Proposal of a method for risk quantification under the multi hazard of the earthquake and tsunami for nuclear power plant

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Abstract: Lessons learned from the Fukushima Dai-ichi Nuclear Power Plant accident caused by the 2011 off the Pacific coast Tohoku Earthquake, Japanese utilities are upgrading their tsunami countermeasures by installing seawalls, watertight doors, and severe accident countermeasures, etc. Risk assessment considering the multi hazard of earthquake and tsunami is required for plants with high tsunami risk, and the identified tsunami/seismic sources that generate both high tsunamis and large seismic motions. In order to understand the residual risk of a plant beyond design basis events, it is crucial not only to assess the seismic and tsunami risk independently but also to understand how the plant risk profile changes when these events occur successively. The following key issues should be considered properly in plant risk quantification. (1) scenarios to consider tsunami effects during accident mitigation of earthquake-induced events, (2) the dependence of earthquakes and tsunamis in the frequency of multi hazards, and (3) fragility that considers correlated effects under the multi hazard of earthquakes and tsunamis in addition to their independent effects. The aim of this study is to propose a risk profile quantification methodology for developing a practical evaluation method using model plants. This paper presents a concept of scenario identification under the multi hazard of earthquakes and tsunamis, a risk profile quantification methodology, and modeling methods, including examples in the system reliability model regarding SSC's correlated failure probability of earthquake and tsunami. This proposal will contribute to establishing a PRA method under the multi hazard of the earthquake and tsunami for nuclear power plants.

Keywords: PRA, multi hazard, seismic, tsunami.

1. INTRODUCTION

The March 11, the 2011 off the Pacific coast of Tohoku earthquake and tsunami damage to several nuclear reactors. The Fukushima Dai-ichi Nuclear Power Plant accident released radioactive materials into the environment through core damage. The Nuclear Regulation Authority (NRA) has implemented new regulatory standards in the safety review of nuclear power plants based on the lessons learned from the nuclear accident. Nuclear operators are taking decisive action to enhance the safety of their plants by introducing comprehensive tsunami protection measures and severe accident measures that comply with the new regulatory standards. Furthermore, the operator must submit a safety assessment report (SAR) after the periodic operator inspection following the plant restart. The SAR requires an assessment of risks related to internal and external events to evaluate the implementation of activities to improve safety. The operation guide for SAR of NRA states that the events covered by the assessment shall be expanded step by step according to the maturity of the probabilistic risk assessment (PRA) method. The guide specifies a superposition of the earthquake and tsunami events. The International Atomic Energy Agency (IAEA) has studied an evaluation of multi hazard PRA on the superposition of earthquake and tsunami (seismic-tsunami PRA) and published a Safety Report [1]. In addition, studies regarding seismic-tsunami PRA have been conducted on evaluation methods such as hazard and fragility evaluation [2] and accident sequence evaluation [3],[4]. This study proposes a risk profile quantification method for developing a practical evaluation methodology of seismic-tsunami PRA using model plants. When quantifying plant risk, it is necessary to consider the following three points. (1) scenarios to consider tsunami effects during accident mitigation of earthquake-induced events, (2) the dependence of earthquakes and tsunamis in the frequency of multi hazards, and (3) fragility that considers correlated effects under the multi hazard of earthquakes and tsunamis in addition to their independent effects. In this report, Chapter 2 describes a framework for quantifying plant risk under the superposition of earthquake and tsunami, Chapter 3 describes a concept of scenario identification for the superposed effects of earthquake and tsunami, and Chapter 4 describes modeling methods and trial assessment examples in the system reliability model due to the superposed damage of earthquake and tsunami.

2. FRAMEWORK FOR QUANTIFYYING THE PLLANT RISK UNDER THE SUPERPOSITION OF EARTHQUAKE AND TSUNAMI

2.1. Prerequisite of proposal

When conducting seismic-tsunami PRA with a view to their utilization in SAR, the evaluation models (ET, FT, hazard assessment data, and fragility assessment data) for previous seismic PRA and tsunami PRA must be utilized. The seismic PRA and tsunami PRA models are based on the internal event PRA models. The seismic-tsunami PRA will integrate the seismic PRA model with the tsunami PRA model. This approach meets all the requirements for a full-scope PRA that covers all modes and hazards. The model requirements are defined by site and plant specifications. The proposal does not consider aftershock effects or the repeated effects of tsunamis.

2.2. Range of hazard input levels on risk quantification

The first step in setting the scope of the superposition risk quantification is to identify the combination of tsunami wave sources and seismic sources affecting the plant using hazard disaggregation. This is done based on the results of the single-event hazard assessment, both earthquakes and tsunamis. The next step is identifying the scope of the impact of the superposition of earthquakes and tsunamis. Figure 1 shows an image illustrating the scope of the risk quantification under the multi hazard of the earthquake and tsunami.

