DEVELOPMENT OF EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILLITIES -FRAGILITY EVALUATION METHODS OF SEISMICALLY ISOLATED NUCLEAR POWER PLANT BUILDINGS-

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ABSTRACT

For nuclear power plants (NPPs) in Japan, an evaluation of "a residual risk" against phenomena exceeding design conditions has been required. As the method of the risk assessment, the probabilistic risk assessment (PRA) has great advantages. This paper proposed a fragility evaluation method for seismically isolated NPP buildings, in order to establish the seismic PRA method for the seismically isolated NPPs. The contents of this paper are the following.
First, we set evaluation criteria for seismic failure modes of seismically isolated NPP buildings. Specifically, we proposed a seismic event-tree and defined the failure modes.
Next, in order to make probabilistic models for response analysis, we proposed a method of setting a limit state of seismically isolated NPPs buildings, and identified uncertainty factors in the seismic behaviour (or response) of the building by sensitivity analyses. In this paper, based on the previous examination results, it was assumed that there were seven uncertainty factors in the seismic behaviour of the seismic isolated layer, the upper structure, and the structural foundation.
Finally, we calculated fragility curves of a seismically isolated NPP building for each failure mode. The fragility analysis results could be used for seismic PRA evaluations of a seismically isolated NPP facility. The result of the trial calculation clearly showed that the failure in the seismically isolated layer was dominant failure mode.

INTRODUCTION

Recently, seismic isolation system, mainly two-dimensional seismic isolators has been adopted in general buildings in Japan, since the system could reduce the seismic force on buildings. On the other hand, conventional seismic force-resisting system has been adopted in NPP buildings. Therefore, the research activity for adopting seismic isolation system is now in progress. After the Fukushima accident, the higher level of safety is strongly expected for NPPs. In addition, the evaluation of “a residual risk” has

been required for the phenomenon exceeding design conditions. It is known that the seismic PRA is effective as an evaluation method for the residual risk.
In this paper, in order to establish the seismic PRA method for seismically isolated NPPs, we propose a scheme of probabilistic fragility evaluation methods focusing on buildings such as shown in Figure 1, and show a trial calculation of the fragility curves of a seismically isolated NPP building.

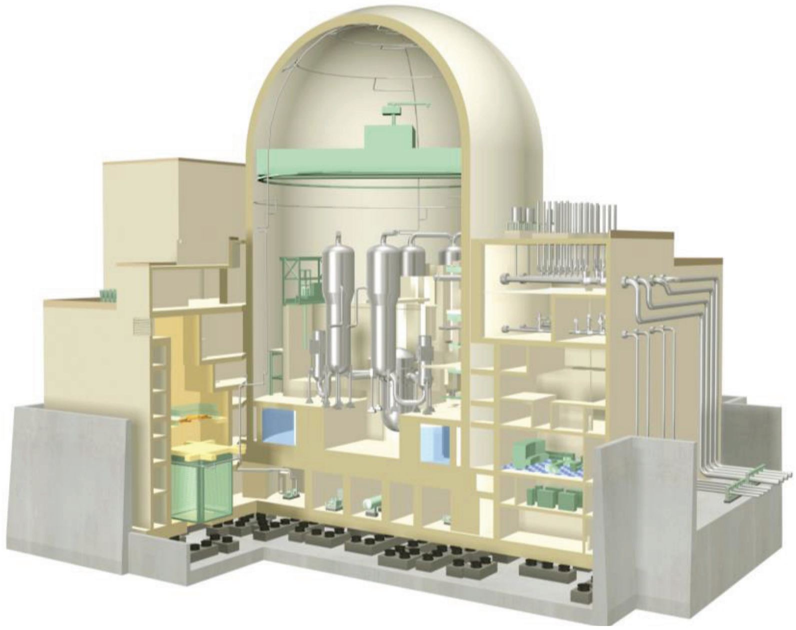

Figure 1. Seismically isolated NPP building (PWR-type reactor building)

FALURE MODES OF SEISMICALLY ISOLATED NPP BUILDINGS

Based on the continuous research and development of application of the seismic isolation system to nuclear facilities for the higher earthquake-resistant safety, we propose an event-tree of seismically isolated NPPs as shown in Figure 2. Major failure modes could be identified as follows;

Mode 1: Failure around seismically isolated layer (red dotted frame in Figure 2)
Mode 2: Failure in seismically isolated layer (blue dotted frame in Figure 2)
Mode 3: Failure in the upper structure due to excessive seismic load or collision to the retaining wall (Light green and deep green dotted frame in Figure 2)

