Toward Standardizing Probabilistic Risk Assessment Procedures for Combined External Hazards: A Focus on Screening Procedures

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Abstract: Probabilistic risk assessment (PRA) methodologies that consider combinations of multiple external hazards have become increasingly important for understanding plant vulnerabilities and complex hazard interactions. Although considerable progress has been made in developing probabilistic methodologies for combined hazard scenarios in recent years, the treatment of such hazards and associated evaluation procedures have not yet been fully standardized. To address this issue, a conceptual framework for standardized PRA procedures for combined external hazards has been developed. This study presents the fundamental concepts underlying the proposed framework and discusses the requirements for ensuring the completeness of hazard combinations and the practical feasibility of screening procedures, particularly given the large number of possible hazard combinations. As a result, a screening framework consisting of prescreening, hazard screening, fragility screening, and system screening was organized, and a preliminary screening matrix applicable to Japanese nuclear power plant sites was developed. The proposed framework provides a basis for the systematic and practical implementation of combined hazard PRA and supports future standardization activities.

1. INTRODUCTION

Probabilistic risk assessment (PRA) methodologies that consider combinations of multiple external hazards have become increasingly important for identifying vulnerabilities in nuclear power plants and understanding the associated complex hazard interactions. Combined external hazard scenarios may involve causal relationships, temporal dependencies, and cascading effects among multiple hazards, requiring more systematic assessment approaches than conventional single-hazard evaluations.

Although various studies have been conducted on the PRA of combined external hazards, practical frameworks for standardized implementation and screening procedures remain underdeveloped. Existing approaches often rely on simplified assumptions or qualitative screening processes for practical implementation. Consequently, systematic procedures that explicitly incorporate hazard interactions, residual damage effects, and time-lagged hazard occurrences are still limited.

In recent years, several studies have explored probabilistic methodologies for combined hazard scenarios, including hazard dependency modeling and multifragility assessment [1-11]. However, the assessment of combined external hazards remains challenging owing to numerous possible hazard combinations and the complex interactions among hazard occurrence, structural fragility, and plant system response. Consequently, there exists a need for a practical and systematic framework that can ensure the complete consideration of hazard combinations and support the practical implementation of combined hazard PRA.

In a previous study, the authors proposed conceptual approaches for multihazard classification and modeling frameworks that account for hazard dependency, temporal relationships, and multifragility effects [12]. However, practical procedures for systematically implementing hazard screening, hazard assessment, fragility assessment, and system analysis, including accident sequence evaluation under combined hazards, have not yet been sufficiently organized into a standardized framework.

To address the aforementioned challenges, this study proposes a conceptual framework for standardized PRA procedures for combined external hazards, with particular emphasis on screening procedures for hazard combinations. The study discusses requirements for effective screening, including completeness, practical feasibility, and risk significance, and proposes a screening framework together with an example screening matrix applicable to Japanese nuclear power plants.

2. CONCEPTUAL FRAMEWORK FOR COMBINED HAZARD PRA

Combined hazard PRA requires consideration of interactions, including causal relationships, temporal dependencies, and residual damage effects, among multiple hazards. In addition, the large number of possible hazard combinations makes the practical implementation of combined hazard PRA challenging. To address these issues, this section summarizes the conceptual framework for combined hazard PRA, including hazard classification, screening processes, and application examples based on a previous study [12].

2.1. Classification of Combined Hazards

Combined hazards can be classified according to the hazard dependency. Existing studies [1, 2, 5, 7, 8] classify combined hazards as independent or dependent hazards. Independent hazards have no causal relationship or common triggering source. In contrast, dependent hazards include consequential hazards, in which one hazard directly triggers another (e.g., seismic ground motion and tsunami), and associated hazards, in which multiple hazards arise from a common cause (e.g., seismic ground motion and landslide).

Furthermore, combined hazards can be categorized according to their temporal relationships, including simultaneous and time-lagged occurrences. Because the timing between hazards can considerably influence accident progression and plant damage, causality and temporal dependency should be considered in combined hazard PRA. Based on these concepts, a general classification framework focusing on causal relationships and temporal dependency was previously proposed [12].

