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FRAGILITY EVALUATION METHOD FOR TSUNAMI-BORNE DEBRIS IMPACT BY SIMULATION-BASED APPROACH FOR GROUP-SPECIFIC TSUNAMI SCENARIO

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ABSTRACT

A tsunami probabilistic risk assessment (PRA) often requires an evaluation of the impact of debris. We propose a simulation-based method for tsunami fragility evaluation, in which debris trajectories are simulated for all possible tsunami scenarios. However, this method incurs high computational costs; thus, it is desirable to develop an approach with lower computational costs. In this study, a less computationally intensive debris-tracking-simulation-based fragility evaluation method is proposed. The proposed method was applied to evaluate a non-existent virtual site to validate it. By using the proposed simplified approach, the computational load for the tsunami inundation and debris tracking simulation of a virtual site was 1/3 of that of the previously proposed method. Through the application of the proposed method to a virtual site, problems that need to be solved for the practical use of the method are also identified.

INTRODUCTION

The Fukushima Daiichi Nuclear Power Plant (NPP) accident (1F accident) has raised the need for probabilistic risk assessment (PRA) methods for NPPs. PRA is an effective technology for risk-informed decision-making processes to improve the safety of NPPs [1] [2]. The PRA methodology for external flood events, such as tsunamis, accelerated after the 1F accident. The ASME/ANS PRA standard [3] specifies the technical requirements for performing three key evaluations that comprise the tsunami PRA: (1) tsunami hazard evaluation, (2) fragility evaluation, and (3) accident sequence evaluation. For the tsunami fragility evaluation of the structure, systems, and components (SSCs), the damage probability at which the response exceeded the capacity is calculated. Subsequently, using this damage probability, the fragility curves of the SSCs are obtained as a function of the severity of the tsunami. In the tsunami fragility evaluation, it is necessary to consider the various kind of tsunami effects on the safety of NPPs as following [6]: (a) submersion of important components, (b) tsunami wave pressure and buoyancy, (c) tsunami debris impact, (d) abrasion of pump bearing due to suspended sand, (e) sedimentation at the intake, and (f) failure of water intake due to the lowering of the water level.

There is substantial literature related to the development of fragility functions for general scenarios, such as earthquakes. However, the literature on tsunami fragility evaluation is comparatively limited and mostly focused on tsunami effects (a) and (b) [7][8][9][10][11]. Therefore, the development of evaluation methods for tsunami effects (c)–(f) is desired. This study focuses on a method for evaluating fragility against tsunami-borne debris impact.

While the fragility evaluation of tsunami effects has been mentioned in various guides, which include considering the effects of debris impact, the evaluation method has not been presented in detail [3][4]. Therefore, several studies have stated that establishing a fragility evaluation method for tsunami-borne debris impact is an issue that needs to be solved in the future [9][10]. The method of evaluating debris impact probability and incorporating the probability into the accident sequence analysis are key issues [10].

For fragility evaluation against tsunami-borne debris impact, the damage probability of the SSCs can be calculated as follows [12]:

$$P_D = P_{dci} P_C \tag{1}$$

where P_C is the debris impact probability, P_{dci} is the conditional damage probability of the SSCs when the tsunami-borne debris collides with the SSCs, and P_D is the damage probability of the SSCs. In the evaluation of P_{dci}, evaluation indexes such as impact speed, deformation, and strain generated in SSCs are typically used.

At NPP sites, tsunami inundation flows are expected to be disturbed by SSCs, becoming site-specific flows. This has a significant impact on the evaluation of P_C and the debris impact speed. Therefore, a numerical model that solves equations of motion for floating debris can be an effective tool in the evaluation of P_C and P_{dci}[13].

