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DEVELOPMENT OF A PROBABILISTIC RISK ASSESSMENT METHOD FOR COMBINED HAZARDS
: APPLICATION EXAMPLES OF MULTI-HAZARD EVENTS

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ABSTRACT

In this Paper, a general framework for multi-hazard assessment for complex external events— such as earthquakes and tsunamis— is proposed, with a focus on developing rational screening concepts and modelling methods. By reviewing existing methods and theories, we classified multi-hazard scenarios and analyzed cascading effects and interdependencies. The proposed methods can be effectively utilized in the multi-hazard Probabilistic Risk Assessment (PRA) of nuclear facilities. Application examples under simple conditions, including earthquake-tsunami and earthquake-strong wind combinations, were evaluated using the multi-hazard classification method proposed.

INTRODUCTION

The Fukushima Daiichi Nuclear Power Plant accident raised the need of developing safety assessment methods that can consider multi-hazard events involving numerous simultaneously or subsequently occurring events such as earthquakes (shaking) and tsunamis (submersion). When addressing such multi-hazard events, the 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 intensively reviewed existing literature on multi-hazard assessment methods, focusing particularly on scenarios involving earthquake and tsunami events. Based on concepts and basic theories, we examined various methods for addressing multi-hazard scenarios and classified their characteristics. Specifically, several multi-hazard scenarios were surveyed, and the relationships between multiple hazards were classified. In addition, common causes leading to combined events, their mutual influences, and potential cascading effects were taken into consideration. In this paper proposes the basic frameworks on how to treat the multi-hazards in more advanced PRA and shows several application examples; specific representative cases (e.g., ground motion + tornado, earthquake + tsunami) using the multi-hazard classification method developed in previous study (Choi et al. (2024)). This study presents the insights of multi-hazard modelling and screening methods for multi-hazard events, ultimately aiming to develop a probabilistic risk assessment method that considers multi-hazard scenarios.

MODELLING METHODS FOR MULTI-HAZARDS

First, multi-hazards are classified and the terminology related to multi-hazards are properly defined since many different interpretations of hazard have been used so far.

Classification Methods for Multi-hazards

When dealing with multiple hazards, the terms “correlated” or “not correlated” are often used to describe their relationships. However, this term is used to indicate statistical relationship between two hazards and does not reflect characteristics such as causality. Sometimes, relationship between two or more hazards can be discussed in terms of their occurrence or the magnitude of each hazard. Note that this difference is not clear yet in this paper.

It is proposed here that multi-hazard should be categorized based on the dependency between hazards, as shown in Table 1 (Choi et al. (2024)). Dependent hazards are further classified into two types; “consequential” and “associated”, both of which are defined as follows. “Consequential hazards” refer to hazards that are triggered by or result from another hazard, which is similar to “a hazard caused by another hazard”. “Associated hazards”, on the other hand, refer to hazards due to the common cause. The examples are written in the table. This classification was originally proposed in the literature. Note that this hazard classification is applicable only to the hazards themselves. This means that factors such as the occurrence frequency and duration of a hazard are considered, while the remaining time of damage or some influence on SCCs due to the hazard is not taken into consideration. This remaining influence on SCCs will be treated in the fragility assessment of SCCs in the next section.

Table 1: Classification and Examples of Multi-hazards (Choi et al. (2024))

Causality / Temporal relationship		Simultaneous occurrence	Time-lagged occurrence
Dependent	Consequential (Causal)	e.g. Seismic motion and liquefaction	e.g. Seismic motion and tsunami
	Associated (Common cause)	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.

Definition of Terms Related to Multi-hazards

We propose the concepts of multi-hazard and multi-fragility (fragility considering the effects of multiple hazards). This approach follows the three steps of hazard analysis, fragility analysis, and system analysis in the conventional PRA methods, positioning complex multi-hazard events within specific analytical domains.

In the following sections, we introduce new concepts of multi-hazard and multi-fragility, focusing on the aspects of hazard and fragility assessments.

Multi-hazard

It refers to multiple hazards that exhibit dependency on each other. This includes hazards where the occurrence of one hazard triggers the occurrence of another due to causal relationship, as well as multiple distinct hazards that arise from a common cause. In general, such hazards are represented by a multidimensional hazard surface. Hazards treated as independent can be considered a special case of multi-hazard; however, in this study, we distinguish them separately and refer to independent hazards as single hazards rather than multi-hazards because of the cut of hazard computation efforts.