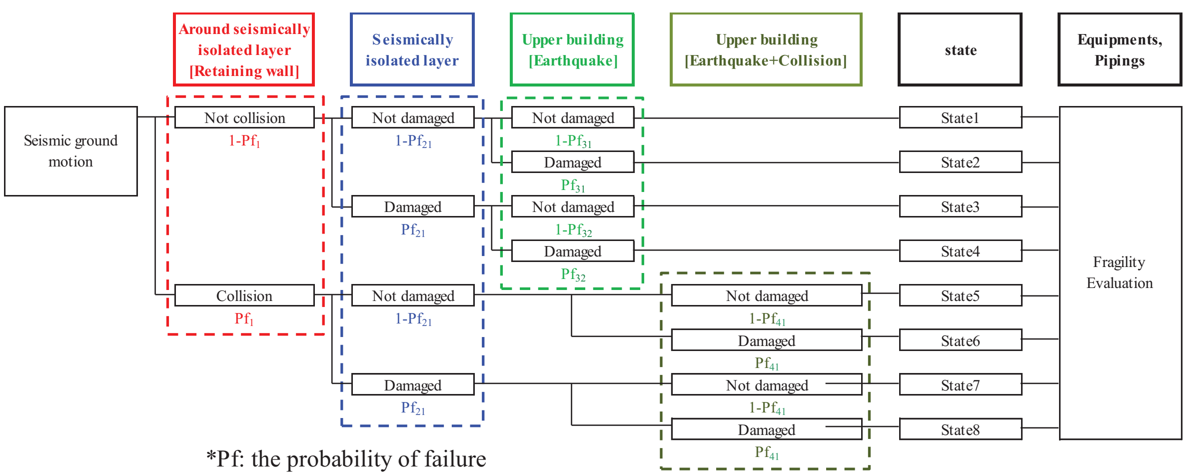

Figure 2.Event-tree of seismically isolated NPP building

The fault-tree of the seismically isolated layer is shown in Figure 3. As a pedestal and anchor bolts can be designed with a margin beyond the rubber break of the isolator (Watanabe, T. et al. (2015)), we focus on "Collision of the seismically isolated building to the retaining wall", "Break of laminated rubber of the seismic isolator", and "Break of structural wall of the upper structure" as evaluation issues.

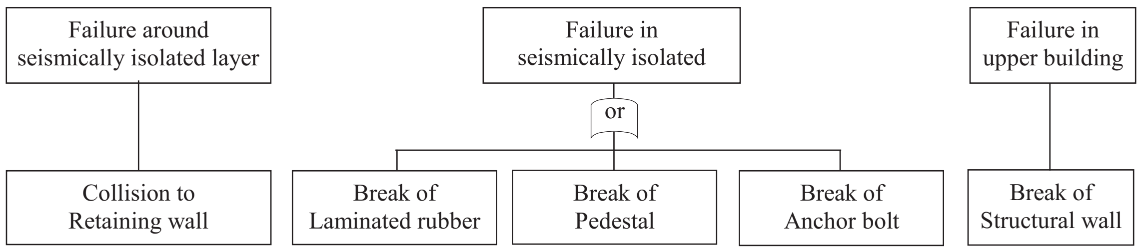

Figure 3.Fault-tree of seismically isolated NPP building

GROUND MOTION USED FOR ANALYSIS

The ground motion used for analysis is an artificial seismic wave corresponding to a seismic hazard level at a general Japanese NPP site, whose annual exceedance probability is about 10^{-4} as shown in Figure 4. The maximum acceleration is 800cm/s^2 and maximum velocity (h=5%) is 200 cm/s. As the vertical direction, 2/3 times the horizontal wave is used. Horizontal ground motion used for analysis as the acceleration time history and the input wave spectra is shown in Figure 5.

