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Division VII

DEVELOPMENT OF SEISMIC COUNTER MEASURES AGAINST CLIFF EDGES FOR ENHANCEMENT OF COMPREHENSIVE SAFETY OF NUCLEAR POWER PLANTS PART 10: AVOIDANCE OF CLIFF EDGE FOR REACTOR VESSEL

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ABSTRACT

The objective of this study is to assess cliff edge effects, which are greatly important for nuclear power plants. Through assessments of failure probabilities (fragility), this study examined seismic margins of simulated two kinds of thin- and thick-walled reactor vessels by using response waveforms of the reactor building with/without a seismic isolation system obtained by seismic response analyses. The fragility analyses showed that the seismic isolation technology largely reduced the structural response effects nearly twice as much as that of the non-isolated plant. In focusing on uncertainty of response factor of components, the seismic isolation plant has a significant margin compared to the non-isolated plant even if factors from 0.5 to 2.0 are taken into account. This study concluded that the seismic isolation technology is effective to avoid cliff-edge effects.

INTRODUCTION

Cliff-edge effects of nuclear power plants (NPPs) have received a lot of attention particularly after the Fukushima Daiichi NPP accident (Takada et al., 2017). A seismic isolation system is one of the key technologies to prevent cliff-edge effects. The objective of this study is to assess cliff edge effects, which are of great importance for NPPs, especially for sodium-cooled fast reactors (SFRs) because their vessel walls are thinner than light water reactors (LWRs). For this objective, this study is intended to assess seismic margins with failure probabilities (fragility) of simulated reactor vessels (RVs) of an SFR by using response waveforms of the reactor building with/without a seismic isolation system obtained by seismic response analyses after identifying important parts in the fragility analysis and current knowledge level of the seismic isolation technology. For the comparison, the fragility analysis is also carried out for a thick-walled RV of LWR with/without the isolation system. Based on the results, the second purpose is to quantitatively evaluate response reduction effects of the seismic isolation system considering uncertainty parameters to assess the seismic margin against cliff-edge effects.

IDENTIFICATION OF IMPORTANT PARTS IN FRAGILITY ANALYSIS

Important Parts of the Thin-Walled Reactor Vessel

For the thin-walled RV in SFRs, a critical evaluation in design is elasto-plastic buckling which was identified as the most important point in the fragility analysis. However, the coolant level does not lose immediately even if the buckling happens, and the failure mode is actually low cycle fatigue after the bucking of the vessel. In addition, the failure of the RV could not result in the loss of cooling function because the RV is covered with a guard vessel (GV). Since it is difficult to quantitatively analyse a double failure mode of the RV and GV, this study assumes that failure corresponds to the occurrence of the buckling of the thin-walled RV although it is very conservative.

Important Parts of the Thick-Walled Reactor Vessel

For the thick-walled reactor vessel in LWRs, this study looked over past studies to identify parts with small seismic margin. According to the PRA standard (AESJ, 2015), a foundation bolt is identified in boiling water reactor (BWR), and a reactor pressure vessel (RPV) is in pressurized water reactor (PWR). In the Kashiwazaki-Kariwa BWR NPPs (KK-NPPs), new RPV stabilizer were replaced as part of seismic strengthening modification (TEPCO, 2011). A comprehensive safety assessment has identified the RPV stabilizer as a cliff edge around the RV for Unit 2 BWR of the Shimane NPP (CEPCO, 2012). A comprehensive safety assessment for Unit 2 BWR of the Tokai NPP has indicated a seismic margin to failure of the RPV stabilizer (JAPC, 2012). Looking at a permission report of construction plan for Unit 7 BWR of KK-NPPs, it was found that small seismic margin parts around RPV were pedestal (reactor body foundation) and RPV bracket (TEPCO, 2013). Recent safety assessment report described RPV pedestal where High-Confidence and Low-Probability of Failure (HCLPF) value was the lowest among various parts around RPV (TEPCO, 2016). According to a permission report of construction plan for Unit 1 PWR of Sendai NPPs, embedded objects of RV support structure were identified as small seismic margin parts around RPV (KEPCO, 2013). The above survey identified that important parts in the fragility analysis in BWRs were the RPV stabilizer supporting the RPV from the side and the pedestal supporting the RPV from the bottom, and the important parts in PWRs were the RPV support structures.

Seismic Isolation System

For LWRs, fracture tests have been performed for laminated rubber bearing embedded by lead plug of 1,600 mm in diameter corresponding to reactor scale. The test results were consistent with half-scale tests (800 mm in diameter) in terms of structural characteristics, such as linear limits and fracture characteristics, and concluded that the half-scale test results were applicable to reactor case (Kosugi et al., 2017).

For thick laminated rubber bearing applied to SFRs, fracture and aging tests have been conducted. The fracture tests included conditions of monotonic loading, cyclic loading, vertical and horizontal combination. Scattering of stiffness in the design range was approx. 5% with 95% of confidence level (Fukasawa et al., 2016). The aging tests indicated approx. 5% increment of stiffness in the design range in accelerated degradation test corresponding to 30 and 60 years under no loading condition (Watakabe et al., 2016). It can be said that the current experimental data are applicable to reactor plant design.

