Research on probabilistic risk assessment of seismic induced tsunami events

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ABSTRACT

Since the Fukushima Daiichi nuclear accident, the importance of enhancing nuclear safety against external hazards, particularly earthquakes and tsunamis—has been widely recognized. Although probabilistic risk assessment (PRA) methods have been developed for individual hazards, comprehensive methodologies for evaluating compound events involving both seismic and tsunami effects remain limited despite their increasing relevance. This study aims to develop a PRA methodology capable of addressing the complex and diverse damage mechanisms resulting from such compound events, using a model plant as the evaluation basis. While three evaluation models, the Independent, Cumulative, and Integrated Seismic-Tsunami Models, were proposed in a previous study [1], they have not been systematically applied within an integrated framework. In this research, these models are refined, integrated, and applied to simulate realistic accident progression scenarios. A case study is conducted using event tree and fault tree analyses, wherein core damage frequencies are quantitatively evaluated for multiple combinations of seismic intensities and tsunami wave heights. The methodology accounts for fatigue failure, inundation, and functional loss due to structural degradation. The results underscore the importance of scenario-based risk modeling and highlight the value of incorporating fragility and uncertainty information into compound event analysis to support more realistic and robust nuclear safety assessments.

Keywords: seismic, tsunami, compound events, PRA

I. Background

Following the accident at the Fukushima Daiichi Nuclear Power Plant, enhancing the safety of nuclear facilities has become an extremely important issue. The significance of risk assessment for external events such as seismic and tsunami hazards, which were the primary causes of the accident, has been increasingly recognized. PRA is now widely employed as part of safety countermeasures. While evaluation methods for individual external hazards, such as seismic or tsunami events, have been developed, comprehensive methodologies for assessing compound events involving both hazards simultaneously have not yet been fully established. Accordingly, further research is needed to address this gap.

II. Objective

In compound events where seismic and tsunami hazards occur simultaneously, a range of complex damage states is anticipated due to the combined effects of both hazards. This study aims to develop an analytical methodology capable of addressing such complex damage states. The approach is based on three evaluation models proposed in previous studies [1] and is intended to establish a PRA methodology that can appropriately assess the impacts of compound seismic and tsunami events. Specifically, the study systematically identifies potential scenarios under compound events and conducts risk assessments based on these scenarios to clarify the progression mechanisms of system functional losses caused by external hazards. Furthermore, the developed methodology is applied to a model plant to verify its practical applicability and validity through case studies.

III. Methodology

The "evaluation models" in this study refer to analytical models developed for conducting risk assessments. In the context of compound events—where both seismic and tsunami hazards occur—four types of component damage scenarios are assumed, as illustrated in Figure 1. These scenarios include damage due to seismic effects alone, tsunami effects alone, and combined effects of both hazards. To address the diversity of damage states, this study categorizes and evaluates them using the following three models:(1) the Independent Seismic-Tsunami Evaluation Model, (2) the Cumulative Seismic-Tsunami Evaluation Model, and (3) the Integrated Seismic-Tsunami Evaluation Model. (1) In this model, damage to each piece of component is evaluated separately for seismic and tsunami effects. This approach is mainly applied to dynamic and electrical components, where the damage modes and indicators differ between seismic and tsunami events. Evaluations are conducted independently for each hazard. Component is considered functionally failed if damage is caused by either hazard, which requires logical coupling through an "OR gate." As shown in Figure 2, an extended fault tree (FT) is constructed for each piece of component to account for both seismic and tsunami damage sources. In the integrated FT, an "OR condition" is applied to all basic events, indicating that failure due to either hazard leads to functional loss, ultimately contributing to core damage.

