FRAGILITY EVALUATION METHOD OF EQUIPMENT IN BUILDING STRUCTURES FOR TSUNAMI INUNDATION

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Since the occurrence of the nuclear accident due to the giant tsunami caused by the Great East Japan Earthquake, the establishment of the tsunami probabilistic risk assessment methodology has become a pressing issue and Atomic Energy Society of Japan published ''Implementation Standard Concerning the Tsunami Probabilistic Risk Assessment of Nuclear Power Plants''. According to the standard, in the fragility evaluation method as to the tsunami, the general idea of four methods, where the Monte Carlo method is the most versatile one, was presented. However, for four methods, the concept of the fragility evaluation method was only explained, demanding the definite method for the practical application. Therefore, we have proposed the fragility evaluation method in the building structures for tsunami inundation (FEMT) in the viewpoint of the inundation causing the loss of function for equipment. The FEMT has been illustrated through the discussion of the estimated distribution using the virtual power plant. We consider that the proposed FEMT contributes to the establishment of the fragility evaluation method and the acquisition of the new knowledge about the nuclear power plant.

I. INTRODUCTION

Since the occurrence of the nuclear accident due to the giant tsunami caused by the Great East Japan Earthquake, the establishment of the tsunami probabilistic risk assessment (TPRA) methodology has become a pressing issue in order to handle the tsunami risk rightly, including the unexpected scale tsunami. In Japan, provoked by the above incident, Atomic Energy Society of Japan published ''Implementation Standard Concerning the Tsunami Probabilistic Risk Assessment of Nuclear Power Plants''[1] referring to the previous studies[2], leading to the consideration of the TPRA in the Kashiwazaki-Kariwa nuclear power plant (NPP)[3] and in the NPPs of Korea[4] and the consideration of the combination of seismic motion and tsunami effects[5]. In the TPRA, the standard stated the fragility evaluation on the analogy of the seismic PRA[6], presenting the general idea of four methods, namely first-order approximation second-moment method, two-point estimate method, Monte Carlo method, and experimental design method[1]. However, for four methods, the concept of the fragility evaluation method was only explained, demanding the definite method for the practical application. In the field of the fragility evaluation as to the tsunami, the fragility evaluation method of equipment in building structures for tsunami inundation (FEMT) is indispensable for judging the loss of function for equipment. Therefore, we focus on the FEMT using the Monte Carlo method, which is the most versatile one in the above four methods.

In this paper, we first propose the FEMT and apply the FEMT to the virtual power plant (VPP) set for its illustration. Then, we discuss the estimated distribution obtained from this application, illustrating the FEMT.

II. FRAGILITY EVALUATION METHOD OF EQUIPMENT IN THE BUILDING STRUCTURES FOR TSUNAMI INUNDATION

In this chapter, we introduce the proposed FEMT and explain the calculation used in the FEMT.

In the FEMT, the evaluation target is the probability of loss of function for equipment (PLFE) arising from the inundation and the fragility is obtained with the repeated calculation using the Monte Carlo method. The simulation takes much time, demanding the efficient way in the use of the Monte Carlo method. In the FEMT, therefore, although it is possible to apply the Monte Carlo method to the tsunami input condition and the fragility of the doors, we apply it to only the tsunami input condition as below.

Figure 1 shows the overview of the proposed FEMT. In the FEMT, a group of tsunami input conditions are set in the first step essentially and a multitude of input conditions should be made up on the basis of tsunami hazard analysis result. However, in this study, instead of the above input conditions, the distribution of the tsunami height, that of the tsunami period, and the tsunami shape are used as a source of the tsunami input conditions and are set in the first step. Here, a combination of the tsunami height, the tsunami period, and the tsunami shape is defined as a tsunami condition. Then, a tsunami condition is extracted from a number of tsunami conditions set in the first step, and a PLFE is calculated for the extracted tsunami condition. The calculation process of the PLFE for a tsunami condition is explained in the next paragraph. Similar extraction of a tsunami condition is repeated with using the Monte Carlo method according to the distribution set in the first step, and a PLFE is similarly calculated for each extracted tsunami condition. With displaying the obtained probabilities of loss of function for equipment in their respective values, the estimated distribution of the PLFE, which presents the relationship between the PLFE and its counts, appears. Note that the estimated distribution obtained here is from a kind of distribution set in the first step. Similar derivation of the estimated distribution is performed in the above way for other kinds of distribution which have a different mean value in the distribution of the tsunami height. From many kinds of the estimated distribution of the PLFE acquired above, the fragility curve of the PLFE, which is the fragility for the mean value in the distribution of the tsunami height, is obtained.

