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EFFECT OF TSUNAMI-BORNE DEBRIS COLLISION EXERTED ON THE WATERTIGHT DOOR ON THE INUNDATION VOLUME OF THE BUILDING

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ABSTRACT

Watertight doors are installed in important buildings on the nuclear power plants to prevent tsunami inundation into buildings. If the watertight door is damaged by wave pressure or debris collision, then it is possible that tsunami inundation into the building may be induced. Therefore, it is necessary to consider these effects in the tsunami PRA. This paper proposes an evaluation method of the inundation volume of the building due to the debris impact exerted on the watertight door, with reference to a method for evaluating the fragility of the watertight door for the hydrostatic pressure (Watanuki et al. 2019). Then, an application example is shown for a watertight door with a large opening of 5m width and 5m height.

INTRODUCTION

Nuclear power plants must have a high level of safety against various natural hazards. The installation of seawalls and watertight doors can significantly contribute to ensuring safety against tsunamis. In recent years, probabilistic risk assessment methods for tsunamis have been developed for nuclear power plants. Compared to the seismic PRA, which has a long history, the research progress is still ongoing. The structure of tsunami PRA is similar to that of earthquake PRA and consists of hazard evaluation, fragility evaluation, and accident sequence evaluation. In order to quantitatively evaluate the risk of tsunamis for nuclear power plants, it is necessary to reflect the results of the fragility evaluation of SSCs (Structure, System and Component), including tsunami countermeasures such as seawalls and watertight doors, for various types of tsunami hazards in the PRA model. In other words, it is necessary to evaluate the failure probability SSC functions due to external forces caused by a tsunami. In the case of damage to various facilities, the scenarios considered in the later phase of the accident sequence evaluation will be changed. In addition, the results of the fragility evaluation of SSCs can be used in the screening of accident scenarios. Therefore, development of the fragility evaluation method for various types of SSCs against the expected external tsunami force is important.

Failure modes of SSCs due to external forces caused by tsunamis includes functional failure due to inundation and also structural/functional failures due to physical damage caused by tsunami wave pressure and debris collision forces. In tsunami fragility evaluation, the damage probability of SSCs is calculated based on the results of best estimate response and best estimate capacity evaluations. Previous studies have proposed methods for evaluating the fragility of seawalls against overtopping and wave forces (Sugino et al., 2009; Kim and Choi, 2011; Kaida et al., 2016; Haraguchi et al., 2017). A probabilistic evaluation method of debris collision velocity, which is important for the evaluation of SSC fragility against tsunami debris collision, has been proposed (Kaida et al., 2020; Kaida et al., 2022) and can be utilized in the best estimate response evaluation. On the other hand, there are very few studies on best estimate evaluation methods of capacity against tsunami debris collision. There are also very few studies on tsunami fragility evaluation of SSCs other than seawalls, such as pipes, tanks, watertight doors, and so on. As mentioned above, there are still many issues to be solved in tsunami fragility evaluation. However, this study focuses on the evaluation of the fragility of watertight doors against tsunami debris collision.

There are several remarkable studies related to the fragility of the watertight doors. Anabuki et al. (2015) conducted an experiment to reproduce the superimposed effects of an earthquake and tsunami on a watertight door. Based on the experimental results, a numerical analysis method was established to model the packing around the circumference of the watertight door in detail, and the sudden increase in the amount of water leakage was reproduced. Smith et al. (2016) and Wells et al. (2019) conducted experiments on damage to non-watertight doors and showed that the amount of leakage varied significantly depending on the damage. While evaluation methods for wave pressure are being developed, there are no studies on debris collision. However, it is known that watertight doors have a very strong capability against hydrostatic pressure acting in the direction of door closure (Watanuki et al., 2019; Kaida et al., 2019; Mihara et al., 2019), and it is considered that they have a certain structural strength against debris collision, even though the mode of action is different from that of hydrostatic pressure.

