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Development of a probabilistic risk assessment method for combined hazards : A classification and modeling framework for multihazard events

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Abstract: The Fukushima Daiichi Nuclear Power Plant accident highlighted the importance of developing safety assessment methods that consider multihazard events involving numerous simultaneously occurring events such as earthquakes (shaking) and tsunamis (submersion). When addressing such multihazard events, traditional methods often focus on assessing the load combinations of general structures in their structural designs and adopt simple selection criteria. However, these methods fall short when evaluating, countering, and screening external events, such as earthquakes, tsunamis, strong winds, and concentrated heavy rainfall, that occur simultaneously or in a chain. To address this, we reviewed existing literature on multihazard assessment methods, focusing particularly on scenarios involving earthquake and tsunami events. Based on concepts and basic theories, we examined various methods for addressing multihazard scenarios and classified their characteristics. Specifically, several multihazard scenarios were surveyed, and the relationships between multiple hazards were organized. In addition, common causes leading to combined events, their mutual influences, and potential cascading effects were analyzed. This study presents the results of the investigation of existing classification, modeling, and screening methods for multihazard events, ultimately aiming to develop a probabilistic risk assessment method that considers multihazards.

Keywords: Probabilistic risk assessment, Multihazards, Combined hazards, Classification methods, Modeling framework, Screening methods

1. INTRODUCTION

Risks associated with nuclear reactor facilities involve not only internal events such as equipment failures and accidents but also external events including earthquakes and tsunamis. In nuclear reactor facilities, although safety is ensured through sufficiently large design margins and protective measures, residual risks remain due to uncertainties related to hazard impacts, capabilities of adopted protective measures, and other factors associated with incomplete knowledge and inherent variability. As part of the regulatory activities of the Nuclear Regulation Authority, it is necessary to comprehensively and holistically evaluate risks associated with nuclear reactor facilities to enhance the rationality, objectivity, and efficiency of assessment methodologies and utilize these evaluation results in regulatory inspections and other regulatory activities. Focusing on various external and combined events—such as earthquakes and tsunamis—the impacts of each event on nuclear reactor facilities need to be identified and a probabilistic risk assessment (PRA) method targeting the rational assessment of combined events resulting from the integration of these individual events be developed.

To assess hazard combinations, various national and international activities are under progress. The biggest initiative in this direction is the ASAMPSA_E international project undertaken by the European Commission [1]. This project primarily focuses on extending PRA methodologies to include external hazards. Another major initiative is the joint task, titled “Combinations of External Hazards – Hazard and Impact Assessment and PSA for Nuclear Installations,” undertaken by the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency Working Groups on Risk Assessment and on External Events [2]. This task involves an extensive survey on the current state of PRA methodologies and issues related to their future improvements for tackling combined hazards (hereinafter referred to as “multihazards”) in OECD countries. Although these studies are progressing, due to the complexity of multihazards, even the terminology has not yet been standardized. Moreover, classification, PRA modeling, and screening methods for multihazards are still far from being applied in practical scenarios to conduct rational PRA.

In this paper, we present insights acquired from a literature review on multihazard assessments. Furthermore, we propose classification and modeling methods for multihazards, along with appropriate screening methods.

2. CLASSIFICATION METHODS FOR MULTIHAZARD EVENTS

Based on the results of our literature survey [1, 3], we propose a method for classifying multihazard events that can cause significant disasters. Specifically, we organize various terminologies related to multihazard events and their mitigation and introduce a general classification method for such multihazard events.

2.1. Terminology Related to Multihazard Events

Owing to the lack of standardized terminology for multihazards, various terms with similar meanings have been used interchangeably throughout the literature (e.g., causally connected, consequential, induced, correlated, and superposed). To resolve this issue, we developed a new terminology framework for multihazards based on their source of origin, causality, and temporal relationships (timing of occurrence). Table 1 details some terms related to hazard, and Table 2 presents a classification of multihazard-related terminology. Figure 1 illustrates the classification of multihazard events.

