Tsunami fragility assessment framework for probabilistic risk assessment of nuclear power plants

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In recent years, safety assessment of nuclear power plants against not only earthquakes but also other external natural events such as tsunamis has been required. However, the probabilistic risk assessment (PRA) methodology for tsunamis, especially tsunami fragility assessment, has not been sufficiently established to be practically applicable to nuclear power plants. This is because tsunamis have various effects on nuclear power plant safety, such as hydrodynamic load, debris impact, sediment deposition, and scour effect. Incorporating fragility assessment of all above-mentioned tsunami effects into the tsunami PRA in all nuclear power plants is unrealistic due to the cost problem and so on. Moreover, tsunami hazard level is different among NPPs. Thus, the tsunami effects evaluated in detail in the PRA of nuclear power plants should be appropriately selected according to the tsunami hazard level of nuclear power plants. To establish the tsunami PRA methodology, the present study proposes a tsunami fragility assessment framework in which tsunami fragility assessment method is selected according to the tsunami hazard level of nuclear power plants in reference to the fragility assessment in the seismic PRA.

I. Introduction

Following the Fukushima-Daiichi Nuclear Power Plant (NPP) accident on March 11, 2011, there have been successive efforts to improve the safety of NPPs. The probabilistic risk assessment (PRA) is an effective technology for risk informed decision making1) processes to improve the safety of NPPs.

The methodology for seismic PRA has been studied for more than 40 years and has been practically applied to a lot of NPPs; therefore, it is highly sophisticated. In recent years, there has been a pressing need for the safety assessment of NPPs against not only earthquakes but also other external natural events, such as tsunamis especially in Japan. However, the PRA methodology for tsunamis, especially the tsunami fragility assessment methodology, has not been sufficiently established to be practically applicable to NPPs. This is because tsunami has various effects on NPP safety2), 3), as shown in Fig. 1. Examples of tsunami effects include the following:

(a) Submersion of important components
(b) Tsunami wave pressure and buoyancy
(c) Tsunami debris collision
(d) Abrasion of pump bearing due to suspended sand
(e) Sedimentation at the intake
(f) Failure of water intake due to the lowering water level

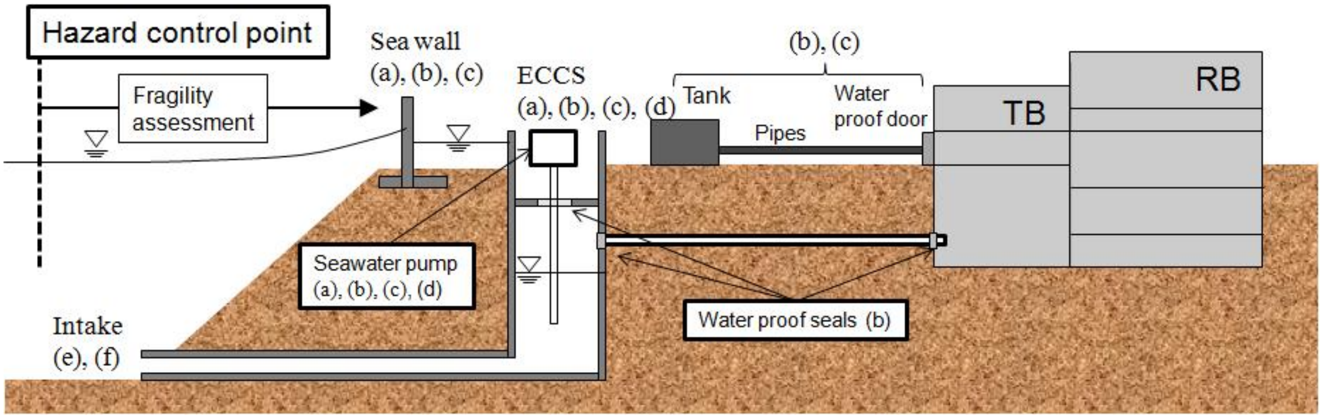

Fig. 1 Tsunami effects on NPP safety.

Above-mentioned tsunami effects (a) – (f) correspond to the numbers shown in **Fig. 1**. As shown in **Fig. 1**, there are two tsunami inundation paths on NPPs. In this chapter, effects of tsunamis on the NPP safety are outlined for each tsunami inundation paths: through water intake facilities, and over seawalls or ground level of the site.