Multi-fragility

The multi-fragility represents the ability of an SSC (Structure, System, Component) or an entire system to withstand damage modes caused by multi-hazard events, expressed in terms of the magnitude of the multi-hazard. In multi-fragility analysis, when multiple hazards are present, it is necessary to consider the condition in which damage or some influence caused by one hazard remain, and another hazard subsequently occurs, further exacerbating the damage. This assessment takes into account the simultaneity of different hazards, time lag, and the residual damage duration. When multiple severe hazards strike within a short period, there may not be sufficient time to repair the damage, leading to cumulative damage. As a result, even a relatively small external force could cause significant damage which remains until repair is completed.

Specifically, the following scenarios can be considered as multi-hazard events that may lead to core damage. First, consider a case where a subsequent hazard strikes while the loading duration of a preceding hazard is still ongoing. This is defined as simultaneous occurrence. In this situation, a certain piece of equipment or building may lose its functionality due to the combined effects of two or more hazards. Additionally, it is possible that one hazard causes the functional failure of a certain piece of equipment or building, while another hazard leads to the functional failure of a different piece of equipment or building, ultimately resulting in core damage.

Next, consider a case where two or more hazards strike at different times, with no overlap in their loading durations. This is defined as sequential occurrence. At first glance, this case may not seem to constitute a multi-hazard event. However, in this scenario, a piece of equipment or a building may sustain damage from the preceding hazard without losing functionality, but before it can be restored, the subsequent hazard may strike, leading to functional failure. Alternatively, one piece of equipment or building may experience functional failure due to the preceding hazard, and before it is restored, another piece of equipment or building may fail due to the subsequent hazard, forming a logical sequence that ultimately results in core damage.

PROPOSAL OF MULTI-HAZARD ASSESSESSMENT FLOW

Multi-hazard Assessment Flow

Based on the above considerations, a proposed flow for multi-hazard assessment is shown in Figure 1.

First, Hazard A and Hazard B (H_A, H_B) are selected for consideration. A simple preliminary hazard assessment $(\nu_A(s_A), \nu_B(s_B), t_A, t_B)$ is conducted for each hazard to determine whether the two hazards are dependent or independent. Here, $\nu_A(s_A)$ is a mean occurrence frequency of Hazard A exceeding the intensity s_A, and t_A is duration of Hazard A (similar to the definition of $\nu_B(s_B), t_B$).
If two hazards are independent, an analysis is performed independently for Hazard A and Hazard B. Then, the mean frequency of simultaneous occurrence of Hazards A and B (overlapping occurrence) with their duration times t_A and t_B, $\nu_{A+B}(s_A, s_B)$ is computed. If the mean simultaneous occurrence frequency $\nu_{A+B}(s_A, s_B)$ is smaller than the screening criteria ν_0, this hazard combination is very rare and to be ignored. It is, however, noted that we should not ignore the combination which may lead to significant consequence.

If the hazards are dependent, appropriate modelling is conducted using a simulation-based approach to account for consequential and associated events. This modelling leads to the derivation of a multi- hazard surface for multi-hazard assessment, in which representation of two-dimensional or higher hazard surface may require a large amount of computation. This process up to this point constitutes the hazard assessment domain. The evaluation of the multi-fragility of SSCs requires further investigation.