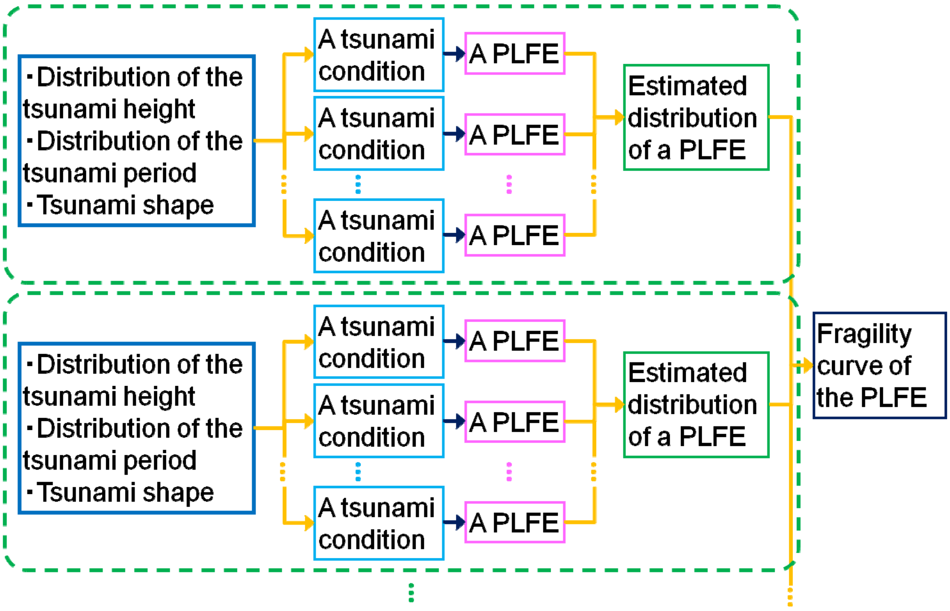


Fig. 1. Overview of the FEMT.

Next, we explain the calculation process of the PLFE for a tsunami condition as schematically shown in the upper part of Fig. 2. With substituting the tsunami height of an extracted tsunami condition in the fragility curve of an entrance door, the fragility of an entrance door is obtained. Here, it is assumed that the inundation between rooms occurs by the damage of doors as shown in the lower part of Fig. 2. Also, with substituting the tsunami height of an extracted tsunami condition in the opening characteristics of an entrance door, the opening ratio of an entrance door is obtained. Note that the opening characteristics present the relationship between the tsunami height (inundation depth) and the opening ratio of a door. From the opening ratio of an entrance door and the tsunami height, the inflow into the room 1 is calculated using the following evaluation formula for the inflow:

$$Q = 0.6Bh\sqrt{2gh} \quad (h<a), \qquad (1)$$

$$Q = 0.6Ba\sqrt{2gh} \quad (a<h), \qquad (2)$$

where Q, B, h, g, and a represent an inflow per unit time into the room, width of a door, inundation depth at a door, acceleration of gravity, and height of a door, respectively. Note that Eq. (1) and Eq. (2) are used depending on the relationship between a and h. An inflow per unit time is integrated over time based on the tsunami period in order to obtain an inflow. The inundation depth of the room 1 is obtained with dividing the inflow into the room 1 by the area of the room 1.

With using the inundation depth of the room 1, fragility curve of the door 1, and the opening characteristics of the door 1, the fragility and the opening ratio of the door 1 are calculated. The inflow into the room 2 is calculated in the similar way to obtain the inflow into the room 1, and the inundation depth of the room 2 is obtained by dividing the inflow into the room 2 by the area of the room 2. The similar calculation is repeated until the inundation depth of the room N is obtained. We assume the loss of function for equipment on condition that the inundation depth of the room N is larger than the setting height of the equipment and calculate a PLFE for a tsunami condition by the product of the fragility of doors on the inundation path.