As mentioned above, information that can be utilized in the screening of accident scenarios and in the subsequent accident sequence evaluation is valuable in a tsunami PRA. Watertight doors have the function to prevent tsunami inundation of critical buildings. If the watertight door completely loses its function, an accident sequence that could lead to risk-dominant accident scenarios will occur. The effects of flooding into an important building through a watertight door strongly depend on the damage condition of the watertight door. Therefore, estimating the amount of flooding into the building corresponding to the damage status of the watertight door is important in PRA. A fragility evaluation method for watertight doors using the inundation volume as an index has been proposed by a previous study (Watanuki et al., 2019; Kaida et al., 2019; Mihara et al., 2019), but no study has been conducted for the collision of debris. In the fragility evaluation of a watertight door against collision of debris, there are a large number of uncertain factors to be considered, such as collision location, type of debris, physical properties, and collision velocity, compared to the evaluation of wave pressure which results in almost uniform force on the watertight door. Therefore, there is no limitation in obtaining experimental data, and it is not realistic to conduct experiments or detailed numerical analysis to cover all the uncertainties. On the other hand, if it is shown that the risk of core damage in the in-building flooding scenario due to deformation of watertight doors caused by tsunami debris collision is sufficiently low at the tsunami height to be considered in the tsunami PRA, it will be possible to screen out the in-building flooding scenario. In such cases, detailed fragility evaluation of watertight doors against collision of debris can also be screened out.

Based on the above background and previous studies that focussed on a probabilistic evaluation method of water leakage when wave pressure acts on a watertight door, this study proposes a probabilistic evaluation method for quantitative water leakage rate through a watertight door due to the collision of debris.

FRAGILITY EVALUATION OF THE WATERTIGHT DOOR FOR THE TSUNAMI WAVE PRESSURE

An evaluation method for the fragility of watertight doors against static tsunami wave pressure has been proposed using the amount of water leakage as an indicator (Watanuki et al., 2019; Kaida et al., 2019; Mihara et al., 2019). This method presents the exceedance probability of the threshold value Q^* for inundation volume into the building through the watertight door, together with its uncertainty. The method proposed in this study for probabilistic evaluation of inundation volume into a building caused by deformation of watertight doors due to collision of debris is based on this previous study. Therefore, this chapter briefly introduces the method and application examples of previous studies (Watanuki et al., 2019; Kaida et al., 2019; Mihara et al., 2019).

An analysis of the results of water pressure tests on several watertight door showed that there is a high correlation between the deformation of the center of the watertight door due to water pressure δ and the amount of water leakage Q. Watanuki et al. modeled the δ - Q relationship including watertight door-specific parameters as shown in Figure 1. The model indicates that no leakage occurs until the central deformation of the door exceeds a certain threshold value δ_0, and that the leakage volume increases linearly with δ for conditions where $\delta > \delta_0$. The relationship between the amount of water leakage Q and the deformation of the center of the door δ is calculated as follows.

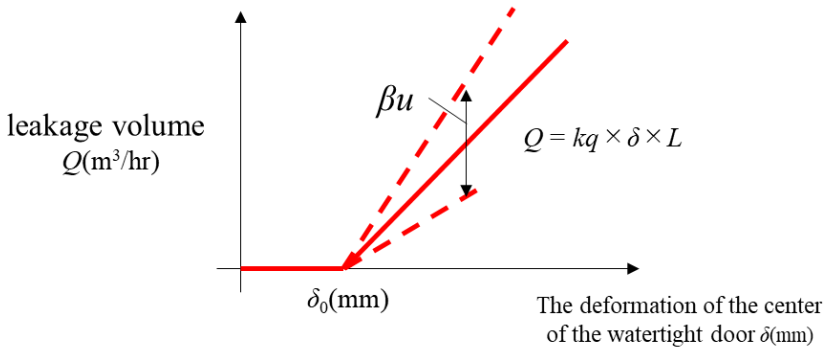

Figure 1: Conceptual diagram of leakage volume model.

