A Tornado PRA Methodology with a Probabilistic Tornado Hazard Assessment

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Abstract: A project on Level 1 tornado probabilistic risk assessments (PRAs) for nuclear power plants (NPPs) is currently underway in Japan. This article outlines this project, with a particular focus on the estimation of wind-speed hazard curves and missile strike probabilities in PRAs. The tools used were developed by the Nuclear Risk Research Center of the Central Research Institute of Electric Power Industry for application under the new regulatory requirements. A proposed methodology for a tornado PRA is also presented. One key feature of the wind-speed hazard curve estimation tool is that it considers specific tornado conditions in Japan, such as the higher frequency of tornados near the coastline. Uncertainty analysis, which is essential to PRAs, is also investigated in detail. Tornado-borne missile trajectory tools can estimate the impact probability spatial distribution on structure surfaces, accounting for both the shape and geometry of the structures as well as the aerodynamics of the missiles. The computational cost of the calculation for a large number of missiles is reduced using a statistical procedure with some realistic assumptions. The PRA methodology is based on a graded approach that can be reasonably applied to NPPs under various hazard and risk conditions. Such PRAs should contribute to the discussion of NPP safety equipment optimization, including tornado protection measures for outdoor facilities.

Keywords: Tornado, High wind PRA, Tornado-borne missile, Wind-speed hazard curve.

1. INTRODUCTION

Tornadoes can cause severe accidents at nuclear power plants (NPPs). NPP safety-related equipment should be designed to withstand impacts from tornado-borne missiles. NPPs should also be robust against aerodynamic forces from wind speed and atmospheric pressure changes caused by tornado vortices [1]. Tornado-borne missiles can strike the structures, systems, and components (SSCs) of NPPs, and such missile impacts can result in physical and functional damage and a possible deviation from normal plant conditions. To understand the risks associated with tornado-borne missiles, missile hazard evaluation methods were intensively studied around 1980 in the United States. Estimation methods for tornado wind-speed hazard curves were developed along with tornado vortex models, which predict the spatial distribution of wind speeds in a tornado vortex. The Electric Power Research Institute (EPRI) developed a probabilistic evaluation code, TORMIS, to compute the SSC damage probability and its uncertainty range [2−4]. TORMIS evaluates tornado wind-hazard curves and the impact probabilities of tornado-borne missiles on SSCs. TORMIS was approved for use by the NRC in 1983 and applied to real sites for tornado-borne missile protection exemptions. Details of the tornado probabilistic risk assessments (PRAs) process with TORMIS were also described in guidelines recently published by EPRI [5, 6]. In addition, a technical report on tornado PRAs, NEI17-02 [7], has been continuously updated by the Nuclear Energy Institute (NEI). NEI17-02 complies with the guidelines on tornado PRAs established by the US Nuclear Regulatory Commission [8] and ASME/ANS [9]. NEI17-02 is an industry guidance document for identifying and evaluating the safety of SSCs exposed to potential tornado-borne missiles using a tornado missile risk evaluator (TMRE) model for a given site. The TMRE is designed to provide operators of commercial nuclear power plants with a cost-effective method to conservatively assess the risks posed by tornado-borne missiles. Such tornado PRA methods have been applied to real NPP sites in the United States for tornado-borne missile protection exemptions [10−13].

In Japan, the Nuclear Regulation Authority (NRA), established after the Fukushima-Daiichi NPP accident in 2011, issued new regulatory requirements for NPPs in 2013. These new requirements include measures for integrity against tornadoes. Figure 1 shows a hazard assessment flowchart from the tornado effect assessment guide for NPPs provided by the NRA [14]. The flowchart consists of (1) setting the region of interest, (2) estimating the basic tornado wind speed from the maximum wind speed reported for the region of interest using observational data or from the tornado wind-speed hazard curve with the addition of statistical procedures, (3) setting the design tornado wind speed considering the topographic characteristics at the site, (4) setting the design missile speed and design loads, and (5) checking the fragility of SSCs to tornado-borne missiles. The Nuclear Risk Research Center (NRRC) of the Central Research Institute of the Electric Power Industry (CRIEPI) has developed tornado hazard and fragility assessment tools for application to the new regulatory requirements for utilities [15, 16]. The flowchart for hazard and fragility assessment procedures, which corresponds to that for tornado PRAs [5−7], could also potentially be applied to tornado PRAs for NPPs in Japan.