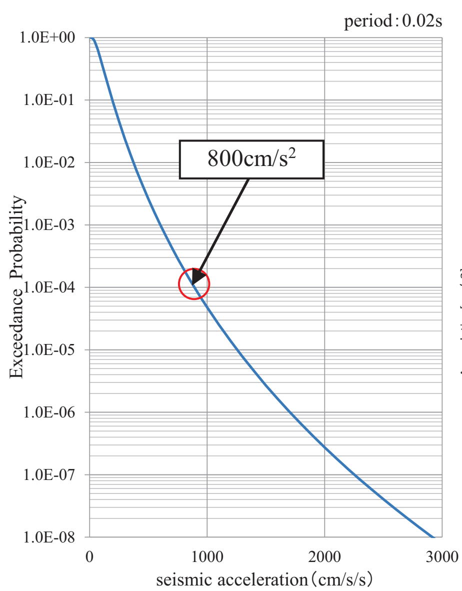

Figure 4. Seismic hazard curve

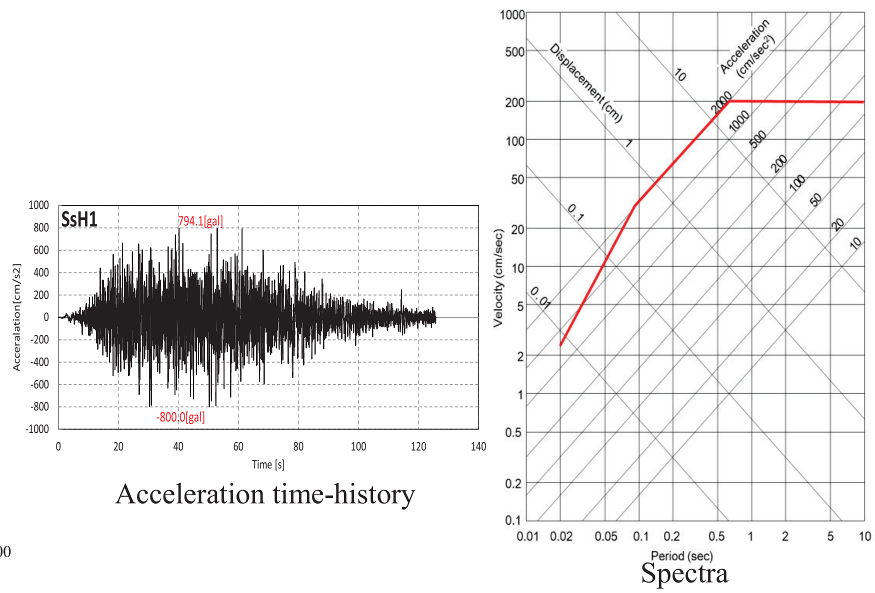

Figure 5. Horizontal ground motion used for analysis

METHOD OF SETTING OF THE VARIATION

Setting of the limit state (capacity)

For the evaluation of probabilistic responses of buildings, limit states of containments must be set. In this chapter, the limit states of containments; capacities, are set for each identified three failure mode: "Collision of the seismically isolated building to the retaining wall", "Break of laminated rubber of the seismic isolator", and "Break of structural wall of the upper structure".

"Collision to the retaining wall" is determined by the clearance between the building and the retaining wall. In this study, the clearance is defined 2.0m as a definite value.

"Break of the laminated rubber" is the limit state of seismically isolated layer, determined by the past fracture test results. Figure 6 shows a distribution of horizontal fracture strain which was provided by the fracture test results of the 800mm diameter LRBs (Takeuchi, Y. et al. (2013)), and Figure 7 shows a break boundary criteria in the shear strain-tensile strain coordinate plane provided by the 1600mm diameter LRBs (Kanazawa, K. et al. (2015)). Between these two tests, there are differences in loading method. In this study, it is presumed that the break limit value in shear strain follows log-normal distribution as shown in Figure 6 and the break limit value in axial strain follows normal distribution as shown in Figure 7. Based on these test results, the break boundary is set as shown in Table 1 and Figure 8.

"Break of the structural walls" in this study is set by reference to Japanese standard for PRA (AESJ, (2007)) shown in Table 2.

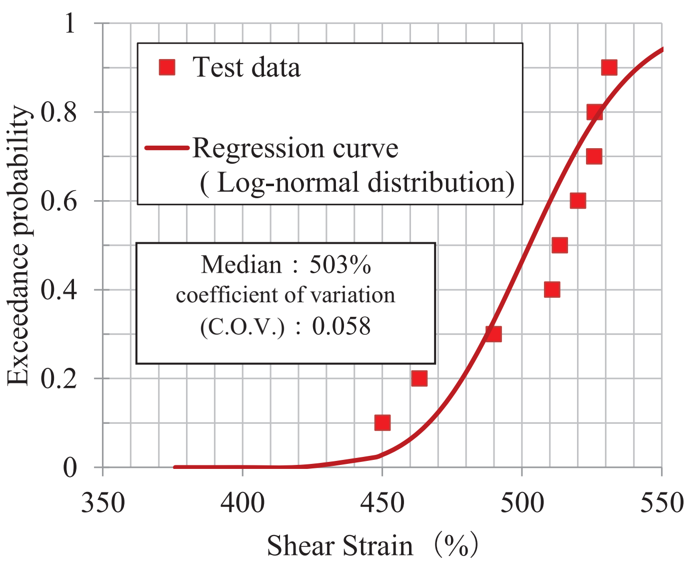

Figure 6. Exceedance probability of break of 800mm diameter LRBs in gradually shaking test (Takeuchi, (2013))

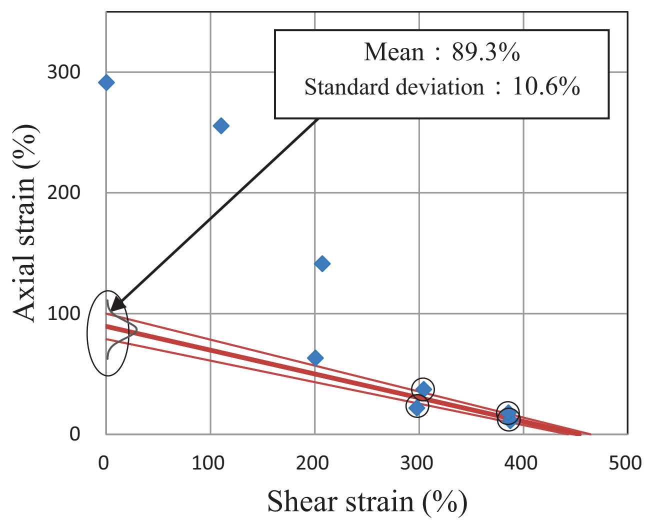

Figure 7. Break boundary criteria in the shear strain-tensile strain coordinate plane of1600mm diameter LRBs in one-way loading test (Kanazawa, (2015))