$$Q = k_q \delta L \tag{1}$$

where k_q: parameter (m3/hr/mm2) for each type of watertight door, L: circumference of the door (mm). k_q is set with reference to experimental results. The deformation δ of the center of the door in response to static wave pressure is obtained by elasto-plastic response analysis. In other words, the relationship between the water level at the front of the watertight door h and Q is obtained from the above. For each discrete tsunami height h, above-described method is applied. And then, the exceeding probability of the threshold Q^* of the inundation volume is calculated as follows:

$$P(h) = 1 - \Phi\left(\frac{\ln(Q^*) - \ln(\mathrm{Q(h)})}{\beta_r}\right) \tag{2}$$

where βr is the aleatory uncertainty, Φ is the cumulative distribution function of normal distribution, respectively. The h-Q relationship obtained above is used as the median value. By fitting the discretely calculated points to a lognormal distribution, the median inundation volume Q_m and the aleatory uncertainty β_r are calculated. Furthermore, by considering the epistemic uncertainty β_u of the leakage model shown in Figure 1, the exceedance probability according to the confidence level is calculated by the following equation:

$$P(h) = \Phi\left(\frac{ln(\,Q(h)) - ln(\,Q_m) + \beta_u \cdot X}{\beta_r}\right) \tag{3}$$

where X is standard normal probability variate corresponding to the confidence level of the fragility curve.

FRAGILITY EVALUATION OF THE WATERTIGHT DOOR FOR THE TSUNAMI-BORNE DEBRIS COLLISION

Based on the previously described method (Watanuki et al., 2019; Kaida et al., 2019; Mihara et al., 2019), this paper proposes a probabilistic evaluation method for the volume of water leakage through a watertight door subjected to the collision of debris. The difference from the previous method is that the deformation amount of the central area of the watertight door due to the collision of debris is used as the deformation amount δ.

The deformation of watertight doors due to collision of debris can be estimated by numerical collision analysis. The time history of the collision force of debris is important for dynamic response of watertight door caused by the debris collision. The collision force is calculated by substituting collision velocity, debris mass, and parameters representing physical properties into an evaluation equation of debris collision forces. Although various estimation equations have been proposed, the following equation (Haehnel and Daly, 2005) has been adopted in many guidelines (ASCE, 2016; FEMA, 2019).

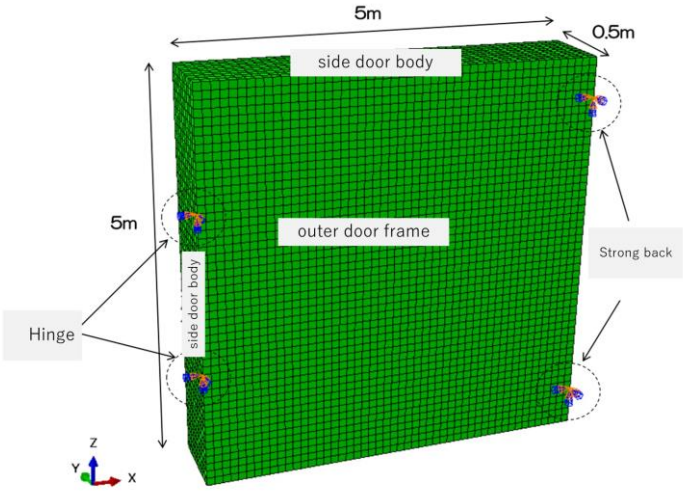

Figure 2: Watertight door modeled in elasto-plastic response analysis.

$$F = u\sqrt{k(m + Cm_f)} \tag{4}$$

Where u is the debris collision velocity (m/s), k is the axial stiffness of debris (N/m), m_f is mass of fluid pushed away by debris, and C is the hydrodynamic mass coefficient respectively. The value of the axial stiffness k expresses the physical properties of the debris. Collision velocity u can be calculated using debris tracking simulation (Goto et al., 1970; Fujii et al., 2005; Kihara et al., 2013; Tomita et al., 2016; Kihara and Kaida, 2019). The position of debris collision on the watertight door can be estimated by using the debris tracking simulation technique. In practice, the maximum flow velocity in the area to be evaluated may be used as the collision velocity (Kaida et al., 2022). The evaluation of debris collision force involves a large uncertainty and requires a probability-based method, but no available method has been proposed. The purpose of this study is to propose an evaluation method for the volume of water leakage through a watertight door. For the simplicity, in the application examples shown in the next section, deterministic evaluation results are used to set collision force and collision position.