First path includes tsunamis which inundate the site through the intake. It is possible that tsunamis through the intake cause sedimentation at the intake and malfunction of water intake due to the lowering water level would lead to the core damage. Tsunami fragility assessment of NPPs against a tsunami through the water intake facilities must be conducted at all NPPs because the tsunami inundation through the intake is a common issue at all NPPs.

In the second path, tsunamis over the ground level of the site or the top height of the seawall. The present study focuses on this type of tsunami. In this path, the most critical problem is the submersion of important components, *e.g.,* the emergency core cooling system (ECCS), due to the tsunami inundation. The tsunami hazard level significantly varies among NPPs. For example, in Japan, NPPs located in the pacific coast area generally have a high tsunami risk. In contrast, the tsunami hazard level of NPPs located in other regions is relatively lower. Following the Fukushima-Daiichi Nuclear Power Plant accident, to improve NPP safety, installation of water proof facilities such as water cut-off wall and water proof seals and doors, construction of a seawall and functional enhancement of these tsunami prevention facilities has been encouraged for NPPs, especially those located in the pacific coast area. Thus, the tsunami risk level of NPPs is thought to be reduced by the above-mentioned counter measures against tsunamis in Japan. Therefore, in tsunami PRA of NPPs, it is important to incorporate tsunami inundation effects such as tsunami wave pressure and tsunami debris collision into fragility assessment of these tsunami prevention facilities.

In the fragility assessment against this type of tsunamis, fragility assessment items correspond to the expansion of the tsunami inundation area which correlates with tsunami hazard level of NPP. Thus, the tsunami effect with high sensitivity to the core damage frequency (CDF) is also different in NPPs depending on the tsunami hazard level of the site. For example, in the case that occurrence probability of tsunami which over the ground level of the site or seawall is sufficiently low, above-mentioned tsunami inundation effects on tsunami prevention facilities installed in NPPs are not sensitive to the CDF. Otherwise, tsunami inundation effects should be considered in fragility assessment of tsunami prevention facilities on NPPs. In addition, incorporating tsunami inundation effects into tsunami fragility assessment in all of NPPs is not rational because fragility assessment against tsunami inundation effects requires much cost and a lot of burdensome works. Thus, tsunami fragility assessment methods should be selected according to tsunami hazard level for NPPs.

In this study, to establish the tsunami PRA methodology, a tsunami fragility assessment framework in which tsunami fragility assessment method is selected depending on the tsunami hazard level of NPPs is proposed.

II. Tsunami fragility assessment framework for PRA of NPPs

As mentioned in the previous chapter, fragility assessment against a tsunami that inundates through the intake must be conducted in all NPPs regardless of tsunami hazard level of NPPs. Thus, the effects of tsunami which enter the site through the water intake facilities on NPP safety are not focused in this paper.

The event tree in the tsunami fragility assessment considering various tsunami effects is shown in **Fig. 2**. The figure shows that the fragility assessment items associated with the expansion of the tsunami inundation area and increase in the tsunami inundation depth. As shown in **Fig. 2**, the assessment item with high sensitivity to the CDF varies depending on the tsunami hazard level of NPPs.