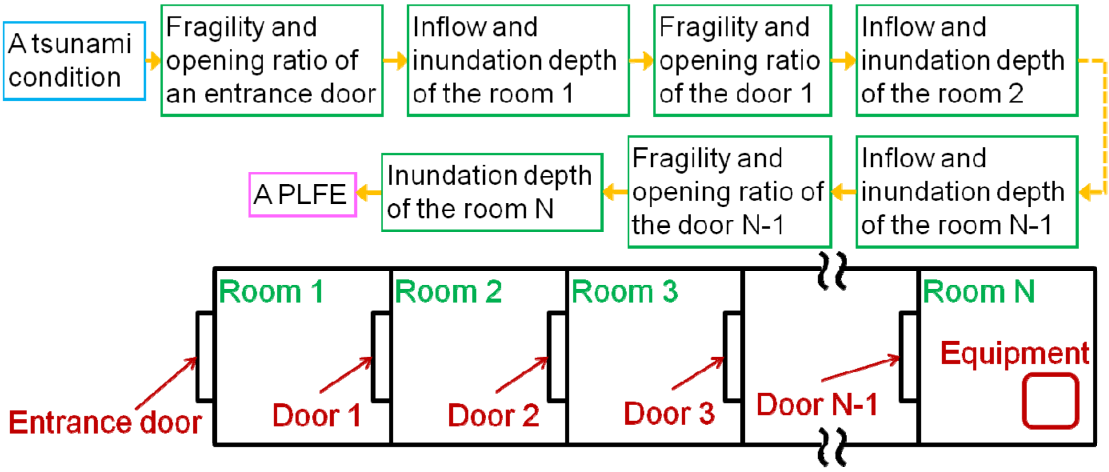


Fig. 2. Overview of the calculation process (upper) and the inundation path (lower).

As discussed in the next chapter, in the illustration of the proposed FEMT, the example of the loss of function for equipment is the loss of function for Reactor Core Isolation Cooling system (RCIC) pump, resulting from the inundation into the RCIC pump room.

III. EVALUATION CONDITION FOR THE ILLUSTRATION

In this chapter, we explain the overview of the VPP set for illustrating the proposed FEMT and the evaluation conditions for this illustration.

III.A. Virtual Power Plant

Figure 3 depicts the schematic diagram of the VPP, where the inundation is assumed. In the VPP, the door of the large object carrying-in entrance (DLOE), from which the tsunami invades into the VPP, is set in the first floor. Also, the RCIC pump room, where the target equipment for the fragility evaluation, namely the RCIC pump is put, is set in the second basement floor, indicating that in the evaluation using the VPP the inundation into the RCIC pump room is the key and the inundation path is from the first floor to the second basement floor. On the inundation path, a DLOE, doors for the stairs, and the door of the RCIC pump room are only taken into account as shown in Fig. 3. However, since the inundation area of the first floor is much larger than that of the second basement floor, it is assumed that the damage of the door for the stairs (DS) in the first floor always leads to that of the doors in the second basement floor, meaning that a DLOE and a DS in the first floor are only considered on the inundation path.

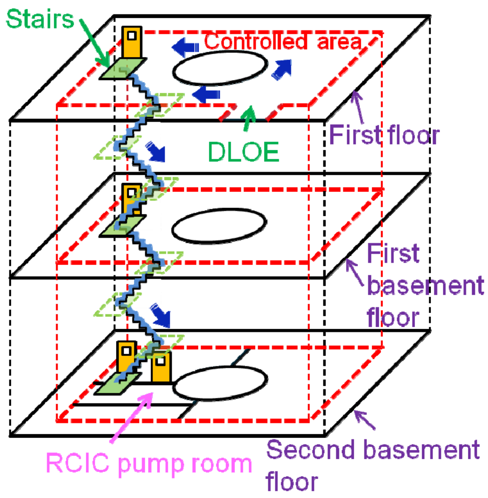


Fig. 3. Schematic diagram of the VPP.