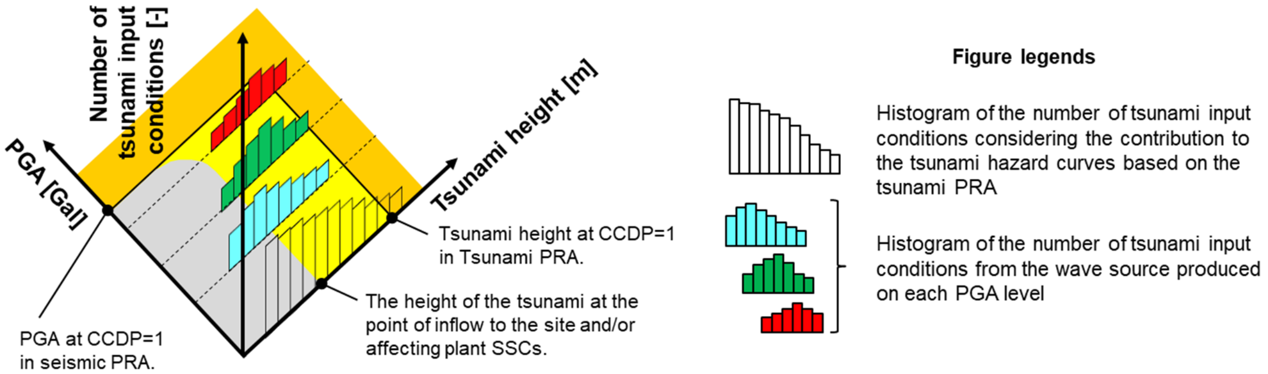

Figure 1. Image illustrating the scope of evaluation of the seismic-tsunami PRA

Figure 1 illustrates the relationship between seismic intensity (PGA) and tsunami height. The gray area indicates an area where the tsunami impact on the plant is not required. Therefore, it may be reasonable to focus only on seismic effects. The area shown in orange color in Figure 1 is the range where the conditional core damage probability is 1.0 for the seismic PRA or tsunami PRA. Hence, quantifying risk under the multi hazard of earthquake and tsunami is unnecessary. Therefore, the area indicated in yellow color in Figure 1 is the range of hazard input levels to be evaluated.

2.3. Framework of the risk quantification under the multi hazard of the earthquake and tsunami

A general framework for the risk quantification under the multi hazard of the earthquake and tsunami is shown in Figure 2. The scope of quantification of plant risk is up to the core damage frequency. This paper proposes the probabilistic hazard assessment information given by previous assessment data on the seismic PRA and tsunami PRA. The evaluation of the probabilistic hazard assessment on the superposition of seismic and tsunami hazards is outside the scope of this study, and the results of the evaluation by Nakajima et al. [5] and other methods will be used. In addition, the following information is also given for single-event PRA data based on the seismic PRA and tsunami PRA.

- Plant information such as design drawings, system design specifications, accident procedures, etc.
- ET model, FT model, Structures, systems, and components (SSCs) list, fragility data, failure rate data, etc.

The following are the concepts of each evaluation.