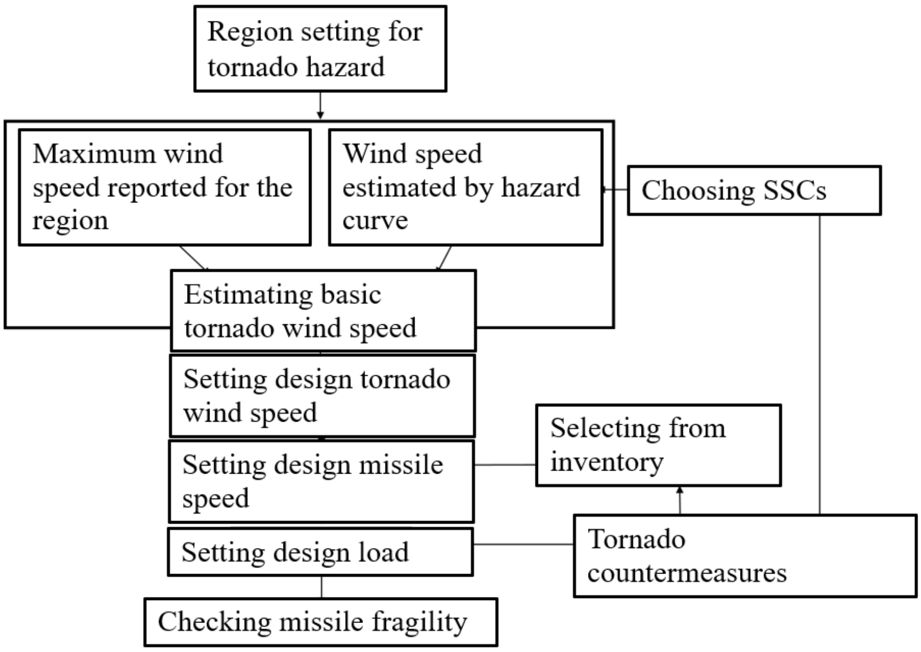

Figure 1. A flowchart of the tornado effect assessment for NPPs in the NRA guide

The tornado PRAs are generally performed by using the methodology developed in the U.S. even in recent years. For instance, Schumock et al. [17] have recently proposed the framework for the integrated risk-informed design of NPPS, and present the computational application for FLEX equipment to potential tornado impacts. The hazard curve and the probability of missile impacts on SSCs, which cause the loss of function, were calculated according to the NUREG/CR-4461 [18] and NEI17-02 [7], respectively. However, applying the U.S. methods to Japanese NPPs yields new issues, related to the specific meteorological conditions and also contour measures against tornadoes of NPPs in Japan. The tornados have been mainly observed near the coast, especially in some local regions, and thus the hazard curve might depend on the location, including the distance from the coastline, and thus a graded approach [19] must become important. Some safety-related facilities are shielded by steel plates and/or steel wire nets against missile impact, which require a detailed calculation of the probability of missile impacts to consider the effectiveness of the countermeasures.

In this paper, we outline the estimation methods for wind speed hazard curves and wind-borne missile strike probabilities for a PRA using the tools developed by the NRRC for application under the new regulatory requirements. Section 2 provides an overview of a key feature of the wind speed hazard curve estimation tool, which is that it considers specific tornado conditions in Japan, such as the high frequency of occurrence near the coast. Uncertainty analysis, which is essential to PRAs, is described in detail. In Section 3, the tornado-borne missile trajectory tools, which can estimate impact probability spatial distributions on the surfaces of structures, are discussed. The shape and geometry of the structures and the aerodynamics of the missiles are considered when calculating the impact probability. In addition, the computational cost of the calculation for a large number of missiles is reduced using a statistical procedure with some realistic assumptions. In Section 4, a tornado PRA methodology is proposed. The PRA methodology is based on a graded approach, including a tornado wind speed and missile hazard assessment, that can be reasonably applied to NPPs under different hazard and risk conditions.