Table 1: Parameter of break boundary of LRBs

	value	coefficient of variation (C.O.V.)
Shear strain (Log-normal distribution)	500% (Median)	0.10
axial strain (Normal distribution)	89% (Mean)	0.12

Table 2: Capacity of structural walls (AESJ, (2007))

	Median of Shear strain	coefficient of variation (C.O.V.)
Shear wall (Box-type)	5.2×10^{-3}	0.24
Shear wall (Cylinder-type)	9.3×10^{-3}	0.32

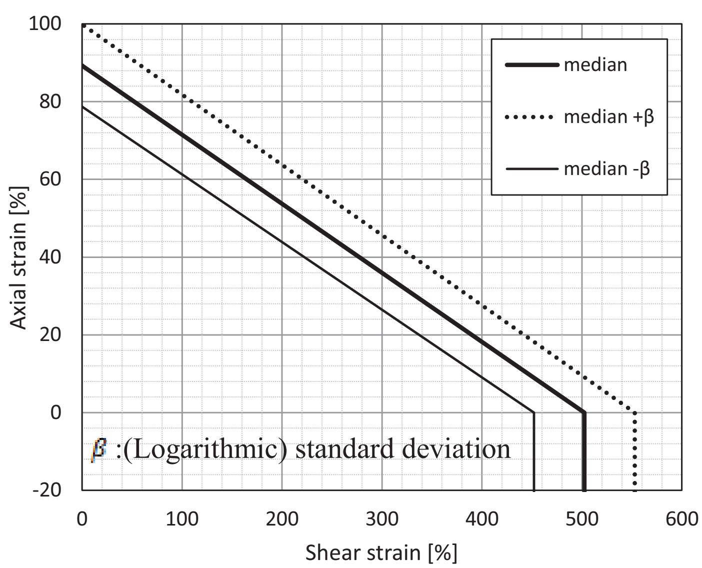

Figure 8. Break boundary of LRBs

Setting of the response variations

In this study, it is presumed that there are seven uncertainty factors having effect on response of seismically isolated buildings. The uncertainty factors are the following.

1. Horizontal stiffness of the laminated rubber (K_R1)
2. Vertical stiffness of the laminated rubber (K_C1)
3. Initial stiffness of the lead plug (K_D1)
4. Shear yield strength of the lead plug (F3)
5. Concrete strength of the upper structure (F_C)
6. Damping ratio of the upper structure (h)
7. Shear wave velocity of the foundation soil (V_S) as the foundation stiffness

These uncertainty factors are presumed to follow log-normal distribution, and their mean values and variations are determined as shown in Table 3 and Table 4.

In seismically isolated layer, there could be four uncertainty factors consisted of seismic isolator's stiffness such as K_R1, K_C1, K_D1, and F3. It has been shown in the previous research (Matsuoka, et al. (2013)) that the uncertainty factors have an upper and lower limit value for the design values as shown in Table 3. Therefore, in this study, the mean value of each parameter is determined as the design value, and the coefficient of variation (C.O.V.) of each parameter is set to be 10% with the assumption that the maximum design range of 30% is consistent with 3 times of the C.O.V. On the other hand, the C.O.V. of the initial stiffness of a lead plug (F3) is intentionally enlarged as 50%, since there was no clear evidence for F3.

In upper structure and structural foundation, it is presumed that there are three uncertainty factors such as F_C, h, and V_S. The mean values and variations of each parameter are determined by reference to Japanese standard for PRA (AESJ, (2007)) as shown in Table 4.

The concept of probabilistic restoring force model of seismic isolator is shown in Figure 9.

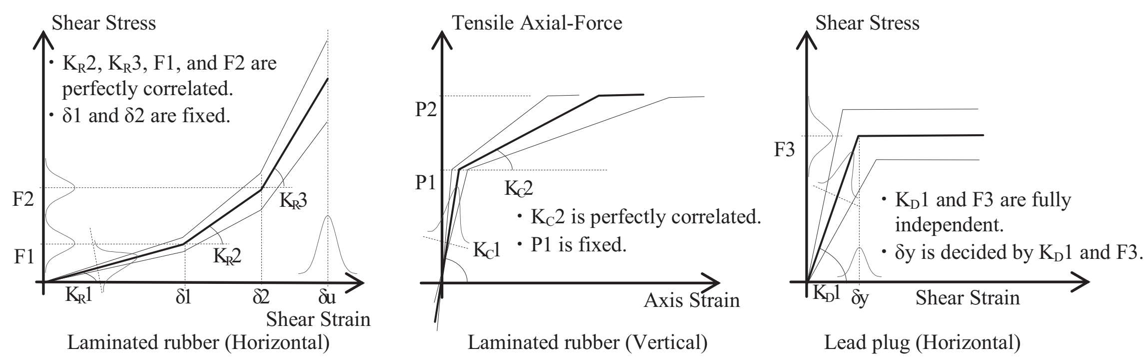

Figure 9. Concept of probability restoring force model of seismic isolator

Table 3: Variation of seismically isolated layer

		(Matsuoka, etc.,2013)		This Study	
		Upper limit	Lower limit	Mean	C.O.V.
Horizontal stiffness of the laminated rubber	K_R1	+35%	-15%	Design value	0.10
Shear yield strength of the lead plug	F3	+30%	-20%		0.10
Vertical stiffness of the laminated rubber	K_C1	+30%	-10%		0.10
Initial stiffness of the lead plug	K_D1	-	-		0.50