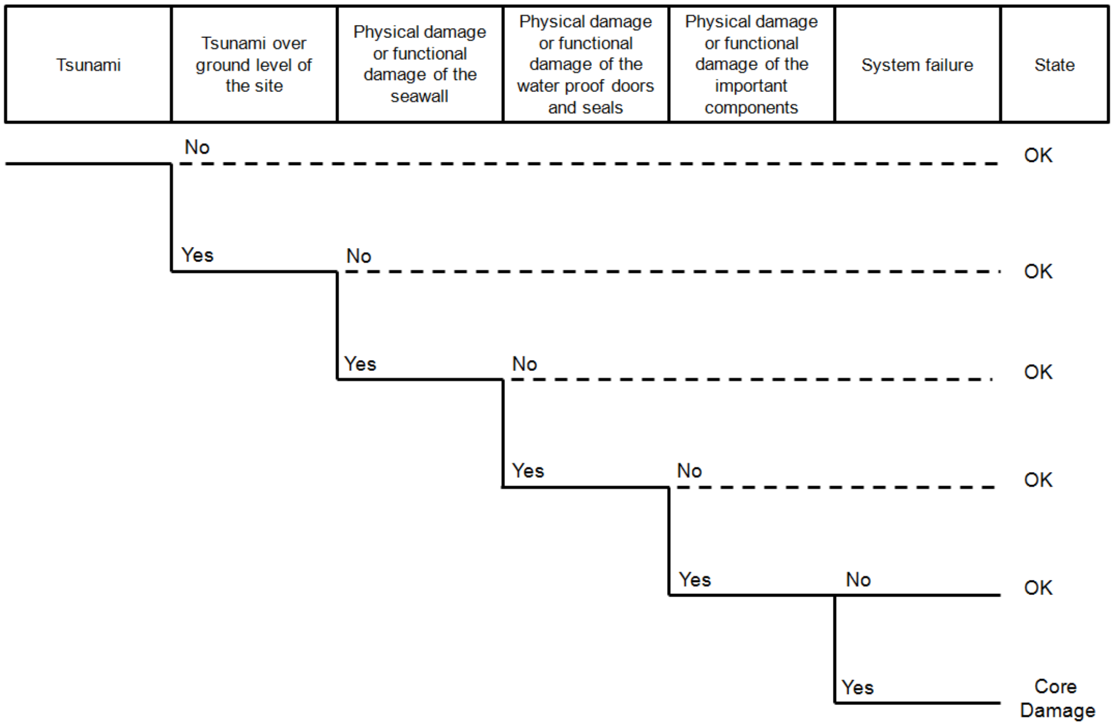

Fig. 2 Event tree in the tsunami fragility assessment of NPPs considering tsunami inundation effects.

Figure 3 shows the flowchart of the tsunami fragility assessment framework proposed in this study. The framework consists of deterministic margin analysis and probabilistic assessment. In the proposed framework, a screening criteria is used to determine the grade of fragility assessment. In the case that the occurrence frequency of an event in each assessment stage is lower than the criteria or the deterministic margin analysis confirms that the capacity of the target of the fragility assessment is sufficient, further assessments are not needed. Note that the criteria should be set after careful consideration.

This chapter outlines the fragility assessment in each stage shown in the proposed framework for tsunami fragility assessment. Methods of the fragility assessment in each assessment stage are documented in the next chapter.

II.A. Tsunami fragility assessment at each tsunami hazard level

II.A.1. Stage 1 tsunami fragility assessment

Tsunami fragility assessment for a tsunami whose height does not beyond the ground level of the site is considered in this stage. In the stage 1, the occurrence frequency of such a situation (OF1) is lower than the criteria. In the event tree, it is assumed that core damage occurs if the tsunami height is larger than the ground level of the site. If OF1 is lower than the criteria, further assessments are not needed.

II.A.2. Stage 2 tsunami fragility assessment

When OF1 exceeds the criteria, fragility assessment of the seawall is needed. The stage 2 tsunami fragility assessment focuses on a tsunami whose height is larger than the ground level of the site but not larger than the top height of the seawall. In this stage, two sub-stages, sub-stage 2.1 and 2.2, are set. Deterministic margin analysis determines which sub-stage is appropriate.

Occurrence probability of tsunami which overflow the seawall is probabilistically evaluated in sub-stage 2.1. On the other hand, in sub-stage 2.2, occurrence probability of physical damage of the seawall due to the tsunami wave pressure and tsunami debris impact force are also evaluated. As mentioned above, the need for the fragility assessment of the seawall is determined according to the results of the deterministic margin analysis of the seawall for tsunami wave pressure and debris collision. If the deterministic margin analysis shows a sufficient capacity of the seawall against tsunami wave pressure and