In probabilistic assessment, epistemic and aleatory uncertainties are considered separately. According to previous experimental studies, randomness due to turbulent diffusion is observed in the motion of floating debris, and there is aleatory uncertainty. In addition, in the numerical simulation of tsunami debris motion tracking, it is necessary to set the form, mass, and various parameters of the debris; however, owing to insufficient data, these settings are nonspecific and wide-ranging (epistemic uncertainty). Probabilistic values, such as the impact probability, which express the effects of aleatory uncertainties are obtained. The range of predicted probabilistic values, such as P_{dci}, has a width owing to epistemic uncertainty, and the true value is considered to be included in the range. Thus, aleatory and epistemic uncertainties must be considered in evaluations of debris impact; probabilistic assessments are appropriate for these evaluations.

Technologies for the numerical simulation of debris motion tracking (hereafter debris tracking simulation) have been developed at length and have been enhanced in recent years [13]. In the evaluation of P_{dci}, the tsunami-borne debris impact force was calculated as a function of the debris impact speed obtained from the debris tracking simulation. While numerous studies have proposed technologies for the deterministic evaluation process for tsunami-borne debris impacts [14][15], few studies on the use of these technologies for fragility evaluation exist. Kaida and Kihara [12] proposed a numerical simulation-based fragility evaluation method for debris impact that reflects strong localized tsunami flow effects. However, in their proposed method, it was necessary to perform a debris-tracking simulation for a large number of tsunami scenarios. Thus, a more practical evaluation method requires considerable reductions in computational resources and burdensome tasks.

In this study, we propose a less computationally intensive debris-tracking-simulation-based fragility evaluation method. Specifically, the number of calculation cases is reduced by limiting the target cases of the debris tracking simulation to representative scenarios among many tsunami scenarios.

REVIEW OF THE NUMERICAL SIMULATION OF DEBRIS MOTION TRACKING

Various debris-tracking simulation methods have been proposed in previous studies. This chapter provides a brief review of these techniques and their characteristics.

In the numerical model of debris motion tracking, debris trajectories are calculated taking into consideration the hydrodynamic force, impact force between debris and SSCs, and friction force on the bed. The most popular numerical simulation model is a combined system comprising a two-dimensional velocity-averaged shallow water model and debris tracking model. Kaida and Kihara[12] conducted a debris tracking simulation using a distinct element model customized to simulate the motion of floating debris (rigid-body model). This model is capable of calculating the motion of floating debris in a four-degree-of-freedom system of horizontal and vertical translational motion, and rotational motion about the vertical axis. Furthermore, a method wherein floating debris is modelled as quality points also exists (quality point model) [13]. This method is less computationally demanding than the rigid-body model; however, it cannot model the rotation of the drifting object. Finally, there is also a method of modelling debris as particles with no mass (particle model).

In the tsunami inundation analysis based on the two-dimensional shallow water equation model, which is used to calculate the external force acting on debris, the depth-integrated flow velocity is used. Therefore, the flow velocity of the component that is directly perpendicular to the structure in the reflected wave formed in front of the structure decreases. However, the velocity and direction of the flow in the reflected wave change in the vertical direction. Near the floor, the flows toward the structure; conversely, the opposite happens near the water surface [16]. These phenomena have a significant effect on the evaluation of debris impact speed and probability. Because inertia is not considered in the particle model, when tsunami-borne debris enters the reflected wave in front of the SSCs, the velocity of the particle is immediately affected by the flow velocity in the reflected wave. This results in a velocity of zero or a velocity directed away from the SSCs, and the debris modeled as the particle will not approach the SSCs any further. Therefore, the particle model is uncapable of quantitatively evaluating the debris impact speed and probability. Kihara and Kaida [17] added a feature to the debris tracking model that can consider the effect of the vertical distribution of flow velocity in the reflected wave (the turbulent bore model). By implementing this function, the histograms of debris impact probability and debris impact speed, which are the results of past hydraulic experiments, can be reproduced well [17].

Using the rigid-body or quality point models to analyze the motion of tsunami-borne debris is desirable as the evaluation of the impact speed and impact probability is crucial for fragility evaluation against tsunami-borne debris impact, albeit the computational costs are higher compared to using the particle model. In addition, it is important to reflect the latest knowledge in the model and to calculate the motion of floating debris as realistically as possible.