Application example

An example of the application of the method described in the previous section is shown for a watertight door with a large opening of 5m width and 5m height. The watertight door is modeled as shown in Figure -2. The material used was SS400, and the thicknesses of the outer and lateral door bodies were 16 mm and 6 mm, respectively. Inside the door, bulkheads whose thickness is 6mm were provided at intervals of 1m x 1m. As leakage parameters for the target watertight door, δ_0 = 0.5(mm), k_q = 1.0×10^{-6} (m^3/hr/mm/mm), β_u = 0.5 were set. Leakage parameters were set with reference to previous studies (Watanuki et al). A car (m = 2,300kg) is assumed as a typical possible debris in a nuclear power plant. The axial stiffness, collision area, and collision velocity are set as shown in Table -1. The values for vehicle axial stiffness were set with reference to previous studies (Takabatake et al., 2015; Kaida et al., 2018). The debris collision area is also shown in Table -1. Maximum debris collision force is calculated by eq.(4). C = 0.3 was set assuming collision in water. Example of the time histories of collision forces set in this application are shown in Figure -3. As axial stiffness changes, the collision force action time changes (Hahenel and Daly, 2004). The collision of debris collision is always superimposed on the tsunami wave pressure. Therefore, the deformation of the door was calculated by elasto-plastic response analysis assuming the superposition of the both. First, a static elasto-plastic response analysis was conducted by applying hydrostatic pressure to the area from the bottom of the door to a height of 2.5 m.

Table 1: Debris collision conditions

Case	Collision position	Collision area (m^2)	Collision speed (m/s)	Axial stiffness (N/m)
1-1	Central of the watertight door	2 m^2 (width: 2m, height:1m)	High (17.4m/s)	High 2.5×10^7 (N/m)
1-2				Low 2.5×10^6 (N/m)
1-3			Low (11.6m/s)	High 2.5×10^7 (N/m)
1-4				Low 2.5×10^6 (N/m)
1-5		0.96 m^2 (width: 1.6m, height: 0.6m)	High (17.4m/s)	High 2.5×10^7 (N/m)
1-6				Low 2.5×10^6 (N/m)
1-7			Low (11.6m/s)	High 2.5×10^7 (N/m)
1-8				Low 2.5×10^6 (N/m)