The aforementioned hazard classification primarily addresses hazard characteristics and does not explicitly consider damage interactions affecting structures, systems, and components (SSCs). To address this limitation, the framework was extended to incorporate interactions among hazard occurrence, structural fragility, and system assessment processes. In this approach, combined hazard PRA is classified according to the dependency characteristics associated with hazard occurrence, fragility behavior, and system interactions, as summarized in Figure 1.

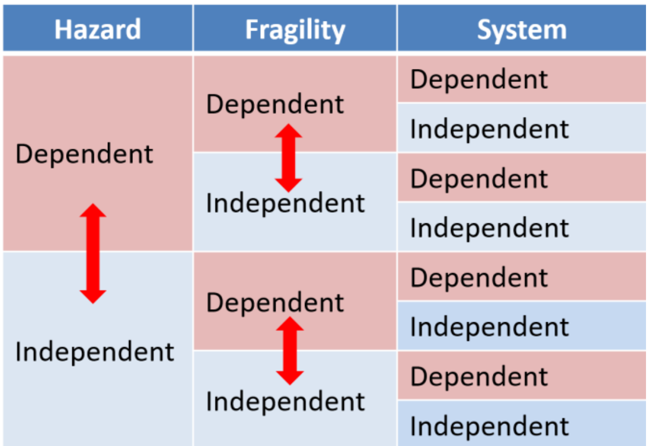

Figure 1: Classification of combined hazard PRA.

2.2. Screening Process for Combined Hazards

Because combined hazard PRA must address numerous possible hazard combinations and interaction mechanisms, an effective screening process is essential to maintain practical feasibility while ensuring sufficient completeness in the consideration of hazard combinations [1, 7, 15]. In a previous study [12], the authors proposed a multiphase screening process comprising prescreening, hazard screening, fragility screening, and system screening [12].

In the aforementioned framework, prescreening is performed qualitatively based on engineering judgment, operational experience, design conditions, and hazard characteristics. The purpose of this process is to identify potentially important hazard combinations at an early stage.

Hazard screening focuses on characteristics such as intensity, occurrence frequency, duration, causality, dependency, and temporal relationships among hazards to determine whether each hazard combination warrants combined hazard. Hazard combinations with negligible occurrence probabilities or insignificant interactions may therefore be excluded from further analysis.

Fragility screening is performed at the SSC level by considering dependencies in SSC behavior and damage characteristics resulting from multiple hazards. Particular attention is given to residual damage effects and the accumulation of time-dependent damage in this process.

System screening is performed at the plant level by considering system interactions, human intervention, accident management, and temporal effects associated with combined hazards. This process evaluates the potential influence of combined hazards on overall plant safety functions. Figure 2 presents the proposed overall assessment flow for combined hazard PRA.