III.B. Evaluation Method and Condition Using the Virtual Power Plant

Figure 4 shows the flowchart of the FEMT using the VPP and the evaluation condition in the FEMT is summarized in Tab. I and Tab. II. Note that this flowchart corresponds to the process which calculates the estimated distribution of the PLFE in Fig. 1.

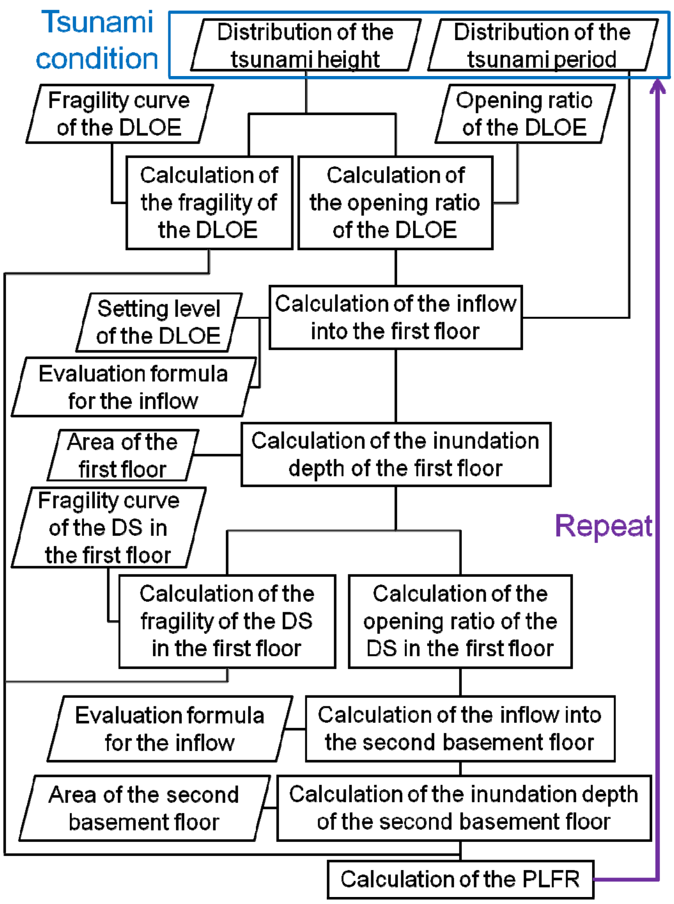


Fig. 4. Flowchart of the FEMT using the VPP.

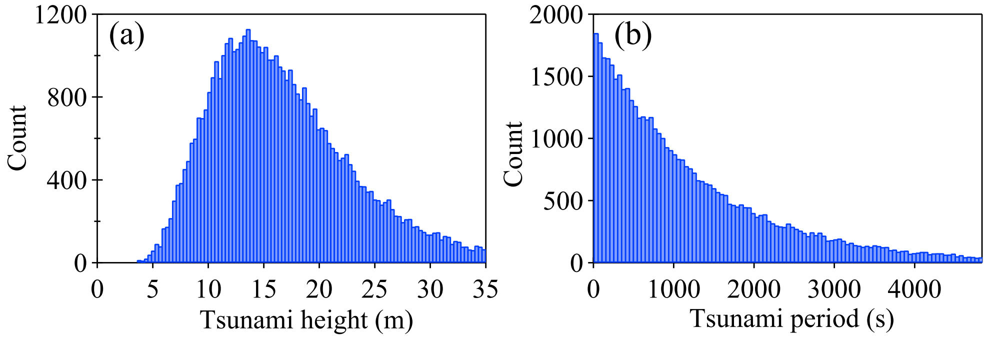
TABLE I. Area and upper limit value set in the first floor and the second basement floor.

	First floor			Second basement floor		
	Area (m^2)	Upper limit value		Area (m^2)	Upper limit value	
		Inflow (m^3)	Inundation depth (m)		Inflow (m^3)	Inundation depth (m)
Value	1000	10000	10	100	1000	10

TABLE II. Size of the DLOE and the DS in the first floor.