SIMPLIFIED FRAGILITY EVALUATION METHOD

Uncertainties

In fragility evaluation against debris impact, as in seismic fragility evaluation, both epistemic and aleatory uncertainties need to be considered separately. Table.1 shows the uncertainties to be considered in the simulation-based fragility evaluation of debris impact.

Kihara and Kaida [17] investigated the uncertainty in debris tracking simulations. They showed that it is desirable to consider the function of reflecting the vertical distribution of flow velocity in the reflected wave developed in front of the structure to the motion of tsunami-borne debris. In addition, the degree of diffusion due to various perturbations are artificially varied in order to account for the effects of diffusion. The above-mentioned reflected wave effects and the intensity of anthropogenic diffusion are considered as epistemic uncertainties. The time required for a target debris, such as a vehicle, to be submerged by the tsunami may be considered as an epistemic uncertainty. The mass and size of a vehicle are defined as product standards. Since there are several types of vehicles on the power plant site, these specifications are considered as epistemic uncertainties. On the other hand, the above specifications include random errors, even though they are specified in the standards. In addition, the mass of the luggage loaded on the vehicle is random. For these reasons, it is also necessary to consider the vehicle specifications as random variations. In addition, disturbances in the flow that affect the random motion of debris during inundation can be considered as aleatory uncertainties.

The selection of the debris-tracking model corresponds to an epistemic uncertainty. Finally, both epistemic and aleatory uncertainties exist in the process of converting the results of the debris tracking

Table 1 Uncertainties to be considered in the fragility evaluation against debris impact

Response /Capacity	Evaluation	Epistemic uncertainty	Aleatory uncertainty
Response	Trajectory of tsunami-borne debris (obtained by using the debris tracking simulation)	✓ Specifications of debris (combination uncertainties of mass, length, width, height, form) ✓ Type of debris ✓ Drag coefficient ✓ Whether the turbulent bore model is incorporated into the numerical simulation ✓ Type of the numerical simulation method of the debris motion tracking ✓ Submersion time of debris ✓ Uncertainty of P_C and V_{max} in the representative scenario ($\beta u1$) ✓ Degree to which the representative wave represents the other scenarios in the group ($\beta u2$) ✓ Prediction accuracy of tsunami current	✓ Specifications of debris (randomness of mass, length, width, height, form) ✓ Perturbations in the flow field
	Evaluation indexes	✓ Response evaluation model (Modeling and analysis methods) ✓ Evaluation method of debris impact force (types of evaluation methods, parameters)	✓ Parameters to be set in the response evaluation ✓ Evaluation method of debris impact force (parameters)
Capacity	Evaluation indexes	✓ Capacity evaluation (Modeling and analysis methods) ✓ Lack of statistical experimental data	✓ Capacity evaluation model ✓ Limit values based on experimental data

simulation into damage metrics (impact loads and strains, shear stresses, bending moments, etc.) in the evaluation of realistic responses.

In the simple simulation-based fragility evaluation method proposed in this study, the number of computational cases was reduced by grouping tsunami scenarios with similar characteristics, as described later. Hence, epistemic uncertainty regarding grouping must be considered.

Evaluation procedure

Through the contribution analysis of the mean hazard curve obtained by the probabilistic tsunami hazard assessment (PTHA), tsunami scenarios used for fragility evaluation at each tsunami height can be determined based on their hazard contributions [18][19]. In general, numerous tsunami scenarios have nonzero hazard contributions.

In the method proposed by Kaida and Kihara [12], a debris-tracking simulation was performed for all tsunami scenarios subjected to fragility evaluation (Figure 1). Therefore, numerous cases that account for aleatory uncertainty for each combination of epistemic uncertainties must be considered. For instance, 50 combinations of epistemic uncertainties and 10 Monte Carlo trials that account for aleatory uncertainties will require 500 debris-tracking simulations for each tsunami scenario. Then, the total number of debris trajectories obtained as a result of the numerical simulation is equal to the number of cases (500) multiplied by the number of debris per case set in the NPP.