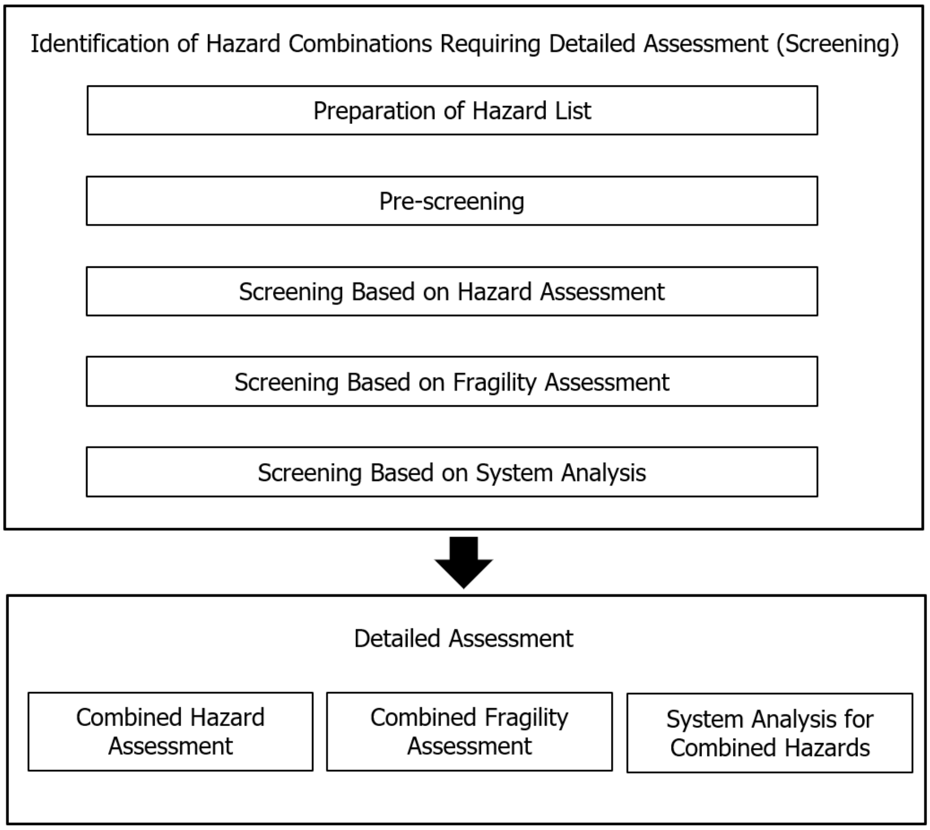

Figure 2: Assessment flow for combined hazard PRA.

3. STANDARDIZED PRA PROCEDURES FOR COMBINED HAZARDS

Based on the conceptual framework described in the previous section, this section presents a proposed framework for standardized PRA procedures for combined external hazards. Because combined hazard PRA involves complex interactions among hazards, fragility characteristics, and plant system responses, systematic implementation procedures are necessary to ensure consistency, completeness, and practical applicability.

A proposed structure for standardized PRA procedures for combined external hazards was developed with a focus on Level 1 PRA applications for core damage frequency (CDF) evaluation based on currently available knowledge and previous studies. The proposed structure summarizes evaluation procedures, technical considerations, and application examples relevant to combined hazard PRA.

Figure 3 illustrates the proposed structure of the standardized PRA procedures for combined external hazards. First, preliminary screening of hazard combinations is performed to identify combinations requiring further consideration. More detailed hazard evaluations are then performed for the selected combinations. If the evaluation results indicate that PRA implementation is necessary, the assessment proceeds to combined fragility evaluation and CDF evaluation that account for combined hazard effects.

More specifically, Chapter 2 defines the terminology and conceptual framework associated with combined hazards. Following the assessment flow shown in Figure 3, Chapter 3 describes procedures for selecting and screening combined hazard scenarios. Chapter 4 presents methodologies for combined hazard assessment. Chapter 5 describes methodologies for combined fragility assessment that consider interactions among multiple hazards and residual damage effects. Chapter 6 presents system analysis methodologies, including accident sequence evaluation, considering the influence of combined hazards on plant systems and accident progression. In addition, appendices are planned to include application examples of combined hazard PRA, such as seismic ground motion + tsunami and seismic ground motion + tornado scenarios.