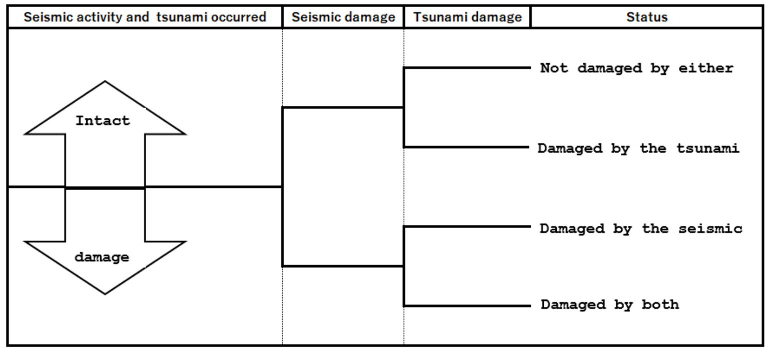

Fig1. Component damage states caused by seismic and tsunami effects

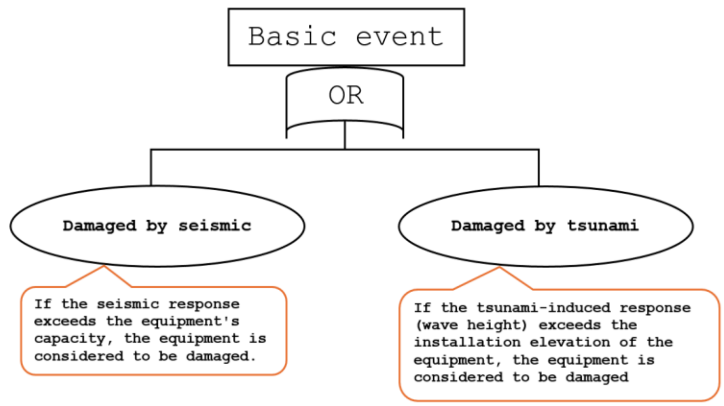

Fig2. Component damage states caused by seismic and tsunami effects

(2) This model assesses whether the cumulative external forces from both seismic and tsunami events exceed a certain damage threshold. It is primarily applied to support structures such as components or piping. The dominant damage mode considered is fatigue. However, based on previous research, no established method exists for evaluating cumulative damage due to tsunami forces, and practical applications of cumulative evaluation for seismic forces are also limited. Therefore, in this study, a simplified model is used to preliminarily assess the effect of cumulative forces. If the cumulative effect is deemed negligible, this model is not applied. When the effect is non-negligible, the cumulative evaluation model is employed. The model simulates stainless steel piping, and cumulative damage is assessed using a cumulative damage rule and S–N curves.

(3) This model focuses on tsunami protection structures such as watertight doors and seawalls, which are assumed to lose functionality due to the combined impact of seismic and tsunami events. Specifically, the model assumes that structures like seawalls, designed for tsunami protection, are damaged by seismic motion, reducing their protective capability during subsequent tsunami inundation. As a result, components are exposed to tsunami effects and become damaged. This model introduces new damage scenarios that consider the compound nature of these events. In constructing such scenarios, it is essential to account for the fact that the tsunami resistance of protective structures may vary depending on the magnitude of the earthquake. Accordingly, the damage states of tsunami protection facilities are classified by seismic magnitude, and progression scenarios are constructed based on these classifications. Target structures are selected with reference to prior studies on tsunami protection. For each structure, damage states are categorized based on seismic intensity [2]. Additionally, the tsunami intrusion process following structural damage is considered, and the sequence of progression is organized chronologically to construct realistic and comprehensive scenarios.

Ⅳ. Current Results and Issues

(1) In setting scenarios for actual quantification, the following events were assumed: loss of offsite power due to

seismic events (e.g. collapse of transmission towers), large-break LOCA, medium-break LOCA, small-break LOCA, and tsunami-induced events such as loss of offsite power (e.g., submersion of bus bars), loss of injection function, and loss of heat removal function. Based on combinations of these events, 12 core damage scenarios were considered. Quantification was performed using these scenarios with reference to the flowchart shown in Figure 4 [3]. This enabled the calculation of core damage probabilities for each scenario corresponding to specific levels of ground motion and tsunami wave height.

(2) A simplified model simulating a pipe was subjected to external forces due to seismic and tsunami loading. The resulting stress was calculated and used to evaluate potential damage. The S–N curve shown in Figure 3 represents the fatigue resistance of structures under cyclic loading, where lower stress levels tend to result in slower progression of fatigue damage. While some materials, such as stainless steel, do not exhibit a clearly defined fatigue limit, there exist stress levels at which the probability of fatigue failure is considered extremely low over the expected service life. In this analysis, the calculated stress was confirmed to fall within such a low-stress region, and therefore, cumulative fatigue damage was deemed unlikely. However, in more realistic models, stresses may reach non-negligible levels, potentially leading to cumulative damage. Continued investigation is thus required.