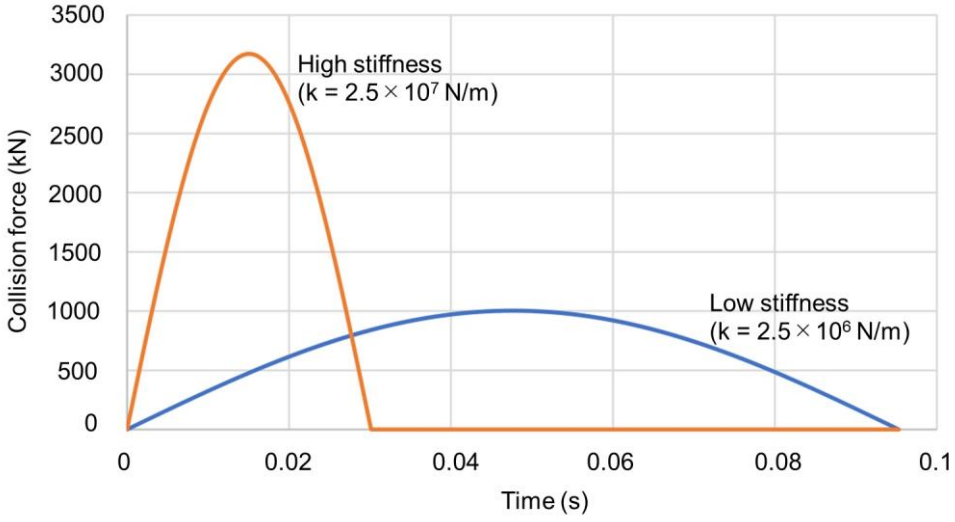

Figure 3: Example of vehicle collision time history set up for elasto-plastic response analysis. (collision speed u = 11.6 m/s).

Then, collision forces were subjected under the conditions shown in Table -1. The collision force was applied to the door model as an equally distributed pressure over the collision area.

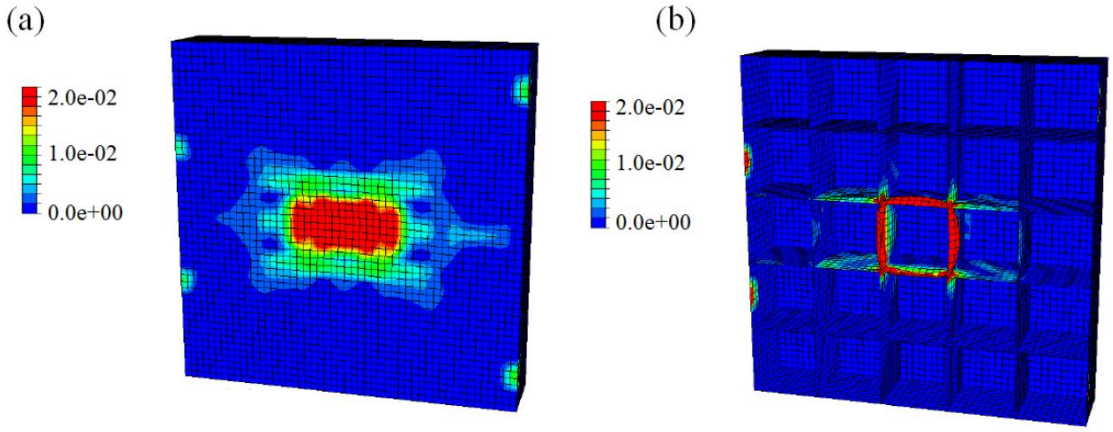

Figure 4: Equivalent plastic strain distribution of the watertight door obtained by elasto-plastic response analysis (case1-5). (a): outer door body, (b): inner door body door body.

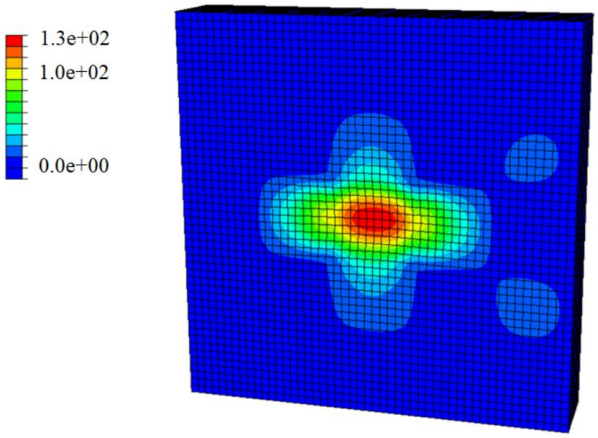

Figure 5: Out-of-plane deformation distribution of watertight door obtained by elasto-plastic response analysis (case1-5).