Table 4: Uncertainty factors other than the seismically isolated layer

		Mean	C.O.V.
Strength of Concrete	Fc	Design value × 1.4	0.13
Damping ratio of upper structure	h	5%	0.25
Shear wave velocity	Vs	Design value	0.10

Sensitivity analysis of uncertainty factors

The sensitivity analyses are performed in order to select major uncertainty factors having effect on response of seismically isolated buildings. For the response analysis, a model of a seismically isolated NPP building (PWR type) is used as shown in Figure 10. Sensitivity of uncertainty factors is calculated by formula (1).

Sensitivity of uncertainty factor : $K_{xi} = \left(\left|R_M - R_{M+\beta_i}\right| + \left|R_M - R_{M-\beta_i}\right|\right)/2 \cdot R_M \ldots (1)$

R_M : Response of median model $R_{M+\beta_i}$: Response of (median+β_i) model

$R_{M-\beta_i}$: Response of (median-β_i) model * β:Logarithmic standard deviation

Sensitivity analyses are conducted for 15 cases, including one case which used the median of parameter and each two case used the parameter varied plus-minus β_i (Logarithmic standard deviation) from median for each of the seven uncertainty factor. The result of sensitivity analyses are shown in Figure. 11.
Figure 11 shows that the dominant uncertainty factors of a PWR type building are *Horizontal stiffness of the lamination rubber (K_R1)*, *Shear yield strength of the lead plug (F3)* and *Shear wave velocity of the foundation soil (V_S)*.

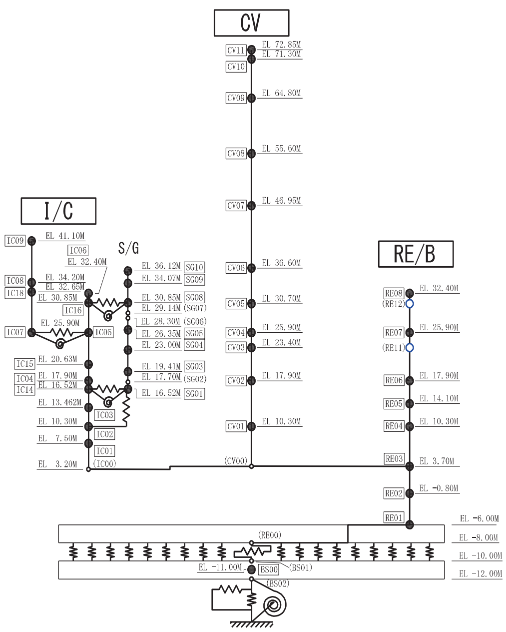

Figure 10. Analysis model (PWR-type)

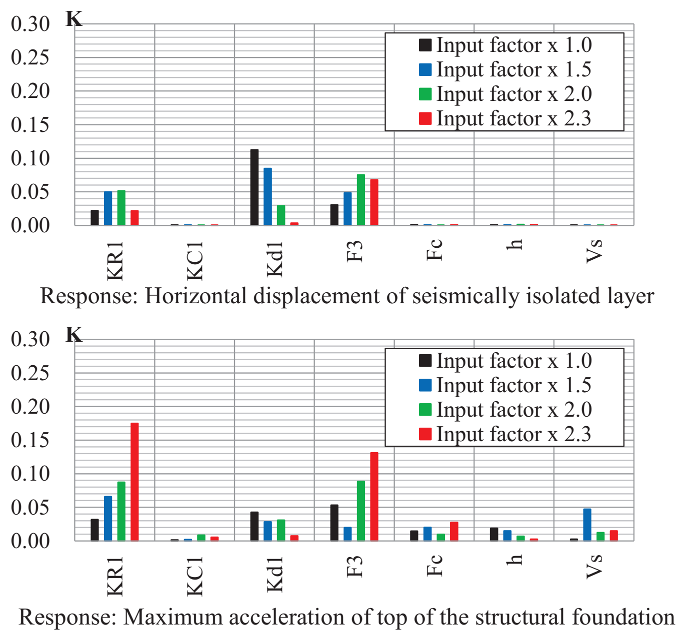

Figure 11. The result of the sensitivity analyses

Comparison of variation evaluation method

To decide on the analytical method which evaluates the variation in responses, a comparison of the two-point-estimation method and the Latin hypercube sampling (LHS) method is performed. Evaluation results of these methods are compared by the PWR model analyses where the ground motions (shown in the previous chapter) are enlarged and the three dominant uncertainty factors are concerned. $2^3 = 8$ cases are employed for the two-point-estimation method and 30 (samplings) cases for the LHS method.
The calculated shear strain of seismically isolated layer by two methods is shown in Figure 12 and Table 5. Figure 12 shows that there are only small differences between the two methods in the response of shear strain of seismic isolated layer, though the input seismic level becomes large. Therefore, considering for shortening analysis time, two-point-estimation method can be sufficient to evaluate the variation in responses of a seismically isolated building. The same is true for BWR type buildings.