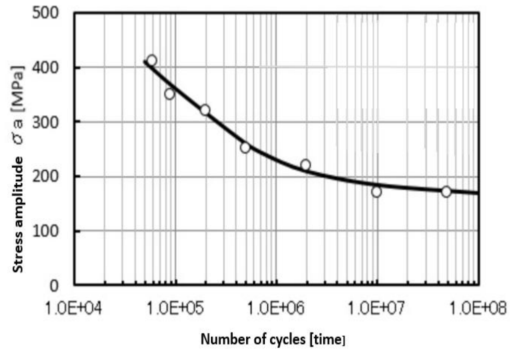

Fig3 S–N curve for stainless steel [4]

(3) The selected tsunami protection structures and their classifications of damage states are presented in Table 1. This table organizes the potential damage states to which each protection structure may transition under seismic impact. However, sufficient quantitative data to validate these state transitions are currently lacking. Accordingly, a hypothetical model representing the gradual degradation of protective functions has been adopted, with the expectation that future accumulation of fragility data will enable refinement of the model. Furthermore, the progression of tsunami-induced inundation following damage to protection structures was analyzed based on a stepwise inflow route: from outside the site to within the site, from within the site to inside buildings, and from inside buildings to equipment rooms. The results of this chronological analysis are summarized in Table 2. This table organizes the inundation pathways based on the assumption that the damage states of each structure presented in Table 1 serve as prerequisite conditions. The pathways are considered to be established when these pre-existing damages are compounded by tsunami wave forces and rising water levels. Based on the information in Tables 1 and 2, a representative Event Tree (ET) illustrating the progression of an accident is shown in Figure 5.

Table1. Damage State Transition Table

Facility	Damage States
<Flood Protection from Outside the Site to Within the Site>	
Seawall	Intact / Minor damage (cracks,) / Severe damage (collapse)
Embankments	Intact / Minor damage (cracks,) / Severe damage (collapse)
Overflow Prevention Wall	Intact / Damage (e.g., collapse)
Discharge Pit/Channel Closures	Intact / Unable to close
<Flood Protection from Within the Site to Inside the Building>	
Facility	**Damage States**
Reinforced/Watertight Doors	Intact / Damage (unable to close)
Building Exterior Walls	Intact / Minor damage (cracks)
Underground Pipe Duct Access Ports	Intact / Damage (unable to close)
Penetration Sealing Measures (Sealants)	Intact / Damage (reduced watertight performance)
<Flood Protection from Inside the Building to Equipment Rooms>	
Facility	**Damage States**
Building Drainage Measures (Pumps, etc.)	Intact / Damage (loss of drainage function)
Equipment Room Flood Protection (Watertight doors, seals, etc.)	Intact / Damage

Table2. Tsunami Inflow Routes and Conditions for Inundation

Route	Prerequisite Condition	Activation Condition
E-1: Residual water inflow after overtopping	Seawalls and embankments are intact	Overtopping occurs when tsunami wave height exceeds 28 meters, leading to inflow into the site
E-2: Inflow through damaged section of seawall	Seawall is partially or severely damaged by the seismic	Damage progresses due to tsunami wave force, allowing inflow into the site
E-3: Inflow from intake pit	Overflow protection wall is damaged	Overflow occurs, leading to inflow into the site
E-4: Inflow from damaged embankment	Embankment is partially or severely damaged	Tsunami overtops the embankment from the side, resulting in inflow
E-5: Inflow through drainage outlet opening	Discharge channel opening cannot be closed	Sea level rises due to tsunami, causing backflow and inflow into the site
I-1: Inflow due to damaged watertight doors	Reinforced/watertight doors are damaged by the seismic	Even if not damaged by the seismic, doors may be damaged by tsunami wave force, resulting in inflow into the building
I-2: Inflow through cracks in external walls	Outer building walls are cracked or otherwise damaged	Damage progresses due to tsunami wave force, leading to inflow into the building
I-3: Inflow through underground duct access ports	Inspection opening is damaged	Even if not damaged by the seismic, the opening may be damaged by tsunami wave force, resulting in inflow into the building
I-4: Inflow through building penetrations	Deterioration of sealing materials	Even if not damaged by the seismic, the parts may be damaged by tsunami wave force, resulting in inflow into the building
R-1: Water level rise due to loss of drainage function	Water level rise due to loss of drainage function	Drainage pump is damaged