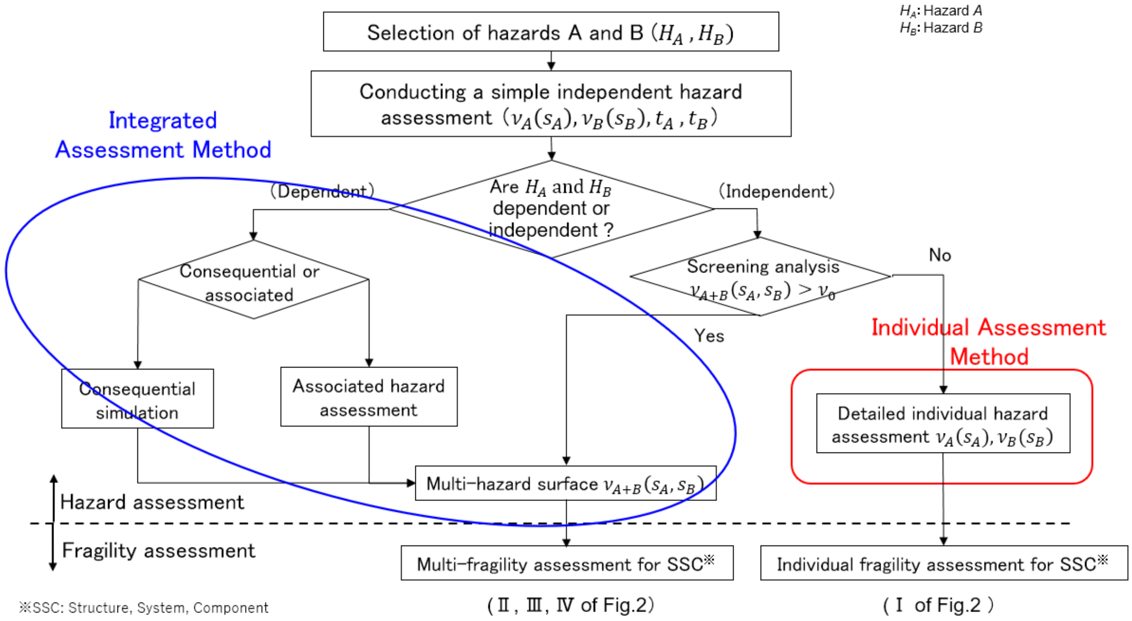


Figure 1. Multi-hazard Assessment Flow

It is necessary to select the assessment methods based on the dependency between the selected hazards and the characteristics of the fragility associated with the protective functions of SCCs. In this study, we classify the assessment methods into two broad categories and organize the related terminology below.

Individual Assessment Method

This PRA method evaluates multiple hazards in the same manner as conventional single-hazard PRA when the hazards are independent, and the scenarios leading to core damage are also independent (i.e., one hazard does not affect the protective function against the other hazard). In this case, it is considered that simultaneous occurrence of multi-hazards is so rare that this case can be ignored.

The final core damage frequency (CDF) due to only the hazard A CDF_A can be evaluated as in the following convolution integral.

$$CDF_A = -\int_0^{+\infty} F_A(s_A) \frac{dH_A(s_A)}{ds_A} ds_A \tag{1}$$

where $H_A(s_A)$ is the hazard curve, and $F_A(s_A)$ is the fragility curve associated with the core damage.

Integrated Assessment Method

This PRA method is required when the hazards are dependent or when a scenario leading to core damage involves the combined effects of multiple hazards. It considers the simultaneous influence of multiple hazards in the assessment process. This method may require a large amount of computation based on multi-dimensional hazard surface. In the case of multi-hazards, the final CDF can be extended to the following double integral.

$$CDF_{A+B} = \int_0^{+\infty} \int_0^{+\infty} F_{A+B}(s_A, s_B) \frac{\partial^2 H_{A+B}(s_A, s_B)}{\partial s_A \partial s_B} ds_A ds_B \tag{2}$$

where $H_{A+B}(s_A, s_{AB})$ is the hazard surface of Hazards A and B, and $F_{A+B}(s_A, s_B)$ is the multi-fragility curve associated with the core damage, which is expressed by the magnitudes of the two hazards.

Concept of Classification for Combined Events

Figure 2 illustrates the classification of PRA methods for combined events. In this classification, assessment methods are categorized based on hazard and fragility characteristics. Here, fragility refers to the overall system fragility related to core damage, rather than the fragility of individual SSCs.