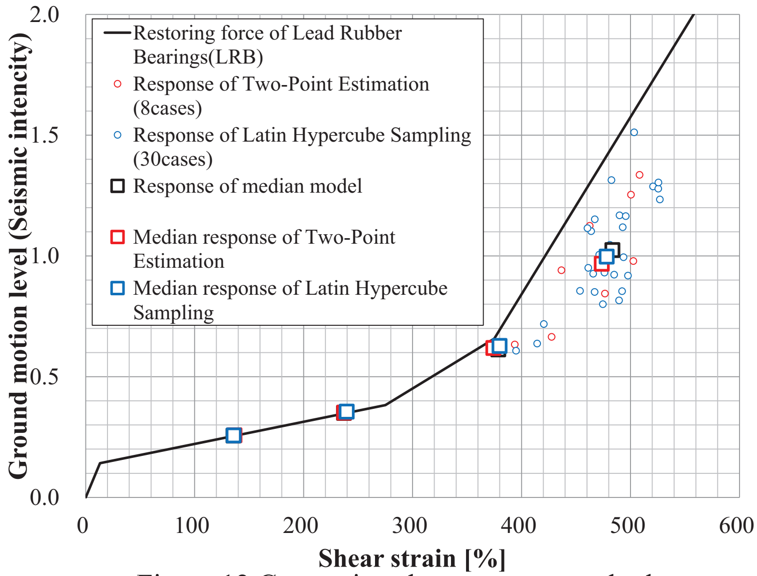

Figure 12.Comparison between two methods

Table 5: The variation of responses of seismically isolated layer

Two-point estimation

Input factor	Shear strain		Seismic intensity	
	Xm	ζ	Xm	ζ
x 2.0	373	0.091	0.619	0.216
x 2.3	472	0.075	0.967	0.238

Latin hypercube sampling

Input factor	Shear strain		Seismic intensity	
	Xm	ζ	Xm	ζ
x 2.0	379	0.075	0.627	0.176
x 2.3	477	0.063	0.997	0.203

※Xm: Median, ζ:Logarithmic standard deviation

TRIAL CALCULATION OF THE FRAGILITY

A fragility curve for a seismically isolated NPP building (PWR type) is calculated using the proposed evaluation methods. The analysis model is shown in Figure 13. This is a model of the PWR type building where seismic isolators are arranged as shown in Figure 14. The input ground motions (both horizontal and vertical) are used as shown in Figure 5. According to the setting method shown in the previous chapter, the probabilities of each failure mode are calculated. The concept of the failure probability of seismic isolators shows in Figure 15. The practical procedure of the calculation method is shown in the following.

1. Conduct eight cases of response analyses by two-point-estimation method, changing the dominant uncertainty factors; K_R1, F3 and $V_{S.}$, while changing the input factor of ground motion level to 1.0, 1.5, 2.0, and 2.5.
2. From the eight results of the response analyses, presume the probabilistic distribution of the responses of the structural foundation; horizontal displacement, the structural wall; shear strain, and the seismically isolated layer; shear strain and axial strain of seismic isolators. Log-normal distribution is adopted for the distribution of responses except for axial strain of seismic isolators. For the distribution of the axial strain of seismic isolators, a normal distribution is adopted, considering positive and negative strain. In this study, we presume that the shear strain and the axial strain are irrelevant.
3. Calculate the probabilistic responses of the building from the probabilistic distribution. The responses of the seismically isolated layer consist of a set of shear strain and axial strain; we calculate the probabilistic responses by Monte Carlo method. In this study, the number of samples of response is 3000.
4. Calculate the probabilistic capacity of elements according to the setting method shown in the previous chapter. In the same way as above, calculate by Monte Carlo method for the capacity of the seismically isolated layer, using the break boundary of LRBs. In this calculation, the number of samples of capacity is 3000.
5. Calculate the failure probabilities. The probability of collision and the probability of failure in structural wall are calculated explicitly. The probability of failure in the seismically isolated layer is provided by counting the number of samples whose response exceeds their capacity. The total number of samples is obtained by multiplying 3000 by 3000.

In this study, we focus on the response of two seismic isolators placed at the edge of E and W-side of the structural foundation as shown in Figure 14.