Table 1. Hazard -Related Terminology [1, 3]

Terminology	Definition	Note
Internal hazard	Hazards originating from the sources located on the site area of the nuclear power plant, both inside and outside of the plant buildings.	e.g. internal fire, internal floods, internal missile, internal explosion, falling heavy objects, chemical release.
External hazard	Hazards originating from sources located outside the site area of the nuclear power plant.	External hazards are classified into natural hazards and human induced hazards.
Natural hazard	Hazards which occur in nature over which human has little or no control over the magnitude or frequency.	e.g. earthquake, tsunami, external fire, strong wind, volcanic eruption, meteorite impact, biological phenomenon, extreme weather.
Human-induced hazard	Hazards origination from any kind of human activity, either accidental or due to malicious acts.	e.g. explosion outside nuclear facilities, external fire, release of chemicals outside nuclear facilities, aircraft crash, intentional unlawful acts.
Combined hazards	The combination of hazards.	e.g. seismic motion-tsunami.

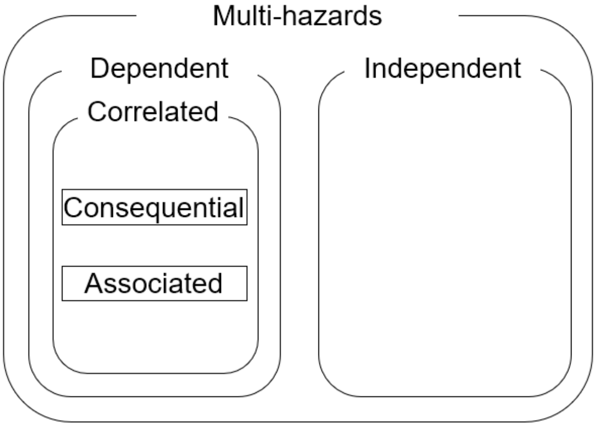


Figure 1. Classification of Multihazards

Table 2. Classification of Multihazard-Related Terminology [1, 3]

Terminology	Definition	Note
Correlated	Combinations where the conditional probability of occurrence of one hazard, given that the other hazard has occurred, is higher than the probability of occurrence of the other hazard alone	“Correlated” can be further classified into “consequential” and “associated”.
Consequential	A hazardous event may result in one or more consequential secondary hazardous events due to a direct causal relationship between the primary and secondary events.	e.g. seismic motion-tsunami, seismic motion-liquefaction
Associated	Multiple external hazardous events may occur as a consequence of a single underlying cause, in which case they are assumed to be correlated or associated. Such hazards are probable to occur under the same conditions and at the same time. The underlying cause (e.g. a meteorological situation) is not necessarily a hazard by itself.	e.g. tsunami-liquefaction (caused by earthquakes)
Mutually exclusive	A combination of hazards with negative dependencies that cannot occur simultaneously due to physical laws	e.g. temperature rise-snow
Independent (unrelated)	A combination in which the occurrence of one hazard does not affect the probability of the occurrence of another hazard	e.g. tornado-earthquake

2.2. Proposed Classification Methods for Multihazards

Multihazard events are generally classified based on three primary perspectives: sources and locations of hazard events, their causal relationships, and their temporal relationships. In this study, we examined event classifications according to causal and temporal relationships. Based on a review of the literature on the classification of multihazards [1-6], three primary categories were identified for causal relationships: “consequential,” “associated,” and “independent.” Meanwhile, two categories were identified for temporal relationships: “simultaneous occurrence” and “time-lagged occurrence.” Table 3 presents the proposed classification methods for multihazard events, along with relevant examples.

Table 3. Classification Methods and Examples of Multihazard events

Causality / Temporal relationship		Simultaneous occurrence	Time-lagged occurrence
Dependent	Consequential	e.g. Seismic motion and liquefaction	e.g. Seismic motion and tsunami
	Associated	e.g. Heavy rainfalls and strong winds (caused by the typhoon)	e.g. Tsunami and liquefaction (caused by earthquakes)
Independent		e.g. Volcanic eruptions and tornadoes*	e.g. Earthquakes and tornadoes**

* Volcanic eruptions and tornadoes are considered under simultaneous occurrence owing to the long durations of volcanic eruptions and their risk of simultaneous occurrence with tornadoes.

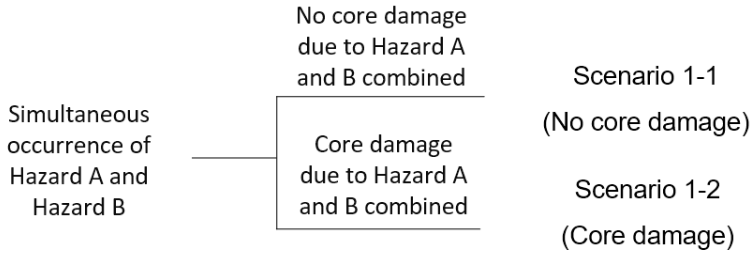
** Earthquakes and tornadoes are considered under time-lagged occurrence owing to the short durations of earthquakes and their low risk of simultaneous occurrence with tornadoes.