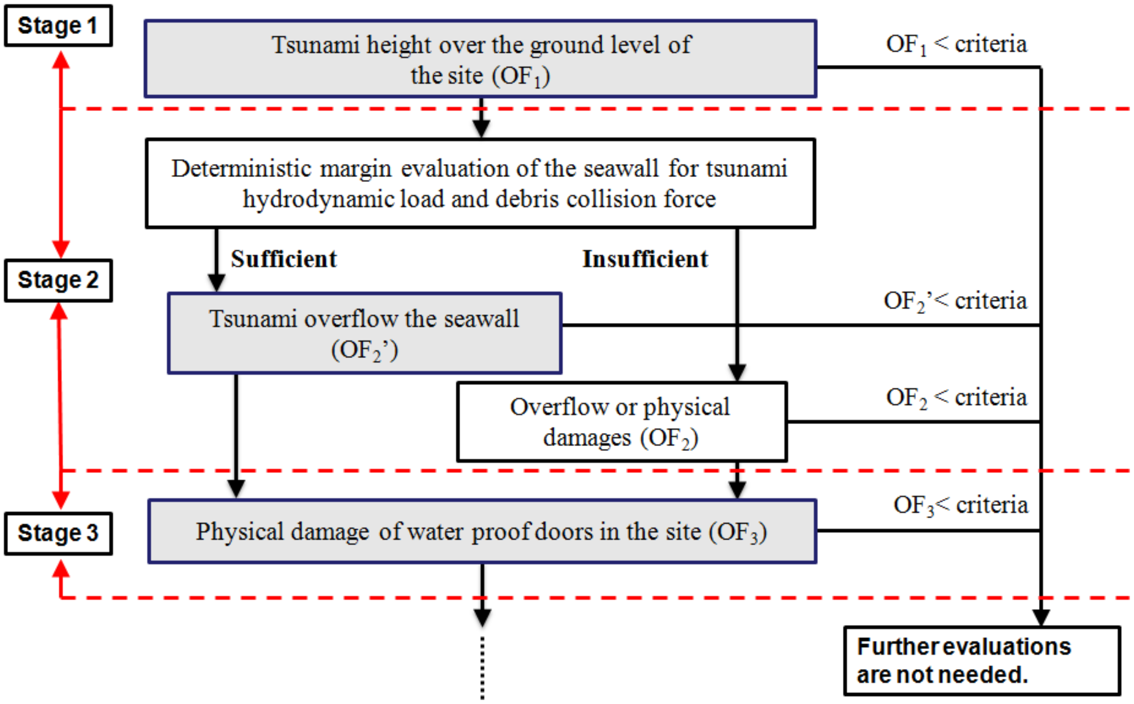

Fig. 3 Flowchart of tsunami fragility assessment framework proposed in this study.

debris collision, only the overflow probability is evaluated in sub-stage 2.1. On the other hand, if the capacity of the seawall against the tsunami loads is insufficient, the probability of both overflow and physical damage should be considered in sub-stage 2.2.

II.A.2.1. Sub-stage 2.1 tsunami fragility assessment

In the case that the deterministic margin analysis of the seawall for tsunami debris collision force and tsunami wave pressure caused by a tsunami whose height is comparable to the top height of the seawall shows a sufficient capacity of the seawall against the tsunami loads, only the overflow probability is evaluated. This sub-stage is appropriate for NPPs where occurrence frequency of a tsunami (OF2'), whose height in front of the seawall is larger than the top height of the seawall, is lower than the criteria. In the event tree, it is assumed that core damage occurs when the tsunami overflows the seawall. If OF2' is lower than the criteria, further assessments are not needed. Otherwise, fragility assessment in the next stage must be conducted.

II.A.2.2. Sub-stage 2.2 tsunami fragility assessment

In the case that the capacity of the seawall against the tsunami loads caused by a tsunami whose height is comparable to the seawall height is insufficient, the overflow probability and the physical damage probability of the seawall due to the tsunami debris collision and tsunami wave pressure should be evaluated. This sub-stage is appropriate for NPPs where occurrence frequency of a tsunami (OF2), that overflows the seawall or causes physical damage to the seawall, is lower than the criteria. In the event tree, it is determined that core damage occurs in this stage where overflow or physical damage of the seawall due to tsunami wave pressure and debris collision occurs. If OF2 is lower than the criteria, further assessments are not needed. Otherwise, fragility assessment in the next stage must be conducted.

II.A.3. Stage 3 tsunami fragility assessment

If OF2' exceeds the criteria, tsunami fragility assessment of the seawall and water proof facilities such as water proof doors, water proof seals and water proof walls is required. Stage 3 covers fragility assessment against tsunami which overflows the seawall and causes inundation of the site. In the event tree, it is determined that core damage occurs in the stage 3 where physical damage of the seawall or functional damage or physical damage of water proof facilities occurs. If