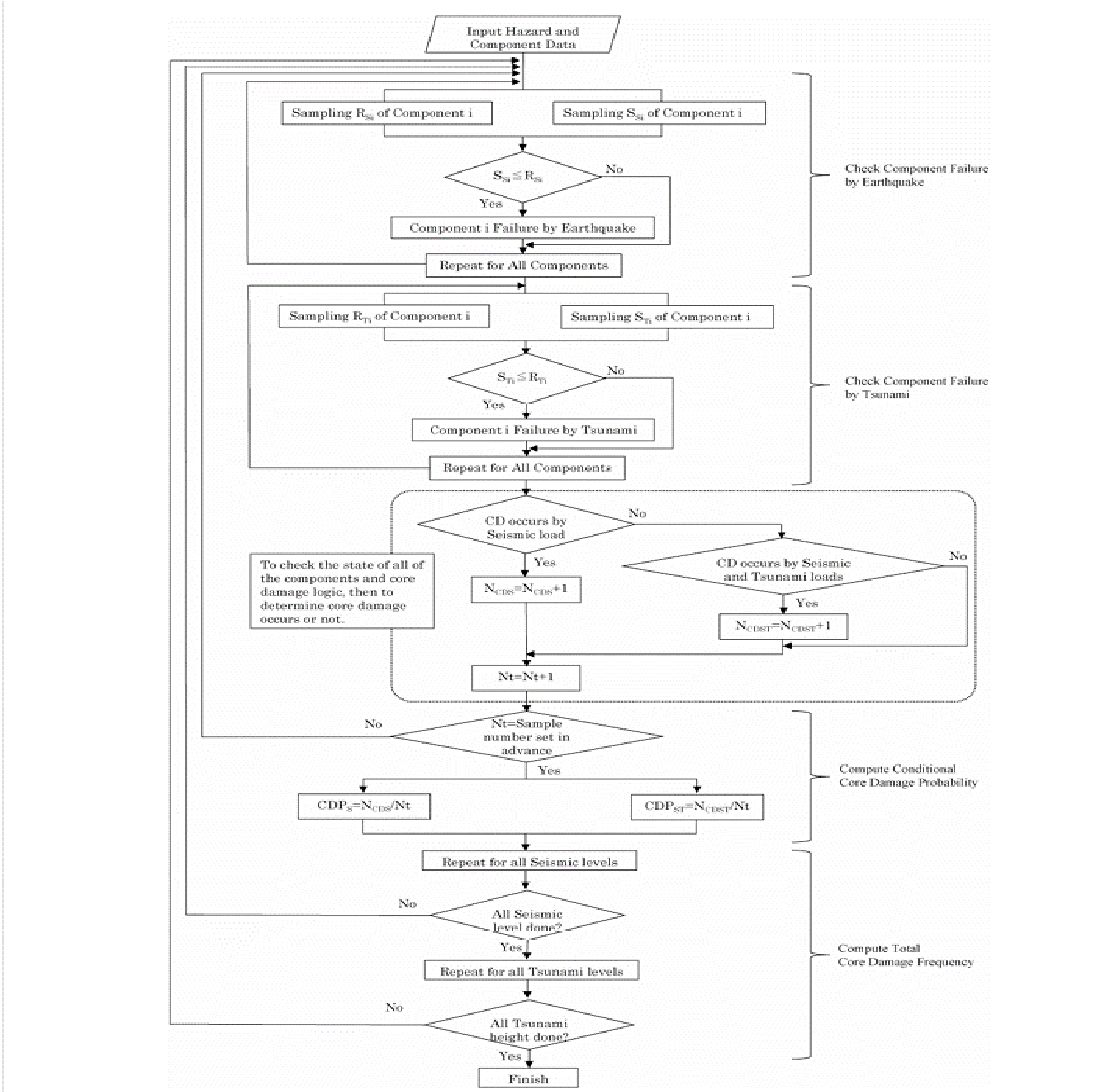

Figure 4. Flowchart for Quantitative Risk Assessment[3]

