform a wind fragility assessment and their possible failure mode was investigated. High wind fragility assessment method was proposed using various safety factors.

Damage of Korea NPPs by typhoon

The NPPs in Korea are located in 4 sites (Ulchin, Wolsung, Kori and Youngwang). To cool a nuclear fuel, all NPPs located in coastal region.

The typhoons influenced in Korea Peninsula moved from the wet-southern sea to the east sea as shown in figure 1. Therefore, the Ulchin and Kori NPPs located in dangerous semicircle of typhoon were damaged such as the break of transmission line, the impact of transformer by wind borne missile, the stop of circulation system by the influx of garbage, the breakdown of insulator units by flashover and lightning from historical typhoon (e.g. Maemi (2003), Gladis (1991), Thelma(1987), Vera(1986)).

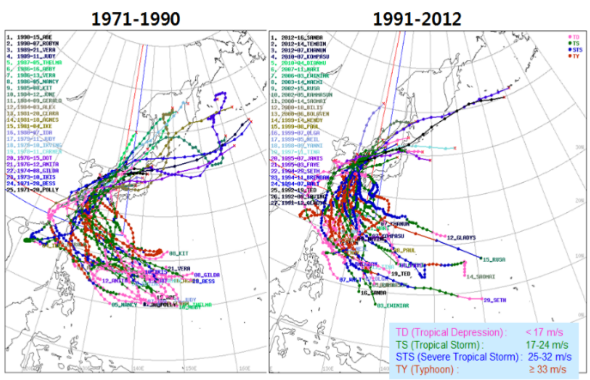

Figure 1. The tracks of typhoons that have affected Korea in the period 1971-1990 (left panel) and 1991-2012 (right panel)

According to the data base of operational performance information system for nuclear power plant (OPIS) (1978~2016), it was reported that the marine organism (e.g. stickleback and jellyfish) most occurred in NPPs as shown in table 1. The installation of net can prevent the marine organism event. From the table 1, it was found that the damage by typhoons was focused on a short circuit of transmission line and a missile impact of transformer. But the damage related on the safety of NPPs doesn't occurred in Korea. The event to resist continuously operation of NPPs just occurred.

In this study, we selected 205 typhoons of RSMC data from 1951 years to 2014 years. Among the 205 typhoon, the 48 typhoons which moved within 300km from the NPP site was finally selected.

Type	Site				Total
	KR	YG	UC	WS	
Typhoon	11	0	0	2	13
Lightning	4	7	1	1	13
Marine organism	2	0	14	0	16
Fire	0	0	2	0	2
Heavy rain	3	0	0	0	3

(KR : Kori, YG: Youngwang, UC: Ulchin, WS: Wolgsung)

Table 1. Occurrence of external events in Korea NPPs

Wind hazard analysis

Wind field model

The climatological characteristics of typhoons include the (1) rate of typhoon occurrence in any given region, (2) difference between atmosphere pressures at the center and periphery of the storm, (3) radius of the maximum wind speeds, (4) speed of storm translation, (5) direction of storm motion, and (6) crossing point coordinate on a line normal to the coast [5]. The physical model of the typhoon wind has been developed using climatological parameters. Holland [6] described the radial distribution of surface pressure in a hurricane in the following form:

$$\mathrm{p(r)} = p_0 + \Delta p exp\left[-\left(\frac{r_{mw}}{r}\right)^B\right] \tag{1}$$

where p(r) is the surface pressure at distance r from the storm center, p_0 is the central pressure, Δp is the pressure difference between the center and periphery of the storm, r_{mw} is the radius of the maximum winds, and B is Holland's pressure profile parameter. The wind profile for a stationary storm is below equation (2)

$$V_g(r) = \sqrt{\frac{r^2f^2}{4} + \frac{B\Delta p}{\rho}\left(\frac{r_{mw}}{r}\right)^B exp\left[-\left(\frac{r_{mw}}{r}\right)^B\right]} - \frac{rf}{2} \tag{2}$$

where $v_g(r)$ is the gradient wind at radius r, ρ is the air density, and f is the Coriolis parameter. The maximum wind intensity is independent of the radius of the maximum winds, but the shape of the pressure profile is required through parameter B.