2. WIND-SPEED HAZARD CURVES

To estimate tornado wind-speed hazard curves, the NRRC has developed the tornado wind speed hazard for limited area (TOWLA) model for coastal nuclear power plants in Japan, where tornados are frequently observed [15]. The wind hazard curve provides information on the relationship between the return period and wind speeds resulting from tornadoes at a given location. Figure 2 shows a schematic of the procedure used to calculate the TOWLA model tornado wind-speed hazard curve. The approach is based on TORMIS [6] and NUREG/CR-4461 ver2 [18], which incorporates both the point strike model and the lifeline model to account for the size of the SSCs. TOWLA calculates the hazard curve using observational data for tornado parameters such as the tornado scale (intensity), width, and length, which are obtained from the tornado database of the Japan Meteorological Agency (JMA). The potential occurrence of tornadoes over the sea leads to potential data incompleteness. In addition, uncertainty analysis, which is essential for applying these tools to PRAs, is implemented to account for the limited region of interest, which is a narrow strip along the coastline and introduces the possibility of under- or over-sampling problems, especially for tornadoes crossing coastal lines. Such analysis provides information on the statistical confidence limits of tornado hazard curves estimated from a limited number of records [20].

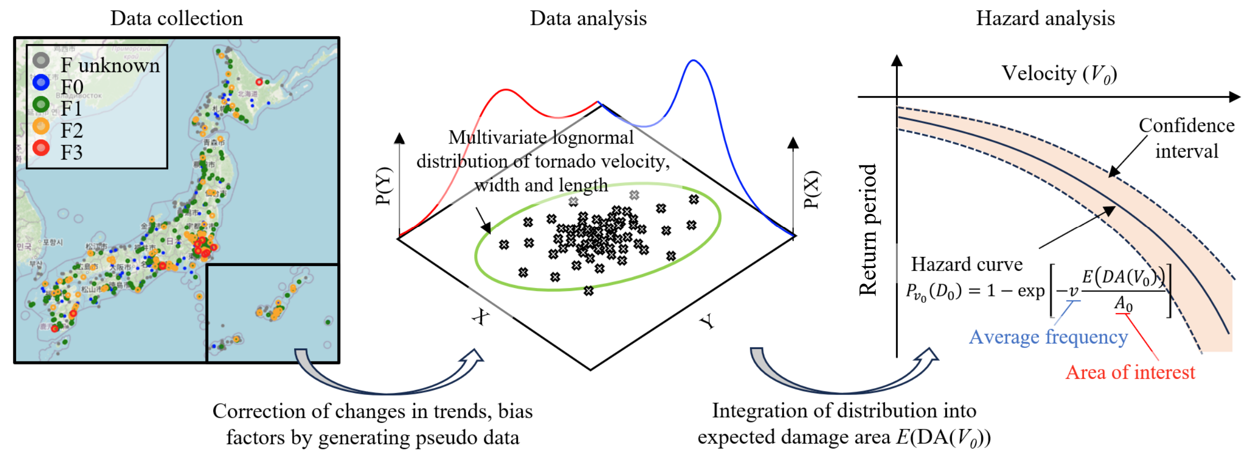

Figure 2. A procedure to calculate the tornado wind-speed hazard curve of the TOWLA model

The NRRC has continued to actively develop the TOWLA model for application to tornado PRAs and for estimating uncertainty factors due to the damage area [21]. Moreover, the effects of synoptic weather conditions on hazard curves have been examined in detail [22], resulting in a tool for determining the epistemic uncertainty in the tornado wind-speed hazard curve due to the chosen region of interest. This tool takes the form of the logic tree shown in Fig. 3.