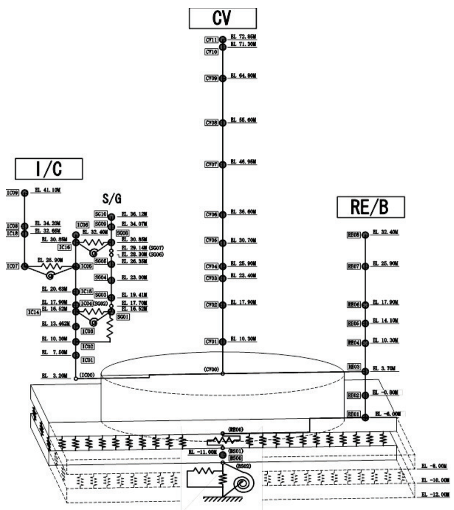

Figure 13. Analysis model

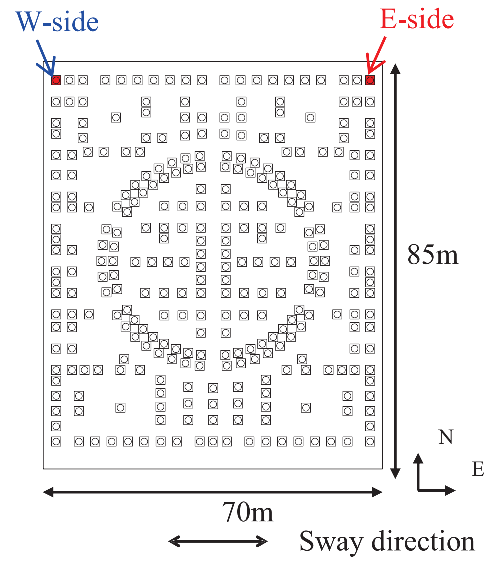

Figure 14. Placement of seismic isolators

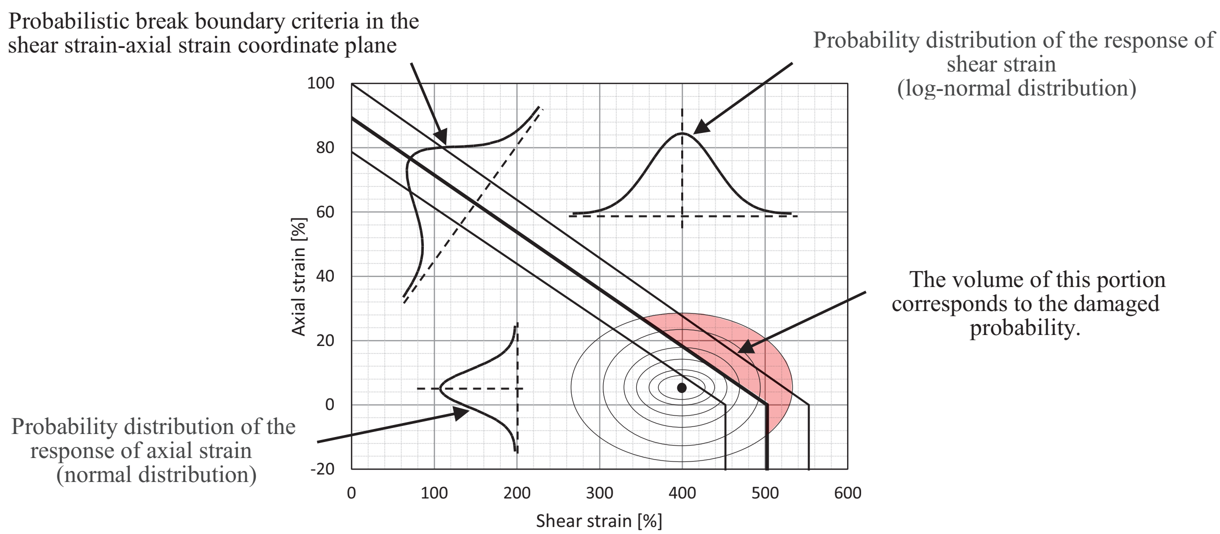

Figure 15. Concept of the failure probability of seismic isolators

The probabilistic responses of the seismic isolators are shown in Figure 16. Compared with the responses of the seismic isolators of the E-side and the W-side, the axial strain of the E-side has a tendency to become large when the input factor is 2.3. This axial strain is caused by a rocking response of the upper structure, and the maximum rocking response is occurred when the E-side vertical displacement goes upward, which makes the axial strain to be in tension.

The fragility curves calculated by the response distribution are shown in Figure 17. Although the response distributions of the both seismic isolators of the E-side and the W-side are different, there is a slight difference in their fragility curves. The result suggests that the shear strain of the seismic isolators largely influences the fragility curves much more than the axial strain.

As shown in Figure17, neither probability of collision to retaining wall nor failure in shear wall of the upper structure affects the fragility. Both of the exceedance probabilities are almost 0% beyond the 2.3

times of the design motion level. Therefore the failure in the seismic isolators has a major influence on the fragility curves of seismically isolated NPP buildings.