The results of the debris tracking simulation can be used to obtain the debris impact probability P_C and the histogram of the debris impact speed for each combination of epistemic uncertainties (Figure 1 (b), (c)). For debris that collide multiple times with the SSC subjected to fragility evaluation, only their maximum impact velocities V_{max} are considered in the histogram. The histogram can be converted into an evaluation index for realistic response evaluation. The conditional damage probability P_{dci} can be calculated using the histogram of the evaluation index of both the realistic response and capacity evaluation. The damage probability, P_D, can then be calculated using Equation (1) (Figure 1 (d)). The number of P_D obtained in each tsunami scenario corresponds to the total number of combinations of epistemic uncertainties, i.e., this width corresponds to the width of epistemic uncertainties related to the numerical simulation of the debris tracking simulation. The above procedure can be applied to several tsunami height bins to obtain fragility curves for debris impact.

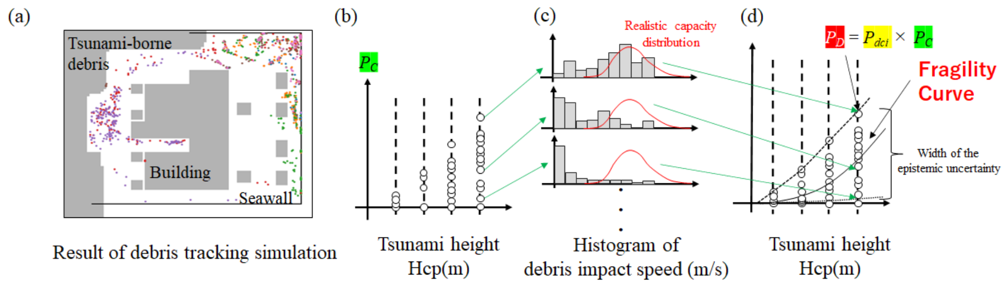

Figure 1. Fragility evaluation method against tsunami-borne debris impact proposed in the previous study.

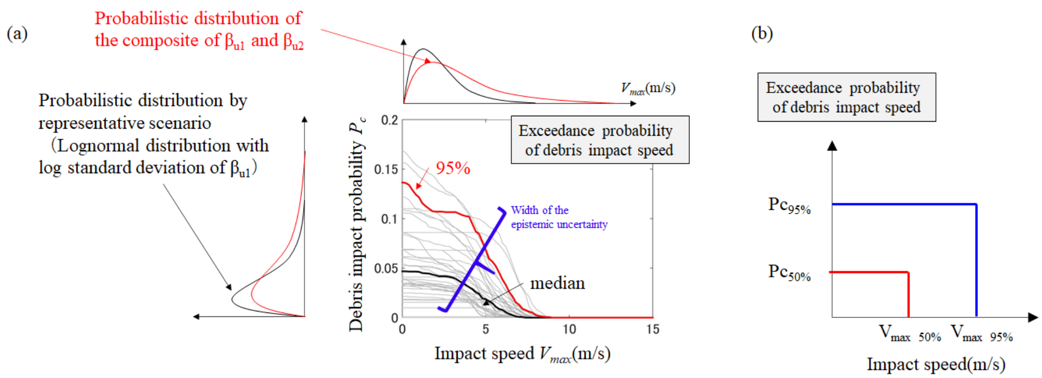

Figure 2. Evaluation method of exceedance probability of the impact speed in the simplified fragility evaluation method against debris impact proposed in this study. In Figure2 (a), the exceedance probability of V_{max} to a given SSC at a given tsunami height and group is created as the sum of the combinations of epistemic uncertainties (gray line). The median value is shown by the black line and the 95% value by the red line. In the results of this method obtained as shown in (b), the exceedance probability of the debris impact speed is modeled conservatively as a rectangle.