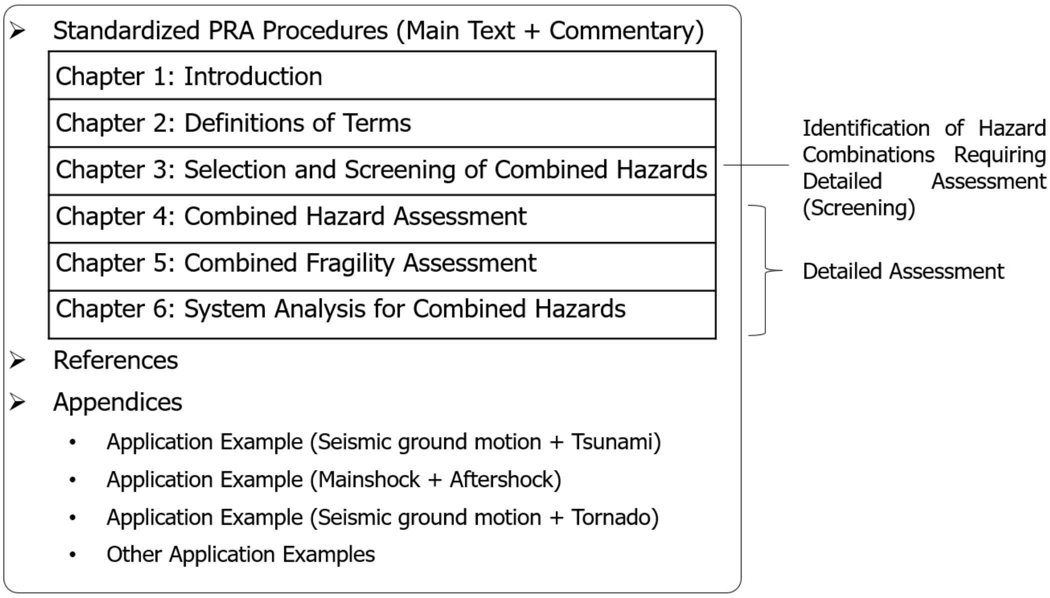

Figure 3: Proposed structure of standardized procedures for combined hazard PRA.

4. SCREENING PROCEDURES FOR COMBINED HAZARD SCENARIOS

One of the major challenges in combined hazard PRA is the extremely large number of possible hazard combinations and interaction scenarios. Because performing detailed PRA evaluations for every possible combination is impractical, systematic screening procedures are essential for identifying combinations that warrant detailed assessment while maintaining sufficient completeness and risk significance.

Based on the conceptual screening framework described in Section 2.2, this section discusses practical implementation procedures for combined hazard PRA, including screening criteria, bounding concepts, and an example screening matrix applicable to Japanese nuclear power plants. The proposed screening procedures are intended to support the practical and efficient implementation of combined hazard PRA.

4.1. Basic Concept of Screening

Screening criteria for combined hazards should consider not only hazard characteristics, but also fragility and system impacts. Therefore, a multiphase screening process comprising prescreening, hazard screening, fragility screening, and system screening is adopted as the fundamental approach.

However, rigorous evaluation of fragility and system interactions for all possible hazard combinations would require detailed PRA analyses for every scenario, potentially reducing the practicality and efficiency of the screening process by hindering early exclusion of combinations with negligible risk significance. Therefore, conservative assumptions and bounding analyses are applied primarily during the fragility and system screening stages. In some cases, reassessment at earlier screening stages may also be necessary based on the results of subsequent screening evaluations.

Quantitative screening is preferably performed using occurrence frequency as the primary metric. In addition, qualitative criteria based on engineering judgment and operational experience are also considered because quantitative evaluation may not always be feasible for all hazards. Furthermore, climate-related hazards such as extreme rainfall, strong winds, storm surge, heavy snowfall, and wildfires should be screened while considering the potential influence of climate change on hazard severity and occurrence characteristics.

4.2. Basic Implementation Procedure for Screening in Combined Hazard PRA

The screening process for combined hazard PRA consists of four stages: prescreening, hazard screening, fragility screening, and system screening.

Prescreening is performed qualitatively based on engineering judgment, operational experience, and bounding analyses to exclude hazard combinations with negligible risk significance at an early stage. Representative screening concepts and practical examples are discussed further in Section 4.3.

Hazard screening is conducted without explicitly considering fragility effects. Therefore, when quantitative evaluation is conducted during this stage, a conservative assumption is adopted in which hazard occurrence is assumed to potentially lead directly to core damage, i.e., fragility is conservatively assumed to be equal to one for all hazard intensity levels. Representative evaluations include conservative frequency-based assessments that consider hazard occurrence probability, temporal dependency, and inter-hazard physical compatibility

Fragility screening and system screening, respectively, involve fragility assessment and system analysis that consider SSC behavior, accident progression, plant response, and human intervention. Compared with prescreening and hazard screening, these stages require more detailed consideration of plant characteristics and interactions among hazards and SSCs. Representative considerations in fragility screening include residual damage effects, SSC behavior dependencies, and potential interactions among damages caused by multiple hazards. Representative considerations in system screening include plant response, system interactions, accident management, human intervention, and temporal effects associated with combined hazards, such as delayed recovery actions and prolonged degradation conditions.