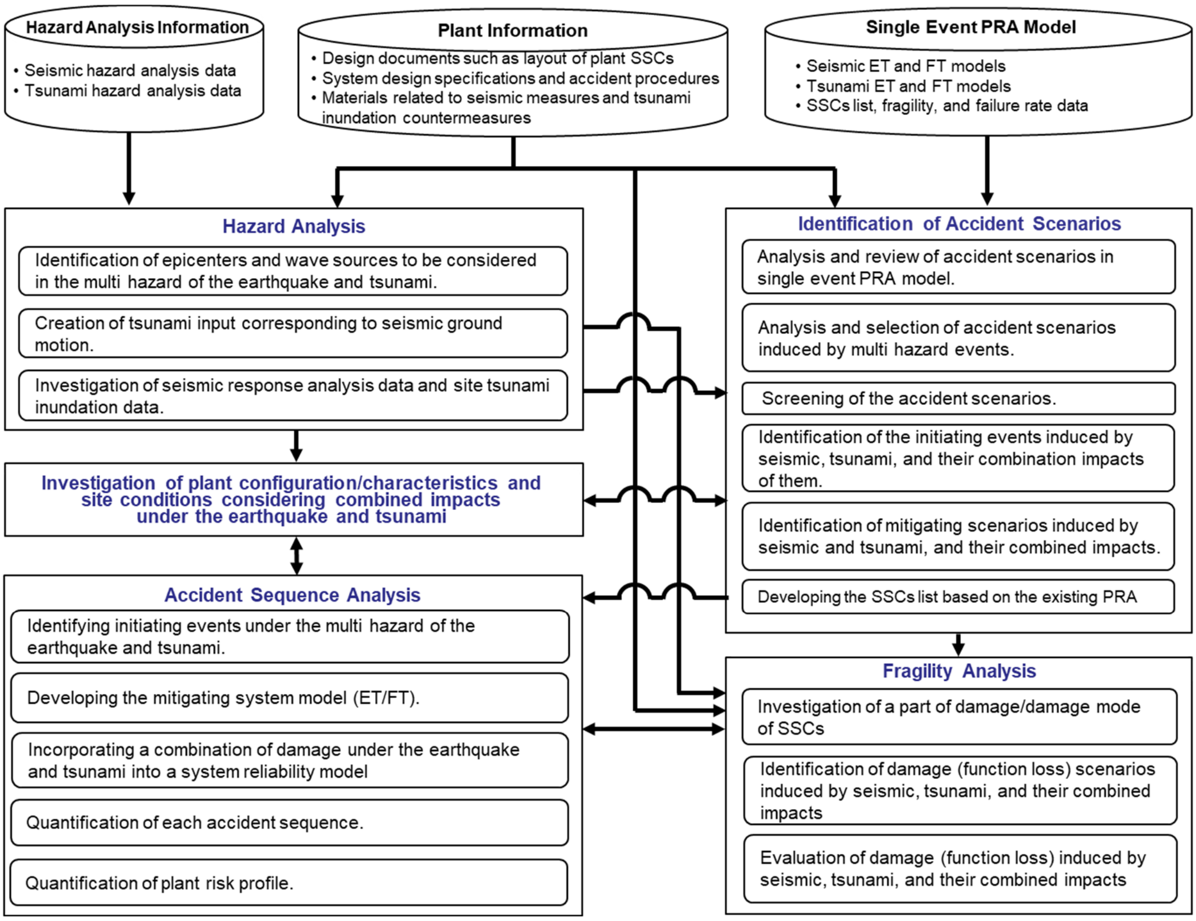

Figure 2. A framework for risk quantification under the multi hazard of the earthquake and tsunami

2.4. Hazard analysis (Excluding the evaluation of superposed hazard curves)

We need to identify tsunami input conditions, such as epicenters and wave sources, included in the yellow or gray area in Figure 1, where the conditional core damage probability (CCDP) is less than 1.0, by referencing the plant's tsunami PRA and seismic PRA. Based on the identified conditions, tsunami inputs for fragility evaluation are created. We can utilize the seismic PRA data to input seismic motions for fragility evaluation. The histogram shown on the tsunami height axes in Figure 1 represents the total number of tsunami input conditions for each tsunami height considering the contribution to the tsunami hazard curve based on the tsunami PRA evaluated at the target site. In contrast, a histogram of the number of tsunami input conditions from the wave source producing each seismic motion level is also presented. Each histogram of seismic motion levels represents the number of tsunami input conditions different from the peak tsunami height of the histogram in the tsunami PRA.

2.5. Site and plant condition surveys under the multi hazard of the earthquake and tsunami

A site impact investigation will be considered based on the site inundation propagation analysis under the tsunami input conditions identified based on the results of the multi hazard assessment of earthquake and tsunami. The PRA evaluator will determine the SSCs to be evaluated by referring to the design documents and conducting a plant walk-down, focusing on the impact area and understanding the superposition of earthquake and tsunami impact on the site and plant.

2.6. Analysis of general plant response scenarios due to multi hazard of the earthquake and tsunami

In addition to the identifications of accident scenarios conducted in the seismic PRA and tsunami PRA, the evaluators involved in the PRA will work together to analyze and establish general scenarios to identify accident scenarios that should be considered due to the multi hazard of the earthquake and tsunami (from now on referred to as "superposition scenario"). One of the characteristics of "superposition scenarios" to note is events in which an earthquake or superposed action affects the behavior of a tsunami response of the plant. Seismic motion acts simultaneously on the SSCs of the nuclear power plant. Therefore, the presence or absence of damage to SSCs is determined with a certain probability according to the characteristics of the seismic motion and the plant and component. On the other hand, it is important to note that a tsunami is an action accompanied by mass transfer in the form of seawater intrusion. The state of damage and probability of damage to SSCs depend not only on the characteristics of the tsunami and accident mitigation SSCs but also on earthquake damage to tsunami protection facilities and other structures in the propagation path. The concept of scenario identification is described in Chapter 3.

2.7. Identification of accident scenarios

In setting the success criteria necessary to prevent core damage after a catastrophic event, scenarios are identified, including the number and combination of SSCs required to achieve safety functions in consideration of a tsunami after an earthquake, and the mission time in consideration of the time difference between the earthquake motion and tsunami arrival time. Since multiple plant responses are expected due to tsunami inflow into the site and building flooding caused by earthquake effects, it is necessary to identify accident scenarios to lead to the comprehensive development of accident sequences through grouping.

2.8. Fragility analysis

In this study, we propose that the fragility evaluation models on seismic PRA and tsunami PRA, along with their evaluation results, could be used to evaluate the fragility under the multi hazard of the earthquake and tsunami (The seismic fragility model is a Separation of Variable Method. The tsunami fragility model is a detailed method considering inundation in the building). If the seismic response of the SSCs only affects the tsunami response of the SSCs and does not affect the capacity of SSCs to withstand a tsunami, then seismic and tsunami damage can be considered independent events. Therefore, it might be helpful to consider the following equation, which could be used to calculate the damage probability considering multi hazard of the earthquake and tsunami (P_{s+T}). Equation 1 shows that the superposition fragility can calculate information on the seismic damage probability (P_s) based on the PGA and the tsunami damage probability (P_t) based on the tsunami height.

$$P_{s+t} = \left((1 - P_t) \times P_s\right) + (P_s \times p_t) + ((1 - P_s) \times P_t) \tag{1}$$

On the other hand, if the seismic response affects the tsunami capacity of SSCs, it would be required to identify the conditions under which the SSCs to be evaluated must maintain its function. Identifying the part of damage, damage modes, and damage scenarios of SSCs considering multi hazard of the earthquake and tsunami are crucial aspects of this process. Moreover, the damage probabilities of SSCs for each scenario need to be evaluated and incorporated into the system reliability model. Modeling methods and examples in the system reliability model for damage probabilities considering the multi hazard of the earthquake and tsunami are described in Chapter 4.