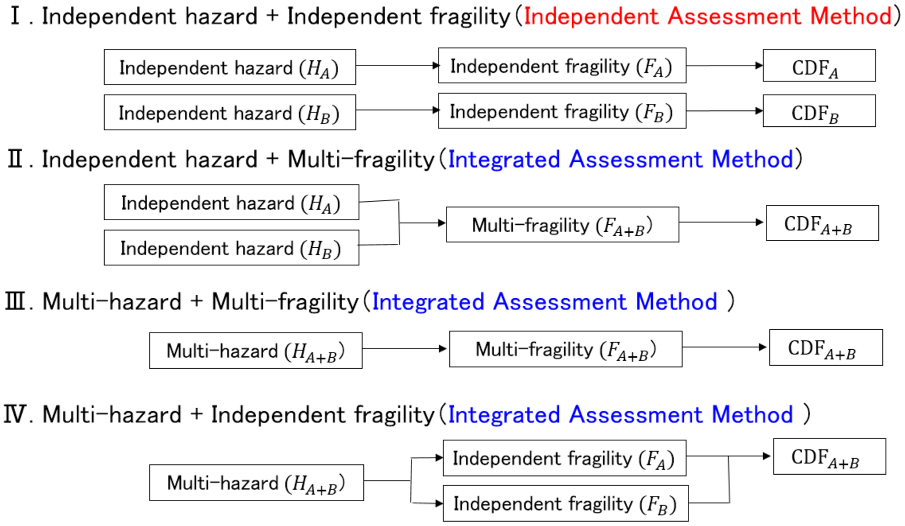


Figure 2. Classification of PRA Methods for Combined Events

Independent fragility refers to a condition where one hazard does not affect the protective function against the other hazard. Multi-fragility applies when such an influence exists. Also, in this classification, independent hazards correspond to hazard combinations categorized as "independent events.", multi-hazards correspond to hazard combinations categorized as "dependent events."

In the case of independent hazards with independent fragility (I), the core damage frequency (CDF) for the combined hazards, CDF_{A+B}, is obtained from CDF_A and CDF_B, which, most of time, leads to negligible quantity. Therefore, the core damage frequency can be evaluated using the same procedure as a single-hazard PRA, classifying this case under the individual assessment method. Cases II and III require an integrated assessment method because one hazard affects the protective function against the other, necessitating an evaluation that considers the combined effects of both hazards. IV is also classified under the integrated assessment method since the hazards are dependent, even though their fragilities are independent. However, as noted in the screening criteria, even in case II, if the frequency of an independent hazard occurring within a certain period (e.g., the time required for a damaged structure to recover after the preceding hazard) is sufficiently low, the hazards do not effectively combine. In such cases, the scenario can be screened out, eliminating the need for an integrated assessment. Additionally, in case IV, if the effect of one hazard dominates, an integrated assessment method for multi-hazards is unnecessary. For example, if $\mathrm{CDF}_A >> \mathrm{CDF}_B$, then even with a precise evaluation, $\mathrm{CDF}_{A+B} \approx \mathrm{CDF}_A$, meaning that the PRA results of the dominant hazard alone can adequately represent the overall risk.

APPLICATION EXAMPLE FOR MULTI-HAZARDS

The individual assessment method and integrated assessment method proposed in the previous section were examined using "earthquake + tornado" and "earthquake + tsunami" as demonstration examples, respectively, under a hypothetical site and simple analysis conditions.

Application Example of Individual Assessment Method

According to Table 1, “Earthquakes + tornadoes” are categorized as a combination without a causal relationship and are considered independent hazards. In this study, we specifically evaluate the multi-hazard scenario where seismic ground motion from an earthquake and strong winds from a tornado occur simultaneously but independently. The conditions for seismic ground motion and tornadoes are as follows.

Earthquakes

1) Earthquake Occurrence Conditions:

An inland crustal earthquake occurring directly beneath a hypothetical site is assumed. The earthquake source is not specified but is treated as an area source. The frequency-magnitude distribution follows the Gutenberg-Richter (G-R) law, with a b-value of 0.9 and a maximum magnitude (M) of 7.5.

2) Seismic Ground Motion Hazard:

Evaluated based on a ground motion attenuation equation for response spectra, with the variability in the attenuation equation assumed to have a common lognormal standard deviation of 0.53.

Tornadoes

1) Tornado Occurrence Conditions:

The wind speed during a tornado event is set to an average of 30 m/s with a coefficient of variation of 0.3, based on the data from Japan Meteorological Agency (JMA). The annual occurrence rate of tornadoes is assumed to be 5.0 E-4 occurrences per unit square kilometer, following the Tornado Impact Assessment Guide of Nuclear Power Plants (NRA, 2013), and the occurrence is modelled as a stationary Poisson process.