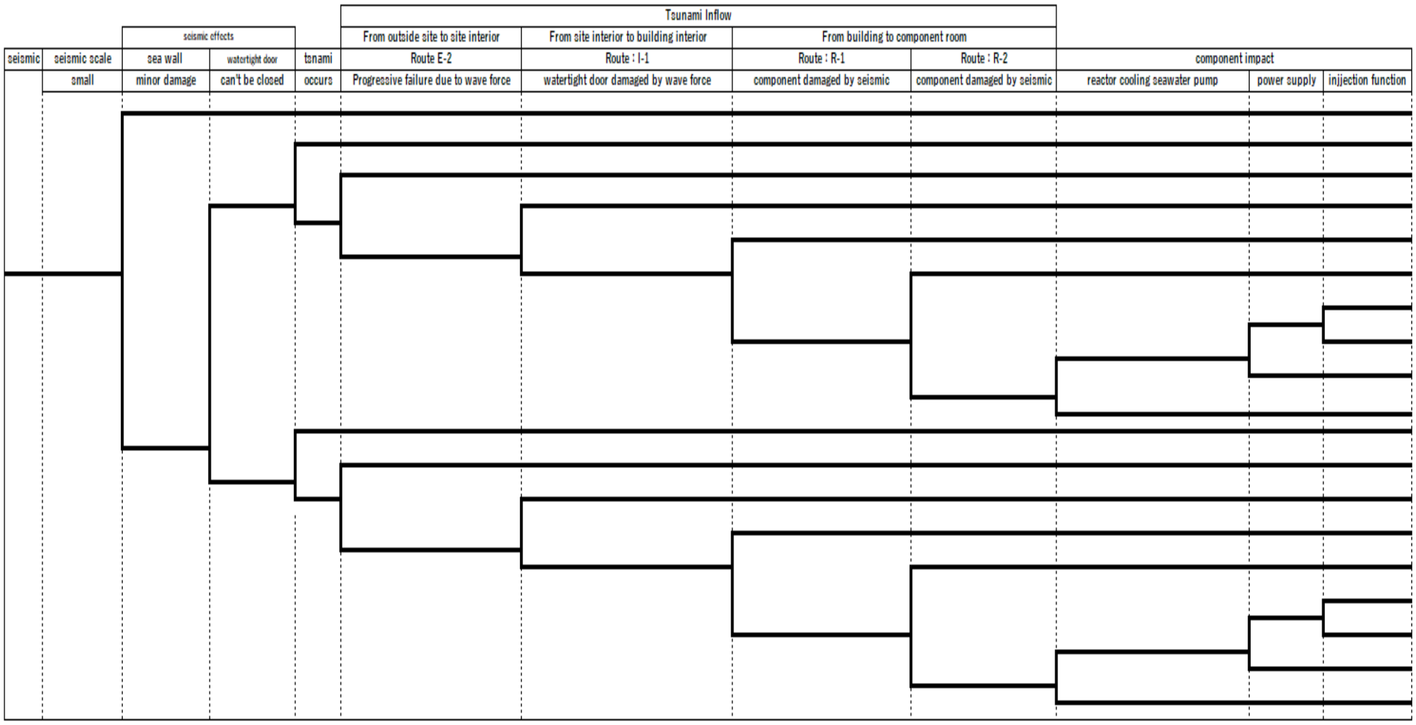

Fig5. Event Tree (ET) for a Small-Scale Seismic Scenario

The event tree (ET) shown in Figure 5 is constructed under the assumption of a small-scale seismic event and targets tsunami protection facilities, specifically seawalls and watertight doors. This ET includes four end states: (1) no initiating event occurs, (2) loss of power supply, (3) loss of injection function, and (4) loss of heat removal function. If any of the three initiating events occur, the ET branches into individual event trees corresponding to each initiating event, where accident progression scenarios are further developed.

V. Summary

V-1. Current Achievements

In this study, 12 core damage scenarios were constructed by combining initiating events such as seismic-induced loss of offsite power and various levels of LOCA with tsunami-induced functional failures (e.g., submersion of bus bars, loss of injection and heat removal functions). Quantification was performed based on these scenarios, enabling the evaluation of core damage probabilities under different levels of seismic intensity and tsunami wave height, as shown in Figure 4. Additionally, a simplified pipe model was analyzed to evaluate cumulative fatigue damage caused by combined seismic and tsunami loads. The calculated stress, assessed against the S–N curve in Figure 3, indicated a low likelihood of fatigue failure under the assumed conditions, though further studies with more realistic models are required. Furthermore, tsunami protection structures were classified by seismic damage states (Table 1), and inundation scenarios were modeled based on a stepwise inflow path from outside the site to equipment rooms (Table 2). Using this information, an event tree representing accident progression under a small-scale seismic scenario was developed, as illustrated in Figure 5.

V-2. Future Work

Moving forward, it is necessary to systematize a comprehensive set of accident progression scenarios based on various combinations of compound events. A key future challenge lies in applying these scenarios in a concrete and quantitative manner to enable practical risk assessments. Additionally, the development of an analytical program capable of simultaneously handling cumulative, integrated, and independent evaluation models is expected to enhance the flexibility and accuracy of risk analysis under complex event conditions.

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