2.9. Accident sequence analysis

Quantify the frequency of occurrence of the initiating event based on the results of the identified "superposition scenarios" that may lead to core damage. The heading of the ET should be modeled by taking steps such as grouping based on the superposed effects to develop the accident sequence comprehensively and to consider the volume of the analysis. The FT model used in the system reliability analysis is constructed by integrating the FT model of the earthquake PRA and the tsunami PRA. In this case, it is necessary to conduct a human reliability analysis that includes the effects of the tsunami through the impact of the earthquake. As a method of quantifying the risk profile of a plant, we propose the idea of using the PGA as the basis for the evaluation axis of the seismic PRA. Core damage frequency under the multi hazard of the earthquake and tsunami (CDF_{S+T}) is obtained as the sum of the product of the conditional probability density function of the tsunami height α_T when PGA is α_s, the CCDP for each combination of the PGA and tsunami height ($\alpha_{S,}$ and α_T), and the frequency of earthquakes at PGA α_s based on the hazard curve in consideration of the correlation between earthquake and tsunami. The proposed basic equation is presented in Equation 2.

$$CDF_{S+T} = \iint -\frac{dH(\alpha)}{d\alpha_S} T(\alpha_T|\alpha_S) \cdot CCDP(\alpha_S, \alpha_T) d\alpha_T d\alpha_S \tag{2}$$

CDF_{S+T} : Core damage frequency on the superposition of earthquake and tsunami [/(reactor·year)]
α_S : Peak ground acceleration (PGA) [Gal, cm/sec^2]
α_T : Tsunami height [m]
H(αs) : Frequency of exceedance of seismic with PGA exceeding α_S [/year]
$T(\alpha_T|\alpha_S)$: Conditional probability density function of the tsunami height α_T when the PGA is α_S
CCDP (α_S, α_T) : Conditional core damage probability when PGA α_S and tsunami height α_T [-]

3. APPROACH TO SCENARIO IDENTIFICATION ON THE SUPERPOSITION OF EARTHQUAKE AND TSUNAMI

Figure 3 presents a schematic chronology of the plant state on the superposition of earthquake and tsunami, including human behavior (including transient state). A superposed scenario is represented as a combination of the occurrence states of characteristics due to multi hazard of the earthquake and tsunami. This scenario takes on multiple processes and end states. The discussion in this paper is limited to scenarios consisting of events that can broadly affect plant conditions.

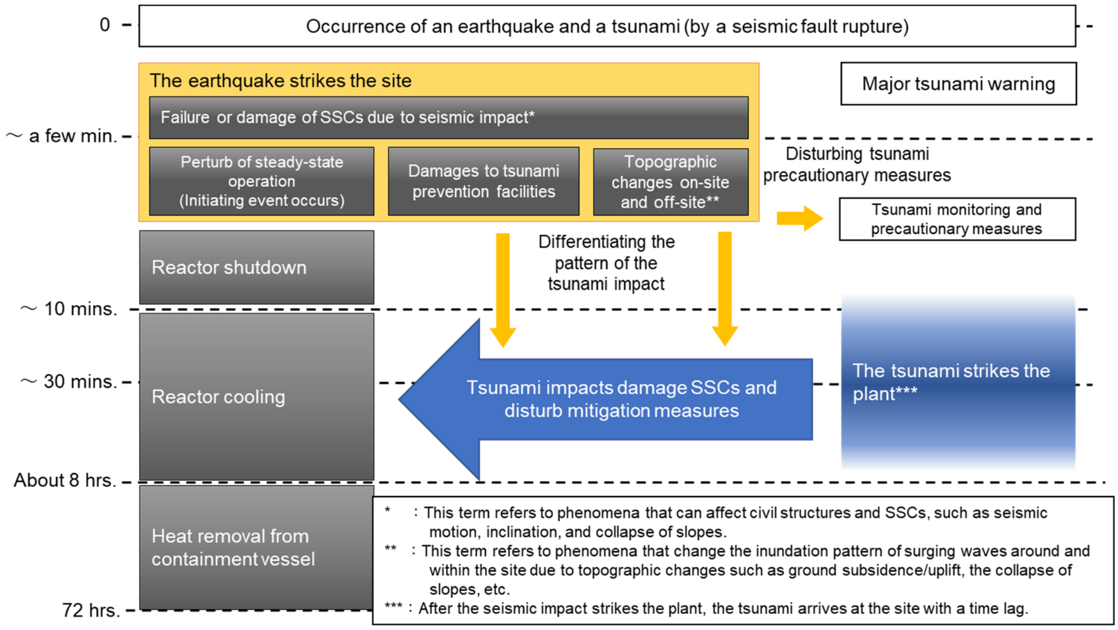

Figure 3. A schematic chronology of the state of the plant on the superposition of earthquake and tsunami [6]