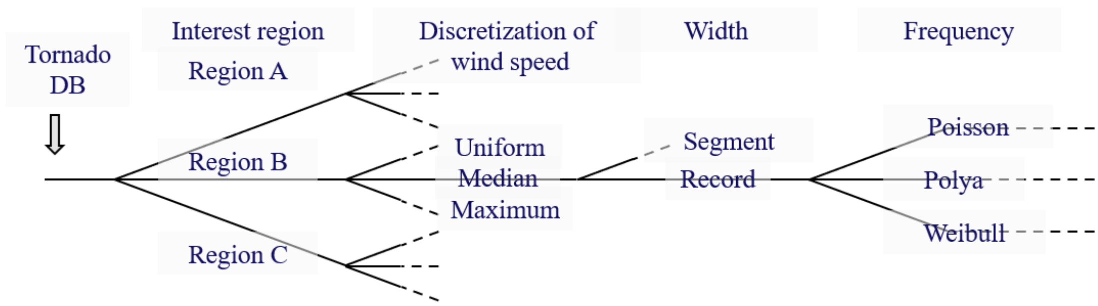

Figure 3. The logic tree for estimating the epistemic uncertainty of a tornado wind-speed hazard curve

3. STRIKE PROBABILITY OF A TORNADO-BORNE MISSILE

To evaluate the degree of potential damage and the probability of tornado-borne missile strikes on SSCs, the NRRC has developed two methods. The first consists of two parts: a deterministic tornado-missile analysis code TONBOS [16] and a probabilistic tornado-missile analysis code TONBOS-pro [23]. The second is an annual missile-strike probability evaluation code TOMAXI-pro [24]. Summaries of these codes and the codes developed in the United States are presented in Table 1. TORMIS [2, 3] and the tornado missile strike calculator (TMSC) were developed by the Westinghouse Electric Company [25] and compute the probability of a tornado missile strike by using the Monte Carlo method and running an enormous number of simulation cases. In contrast, TONBOS, TONBOS-pro, and TOMAXI-pro efficiently evaluate the probability of a tornado missile strike without employing the Monte Carlo method and numerically compute the probability, especially for unconstrained objects (possible missiles) sitting on the ground. TONBOS can evaluate the lift-off and flight behaviors of unconstrained objects on the ground driven by a tornado. In TONBOS, the tornado wind field is modeled using Fujita's DBT-77 model [26] as well as the Rankine vortex model [27, 28], while the motion of objects in flight is modeled with three-degrees-of-freedom translational equations that take into account the aerodynamic drag force and gravity [27, 28]. In addition, TONBOS-pro [23], based on TONBOS, considers changes in the initial orientation and random aerial orientation of missiles. TONBOS-pro considers the aerodynamic forces acting on a missile of arbitrary orientation using cross-flow theory. The change in the missile orientation in the air is simulated using the random-orientation model. TOMAXI-pro [24] enables us to evaluate the annual strike probability of tornado-borne missiles on a target of arbitrary shape. The scattering characteristics of the tornado-borne missiles are obtained using a probabilistic tornado-borne missile analysis code, TONBOS-pro. This code provides consistent data on the wind speed hazard curve and missile scattering properties to rigorously evaluate the annual missile strike probability on the target surface.

Table 1. Codes for the trajectories of tornado missiles and the probability of missile strikes on SSCs

Code name	Developer	Note
TORMIS	EPRI	- Monte Carlo method - approved for use by NRC in 1983 - very costly to set up input data
TMSC	WEC	- Monte Carlo method - compatible with usual PC environments - not approved by NRC yet
TONBOS	CRIEPI	- computes trajectories and speeds of missiles - currently used for tornado missile assessment to meet the new NRA requirements in Japan
TONBOS-pro	CRIEPI	- probabilistically compute trajectories and speeds of missiles - change in object orientation intermittently and randomly
TOMAXI-pro	CRIEPI	- compute spatial distributions of missile strike probabilities - statistical isotropy of tornado path direction is assumed

The NRRC has continued to actively develop codes to calculate the trajectories of tornado-borne missiles and the probability of missile strikes on SSCs for the purpose of tornado PRAs. The effects on missile trajectories of the wind field model, such as Fujita's DBT-77 model and the Rankine vortex model, have been examined in detail. The spatial distributions of the wind speed, including fluctuation components, in the tornado vortex have been investigated using a large-scale tornado vortex generator [28–31] and computational fluid dynamics based on a large-eddy simulation technique [32]. Understanding the best estimate plus uncertainty (BEPU) is critical to tornado vortex and tornado-borne missile hazard assessments.