The number of cases for the debris tracking simulation of Kaida and Kihara [12] is proportional to the number of tsunami scenarios subjected to fragility evaluation. Tsunami scenarios considered for fragility evaluation are selected based on the results of the contribution analysis of tsunami scenarios conducted for each tsunami height. Since the number of tsunami scenarios is extremely large, only the tsunami scenarios that constitute a set threshold value are often selected for fragility evaluation. That is, the higher the threshold value, the more tsunami scenarios need to be included in the fragility assessment. In cases where the threshold is high, for example 99%, high computational resources are required to conduct inundation and debris tracking simulations. To reduce the computational resources and the amount of burdensome work related to pre- and post-processing required by the sequence of the numerical simulation, it is reasonable to reduce the number of tsunami scenarios to be subjected to debris tracking simulation.

The tsunami sources corresponding to the target tsunami scenarios were determined for tsunami fragility evaluation at each tsunami height using the results obtained via the deaggregation of tsunami hazard curves [18]. By considering similarities in the tsunami waveform and current direction, tsunami scenarios were grouped, and a representative scenario were determined. To reduce the computational load, we propose a fragility evaluation method for tsunami-borne debris impact using a simulation-based approach for representative group-specific tsunami scenarios. In this method, a representative wave representing multiple tsunami scenarios was determined for each group, and only the motion of tsunami-borne debris driven by the representative scenario was calculated. Because the realistic response of each group was evaluated based only on the results of the representative wave, epistemic uncertainty was considered as the degree to which the representative wave represents the other scenarios in the group.

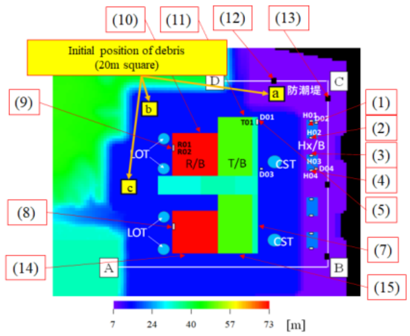

Figure 3. Plan view of the virtual site. Initial placement area of debris and the SSC to be evaluated are shown by yellow rectangular.

The conceptual flow of this method is illustrated in Figure.2. First, a debris tracking simulation was performed for the representative waves of each group at each tsunami height. The number of cases for the debris tracking simulation for each tsunami scenario (representative wave) was the same as that proposed by Kaida and Kihara [12]. Next, the exceedance probability of the debris impact speed was created using P_C and the histogram of V_{max} (Figure 2(a)). The total number of plots for the exceedance probability of the debris impact speed to be created was equal to the sum of the epistemic uncertainty combinations related to the debris tracking simulation. The value of the y-axis for each plot when the x-axis is zero corresponds to the P_C. The value on the x-axis of each plot when the y-axis is zero is the maximum value of the impact speed, V_{max}. The median and 95% values of P_C and V_{max} were used to determine the epistemic uncertainty of P_C and V_{max} in the representative scenarios (βu_1^{Pc} and βu_1^{Vmax}, respectively). The epistemic uncertainty related to the degree to which the representative wave represents other scenarios in the group must be set (βu_2^{Pc} and βu_2^{Vmax}, respectively). By combining β_{u1} and β_{u2} and assuming a lognormal distribution for the probabilistic distribution, we obtained the distribution of the debris impact speed and impact probability with the added grouping uncertainty (Figure 2(a)). This distribution was used to determine the 95% values of P_C and V_{max} and the exceedance probability of the debris impact speed. Although the realistic response was essentially a probabilistic distribution, a rectangular distribution was assumed to obtain conservative evaluation results (Figure 2(b)). Realistic response evaluation was possible by converting the impact speed obtained above into an evaluation index of realistic response and capacity. The application of this method is demonstrated in the next chapter.

APPLICATION

In this section, we apply the simplified simulation-based evaluation method to a realistic response evaluation against debris impact to a case study for a virtual site [18][19] and summarize future issues.