Accident scenarios caused by each effect regarding earthquakes or tsunamis have been adequately considered in existing seismic PRA and tsunami PRA. On this basis, the following three points should be focused on for the specific events and scenarios.

a. Changes in the mode of action of a subsequent hazard due to an initial hazard acting on the plant
  - Change in the route of tsunami inundation due to ground deformation (Different from the impact of tsunami only).
  - Tsunami inundation due to damage to tsunami protection facilities, etc., caused by preceding seismic hazards or tsunami superposed effects.
b. Occurrence of scenarios that were not expected to occur in a single hazard
  - A superposition of structural damage to SSCs. It has resulted in a cumulative total of damage under the multi hazard of the earthquake and tsunami (including secondary effects).
  - Incident response due to a tsunami effect during the implementation of an incident response to an earthquake event.
  - Impact of the difference in arrival times of earthquakes and tsunamis on accident response.
c. Events and scenarios caused by combining the above a. and b.

Our other paper [6] provides a more comprehensive examination of the scenario identification for the superposition of earthquakes and tsunamis, including classifying superposition effects and their implications in the context of PRA.

4. MODELLING APPROACH TO SYSTEM RELIABILITY MODEL OF THE SEISMIC-TSUNAMI SUPERPOSITION DAMAGE

4.1. Assumptions

In the case of damage to SSCs, where the damage modes and damage parts are identical for earthquakes and tsunamis, it is necessary to evaluate the response due to tsunamis according to whether or not the seismic motion has reduced the capacity of SSCs. This study focused on the structural strength of the component. The effects of the earthquake were classified into three categories: ‘within elastic range,’ ‘plastic deformation’, and ‘fracture’.

4.2. Subject SSC of evaluation

The outdoor condensate tank was targeted, and the various parameters for the evaluation were based on published information [7].

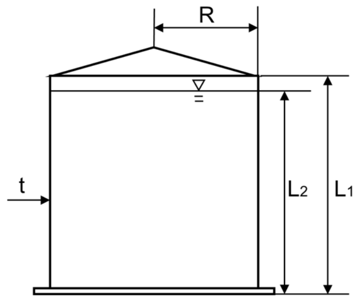

Figure 4. Schematic drawings of condensate tank

Table 1. Specifications of the condensate tank

Item	Specification
Material (Body plate, Anchor bolt)	SS400
Plate thickness t [mm]	6
Height L_1 [mm]	12000
Liquid level (Height) L_2 [mm]	11680
Radius R [mm]	4400
R/t	733
L_1/R	2.73

4.3. Investigation of damage part and mode

For seismic events, the “damage part” are the body and anchor. The “damage mode” is identified as body plate buckling and shear failure at the anchor, as shown in Table 2. Tsunami events may include body plate buckling due to wave forces, anchor damage due to buoyancy, boundary damage due to drifting debris, and loss of ground support due to scour. The loads acting on the body plates during earthquakes and tsunamis are the accumulation of the stress due to seismic motion, load effects of wave forces, and drifting object impact in the main body. For anchor sections and ground, loads may be due to seismic motions, wave forces, loads and accumulated effects of drift impact, and ground deformation due to scouring. In addition, damage to the anchorages or supporting ground may cause the tank to become a driftage.

Table 2. Investigation of damage part and mode

S	Damage part	1) Body plate 2) Anchor bolt
	Damage mode	1) Buckling fracture 2) Shear failure due to seismic motion
T	Damage part	1) Body plate 2) Anchor bolt 3) Soil
	Damage mode	1) Buckling fracture due to wave force 2) Tensile fracture due to buoyancy 3) Loss of ground support due to corrosion
S + T	Damage part	1) Body plate 2) Anchor bolt
	Damage mode	1) Buckling fracture 2) Shear failure due to seismic motion, and tensile fracture due to seismic motion and buoyancy 3) Ground support failure due to seismic, and tsunami wave forces and corrosion
	Adjoint scenario	1) None. 2) Damage to the anchorages or supporting ground may cause the tank to become a driftage.

Note of symbols
S: Seismic event
T: Tsunami event
S+T: Superposition of the seismic and tsunami event

4.4. Damage scenarios of the outdoor tank

A scenario flow for outdoor tanks under the multi hazard of the earthquake and tsunami is shown in Figure 5. As this paper aims to present the modeling approach to the system reliability model, the subsequent descriptions will not include scenarios for damage caused by drifting debris and the tank themselves to driftage materials. In the event of the body plates of tanks, the boundary function of maintaining the water remains uncompromised. Therefore, the anchor section is the first focus of attention when considering damage scenarios.