The term "conservative evaluation" refers to screening evaluations wherein fragility is conservatively assumed to be equal to one, while more refined evaluations may explicitly account for fragility characteristics and system interactions. Feedback processes between screening stages remain a subject for future consideration.

4.3. Example Screening Matrix for Japanese Nuclear Power Plants

Screening matrices are widely used as prescreening tools for combined hazards because they help ensure the completeness of consideration of potential hazard combinations [3]. The purpose of prescreening is to efficiently identify risk-significant combinations from among numerous possible external hazard combinations.

The screening matrix considers not only simultaneous occurrences of multiple hazards but also scenarios in which one hazard or its effects remain while another hazard occurs subsequently. In addition, attention is given to interaction scenarios that may not be apparent in single-hazard assessments but could become conspicuous under combined hazard conditions.

For practical application to Japanese nuclear power plants, a screening matrix intended to serve as a minimum common screening framework applicable across Japanese nuclear power plants was developed based on the hazard list provided in the Atomic Energy Society of Japan standard for the selection of risk assessment methods for external hazards (2025) [14].

Screening is performed from single- and combined-hazard perspectives. This is because some hazards that may be screened out in a single-hazard assessment could still affect plant safety when combined with other hazards. For example, chemical releases may be screened out as a single hazard; however, they could impair operator actions and site accessibility and thereby influence plant safety when combined with other hazards. Consequently, such hazards may still need to be considered during combined hazard screening.

More specifically, the following screening criteria were established by integrating Criteria 1–5. Hazards satisfying at least one of these criteria are screened out.

(1) Occurrence frequency: Hazards for which quantitative evaluation is difficult (e.g., direct meteorite impact) and whose occurrence frequency is below the target CDF level.
(2) Separation distance: Hazards with fixed occurrence locations (e.g., railway accidents) that cannot physically occur near the plant site.
(3) Mitigability: Hazards such as snowfall and typhoons, for which sufficient time is available to implement preventive measures (e.g., snow removal and fixation measures), and for which the hazard source itself can be eliminated or the impact on plant safety can be significantly reduced.
(4) Bounding: Hazards that are clearly bounded by other hazards with similar effects, such as hail being bounded by tornado-generated missiles.
(5) Cliff-edge effect: Hazards for which the possibility of reactor trip or core damage can be excluded even if the hazard occurs.

To improve screening efficiency, single hazards subject to combined hazard assessment were first screened individually. Subsequently, the screened-in hazards were grouped into several hazard categories and combined hazard screening was performed using combinations of these groups. This approach reduced the number of combined hazard scenarios requiring consideration.

Table 1 presents an example of grouped hazards derived from the preliminary screening process. In this example, 25 screened-in hazards (including those that may become significant only in combination with other hazards) were grouped into 16 hazard groups.

The preliminary screening matrix for Japanese nuclear power plant sites developed through this process is shown in Table 2. The matrix may be revised in the future based on additional investigations and technical discussions. The matrix summarizes common considerations applicable to Japanese nuclear power plants, including physical exclusivity between hazards, temporal relationships among hazard occurrences, and common screening considerations across different sites.

During the screening process, including prescreening, particular attention should be given to incorporating common considerations related to climate change effects, such as sea level rise and the increasing severity of meteorological hazards, into the screening framework.

Hazard screening, fragility screening, and system screening are conceptually described in this paper and will be further developed in future work.

Table 1: Example of grouping hazards screened in through preliminary screening.