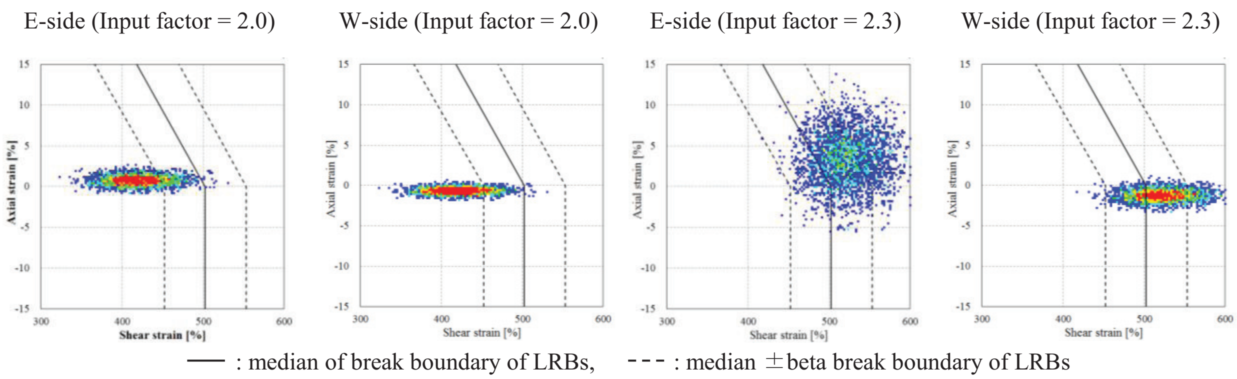

Figure 16. Probabilistic responses of seismic isolators

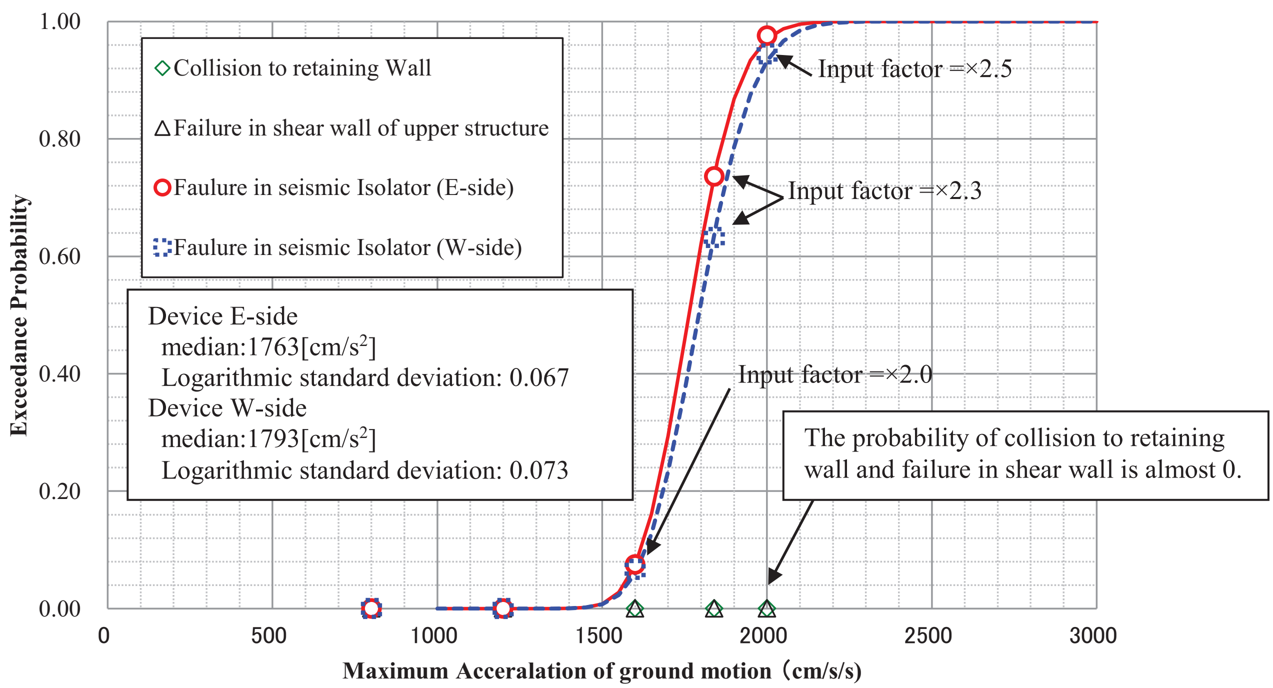

Figure 17. Fragility curves of the seismically isolated NPP building

CONCLUSIONS

This paper proposed a scheme of probabilistic fragility evaluation method focusing on seismically isolated NPP buildings and provided a trial calculation of the fragility curves. The findings are the following.

- Failure modes of seismically isolated NPP buildings were proposed, and the limit states corresponding to each failure mode were defined.
- According to the previous examination results, the method of setting the variations in capacities and responses was proposed, and the uncertainty factors which affected responses were clarified by a sensitivity analysis. Furthermore, by comparison of two evaluation methods for variations in

building responses; the two-point-estimation method and the LHS method, the results of each method were confirmed to be almost the same.

- An evaluation method for the failure probability of a seismically isolated NPP building was proposed, considering the probabilistic responses and capacities.
- A trial calculation for fragility curves of a seismically isolated NPP building was performed. The results clearly showed that the failure in the seismically isolated layer was dominant among the failure modes of the seismically isolated NPP buildings.

Since the variation value of the lead plug used in this study were not based on sufficient data, more accumulation of test results and data analyses might be necessary for improvement in the reliability of the evaluation.

In this study, it was assumed that the dominant failure mode (the failure in seismic isolated layer) is decided by the break of laminated rubber. In order to develop the evaluation of the “residual risk” to be more advanced, it would be necessary to estimate the behaviour of seismically isolated NPP buildings after the break of laminated rubber.

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