The NRRC has introduced the "site-specific MIP" approach to reduce the computational cost of calculations for a large number of missiles using statistical procedures. The site-specific MIP is based on the concept of a missile impact parameter (MIP) proposed by the NEI for tornado PRAs using the TMRE [7]. It is the probability of a tornado-borne missile impacting an SSC per unit area of the SSC, per missile, per tornado. The MIP values were calculated using TORMIS [2, 3] for NPP missile conditions in the United States. The MIP values are provided in Table 2 for each tornado intensity (scale). The TMRE uses the look-up-matrix method with a table to calculate Exposed Equipment Failure Probability (EEFP) values. The EEFP values represent the failure probability of exposed SSCs and yield a low-cost calculation of the missile impact probabilities on SSCs. However, one issue with the MIP is the generality of the values: the MIP values depend on specific missile conditions. To extend the MIP concept from the United States to Japan, we have developed an MIP that depends on the missile conditions of a specific NPP, called the "site-specific MIP". The required inputs for estimating the site-specific MIP are the trajectory of the missiles and the location and dimension of the SSCs. The missile trajectories were previously calculated using TONBOS [16] and TONBOS-pro [23]. Such estimations, which require data on the missile trajectory and the geometry and location of the SSC, can be used to determine the spatial distribution of the probability by considering the aerodynamic characteristics of the missiles and the relative positions between SSCs and the missile inventory. An example of the calculated missile impact probability, which considers the relative position between missiles and the SSCs and also the geometry of the SSCs (Fig. 4), is presented in Table 2. The results clearly show that the missile impact probabilities strongly depend on the location of the missiles and also the geometry of SSCs, suggesting that the accuracy can be improved by considering site-specific conditions for missiles and SSCs.

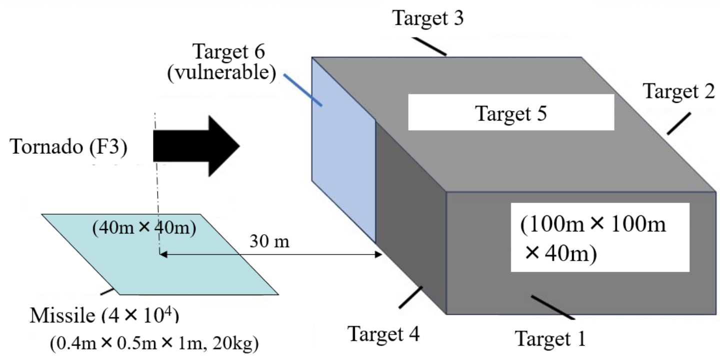

Figure 4. An example of the configuration of a missile and SSC for calculating the site-specific MIP

Table 2. Calculated missile impact probability for each target in Fig. 4

Target number	**1**	**2**	**3**	**4**	**5**
Impact probability (per missile and per km^2)	0.17	0	9.20	130.34	0.74

4. PRA METHODOLOGY

A flowchart of the tornado PRA methodology developed by the NRRC of CRIEPI, which is based on the TMRE in NEI17-02 [7], is shown in Fig. 5. The TMRE procedure involves three major steps: (1) site walkdowns to check that SSCs that are not protected against tornado-generated missiles and missile characteristics; (2) calculation of failure probabilities using the EEFP; and (3) calculation of failure probabilities using the TMRE PRA. The flow chart is focused on steps (2) and (3). The details of the (1) site walkdowns with preliminary results for calculating failure probabilities will be presented in [33]. The flowchart mainly consists of (1) setting the hazard curve of the tornado wind speed against the return period at a given location; (2) the calculation of the missile impact probability on the SSCs using tornado vortex and missile data; (3) the estimation of the functional damage to SSCs due to tornados; and (4) the calculation of failure probabilities using a PRA tool, such as CAFTA [34] or RiskSpectrum [35].