The Holland model is an axisymmetric model, which cannot represent the asymmetric structures of a hurricane. To overcome this limitation, Georgiou [7] introduced an advanced model to represent the asymmetric structures in a land-falling hurricane and to predict the surface wind speeds quite well at inland sites and at sites close to the ocean when the wind was blowing from the ocean:

$$V_g(r,\alpha) = \frac{V_T sin\alpha - rf}{2} + \sqrt{\frac{(V_T sin\alpha - rf)^2}{4} + \frac{B\Delta p}{\rho}\left(\frac{r_{mw}}{r}\right)^B exp\left[-\left(\frac{r_{mw}}{r}\right)^B\right]} \tag{3}$$

where α is the angle from the direction of the hurricane movement and is the hurricane translation speed. To perform wind load analysis/design of structure, the surface wind speeds ($V_{s,10}$) were calculated by reducing the gradient wind speed in a manner appropriate for the terrain using equation (4) proposed by Vickery and Twisdale [8].

$$V_{s,10} = \begin{cases} \frac{0.825V_{g,1}}{1.18} & r \le 2r_0 \\ \frac{V_{g,1}}{1.18}\left[0.825 - 0.0375\left(\frac{r}{r_0} - 2\right)\right] & 2r_0 < r < 4r_0 \\ \frac{0.75V_{g,1}}{1.18} & r \ge 4r_0 \end{cases} \tag{4}$$

Probabilistic distribution model for typhoon model parameters

In this study, probabilistic process models were used to perform the Monte Carlo simulations. Five parameters were used to characterize the wind field in this study: frequency, pressures deficit, translation velocity, distance and approach angle. From the wind speed equation (3), suitable probability distribution functions (PDFs) should be selected to calculate the wind speed of typhoon. The PDFs of parameters were selected based on the previous analysis results [8, 9].

Four goodness of fit (GOF) tests, i.e., Chi-square (χ2) test, Kolmogorov-Smirnov (K-S) test, Cramer-von Mises (CVM) test, and probability plot correlation coefficient (PPCC) test, were used to determine the probability distributions for typhoon wind parameters, as shown in Table 2. From the GOF tests, it was concluded that the selected PDF was suitable to simulate the typhoon wind speed.

Parameters	PDF	Goodness and fit test			
		χ^2	K-S	CVM	PPCC
Frequency	Uniform Poisson	-	-	-	-
Pressure deficit	Shift Weibull	5.59	0.12	0.10	0.98
Translation velocity	Linear step function	2.29	0.10	0.07	0.98
Distance	Uniform	3.00	0.10	0.08	0.98
Approach angle	Linear step function	1.84	0.08	0.04	0.98

Table 2. Probability distribution functions (PDFs) and GOF tests

Logic tree for wind hazard analysis

Epistemic uncertainty is considered by using alternative models and/or parameter values for the central deficit, maximum wind radius and typhoon profile. For each combination of alternative models, the hazard is recomputed resulting in a suite of alternative hazard curves. In this study, a logic trees were used to handle the epistemic uncertainty.

A logic tree consists of a series of branches that describe the alternative models and/or parameter values. At each branch, there is a set of branch tips that represent the alternative credible models or parameter. The weights on the branch tips represent the judgment about the credibility of the alternative models. The branch tip weights must sum to unity at each branch point. Only epistemic uncertainty should be on the logic tree. A common error in seismic hazard analyses is to put aleatory variability on some of the branches.

Wind hazard curves

The wind hazard analysis estimates the annual probability of exceedance for a given wind speed. This analysis is typically presented in the form of cumulative distribution function curves.

In this study, Kori NPPs site was selected considering the track of typhoon. The risk target in probability risk assessment focused on the analysis of the 10^{-6}~10^{-7} wind hazard (annual probability of exceedance). Therefore, the hazard curves of typhoon wind speed should be represented as shown in figure 2. From the wind hazard assessment, it was concluded that mean wind speed was 85 m/s at 10^{6} return period. In addition to the return period of super-typhoon (65 m/s) was to 10E4.