Virtual nuclear power plant

The virtual site was a non-existent NPP located on the Pacific coast of the Tohoku region of Japan. The virtual site had a high tsunami hazard level as it was directly affected by tsunamis generated by earthquakes along the Japan trench. A plan view of the virtual site is shown in Figure 3. The site had two ground levels of T.P.+7 m and T.P.+15 m with a seawall of height T.P.+27 m.

A PTHA for virtual sites was conducted in previous studies [18]. The contribution of each tsunami source to the mean hazard curve to determine tsunami scenarios for tsunami fragility evaluation at each tsunami height was analyzed [18]. For the grouping of tsunami scenarios for the virtual site, see Takahashi et al (2020)[19]. In this section, an example of a realistic response evaluation against debris impact conducted for one group (JTC2A[19]) is presented. There are three types of tsunami scenarios belonging to JTC2A (JTC2A-9, 10, and 15). JTC2A-10, which had the highest contribution, was selected as the representative tsunami scenario for JTC2A.

Table 2 Uncertainties considered in the debris tracking simulation for the virtual site.

Epistemic / Aleatory	Uncertainties considered in the evaluation	Parameters associated with the uncertainties
Epistemic	Drag coefficient of debris	0.75, 1.5, 3.0
	Strength of debris diffusion	Three kinds of manning coefficient are set : 0.02, 0.05, 0.09.
	Presence of the turbulent bore model.	ON / OFF
	Submersion time of the vehicle	1, 300, 1200(sec)
Aleatory	Turbulent diffusion	Random variable
	Initial position of debris inside the initial placement area	Random variable

Numerical simulation of the debris motion tracking considering uncertainties

Various types of debris should be considered in tsunami PRA in NPPs. However, for simplicity, a vehicle (height 2.0 m, 2.0 m, length 4.8 m, mass 2500 kg) is considered as a tsunami-borne debris in this study. The initial position of the debris was set with reference to the fragility evaluation method for tornado-borne missiles [20]. Three areas of 20 m^2 were set up on the virtual site (Figure 3) where vehicles may be parked, and 200 pieces were initially placed in random in each area. Therefore, 600 trajectories of debris were obtained in the debris-tracking simulation. As collisions between floating debris are not considered, their trajectories are independent of each other.

The tsunami flow field was calculated using a two-dimensional shallow water model with seven nesting stages. The flow field at the virtual site (Figure 3) was resolved in the innermost grid, with a horizontal resolution of 5 m. The same numerical code employed by Kihara and Kaida [17] was used to calculate the motion of tsunami-borne debris. As shown in Table 2, both epistemic and aleatory uncertainties regarding the debris-tracking simulation were considered, referring to Kihara and Kaida [18]. Under this condition, for one tsunami scenario belonging to a certain tsunami height, the total number of epistemic uncertainties: 54 cases (3 x 3 x 3 x 2), were set. For all 54 cases, 10 Monte Carlo simulations were performed to reflect aleatory uncertainty. Therefore, 324,000 (54 x 10 x 3 x 200) trajectories of drifting objects were calculated for each representative tsunami scenario. In this section, for simplicity, only the debris initially placed in area "a" (Figure 3) are considered in the response evaluation.

Results of numerical simulation of the debris motion tracking and realistic response evaluation

In some cases, the impact speed and the impact probability did not correspond to an increase in the tsunami height. The complex tsunami flow field in the NPPs significantly affects tsunami-borne debris trajectories. Previous studies have shown that the longer reflected waves that develop in front of the SSC result in lower debris impact speed and the probability of collision with the SSC. When the tsunami height is high, reflected waves are expected to develop more quickly, thus the impact speed of debris may be lower than that of the low tsunami height in some cases.