2) Tornado Wind Speed Hazard:

Based on the Tornado Impact Assessment Guide of Nuclear Power Plants (NRA, 2013), the probability of a structure being affected by a tornado is calculated using the method of Garson et al. (1975).

Multi-hazard assessment result

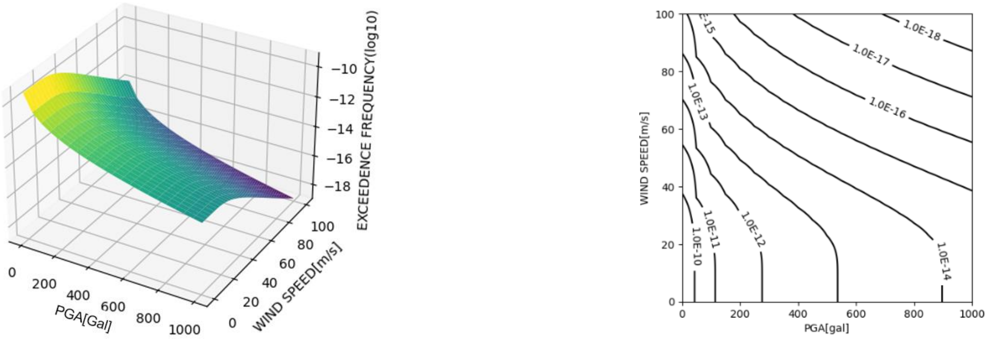
Based on ANS (1978), the multi-hazard of simultaneous occurrence of independent events can be calculated using the following equation.

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

Here,

$\nu_{A+B}(s_A, s_B)$:	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). One year is used for Y.

The calculated “earthquake + tornado” multi-hazard results are shown in Figure 3. Duration times of ground motion and tornado wind are set as $t_A = 60$ seconds and $t_B = 10$ minutes, respectively, the multi-hazard surface is shown in Figure 3. Form the figure, the frequency of simultaneous occurrence of an earthquake and a tornado is less than 1E-10 per year, which is extremely low. This is significantly lower than the design-level hazard frequency of 1E-5 per year suggested by EPRI (2015), indicating that it can be screened out.



(a) 2D surface (b) Contour map

Figure 3. “earthquake + tornado” multi-hazard results

Multi-fragility assessment result

Since “earthquake + tornado” is classified as an independent event, the individual assessment method can be applied if the fragilities are also independent. A fragility evaluation was conducted for the shear failure of steel structure walls to examine whether the individual assessment method is applicable. Using a steel-framed building at a nuclear facility, as shown in Figure 4, a fragility evaluation was performed for structural damage. The damage mode was defined as the shear failure of the building walls, with a median interstory drift ratio of 1/30 as the criterion. A lognormal distribution was assumed, with a lognormal standard deviation of 0.2.

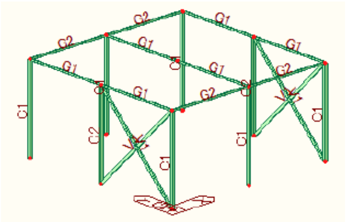
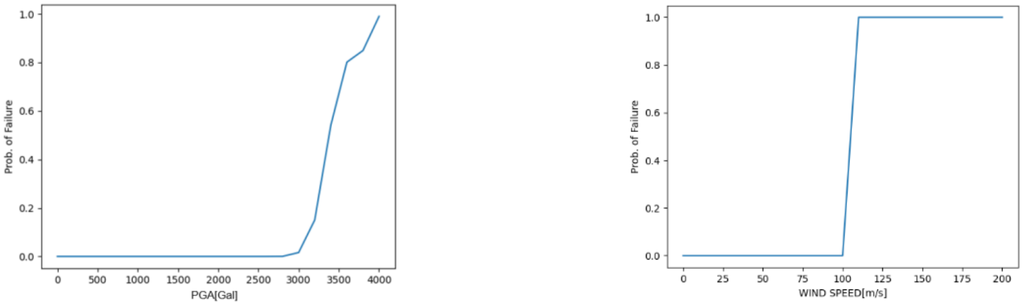