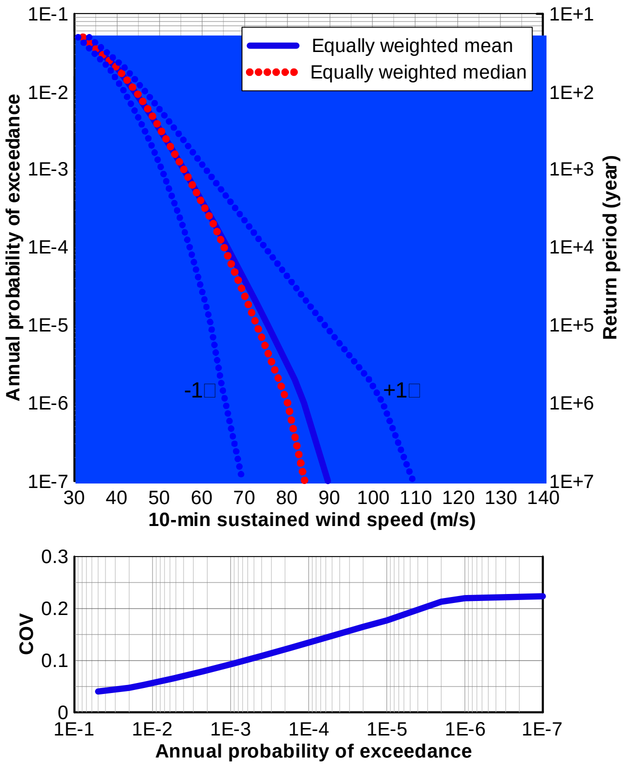

Figure 2. Wind hazard curves of Kori NPPs site

Wind fragility analysis

Selection of important structure, system and components

According to the OPIS DB, it was showed that the damage of NPPs by typhoon was mainly occurred by high wind and heavy rain. Therefore, the important SSCs should be selected to perform the high wind fragility analysis. Table 3 shows the selected important SSCs related on the high wind. The damage by high wind induced by typhoon can be divided into categories: structural and non-structural. The representative structural damage by high wind was the collapse and overturning. In addition, the representative non-structural damage was the spalling of claddings and impact by wind borne missile.

For the wind fragility analysis, it is important to define a failure mode and criteria for the selected SSCs. A seismic load than wind load governed a reactor containment building and an auxiliary building. Therefore, two buildings were excluded for a wind fragility analysis. The wall of turbine building can be spalled by high wind because the wall was made by a thin steel plate. However, the spalling cannot lead to a critical structural damage of building the functional failure of components inside structure can occur. Transmission towers and transformers of switch yard can suffered a wind damage (collapse, line break, wind borne missile etc.). When the wind borne missile hits the tanks (oil storage tank, water storage tank), the loss of aux feed water in NPPs can occur.

High wind induced by typhoon can apply the lateral load to the structure. Therefore, the SSCs should be designed to resist a bending moment, shear force and spalling of claddings.

		Failure mode	Note
Structures	Reactor bldg.	-	Except
	AUX bldg.	-	Except
	Turbine bldg.	Functional	Pull out
Components	Transmission tower	Structural Functional	Collapse Line break
	Transformers	Functional	Wind born missile
	CST	Structural	Wind born missile
	Crane	Structural	Overturn Collapse
	ESW pump room	Structural	Wind born missile
	CCW HX	Structural	Wind born missile
	EDG oil tank	Structural	Wind born missile

Table 3. Selection of important SSCs on typhoon

Wind fragility analysis using safety factors

High wind fragility was to calculate the probability of failure for structure and components under a given wind load. For performing the high wind fragility assessment, it was required to evaluate the ultimate capacity and the response of selected SSCs.

In this study, safety factor methods were used to calculate the probability of failure under wind load. The median capacity (V_m)of wind load of selected SSCs calculated considering the design wind load (V_d) and safety margin (F_{vm}) of SSCs as shown in equation (5). The safety factors for wind fragility assessment included the strength factor, the modelling factor, the factor related to wind pressure as shown in table 4. The wind pressure factor includes the wind profile factor to consider a variation of exposure factor, wind coefficient factor to consider wind reduce factor of wind design code and wind direction factor. The randomness and uncertainty of each safety factors was defined by using the results of previous researchers [10, 11]. When the median capacity was calculated, the probability of a failure of a structure $P_f(v)$ at any non-exceedence probability level Q can be obtained from the following equation (6).