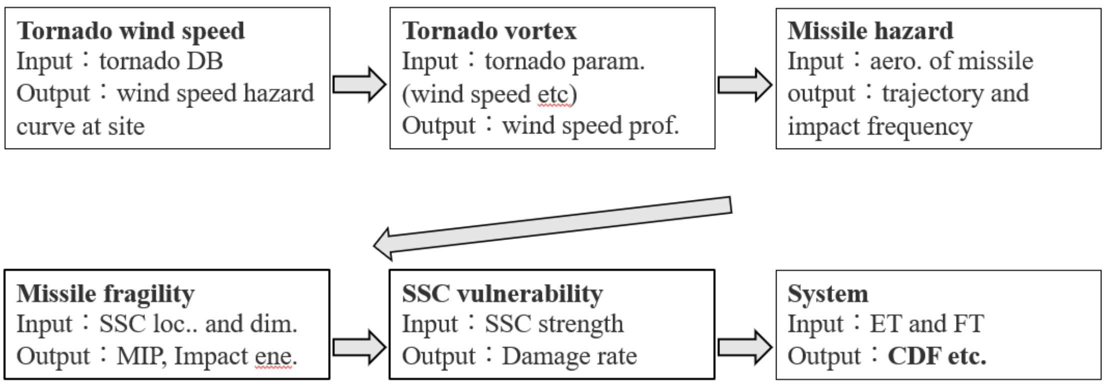

Figure 5. Flowchart of the tornado PRA

The graded approach [19] can also be reasonably applied to NPPs under various hazard and risk conditions. The tools and methods for each grade are summarized in Table 3. For both the screening and simplified PRA, the tornado wind speed is calculated from the hazard curve calculated by TOWLA for the NRA review, which includes a conservative calculated wind speed. The probability of missile impacts on SSCs is estimated using simplified MIP values obtained under conservative conditions for tornado-borne missiles and SSCs, corresponding to the estimation of the probability of missile impacts of TMRE. In contrast, the detailed PRA requires the BEPU for the tornado wind hazard curve obtained using the methods and tools described in Chapter 2. In addition, detailed tornado missile hazard analysis using the site-specific MIPs or TOMAXI-pro presented in Chapter 3 should be performed. We also stress that the setting of the high wind equipment list (HWEL) is closely related to the tornado-borne missile hazard assessment, i.e., the missiles and SSCs considered in the assessment should be selected using HWEL information. The HWEL is selected based on the plant walkdown [6, 36]. In addition, the setting of the HWEL and the tornado hazard assessment is also related to the selection of the internal event of PRA, such as LOOP.

Table 3. Codes for tornado PRAs

Item	Screening	Simplified PRA	Detailed PRA
Tornado wind speed hazard	Tornado wind-speed hazard curve calculated by TOWLA for NRA review	Tornado wind-speed hazard curve calculated by TOWLA for NRA review	Tornado wind-speed hazard curve calculated by TOWLA for BEPU
Tornado vortex and tornado-borne missile hazard	Simplified MIP	Simplified MIP	Site-specific MIP/ TONBOS/TOMAXI
Missile fragility and SSC vulnerability	Assumption of functional loss due to missile impact	Assumption of functional loss due to missile impact	Based on detailed structural analysis using FEM
PRA sequences in system analysis	Existing internal PRA results	RiskSpectrum/CAFTA w/ simplified HWEL	RiskSpectrum/CAFTA w/ detailed HWEL

5. CONCLUSION

In this paper, we have presented an outline of methods for estimating wind speed hazard curves and tornado-borne missile strike probabilities for a PRA based on tools developed by the NRRC for the new regulatory requirements for utilities. We have also proposed a new methodology for a Level 1 tornado PRA for NPPs in Japan. One key feature of the wind speed hazard curve estimation tool is its consideration of specifically Japanese tornado conditions, such as the high frequency of tornados near the coast. The uncertainty analysis, which is essential to PRAs, has been explained in detail. The presented wind-borne missile trajectory tool can estimate the impact probability spatial distributions on the surfaces of structures, which depend on the shape and geometry of the structures as well as the aerodynamics of the missiles. The computational cost of the calculation for a large number of missiles is reduced by a statistical procedure with some realistic assumptions. The PRA methodology is based on a graded approach that can be reasonably applied to NPPs under different hazard and risk conditions. Such a PRA should contribute to the discussion on NPP safety equipment optimization, including tornado protection measures for outdoor facilities [33, 34].

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