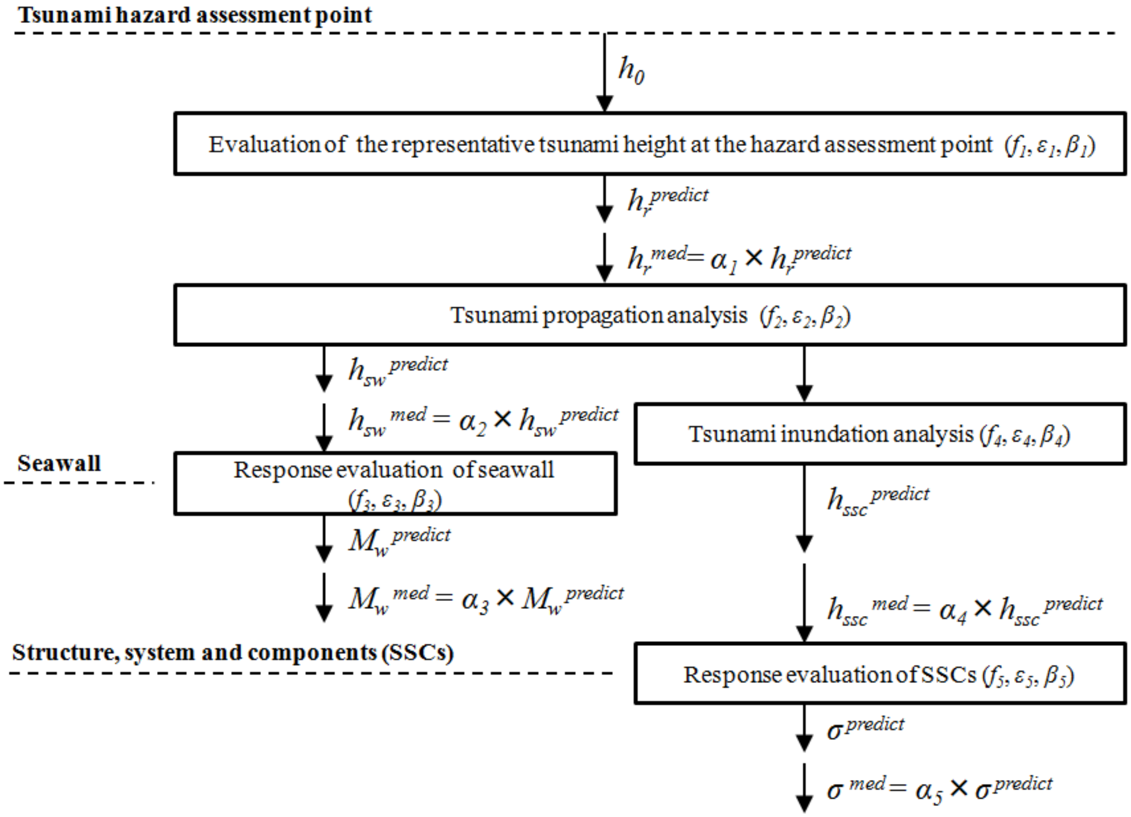

Fig. 4 An example schematic chart of the tsunami response evaluation.

physical damage or functional damage probability of the seawall and water proof facilities (OF3) is lower than the criteria, further assessments are not needed.

It should be noted that there are two kinds of physical damage of the seawall according to the degree of breakage of the seawall; (1) the seawall is completely destroyed, (2) the seawall is partially destroyed. Difference between both physical damage types should be considered in the tsunami fragility assessment because the degree of breakage of the seawall has considerable impact on the subsequent fragility assessment. Moreover, in the case that the seawall is partially destroyed, the degree of breakage is also significant in the subsequent fragility assessment. For simplicity, the case that the seawall is completely destroyed is considered in this study. And thus, in the present study, it is assumed that water proof facilities lose their functions due to the physical damage of the seawall.

II.B. Response evaluation in tsunami fragility assessment

In the seismic fragility assessment, realistic response is evaluated considering the uncertainty and conservativeness according to the response transfer step of seismic motion[4)-7)]. Two methods for response evaluation has been developed; the detailed method and the simplified method.

In the detailed method, seismic response analysis is carried out by using specification of structures, buildings and components. Although response analysis method can accurately evaluate realistic response, the method takes a high cost with requiring a burdensome calculation amount or a lot of time.

On the other hand, in the simplified method which assumes a linear response transfer, realistic response is evaluated by multiplying the coefficient (hereafter called response factor) with the design response value. Although accuracy of realistic response using the simplified method is lower than that of the detailed method, the simplified method requires low cost and small amounts of calculation. For this reason, the simplified method has often been adopted in seismic PRA.