Figure 4 shows the impact speed distributions of tsunami-borne debris for all 15 SSCs shown in Figure 3 obtained from the debris tracking simulation for all tsunami scenarios belonging to JTC2A and JTC2B for H_{cp} = 39 m. From Figure 4, the characteristics of the impact speed distributions obtained by the tsunami scenarios belonging to each group were similar to each other within the group. Therefore, based on previous studies, grouping appears to be appropriate for evaluating the impact of tsunami debris.

Figure 5 shows the exceedance probability of debris impact speed for SSC1 and SSC15 (Figure 3). In Figure 5, plots for each epistemic uncertainty combination are created for each tsunami scenario. The results of all tsunami scenarios belonging to a group were drawn, and representative waves were distinguished. As mentioned earlier, the origin of the drifting debris in the realistic response evaluation is limited to one initial placement area. For each combination of epistemic uncertainties, 10 Monte Carlo calculations are performed. Thus, the plot in Figure-5 is calculated using 200 x 10 = 2,000 drift trajectories. Although some debris may collide with the SSC more than once, only the collision event with the maximum

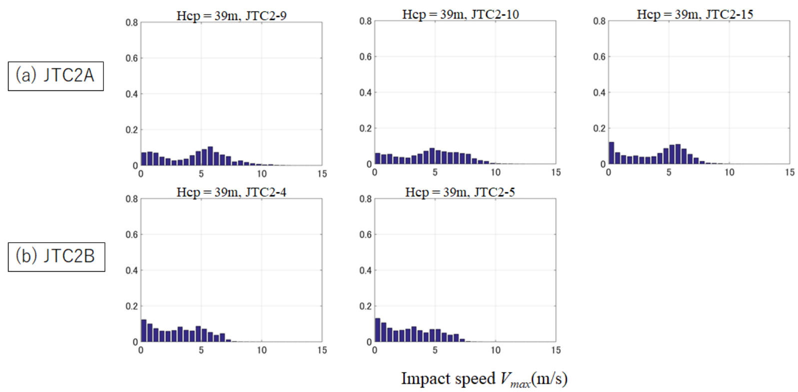

Figure 4. Histogram of the debris impact speed at H_{cp} = 39 m at the virtual site. The results from tsunamis belonging to each group are placed in each column.

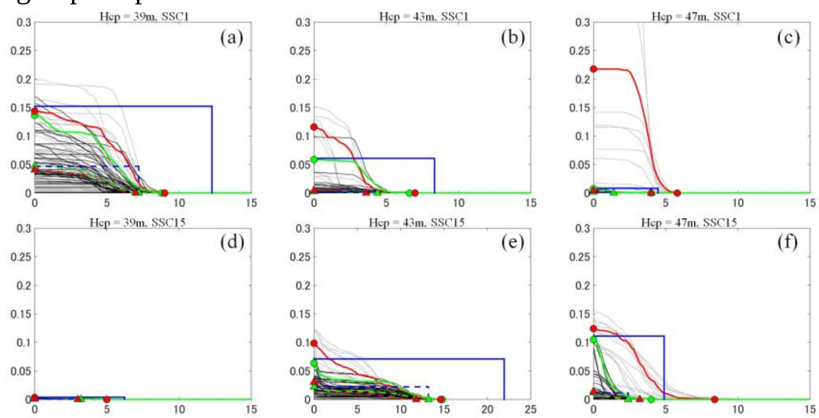

Figure 5. Exceedance probabilities of the impact speed by the tsunami belonging to JTC2A at the tsunami heights H_{cp} = 39 m(a)(d), 43 m(b)(e) and 47 m(c)(f) in front of the seawall at the virtual site. Black: representative scenario, gray: scenarios belonging to the group, red: 95% value (solid line) and median (dashed line) of all scenarios belonging to the group, green: 95% value (solid line) and median (dashed line) of representative scenario, blue: 95% value (solid line) and median (dashed line) of the exceeding probability of the impact speed obtained by the method proposed in this study.

collision velocity was considered in this study. In other words, the effect of multiple impacts was not considered.