3. MODELING FRAMEWORK FOR MULTIHAZARD EVENTS

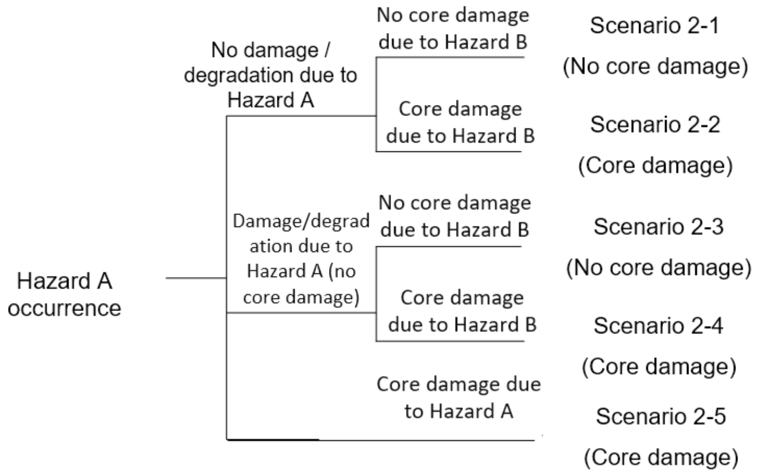
Based on the classification methods presented in Section 2, we proposed a general multihazard scenario and modeling framework using mathematical equations tailored to each type of multihazard situation.

3.1. General Multihazard Scenarios

Figure 2 illustrates an example of a multihazard scenario. For simplicity, the number of hazards was assumed to be two, and a causal relationship was classified into two types: dependent and independent. Additionally, their temporal relationship was categorized into two types: simultaneous occurrence and time-lagged occurrence. Here, scenarios were examined based on the presence or absence of core damage. Specifically, for simultaneous occurrence (Figure 2 (a)), we considered two scenarios: core damage and without core damage. Meanwhile, in the case of time-lagged occurrence (Figure 2 (b)), we considered three scenarios for hazard A: core damage, without core damage, and damage to safety-critical equipment without core damage.



(a) Simultaneous occurrence



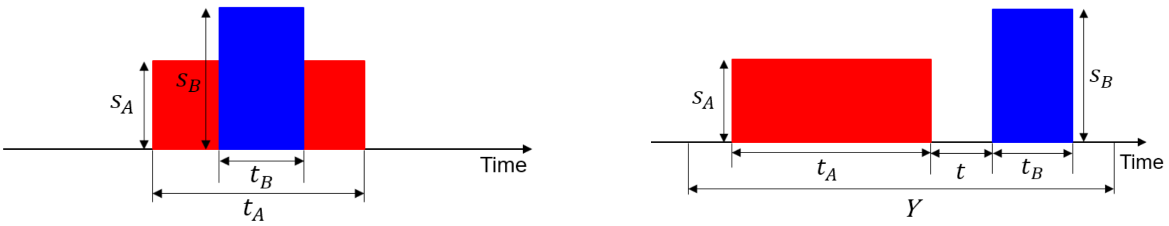
(b) Time-lagged occurrence

Figure 2. Example of a Multihazard Scenario

3.2. General Mathematical Equations for Modeling Multihazard Scenarios

3.2.1. Dependent Hazards

To model multihazard scenarios under dependent conditions, we used mathematical expressions based on probabilistic concepts. For instance, Equations (1) and (2) correspond to the simultaneous occurrence and time-lagged cases, respectively. Figure 3 shows a conceptual diagram of multihazard scenario.