In reference to Kennedy and Ravindra[5)], following four types of response factor are set in the simplified method in AESJ seismic PRA standard[4)].

(F1) Evaluation of the seismic motion on free rock surface

(F2) Evaluation of the input seismic motion for buildings and structures
(F3) Seismic response evaluation of buildings and structures
(F4) Seismic response evaluation of components and pipes

As following the above response evaluation steps, this study proposes six response evaluation steps (1) – (6) in the tsunami fragility assessment framework as follows.

(1) Evaluation of tsunami height at the hazard reference point
(2) Evaluation of input tsunami height for the site and seawall
(3) Tsunami response evaluation of the seawall
(4) Evaluation of input tsunami for buildings, structures, and pipes in the site
(5) Tsunami response evaluation of buildings, structures, and pipes in the site
(6) Tsunami response evaluation of components

In the tsunami fragility assessment, uncertainty in the response evaluation steps should be considered as in the fragility assessment in seismic PRA. However, it should be noted that the definition of the response factor ((1) – (6)) based on the simplified method is often inappropriate because tsunami effects are nonlinear as mentioned in the previous chapter. Therefore, in the tsunami fragility assessment for PRA of NPPs, it is considered to be appropriate to set the response transfer factor in each step ((1) – (6)) instead of the response factor. Here, the response transfer function f_i , uncertainty β_i, random variables with unit median ε_i, and correlation factor α_i are defined. The response transfer function f_i is estimated by numerical simulation or approximated based on the result of numerical analysis. Uncertainties in the estimation of f_i are represented by ε_i and β_i. The difference between the numerical result and realistic response is correlated by α_i. Thus, multiplication of f_i and α_i corresponds to the safety factor proposed in Kennedy *et al*[5]. For example, the tsunami response evaluation of the seawall represented by the bending moment on the base of the seawall M_w is evaluated as follows:

$$
\begin{aligned}
M_w = & \left\{ \frac{\text{The bending moment on the seawall base}}{\text{The tsunami height in front of the seawall}} \right\} \\
& \times \left\{ \frac{\text{The tsunami height in front of the seawall}}{\text{The representative tsunami height at the tsunami hazard assessment point at a givin hazard level}} \right\} \\
& \times \left\{ \frac{\text{The representative tsunami height at the tsunami hazard assessment point at a givin hazard level}}{\text{The tsunami height at the tsunami hazard assessment point}} \right\} \\
& \times \text{The tsunami height at the tsunami hazard assessment point} \\
= & f_3 \times f_2 \times f_1 \times \alpha_3 \times \alpha_2 \times \alpha_1 \times \varepsilon_3 \times \varepsilon_2 \times \varepsilon_1 \times h_0
\end{aligned}
\tag{1}
$$

where f_1 is the relationship between the tsunami height at the tsunami hazard assessment point h_0 and the estimated value of the representative tsunami height at the tsunami hazard assessment point at a given tsunami hazard level, f_2 is the relationship between the representative tsunami height at the tsunami hazard assessment point at a given tsunami hazard level and the estimated value of the tsunami height in front of the seawall, f_3 is the relationship between the tsunami height in front of the seawall and the estimated value of the bending moment on the seawall base, h_0 is the tsunami height in the tsunami hazard assessment point, and ε_1-ε_3 are the random variables with unit median. Here, ε_1 is the random variable which represent the uncertainty in the evaluation of the representative tsunami height at the tsunami hazard assessment point, ε_2 is the random variable which represent the uncertainty in the evaluation of the tsunami height in front of the seawall, ε_3 is the random variable which represent the uncertainty in the evaluation of the bending moment on the base of the seawall, and α_1-α_3 are bias between estimated response and realistic response in each evaluation. Following Kennedy *et al.*[6],[7], it is assumed that that random variables ε_1-ε_3 (with unit median) that represents uncertainties are log-normally distributed and their variation is expressed by their logarithmic standard deviation β_1-β_3 respectively. An example of schematic chart of the response evaluation in the proposed fragility assessment framework is shown in **Fig.4**. Where, h_r is the representative tsunami height at the tsunami hazard assessment point, h_{sw} is the tsunami height in front of the seawall, h_{ssc} is the tsunami height around the

SSCs and σ is response evaluation index of the buildings, structures and pipes on the site ground. Here, superscript "predict" and "med" in **Fig. 4** mean predicted value and median value respectively.