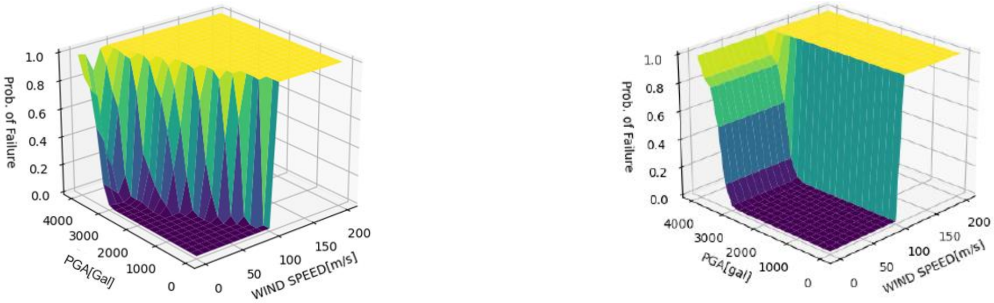
Figure 4. Target steel structure

The fragility curve for single-hazard conditions is shown in Figure 5, while the fragility surface for multi-hazard conditions is shown in Figure 6. According to Figure 6, under simultaneous occurrence, the combined effects of earthquake-induced and tornado-induced damage are evident, resulting in an increased fragility. However, in the case of time-lagged occurrence, the results resemble a simple addition of the individual fragility curves from single-hazard conditions.



(a) Seismic ground motion (b) Tornados

Figure 5. Fragility curve for single-hazard conditions



(a) Simultaneous occurrence

(b) Time-lagged occurrence (earthquake-tornados)

Figure 6. Fragility surface for “earthquake + tornado” multi-hazard conditions

Application Example of Integrated Assessment Method

According to Table 1, “Seismic motion and tsunami wave” are hazards caused by a common cause—an earthquake, making them a dependent hazard combination with a consequential nature. Additionally, since the propagation speed of a tsunami is slower compared to seismic ground motion, their loading durations do not overlap in case only main shock is considered, classifying this as a sequential occurrence event. The conditions for seismic ground motion and tsunami are described as follows. Overview of the evaluation model is shown in Figure 7.

Earthquakes

1) Earthquake Occurrence Conditions:

To account for tsunami damage, a large number of plate-boundary earthquakes of magnitude 7 or greater are assumed as seen in Figure 7. A hypothetical site and seismic activity area are set. The frequency-magnitude distribution is assumed to follow the Gutenberg-Richter (G-R) law, with a b-value of 0.9 and a maximum magnitude (M) of 9.0. Fault parameters are set based on the Headquarter of Earthquake Research Promotion (HERP) recipe (2020).

2) Earthquake Hazard:

Evaluated based on a ground motion attenuation equation for response spectra, assuming a common lognormal standard deviation of 0.53 for variability.

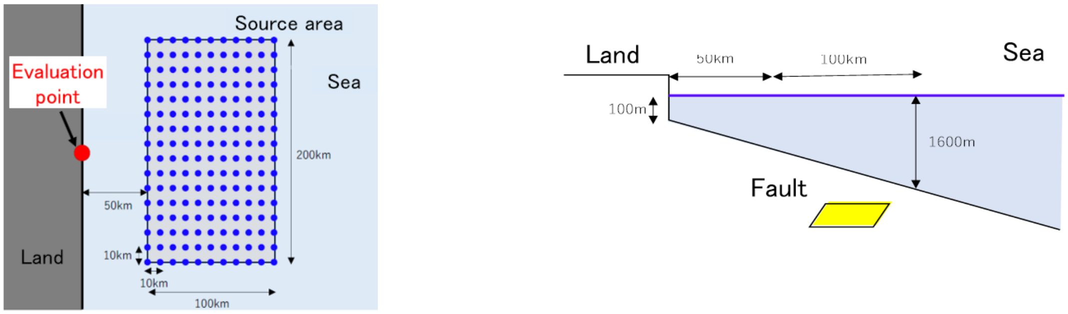
Tsunami

1) Tsunami Occurrence Conditions:

It is assumed that a tsunami generated by the earthquake occurs after the earthquake event.

2) Tsunami Hazard:

Evaluated using the Abe (1989) tsunami wave height attenuation equation.