Safety factors	Description	note
Strength	Ratio design load to ultimate load	
Modeling	Accuracy of modeling	β_U:0.1~0.2
Wind pressure	Wind profile	β_U:0.16 [10]
	Pressure coefficient	β_R:0.13, β_U:0.17 [11]
	Gust response	
	Wind direction	

Table 4. Safety factors for wind fragility assessment

$$V_m = F_{vm} V_d$$
$$F_{vm} = (F_{pm})^{0.5} \quad (5)$$

where V_m is median capacity, F_{vm} is safety factors related on wind load, V_d is design wind load and F_{pm} is safety factor related on wind pressure.

$$P_f(v) = \Phi\left[\frac{ln(R_m(v)/V_m) + \beta_U \Phi^{-1}(Q)}{\beta_R}\right] \quad (6)$$

where $R_m(v)$ is the wind response at a given wind speed v, β_R and β_U are the lognormal standard deviations of the randomness and uncertainty of $R_m(v)$ and V_m respectively.

Conclusions

According to the past typhoon damage in Korea, typhoons caused many casualties and economic loss. Although the occurrence of super-typhoon was expected by global warming, typhoon risk assessment in Korea did not conduct. Moreover, a typhoon safety evaluation of NPPs was performed by a deterministic approach. Therefore, previous typhoon analysis method can lead to the non-realistic results. In this study, a probabilistic high wind risk assessment method was developed to quantify the high wind risk of NPPs and to deduct realistic results.

Typhoon wind speeds were estimated for different return periods by the Monte-Carlo simulation using the typhoon data, which include historical observed typhoons and simulated typhoons. In addition to a logic trees were used to handle the epistemic uncertainty.

The wind fragility method of NPPs was developed by using the safety factors (strength, modelling, and wind pressure).

By developing a probabilistic typhoon risk assessment method, it is possible to evaluate quantitatively the typhoon risk of NPPs and establish a response system to prepare for a super typhoon.

Acknowledgments

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References

[1] H. Charkas and L. Shanley, EPRI High Winds Research, *10th Nuclear Plants Current Issues Symposium (NPCIS)*, December 12, 2016.

[2] EPRI, High Wind Risk Assessment Guidelines, TR-3002003107, 2015.

[3] RIS-2015-06, *Tornado Missile Protection*, June 10, 2015, ADAMS Accession No. ML15020A419.

[4] S. M. Oh and I.J. Moon, Typhoon and Storm Surge Intensity Changes in a Warming Climate around the Korean Peninsula, *Natural Hazards*, Vol.66, pp.1405-1429, 2013.

[5] M. E. Batts, L. R. Russell, E. Simiu, Hurricane Wind Speeds in the United States, *Journal of the Structural Division*, Vol.106, pp.2001-2016, 1980.

[6] G. J. Holland, An Analytic Model of the Wind and Pressure Profiles in Hurricanes, *Monthly Weather Review*, Vol.108, pp.1212-1218, 1980.

[7] P. Georgiou, *Design Wind Speeds in Tropical Cyclone Prone Regions*, Ph.D. thesis, University of Western Ontario, 1985.

[8] P. J. Vickery and L. A. Twisdale, Wind field and filling models for hurricane wind-speed predictions, *J. of Structural Engineering*, ASCE, vol. 121(11), 1995.

[9] S.d. Kwon, and J.H. Lee, Estimation of Extreme Wind Speeds in Southern and Western Coasts by Typhoon Simulation, *J. Korean Soc. Civil Eng*., 28(4), pp.431-438, 2008.

[10] M.K. Ravindra, W.H. Tong, T.R. Kipp and L.J. Bragagnolo, *Seismic and Wind Fragility Evaluation of KORI NPP UNIT4*, NUS Co. EQE project Num.: 52042.01, 1991

[11] B. Ellingwood, et al., Development of a Probability Based Load Criterion for American National Standard A58, Special publication No. 577, *National Bureau of Standards*, 1982