	Group	Hazards Screened In Through Preliminary Screening for Single Hazards
Natural Hazards	G1 Seismic / Ground	N1 Seismic Ground Motion
		N6 Ground Deformation
	G2a Seawater (Tsunami)	N7 Tsunami
		N61 Submarine Landslide
	G2b Seawater (Tide)	N18 Sea Water Level (High Waves, Tide)
	G3 Wind (Tornado)	N41 Tornado
		N46 Tornado-Generated Missiles
	G4 Rain	N8 Flash Flood / Flooding
	G5a Snow (Snow Accumulation)	N25 Heavy Snowfall
	G5b Snow (Avalanche)	N47 Avalanche
	G6 Biological Hazards	N56 HVAC Failure Caused by Birds or Insects
		N57 Cable Damage Caused by Rats or Moles
	G7 Volcano	N69 Volcanic Ash (Including Reduced Visibility)
	G8 Solar	N52 Geomagnetic Storm Caused by Solar Flare
	G9 Lightning	N39 Lightning Strike
	G10 Fog / Mist	N51 Fog (Whiteout)
Human-Induced Hazards	G11 Chemical Substances	M12 Chemical Release Caused by Vehicle Accident Near the Site
	G12 Ship	M7 Collision with Seawall
		M8 Impact on Water Intake
	G13 Offsite Power Supply	M18 Underground Cable Damage Caused by Construction Work
		M19 Disturbance of Offsite Power Grid
		M21 Electromagnetic Interference
		M22 High-Voltage Eddy Current
	G14 Fire	M73 Toxic Gas / Fire Spread Caused by Forest Fire
		M24 Human-Induced Forest Fire

Table 2: Preliminary screening matrix for Japanese nuclear power plant sites.

Preceding / Subsequent	G1	G2a	G2b	G3	G4	G5a	G5b	G6	G7	G8	G9	G10	G11	G12	G13	G14
G1(Earthquake / Ground Conditions)		(b)				(b)	(c2)		(b) (c2)				(b)		(b)	(b)
G2a(Seawater (Tsunami))													(b)	(a)		
G2b(Seawater (Tide))																
G3(Wind (Tornado))													(b)		(b)	(b)
G4(Rain (Flood))									(c2)							
G5a(Snow (Avalanche))													(b)		(b)	
G5b(Snow (Snowfall))	(c2)														(b)	
G6(Biological Hazards)																
G7(Volcano (Volcanic Ash))	(c2)				(c2)										(b)	
G8(Solar Hazards)															(b)	
G9(Lightning)															(b)	(b)
G10(Fog / Mist)							(b)		(b)							
G11(Chemical Substances)							(b)		(b)							
G12(Ships / Marine Vessels)		(a)														
G13(Off-site Power Supply)																
G14(Fire)							(b)		(b)						(b)	

※ (a): Common-Cause Hazards, (b): Associated Hazards, (c1): Independent Hazards (Short Duration) , (c2): Independent Hazards (Long Duration)

5. CONCLUSIONS

This study presented a conceptual framework and standardized PRA procedures for combined external hazards, with particular emphasis on screening procedures for combined hazard scenarios. Combined hazards were classified according to hazard dependency and temporal relationships, and a multiphase screening process consisting of prescreening, hazard screening, fragility screening, and system screening was proposed.

In addition, a proposed structure for standardized PRA procedures for combined external hazards was developed for Level 1 PRA applications. The proposed framework systematically organizes the processes of hazard selection, screening, combined hazard assessment, fragility assessment, and system analysis.

To support practical implementation, this study investigated screening concepts and criteria for combined hazard PRA, including the application of conservative assumptions and bounding analyses. Furthermore, a preliminary screening matrix for Japanese nuclear power plant sites was proposed that considers common hazard combinations, temporal relationships, physical exclusivity, and potential climate change effects.

The proposed framework is expected to contribute to the systematic and practical implementation of combined hazard PRA and to the future development of risk-informed nuclear safety regulations that consider multiple external hazards. Future research will include refinement of feedback processes between screening stages, improvement of quantitative screening methodologies, and expansion of practical application examples for actual nuclear power plant sites.

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