From these figures, it can be inferred that there are cases where the group representative scenario can represent other tsunami scenarios belonging to the group (Figure 5((a), (e)), and cases where it does not (Figure 5(c)). This may be owing to minor differences in the results of inundation analysis between the representative scenario of the group and other tsunami scenarios. From the plots of representative waves, the 95% and median values for the impact speed and impact probability were obtained, and βu_1^{Pc} and βu_1^{Vmax} were calculated using these values as described in Table 3. However, it was difficult to define specific values for uncertainty of selecting representative tsunami scenarios (βu_2^{Pc} and βu_2^{Vmax}) because of the difficulty in quantifying the degree of representativeness of representative scenarios. Therefore, it was set here based on the engineering judgment. The value of uncertainty β_{u3}, which is a composite of β_{u1} and β_{u2}, can be calculated as shown in Table 3.

For each SSC and group, the exceedance probability of the debris impact speed obtained by adding the above uncertainties to the results of the debris tracking simulation of the group representative tsunami scenario is also shown in Figure 5. If the rectangular distribution can embrace the exceedance probability plots of the debris impact speed owing to tsunami scenarios other than the group representative scenario, the application of the proposed method can produce conservative results. As shown in Figure 5 (a), (e), and

Table 3. The results of the epistemic uncertainty calculations and the 95% values obtained by the proposed method.

H_{cp} (m)	SSC	P_c					V_{max}				
		Representative scenario			β_u3	95% value obtained by the method proposed in this study	Representative scenario			β_u3	95% value obtained by the method proposed in this study (m/s)
		95%	median	β_u1			95% (m/s)	median (m/s)	β_u1		
39	SSC-1	0.137	0.047	0.649	0.715	0.152	8.8	7.2	0.122	0.324	12.283
	SSC-15	0.004	0.001	1.179	1.217	0.004	5	3.2	0.270	0.404	6.232
43	SSC-1	0.059	0.002	1.975	1.997	0.061	6.6	4.4	0.246	0.388	8.343
	SSC-15	0.064	0.022	0.642	0.709	0.071	14.8	13.2	0.069	0.308	21.939
47	SSC-1	0.008	0.002	0.975	1.021	0.008	4	1.4	0.636	0.703	4.469
	SSC-15	0.105	0.012	1.340	1.374	0.111	4	2.4	0.310	0.431	4.888

(f), most of the tsunami scenarios belonging to a group can be embraced using only the computational results for the representative scenarios with uncertainties listed in Table 3. In contrast, in Figure 5 (c), the proposed method shows nonconservative evaluation results. This is because the representative scenario was not sufficiently representative of the tsunami scenarios belonging to the group in this case.

Using the proposed simplified method, the computational amount of the tsunami inundation simulation and debris tracking simulation was reduced to 1/3. This makes it possible to perform a fragility evaluation of tsunami-borne debris impacts more efficiently. However, when the representativeness of the representative wave was low, the evaluation results were nonconservative. Identification of cases where the selected representative wave was not sufficiently representative and investigation of evaluation methods for such cases are potential avenues for future research.

CONCLUSIONS

A less computationally intensive debris-tracking-simulation-based fragility evaluation method was proposed and applied to a virtual site. In the proposed method, compared with conventional methods, the number of cases for numerical analysis can be reduced. Therefore, the method can be utilized as a reasonable method for evaluating the fragility of tsunami-borne debris impacts.

The proposed method intended to reduce computational resources and burdensome tasks compared with detailed evaluation methods. The computational results should show conservative results compared to the detailed evaluation method. However, it did not satisfy this requirement under some conditions. For the practical application of the proposed method for tsunami PRA, the certainty of the method should be improved which is one of the issues to be solved in the future.

The evaluation method used for tsunami PRA should be selected according to the risk level assumed for each NPPs. Based on the concept of the graded approach [21], a simple and conservative evaluation method that does not require drift tracking simulation is needed for fragility evaluation for sites with low tsunami risk. In addition to the future issues already mentioned, it will be necessary to develop a simplified method in the future.

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