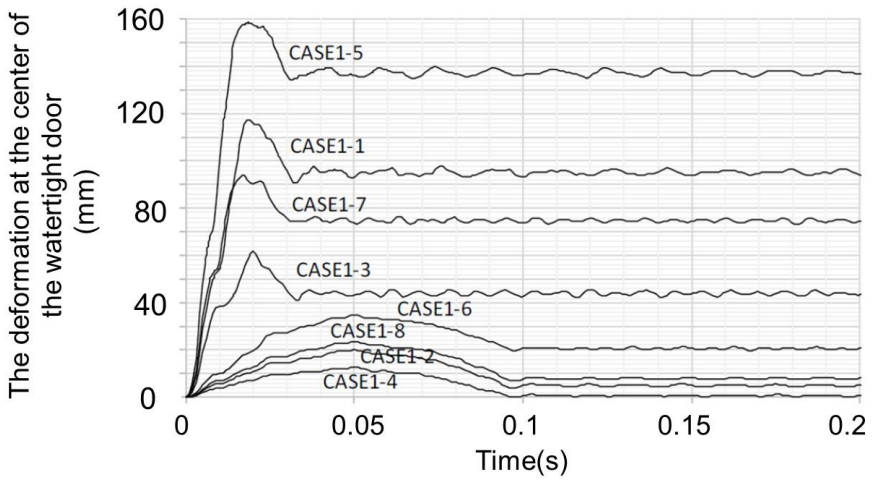

Figure 6: Time series of the deformation at the center of the watertight door caused by the vehicle collision.

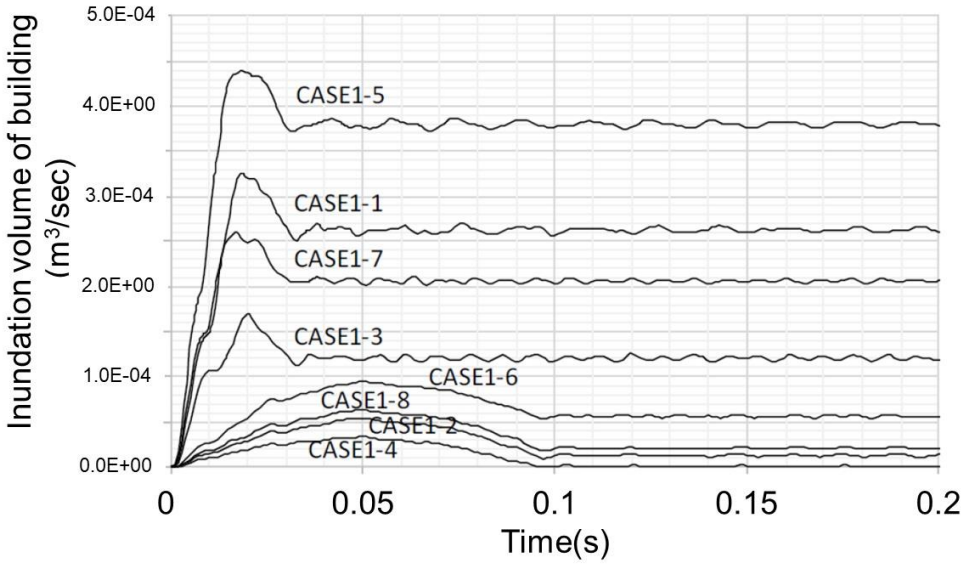

Figure 7: Time series of the inundation volume of the buildings caused by the deformation of watertight doors due to the vehicle collision.