Moreover, to evaluate uncertainties in each response transfer step (1) – (6) in detail, sub-response transfer factors should be set to sub-divide the response transfer factor. References[2)-6), 8)-12)] would provide significant reference to set the sub-response transfer step. It is noted that above-mentioned f and α are must be obtained in both the simplified and the detailed fragility assessment method.

III. Tsunami fragility assessment in each assessment stage

In this chapter, tsunami fragility assessment methods in each assessment stage based on the above-mentioned response transfer steps are outlined. For the tsunami fragility assessment of an NPP, the damage probability at which the response exceeds the capacity is calculated. Using this damage probability, the fragility curves of the assessment target are constructed. Thus, both response and capacity evaluations are absolutely essential.

In this study, the response evaluation in each fragility assessment stage in the proposed tsunami fragility assessment framework is especially documented. Recently, researches on the fragility assessment against external flooding including tsunamis, have been conducted[8)-13)]. These studies would provide significant reference for the tsunami fragility assessment.

III.A. Stage 1

In the probabilistic tsunami hazard assessment[14)-17)], many tsunami propagation analyses are conducted that cover the area between the tsunami source and the front side of the NPP. The tsunami hazard curve is constructed using the tsunami height evaluated at the tsunami hazard assessment point. By using the results of the tsunami propagation analyses, the tsunami height in front of the site is probabilistically evaluated. In this stage, although uncertainties in the response transfer step (2b) should be considered, it has already been evaluated in the tsunami hazard assessment.

III.B. Stage 2

There are two evaluation methods for the tsunami height in front of the seawall. In the first method, the tsunami height in front of the seawall is evaluated using the results of a tsunami propagation analysis in the tsunami hazard assessment. Hazard disaggregation is widely used in the seismic hazard assessment[18), 19)] and provide relative contribution of components of hazard assessment model. The second method uses some representative tsunamis which are created by tsunami hazard disaggregation. In the second method, the representative tsunamis are constructed at each tsunami hazard level on the basis of the disaggregation of the hazard curve at the tsunami hazard assessment point. The tsunami height in front of the seawall is estimated by the tsunami propagation and inundation analysis using the representative tsunamis. In the second method, uncertainties in response transfer steps (1) and (2) should be considered.

As shown in **Fig.3**, in the proposed fragility assessment framework, the deterministic margin analysis of the seawall for tsunami wave pressure and debris impact force is conducted before the evaluation of OF2 and OF2'. When the deterministic margin analysis shows that the seawall has a sufficient capacity against the tsunami loads, only the overflow probability is evaluated.

III.B.1. Deterministic margin analysis of the seawall for tsunami wave pressure and debris impact force

Debris impact force is generally evaluated by the debris impact speed, stiffness and mass of debris, and the hydrodynamic mass coefficient[20), 21)]. In the evaluation of debris impact speed, effects of flow field around the debris on the tsunami debris behavior should be considered. However, in the case that the tsunami does not overflow the seawall, the velocity in the direction normal to the upstream side of the seawall is zero. Thus, the debris does not collide with the seawall unless the debris approaches the seawall with the tsunami front. Therefore, it is assumed that the debris does not collide with the seawall in the case that there are no wave-dissipating works, which is likely to move, and ships anchored in front of the seawall.

If ships are periodically anchored in front of the seawall, the impact force of ships acting on the seawall is estimated using the maximum flow velocity approaching the seawall as the debris impact speed in this deterministic evaluation. The flow velocity and depth of the tsunami in front of the seawall are given by the results of tsunami propagation and inundation analyses. Then, both the tsunami wave pressure given by the tsunami height corresponding to the top height of the seawall and the debris impact force which is multiplied by the dynamic response magnification, which is conservatively set to 2.0, are statically exerted on the seawall. Here, tsunami wave pressure acting on the seawall can be estimated using previous evaluation equations (*e.g.*, Asakura *et al.*[22)]).

When the median value of the realistic capacity of the seawall has a double ore more sufficient margin against above-mentioned tsunami loads, the probabilistic assessment of the wave pressure and debris impact force acting on the seawall is not needed. Then, only the tsunami overflow probability should be evaluated in the sub-stage 2.1.