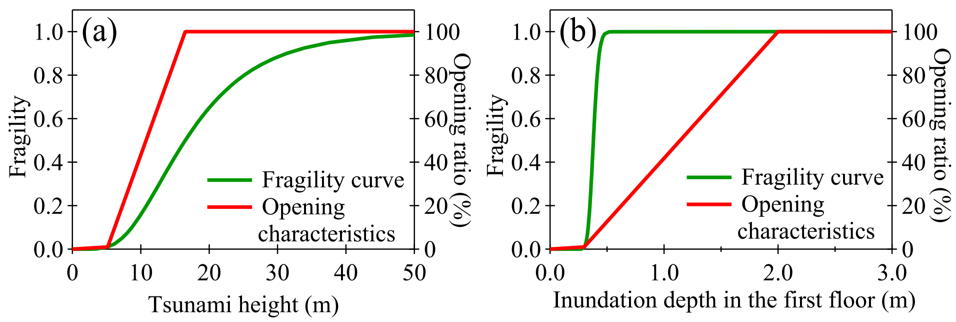
	DLOE			DS in the first floor		
	Height (m)	Width (m)	Area (m^2)	Height (m)	Width (m)	Area (m^2)
Value	6	5	30	2	1	2

In FEMT using the VPP, the distribution of the tsunami height and that of the tsunami period are set in the first step, as shown in Fig.4. Figure 5(a) and 5(b) present the distribution of the tsunami height and that of the tsunami period used in this FEMT, respectively. Here, the tsunami height is assumed to follow the logarithmic normal distribution, and the mean value of the distribution is set to 17 m. On the other hand, the tsunami period is assumed to follow the exponential distribution, and the median value of the distribution is set to 900 seconds. Also, the tsunami shape is set as the sine wave.



(a) Distribution of the tsunami height. (b) Distribution of the tsunami period.
Fig. 5. Distribution set in the first step for the tsunami height and the tsunami period.

The tsunami height is extracted from the distribution of the tsunami height set above, and the extracted tsunami height is substituted in the fragility curve and the opening characteristics of the DLOE (Fig. 6(a)), leading to obtaining the fragility and the opening ratio of the DLOE. As explained in the previous chapter, the inflow in the first floor is calculated with the opening ratio of the DLOE and the evaluation formula for the inflow, time-integrating the inflow per unit time. The inundation depth in the first floor is calculated by the division of the inflow into the first floor by the area of the first floor.



(a) DLOE. (b) DS in the first floor.
Fig. 6. Fragility curve and opening characteristics.

Similarly, the fragility and the opening ratio of the DS in the first floor are calculated with substituting the inundation depth in the first floor in the fragility curve and the opening characteristics of the DS in the first floor (Fig. 6(b)). Also, the inflow into the second basement floor is calculated with the opening ratio of the DS in the first floor and the evaluation formula for the inflow, taking into account the above assumption that the damage of the DS in the first floor causes that of all doors of stairs in the second basement floor. The inundation depth in the second basement floor is obtained by the division of the inflow in the second basement floor by the area of the second basement floor. Note that the inundation depth in the second basement floor is equal to that in the RCIC pump room because all doors in the second basement floor are in the same state for the tsunami inundation.