(a) Simultaneous occurrence (b) Time-lagged occurrence

Figure 3. Conceptual diagram of a Multihazard Scenario

1) Simultaneous occurrence of dependent hazards

$$\nu_{A+B}(s_A, s_B) = \nu_A(s_A) \times \int_0^{+\infty} f_{T_A}(t_A|s_A) \times f_{s_A,s_B}(s_B|s_A, t_A)dt_A \tag{1}$$

where

$\nu_{A+B}(s_A, s_B)$:	two-dimensional density function representing the simultaneous occurrence frequency of Hazards A and B, with intensities s_A and s_B, respectively.
$\nu_A(s_A)$:	density function representing the occurrence frequency of Hazard A with intensity s_A.
$f_{T_A}(t_A\|s_A)$:	conditional probability density function for the duration of load t_A, given the intensity s_A of Hazard A.
$f_{s_A,s_B}(s_B\|s_A, t_A)$:	conditional probability density function of Hazard B occurring with intensity s_B within the duration of load t_A, given the intensity s_A of Hazard A.

2) Time-lagged occurrence of dependent hazards

$$\nu_{A\Rightarrow B}(s_A, s_B, t) = \nu_A(s_A) \times f_{s_A,s_B}(s_B|s_A, t) \tag{2}$$

where

$\nu_{A\Rightarrow B}(s_A, s_B, t)$:	two-dimensional density function representing the frequency with which Hazards A and B occur in a time-lagged manner, with intensities s_A and s_B, respectively.
$\nu_A(s_A)$:	density function representing the occurrence frequency of Hazard A with intensity s_A.
t:	time difference between the assumed occurrences of Hazards A and B.
$f_{s_A,s_B}(s_B\|s_A, t)$:	conditional probability density function of Hazard B occurring with intensity s_B within time difference t, given the intensity s_A of Hazard A.

Based on these equations, multihazard scenarios involving dependent hazards can be modeled by combining Hazards A and B through a parametric analysis of the parameter θ associated with a causal event. The modeling procedure for dependent hazards is illustrated in Figure 4.

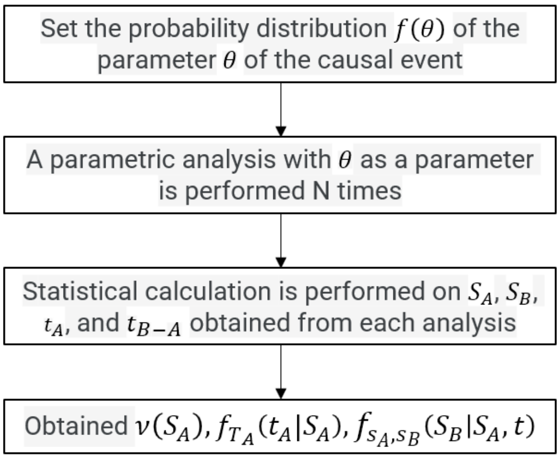


Figure 4. Modeling Procedure for Dependent Hazards

3.2.2 Independent Hazards

To model multihazard scenarios under independent conditions, we used mathematical equations based on probabilistic concepts. For instance, Equations (3) and (4) correspond to the simultaneous occurrence and time-lagged cases, respectively. Unlike dependent hazards, when modeling independent hazards, the parameters associated with Hazards A and B can be evaluated independently. Furthermore, when dealing with independent hazards, the duration of each hazard becomes important.

1) Simultaneous occurrence of independent hazards

$$\nu_{A+B}(s_A, s_B) = \nu_A(s_A) \times \nu_B(s_B) \times \int_0^{+\infty} \int_0^{+\infty} \frac{t_A + t_B}{Y} f_{T_A}(t_A|s_A) f_{T_B}(t_B|s_B)\, dt_B dt_A \tag{3}$$

where

$\nu_{A+B}(s_A, s_B)$: two-dimensional density function representing the simultaneous occurrence frequency of Hazards A and B with intensities s_A and s_B, respectively.

$\nu_A(s_A)$: density function representing the occurrence frequency of Hazard A with intensity s_A (similar to the definition of $\nu_B(s_B)$).

$f_{T_A}(t_A|s_A)$: conditional probability density function for the duration of load t_A, given the intensity t_A of Hazard A (similar to the definition of $f_{T_B}(t_B|s_B)$).

Y: evaluation period (e.g., the entire duration over which Hazards A and B are likely to occur).

2) Time-lagged occurrence of independent hazards

$$\nu_{A\Rightarrow B}(s_A, s_B, t) = \nu_A(s_A) \times \nu_B(s_B) \times \frac{t}{Y} \tag{4}$$

where

$\nu_{A\Rightarrow B}(s_A, s_B, t)$: two-dimensional density function representing the frequency with which Hazards A and B occur in a time-lagged manner, with intensities s_A and s_B, respectively.