4.5. Calculation of damage probability

a. Damage probability due to earthquake only (P_1)
The seismic damage probability ($P_{S\ fracture}$) is considered a 'fracture' due to an earthquake.

$$P_1 = (P_{S\ fracture}) \quad (3)$$

b. Damage probability due to earthquake and tsunami (P_2)
If the seismic load leads to 'fracture' for the damage part of SSCs, the superposition with the load due to tsunami is not considered. The seismic and tsunami superposition damage probability (P_{S+T}) considers the transition as the damage occurs due to tsunami loads following plastic deformation caused by seismic loads.

$$P_2 = (1 - P_{S\ fracture}) \times (P_{S+T}) \quad (4)$$

c. Damage probability due to tsunami only (P_3)
If the seismic load only causes elastic deformation and does not result in 'fracture' there will be no combined damage from seismic and tsunami loads. In this case, we should only consider the probability of damage from the tsunami load (P_T). The following equation can be used to calculate this probability."

$$P_3 = (1 - P_{S\ fracture}) \times (1 - P_{S+T\ damage}) \times P_T \quad (5)$$

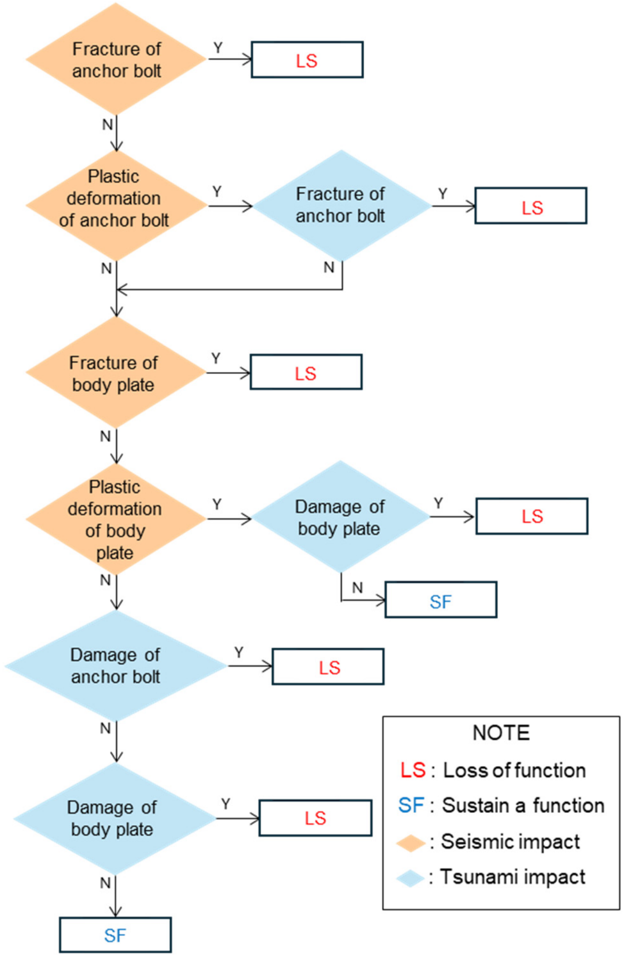

Figure 5. Damage scenario of the outdoor tank

4.6. System reliability model on the seismic and tsunami superposition damage (FT model)

Figure 6 shows a fault tree representing the function loss of an outdoor tank constructed based on the concept of damage scenarios and damage probabilities. The base event due to the earthquake only is expressed in Equation 3. The base event due to the earthquake and tsunami is expressed in Equation 4. The base event due to the tsunami only is expressed in Equation 5.

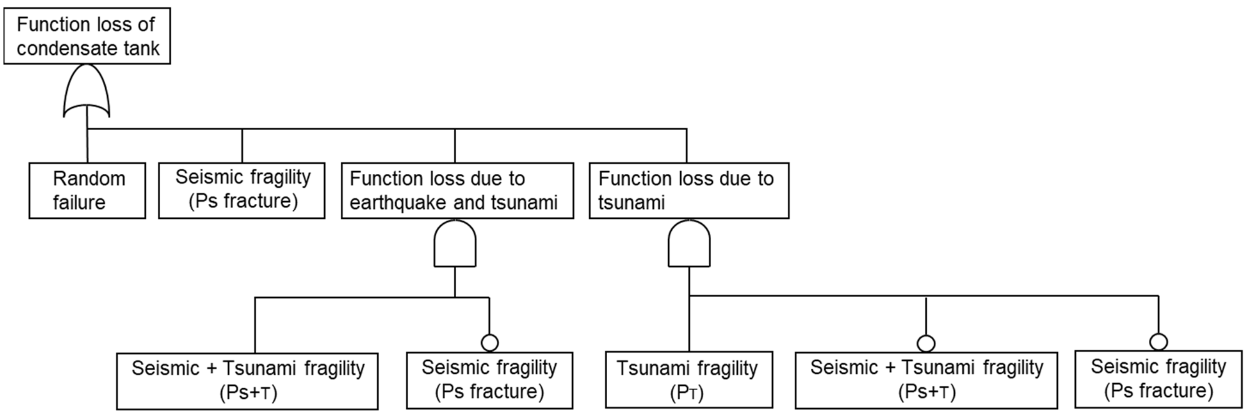

Figure 6. System reliability model on the seismic and tsunami superposition damage