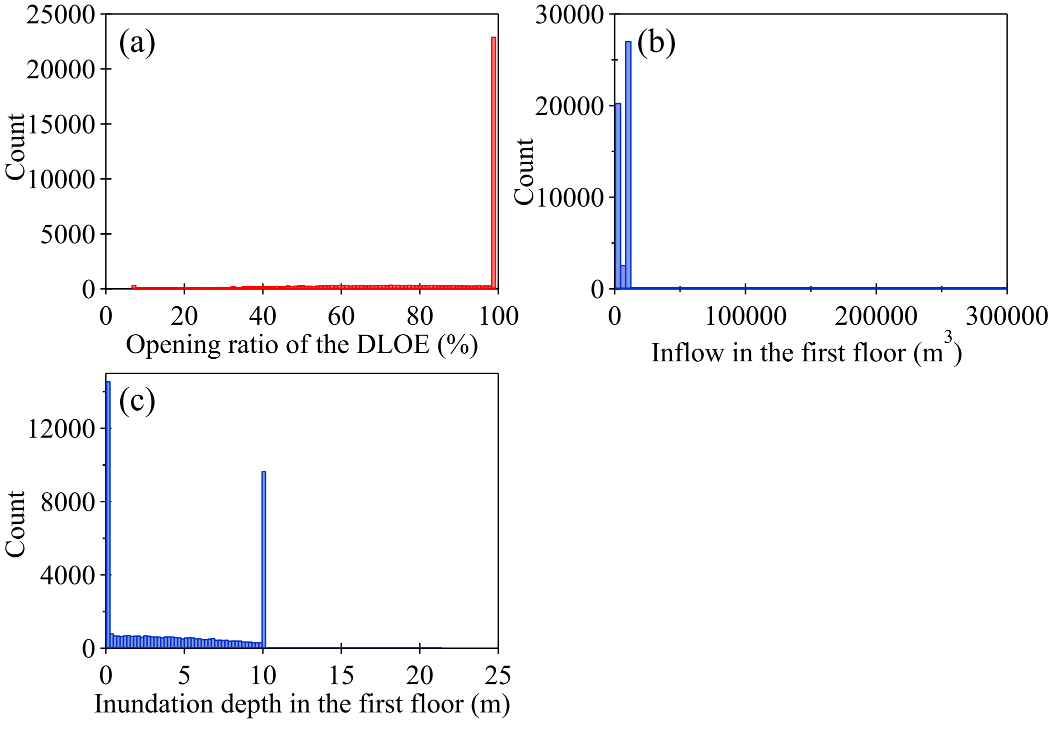
When the inundation depth in the RCIC pump room is larger than one meter, the loss of function for the RCIC pump is assumed to occur and the probability of loss of function for RCIC (PLFR) is calculated with the product of the fragility of the DLOE and that of the DS in the first floor.

IV. DISCUSSION OF THE ESTIMATED DISTRIBUTION

In this chapter, the estimated distribution obtained from the FEMT using the VPP is shown and discussed in the viewpoint of the consistency with the expected phenomenon. Here, the estimated distribution is the relationship between the calculation result and the count obtained from the Monte Carlo calculation.

Figure 7(a) shows the estimated distribution of the opening ratio of the DLOE. In the opening characteristics, since the opening ratio of the DLOE is set to the 100 % in the larger range than 0.5 in the fragility of the DLOE, many counts appear at the 100 % in the opening ratio of the DLOE.

Figure 7(b) and 7(c) show the estimated distribution of the inflow and that of the inundation depth in the first floor, respectively. The count at 1000 m^3 in the distribution of the inflow and that at 10 m in the distribution of the inundation depth are large, reflecting the upper limit value set to 1000 m^3 and that set to 10 m, respectively. Also, in the estimated distribution of the inflow, many counts appear at 0 m^3, reflecting that the inundation into the VPP does not occur for the extracted tsunami condition which has the tsunami height below the setting level of the VPP. Since the inundation depth in the first floor is obtained with the division of the inflow by the area of the first floor, the count at 0 m becomes large.