$\nu_A(s_A)$: density function representing the occurrence frequency of Hazard A, with intensity s_A (similar to the definition of $\nu_B(s_B)$).

t: time difference between the assumed occurrence of Hazards A and B.

Y: evaluation period (e.g., the entire duration over which Hazards A and B are likely to occur).

Table 4. Screening Criteria for Multihazards

Screening method	Criteria
Mutually exclusive Hazards	Combinations of hazards that are mutually exclusive, such as high temperatures and snow, can be excluded when one hazard occurs.
Inclusion of hazard	If one hazard is included in the definition of another hazard, their combination can be excluded. For example, aircraft accidents and fog, because the impact of fog is included in the definition of an aircraft accident.
Enveloping	When the impact of compound events does not exceed the impact of a single hazard, it is unnecessary to consider the compound event. For example, if it can be confirmed that one of the hazards does not occur near the site to an extent that has any impact, or if the progression speed of one hazard is slow compared to the time required to eliminate its impact, the influence can be disregarded.
Rate of hazard progression	If there is sufficient time to implement adequate measures to mitigate the threat posed by the hazard relative to the speed of its progression, the impact of that hazard can be screened out as negligible.
Hazard frequency	If the frequency of the design-level hazard is less than 10^{-5} per year and the conditional core damage probability (CCDP) under this condition is less than 0.1, screening can be screened out[4].
CDF and LERF	In cases where criteria cannot be established based on hazard frequency, screening can be considered using Core Damage Frequency (CDF) and Large Early Release Frequency (LERF). For example, a criterion of CDF < 10^{-6}/year (or LERF <10^{-7}/year if the containment is damaged) can be established [4].

4. SCREENING METHODS FOR MULTIHAZARD EVENTS

Based on the findings of our literature review, we evaluated screening methods and criteria for developing PRA methods considering multihazard events [1, 2, 4, 7, 8].

4.1. Selection Methods for Multihazard Events

According to the literature survey on multihazard selection methods, numerous approaches recommend and adopt the method of representing single event × single event in a two-dimensional table [1, 2]. This method effectively eliminates arbitrariness in multihazard extraction by mechanically enumerating all possible combinations of individual hazards. For guidance on the hazard list to be considered during PRA, refer to [1].

4.2. Screening Criteria for Multihazard Events

Commonly used criteria for multihazard screening include mutually exclusive hazards, envelopment, hazard progression rate, hazard frequency, and CDF. These criteria are presented in Table 4.

For instance, according to the mutually exclusive hazard criterion such as if one hazard occurs and the other does not occur, the latter can be screened out. According to the inclusion of hazard criterion, if one hazard is inherently included in the definition of another hazard, their combination can be excluded. According to the enveloping criterion, if the impact of a combined hazard event does not surpass the impact of a single hazard, the combined hazard event can be disregarded. According to the rate of hazard progression criterion, if sufficient time is available to implement adequate measures to mitigate the threat posed by the hazard relative to its progression speed, the impact of that hazard can be ignored. According to the hazard frequency criterion, if the frequency of the design-level hazard is less than 10^{-5} per year and CCDP under this condition is less than 0.1, the hazard can be screened out. Finally, according to the CDF or LERF criterion, if criteria cannot be established based on the hazard frequency and if it can be estimated that the CDF or LERF is smaller than the criteria using simplified methods such as bounding analysis, screening can be performed using CDF and LERF. For instance [4], events for which the CDF is <10^{-6}/year (or LERF is <10^{-7}/year if the containment is damaged). However, specific adjustments may be necessary for the application of these criteria in Japan.

5. CONCLUSION

In this paper, we presented the results of a comprehensive literature survey on multihazard events and their evaluation cases. Additionally, we proposed classification and modeling methods for multihazard events, along with appropriate screening methods. The findings obtained from this study are as follows:

- ✓ We developed a new terminology framework for multihazard events and introduced a general classification method for their categorization.
- ✓ We proposed a modeling framework for multihazard events using mathematical equations based on probabilistic concepts.
- ✓ We performed a literature survey for selection methods and screening criteria for the development of a PRA method considering multihazards and summarized the results of the survey.

In the future, to contribute to nuclear regulation that utilizes risk information, we want to work on developing a PRA method considering multiple hazards.

Acknowledgements

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