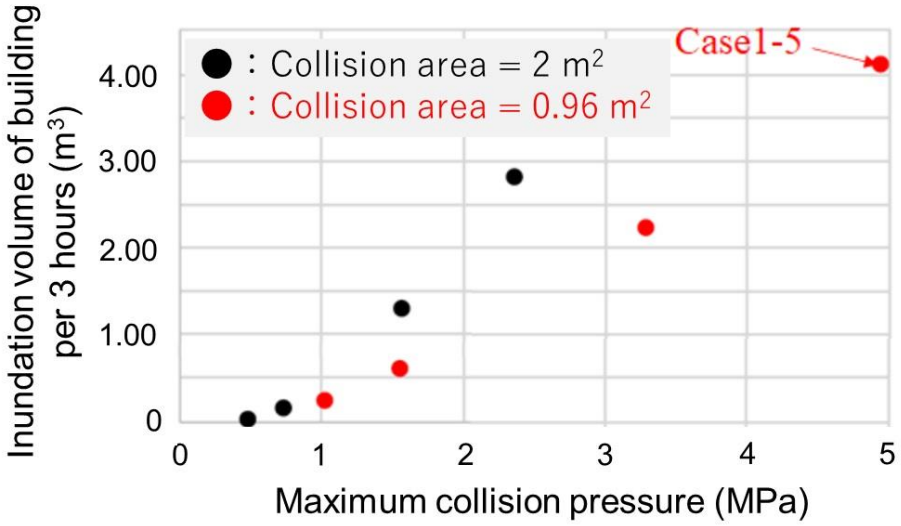

Figure 8: Relationship between the 3-hour integral of the leakage volume estimated using the central deformation of the watertight door obtained by elasto-plastic response analysis and the maximum collision pressure due to the collision of vehicle.

the equivalent plastic strain distribution and out-of-plane deformation distribution of the watertight door, using case 1-5, in which the deformation at the center of the door was most significant (Figure 6). Figures -4 and -5 show that in the case where the vehicle collided with the center of the watertight door, the center of the door and the pins and cankers that fix the door body became plasticized and the deformation was limited to the area around the center. As shown in Figure 6, in some cases, residual deformation occurs in the center of the watertight door, although it is small.

Figure -7 shows a time history of the volume of water leakage calculated from the central deformation of the watertight door (Figure -6) and method proposed in previous studies (Watanuki et al., 2019; Kaida et al., 2019; Mihara et al., 2019). Since water pressure resistance tests are conducted in some cases to evaluate the performance of watertight doors, the relationship between the watertight door-specific load, deformation at the center of the watertight door, and water leakage volume are used in this evaluation as quantities that can be obtained through experiments. The deformation at the center of the watertight door does not reach the circumference of the watertight door, which is the route of

water leakage through the watertight door (Figure -5). For each case where the collision of debris is at the center (Table -1), the leakage rate is as small as 0.00045m^3/s even in the case with the largest leakage volume, even though the proposed model, in which the leakage volume increases linearly with the deformation of the door center above a certain threshold value, is a conservative model (Figure -7).

In the estimation of the inundation volume into the building, it is necessary to consider that the tsunami inundated into the site will continue to flow into the building until it is drained out of the site and the inundation depth around the watertight door becomes less than the bottom surface of the watertight door. Figure -8 shows the relationship between the estimated volume of water leakage and the maximum collision pressure associated with the debris collision, assuming that the duration of the inundation into the building is 3 hours. Leakage volume increases linearly with the maximum collision pressure, as is obvious from the relationship between residual deformation and the maximum collision pressure and from the method used to estimate leakage volume. Although this study is based on conservative conditions using the results of previous studies (Watanuki et al., 2019; Kaida et al., 2019; Mihara et al., 2019), the leakage rate per 3 hours is still less than 5m^3 .

CONCLUSION

An evaluation method of the inundation volume of the building due to the debris collision exerted on the watertight door is proposed and an example of its application is presented. The method enables a probabilistic evaluation of the inundation volume of a building due to the debris collision. The results of the example calculations indicate that the volume of water leakage into the building expected in the case of vehicle collision with the center of the watertight door (5m x 5m) is very small. Proposed method can contribute to more appropriate risk assessment of the nuclear power plant and the development of safety measures based on the risk information. For example, the proposed method is a core technology in the establishment of a screening method for evaluating the effects of inundation in a building. In the method proposed in this study, the position of debris collision is constrained to the central part of the watertight door. In practice, collision of debris is likely to occur at various positions of the watertight door. Therefore, understanding the effects of different collision positions on the inundation volume in the building via the watertight door is needed in the future.

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