In this study, tentative dynamic response magnification is used in this stage and stage 3. The setting method of the dynamic response magnification should be discussed.

III.B.2. Fragility assessment of seawall against tsunami wave pressure and debris impact force in sub-stage 2.2

In the case that the median value of the realistic capacity of the seawall is insufficient against the convolution of the tsunami effects, fragility assessment of the seawall against the tsunami effects is conducted.

The tsunami wave pressure given by the tsunami height in front of the seawall is probabilistically evaluated using the results of the tsunami propagation and inundation analyses. In the evaluation of tsunami wave pressure, uncertainties in the response transfer step (3) should be considered.

Evaluation of the damage probability of the tsunami prevention facilities such as seawall due to debris impact is more complicated than that due to the tsunami wave pressure because probabilities of debris occurrence, approaching and collision and their uncertainties should be considered. Moreover, the complex flow field around the facilities affects the debris behavior. For example, previous studies show that debris collision avoidance and reduction in the collision probability are caused by the reflected wave from the front of the structure. In the case that the effect of tsunami wave pressure is dominant in the fragility assessment of the seawall compared with that of the debris impact force, detailed evaluation of the debris impact force is not necessarily essential in the fragility assessment.

Thus, the present study proposed the following gradual evaluation of the tsunami debris impact force exerted on the seawall on the basis of the deterministic evaluation results. For example, if the response of the seawall due to the debris impact R_d is less than 1% of that due to the tsunami wave pressure R_p, effects of debris impact force can be neglected. Here, R_d and R_p are obtained by the deterministic margin analysis of the seawall. On the other hand, if the response of the seawall due to the debris impact force is not negligible, the response should be appropriately considered. If R_d is more than 1% and less than 30% of R_p, the deterministic debris impact force multiplied by a realistic dynamic response magnification (1.5) is added statically to the tsunami wave pressure. Furthermore, detailed evaluation of the damage probability of the seawall due to the debris impact force, considering the probability of debris occurrence, approaching, collision and their uncertainties, should be conducted in the case that R_d is more than 30% of the R_p. Although the realistic dynamic response magnification and the values which separate the grade of fragility analysis against debris collision are set as above, it should be noted that these values are for example only. Thus, engineering judgement would be needed to conduct the appropriate fragility analysis against debris collision.

III.C Stage 3

In this stage, the fragility assessment of the water proof facilities, such as water cut-off wall and water proof doors and seals, against the effects of a tsunami that overflows the seawall and inundates the site is considered. The evaluation process follows the gradual fragility assessment of the seawall against debris impact force in stage 2 (*c.f. II.B*).

First, maximum tsunami wave pressure acting on the water proof facility is deterministically evaluated. The wave pressure is given by the tsunami height corresponding to the maximum inundation depth around the evaluation target. Flow field around the target structures is evaluated by tsunami inundation analyses. In the deterministic margin analysis of the water proof facilities, it is conservatively assumed that the tsunami debris, which are possible to collide with the facilities, collide with the facilities at the maximum flow velocity around the facilities. Then, both the wave pressure given by both the tsunami height corresponding to the maximum inundation depth around the target and the debris impact force which is multiplied by the dynamic response magnification (2.0) are statically exerted on the seawall. When the median value of the realistic capacity of the water proof facilities has a sufficient margin against the convolution of the debris impact force and tsunami wave pressure, further fragility assessment of the water proof facilities described below are not needed.

If the median value of the realistic capacity of the water proof facilities is insufficient against the tsunami effects, a fragility assessment of the water proof facilities against the tsunami loads should be conducted. Here, uncertainties in response transfer steps (4) and (5) should be considered. The methodology of fragility assessment in this stage follows the method of the gradual fragility assessment of the seawall (see *II.B.2*).

IV. Summary

To establish the tsunami PRA methodology, the present study proposed a tsunami fragility assessment framework in which tsunami fragility assessment method is selected according to the tsunami hazard level of NPPs in reference to the tsunami fragility assessment framework in the fragility assessment in the seismic PRA (*e.g.*, Kennedy *et al* 5)-7)). Moreover, the present study outlined methods of tsunami fragility assessment at each tsunami hazard level. In the future work, further investigation and discussion on the proposed framework are needed for the purpose of more practical tsunami fragility assessment.

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