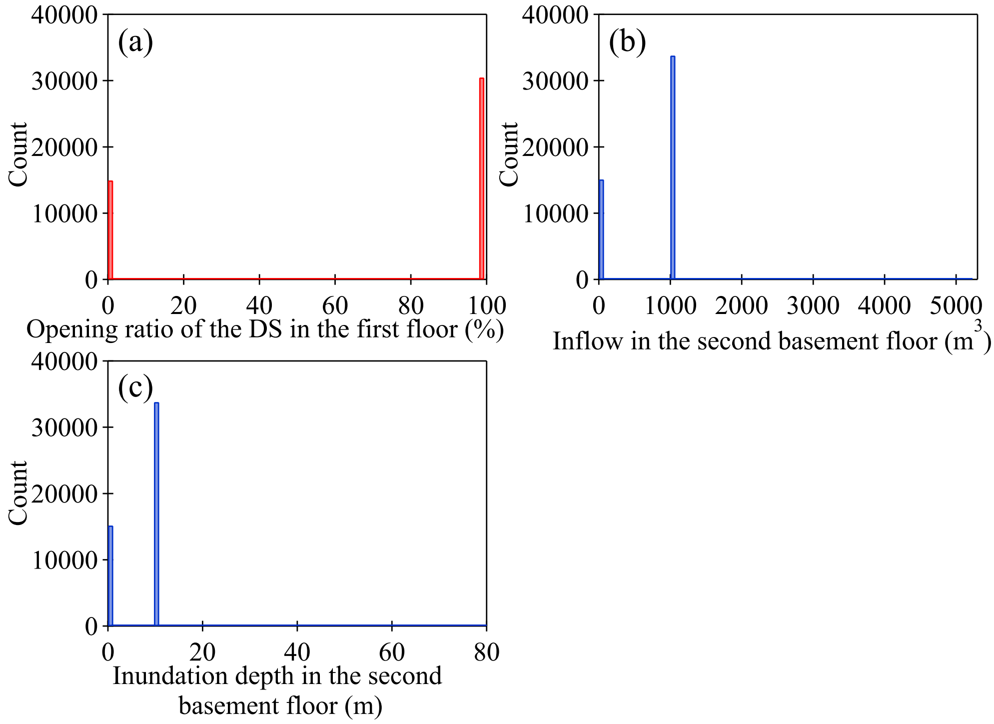


(a) Estimated distribution of the opening ratio of the DLOE. (b) Estimated distribution of the inflow in the first floor. (c) Estimated distribution of the inundation depth in the first floor.

Fig. 7. Estimated distribution of the fragility, the opening ratio, the inflow and the inundation depth.

Figure 8(a) shows the estimated distribution of the opening ratio of the DS in the first floor. The opening characteristics of the DS in the first floor have the steep slope between 0.3 m and 2.0 m in the inundation depth in the first floor, causing many counts at 0 % and at 100 % in the estimated distribution of the opening ratio.

Figure 8(b) and 8(c) show the estimated distribution of the inflow and that of the inundation depth in the second basement floor, respectively. With the similar reason to the case in the first floor, the count at 0 m^3 and at 1.0 m^3 is large in the estimated distribution of the inflow, leading to the many counts at 0 m and at 1.0 m in the estimated distribution of the inundation depth.



(a) Estimated distribution of the opening ratio of the DS in the first floor. (b) Estimated distribution of the inflow in the second basement floor. (c) Estimated distribution of the inundation depth in the second basement floor.
Fig. 8. Estimated distribution of the fragility, the opening ratio, the inflow and the inundation depth.

Figure 9 shows the estimated distribution of the PLFR. The count at 0 is large, reflecting that the count at 0 m in the estimated distribution of the inundation depth in the second basement floor is large. Also, the count is 0 between 0 and 0.3, reflecting that the fragility of the doors is 0 in the tsunami height below the setting level of the DLOE.

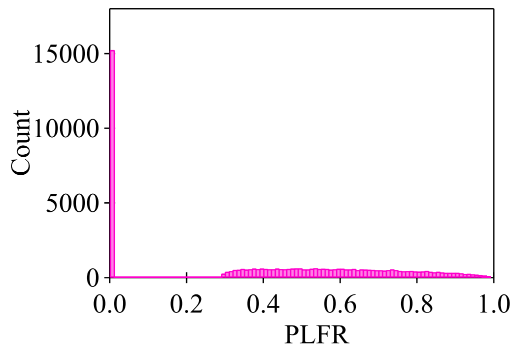


Fig. 9. Estimated distribution of the PLFR.

V. CONCLUSIONS

In conclusion, we have proposed the FEMT using the Monte Carlo method in order to evaluate the effect of tsunami on the actual NPP. The FEMT is illustrated by using the VPP from the investigation of the estimated distribution. We consider that the proposed FEMT contributes to the establishment of the fragility evaluation method and the acquisition of the new knowledge about the NPP.

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