(a) Plan

(b) Section

Figure 7. Overview of the Evaluation Model

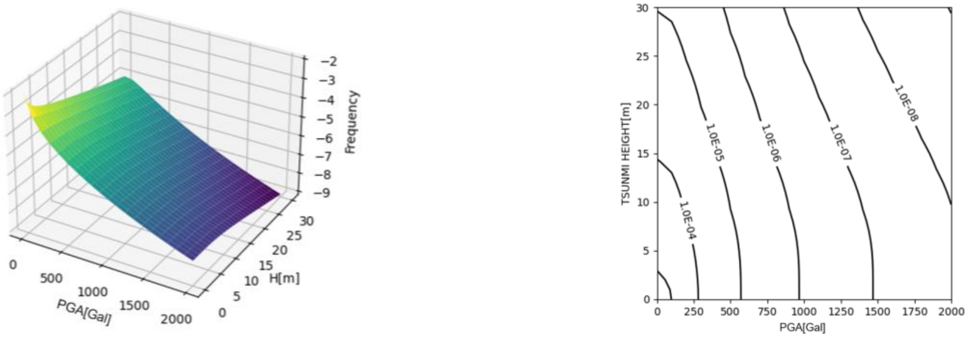
Multi-hazard assessment result

The multi-hazard of dependent events with time-lagged occurrence can be calculated using the following equation. The calculated “earthquake + tsunami” multi-hazard results are shown in Figure 8. According to Figure 8, Since “earthquake + tsunami” cannot be screened out from a hazard perspective, it is evaluated using the integrated assessment method.

$$\nu_{A\Rightarrow B}(s_A, s_B, t) = \nu_A(s_A) \times f_{s_A,s_B}(s_B|s_A, t) \tag{4}$$

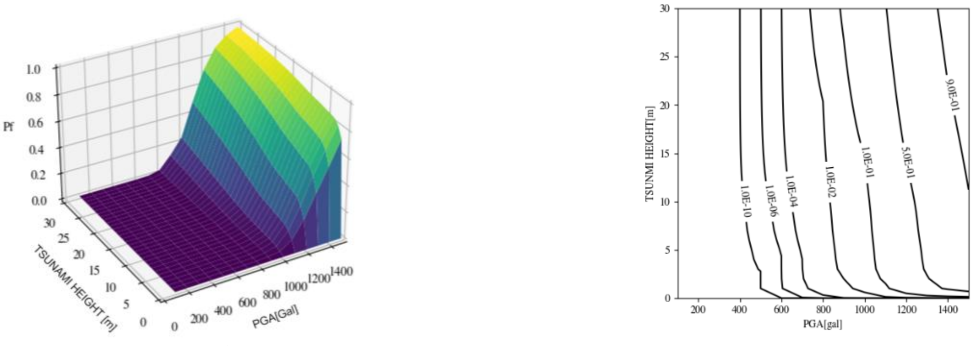
Here,

$\nu_{A\Rightarrow B}(s_A, s_B, t)$:	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.



(a) 2D surface
(b) Contour map

Figure 8. Hazard surface of “earthquake + tsunami” multi-hazard



(a) 2D surface
(b) Contour map

Figure 9. Fragility surface for “earthquake + tsunami” multi-hazard conditions

Multi-fragility assessment result

It is assumed that the critical equipment inside the building is installed on a 150 mm mechanical foundation. The failure mode considered in this study occurs when a specific combination of seismic acceleration and tsunami height leads to flooding of the critical equipment, resulting in functional failure. The tsunami duration is assumed to be 10 minutes. The building was modelled using a 3D FEM (Finite Element Method), and an analysis was conducted considering water leakage through wall cracks caused by the earthquake.

The inundation probability of the critical equipment was calculated for different combinations of peak ground acceleration (PGA) and tsunami height. The results of the multi-fragility evaluation are shown in Figure 9.

CONCLUSION

In this paper, the concepts of multi-hazard and multi-fragility were examined, and an Multi-hazard assessment flow was proposed. Based on the characteristics of each hazard combination, individual assessment methods and integrated assessment methods were proposed.

Furthermore, "earthquake + tornado" and "earthquake + tsunami" were selected as application examples, and under hypothetical site and analysis conditions, they were examined as application examples of multi-hazard and multi-fragility assessments.

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

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