4.7. Evaluation example of damage probability under the multi hazard of the earthquake and tsunami

(1) Evaluation of realistic bearing capacity and realistic response

In this study, we focused on the amount of strain exerted by the tsunami load while the seismic load and residual strain plastically deformed the damaged part was generated. It is assumed that the absolute sum of the maximum strain produced at the evaluated part of the tank by the earthquake and the strain created by the tsunami represents the final strain in the realistic response. Residual strain due to seismic loading from seismic response was assumed to be the maximum strain. The strain due to the tsunami is evaluated from in sound conditions. These points are considered uncertainties in the amount of strain. The lumped mass model was constructed for the seismic response analysis, and a static load analysis model was for the tsunami response analysis. These models cannot calculate the strain after tank buckling, so we replaced the maximum strain with the displacement of the apex of the tank roofs concerning the research report [7]. We used the displacement of the apex of the tank roof as the fragility evaluation index.

(2) Capacity

Table 3 shows the evaluated values on the bearing capacity of the tank based on the proposed approach. In this study, body plate buckling was assumed to be the dominant failure mode of the tanks based on the reference report [7]. The median bearing capacity under the multi hazard of the earthquake and tsunami was assumed to be the sum of the earthquake-induced displacement and the tsunami-induced displacement of 333 mm for structural damage.

Table 3. Specifications of the condensate tank

Type of external force	Tolerance limit	Capacity (Displacement of the apex of the tank roof)
Seismic (Dynamic load)	Buckling of body plate	50 mm
Tsunami (Static load)	Buckling of body plate	333 mm
	Breakage of the body plate due to buckling	720 mm (Based on the breaking strain of SS400 is 17% or more.)
Seismic and tsunami (Dynamic load + Static load)	Defined structural damage against buckling of body plate	333 mm

(3) Seismic response analysis and tsunami response analysis

In the seismic response analysis, the reference seismic motion level was set to 1.0, the seismic input for the analysis was configured at the level at which a portion of the tank was plastically deformed, and the displacement of the apex of the tank roof was calculated by nonlinear time historical analysis. In the tsunami response analysis, the maximum wave force calculated by the existing wave force formula was conservatively input as a static (constant) load. Horizontal wave forces were considered up to the height of the tank, and the weight of the seawater present above the tank was added to the tank roof for buckling evaluation. The results of the response analysis are shown in Table 4 and Table 5.

Table 4. Result of the seismic response analysis

Seismic input level	Displacement (Absolute value)	Deformed state
0.2 x	5.5 mm	Elastic
0.5 x	13.8 mm	After buckling (Buckling occurred at 12.3 mm)
1.0 x	27.3 mm	After buckling
1.5 x	35.9 mm	After buckling
2.0 x	43.4 mm	After buckling
3.0 x	79.1 mm	After buckling
3.5 x	91.1 mm	After buckling

Table 5. Result of the tsunami response analysis

Tsunami input level	Displacement (Absolute value)	Deformed state
12 m	21.5 mm	After buckling
14 m	27.9 mm	After buckling
16 m	62.2 mm	After buckling
17 m	97.1 mm	After buckling
18 m	143.4 mm	After buckling
19 m	202.2 mm	After buckling
20 m	282.0 mm	After buckling

(4) Logarithmic standard deviation of realistic capacity and realistic response
The realistic capacity and realistic response under the multi hazard of the earthquake and tsunami were assumed to follow a log-normal distribution. The values for the legalistic standard deviations of the aleatory uncertainties (β_r) and epistemic uncertainties (β_u) are evaluated based on engineering judgment. The evaluation results are shown in Table 6.

Table 6. The logarithmic standard deviation of uncertainties

	Seismic	Tsunami	Seismic + Tsunami
Capacity	β_r=0.32, β_u=0.32	β_r=0.24, β_u=0.24	β_r=0.24, β_u=0.24
Response	β_r= - *, β_u=0.19	β_r=0.15, β_u=0.15	β_r=0.21, β_u=0.21

*: The uncertainty from the epicenter to the installation ground is not taken into account because the input seismic motion is assumed to be at the tank installation location.

(5) Realistic response under the multi hazard of the earthquake and tsunami
The probability density function $f_R(A,x)$ of the realistic response for a given value of input A due to an earthquake or tsunami is expressed as a log-normal distribution with median $R_m(A)$ and logarithmic standard deviation $\beta_R(A)$ as follows.

$$f_R(A,x) = \frac{1}{\sqrt{2\pi}\beta_R(A)\cdot x} exp\left\{-\frac{1}{2}\left(\frac{\ln(x/R_m(A))}{\beta_R(A)}\right)^2\right\} \tag{6}$$

$f_R(A,x)$: Probability density function of realistic response (lognormal distribution)
A : Seismic input (PGA [Gal]) and tsunami input (Tsunami height [m])
x : Parameters representing realistic response values (displacement of the apex of the tank roof)
$R_m(A)$: Median of the realistic response
$\beta_R(A)$: Logarithmic standard deviation

As mentioned earlier, the displacement of the apex of the tank roof is the sum of the displacements that would occur in response to an earthquake and tsunami occurring independently. The probability (P_X) that the displacement of the apex of the tank roof due to the superposition of earthquake and tsunami is x, which is discretized by dividing the displacement x into the smallest unit Δx (1mm in this case), where n is the displacement of the apex of the tank roof due to earthquake and x-n (n is a discrete value (integer) with 0 ≤ n ≤ x) is the displacement of the apex of the tank roof due to tsunami. Therefore, the probability P_X that the displacement due to the earthquake and tsunami will be x is obtained by the following equation 7.

$$P_x = \sum_{n=0}^{x}\{P_{S_n} \times P_{T_{x-n}}\} \tag{7}$$

$P(_{Ti})$: Probability when the amount of the displacement due to the tsunami is i
$P(_{Si})$: Probability when the amount of the displacement due to the seismic is i

The probability density function of the realistic response under the multi hazard of the earthquake and tsunami is evaluated as shown in Figure 7. The figure shows an example of realistic response evaluation at the seismic input level 3x and the tsunami height of 18m. The blue dashed line represents the distribution of realistic responses regarding the tsunami input with a tsunami height of 18 m, which only considers tsunami uncertainty (β_T). The solid blue line in the figure shows a realistic tsunami response when uncertainties are considered in the case of a superposition of earthquake and tsunami (β_{S+T}). The solid purple line in the figure shows the realistic response to the accumulated seismic and tsunami responses. In addition, the green line shown in Figure 7 represents the realistic capacity.

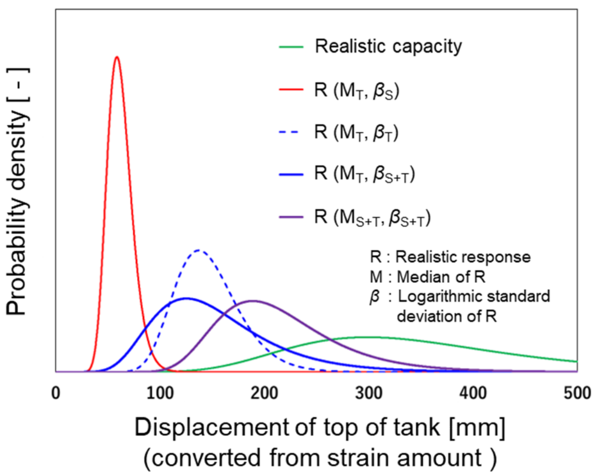

Figure 7. Realistic capacity and realistic response

(6) Superposition fragility evaluation under the multi hazard of the earthquake and tsunami

The superposition damage probability is evaluated as the damage probability value for each tsunami height level in the case of seismic PGA using the realistic capacity and response obtained in the previous section. The damage probability for a tsunami height H at a given seismic acceleration is expressed as $F(H)$. $F(H)$ is calculated as the conditional probability that the probability density function $f_R(H, x_R)$ of the realistic response at the tsunami height H exceeds the probability density function $f_S(x_R)$ of the realistic capacity, as shown in equation 8.

$$F(H) = \int_0^{\infty} f_S(x_R) \left(\int_{x_R}^{\infty} f_R(H, x_R) dx \right) dx_R \qquad (8)$$

Figure 8 shows an example of the fragility evaluation results under the multi hazard of earthquakes and tsunamis.

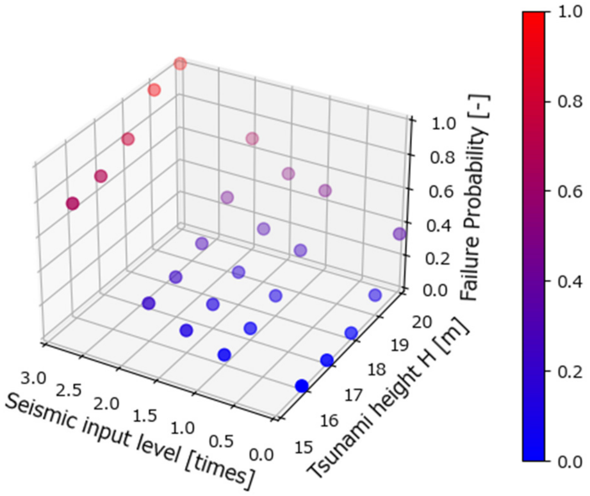

Figure 8. Example of fragility evaluation result for an outdoor tank

5. CONCLUSION

In this study, we proposed a framework of risk quantification method under the multi hazard of the earthquake and tsunami and a basic equation for quantification. In addition, the concept of scenario identification for superposition effects based on perspectives not considered for single earthquake and tsunami events is presented. A modeling approach to the system reliability model of the combined damage due to earthquakes and tsunamis and an example of fragility evaluation for an outdoor tank were presented. The proposal in this study will contribute to establishing a PRA method under the multi hazard of the earthquake and tsunami for nuclear power plants.

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