FRAGILITY ANALYSIS

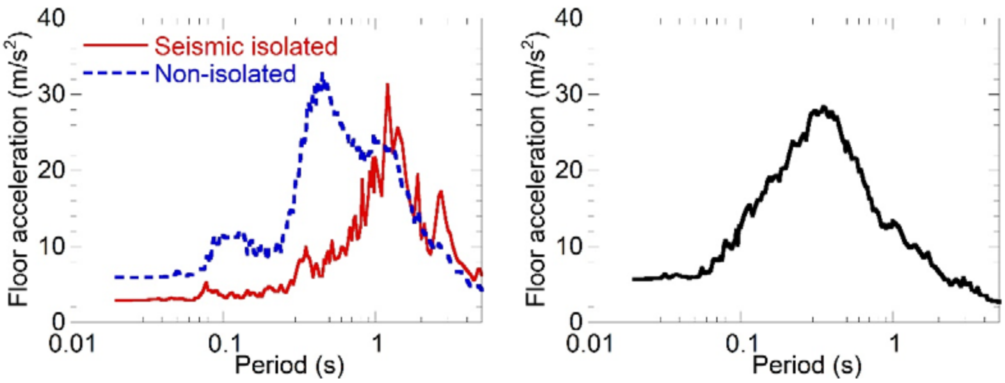
Fragility of the Thin-Walled Reactor Vessel

Seismic response analyses were conducted by using a point-mass model technique for the thin-walled RV with and without the seismic isolation system based on the response waveforms. The RV was modelled by simulating shape and mass which were consistent with natural frequencies of 4 Hz in the horizontal and 10 Hz in the vertical direction. In this analysis, the material used was stainless steel Type 304 at 400 °C. This study defined a design-basis earthquake (hereinafter referred to as Ss) of floor response curves for seismically isolated plant and non-isolated earthquake-proof one shown in Figure 1, which was evaluated by Nishida et al. (2018). The buckling evaluation of the RV was conducted by the following equation (Matsuura et al., 1993, 1994),

$$\left\{\left(\frac{Q}{Q_{cr}}\right)^5+\left(\frac{M}{M_{cr}}+\frac{F_C}{F_{cr}}\right)^5\right\}^{-\frac{1}{5}} > f_B \tag{1}$$

where Q is the shearing force, Q_{cr} is the shear buckling strength, M is the bending moment, M_{cr} is the bending buckling strength, F is the axial compression load, F_{cr} is the axial compression buckling strength, and f_B is the safety factor. As a result, the design margin was evaluated to be 2.8 in the isolated plant, whereas was 1.1 in the non-isolated plant.

This study performed a fragility analysis by setting uncertainty parameters obtained from past studies in JAEA, which are listed in Tables 1 and 2. Safety factor is calculated by the product of all values of the response factors and capacity factors. Uncertainty values are calculated by the root mean square of all values of these factors. When exceeding 2 Ss, the response factor of seismic isolation system increases to 1.2 because the hardening effect of laminated rubber bearing is taken into account.



(a) Horizontal direction (b) Vertical direction

Figure 1. Floor response spectra of design-basis earthquake.

Table 1: Safety factors and uncertainty parameters in the fragility analysis for the thin-walled reactor vessel in the non-isolated plant.

		Safety factor (F)	Uncertainty (β)	
Margin in the buckling evaluation in 1.5 of safety rate		1.1	Aleatory uncertainty (β_r)	Epistemic uncertainty (β_u)
Response factor of reactor building	Ground behavior: F1	1.0	0.4	0.2
	Isolation system behavior: F2	-	-	-
	Building behavior: F3	1.0	0.3	0.2
Response factor of components	Model: F4	1.3	0.1	0.2
	Attenuation rate: F5	1.2	0.1	0.1
	Combination of horizontal and vertical motions: F6	1.4	0.1	0.2
	Response reduction effects of ductility: F7	1.6	-	0.2
Capacity factor	Equation of buckling evaluation: F8	1.8	0.1	0.1
	Yield stress: F9	1.3	0.1	0.1
Total		8.1	0.6	0.4

Table 2: Safety factors and uncertainty parameters in the fragility analysis for the thin-walled reactor vessel in the isolated plant.

<table>
<tr><td colspan="2"></td><td colspan="5">Safety factor (F)</td><td colspan="2">Uncertainty (β)</td></tr>
<tr><td colspan="2">Seismic conditions</td><td>Ss</td><td>1.5Ss</td><td>2Ss</td><td>2.5Ss</td><td>3Ss</td><td rowspan="2">Aleatory uncertainty (β_r)</td><td rowspan="2">Epistemic uncertainty (β_u)</td></tr>
<tr><td colspan="2">Margin in the buckling evaluation in 1.5 of safety rate</td><td>2.8</td><td>1.7</td><td>0.9</td><td>0.6</td><td>0.4</td></tr>
<tr><td rowspan="3">Response factor of reactor building</td><td>Ground behavior: F1</td><td colspan="5">1.0</td><td>-</td><td>-</td></tr>
<tr><td>Isolation system behavior: F2</td><td>1.0</td><td>1.0</td><td>1.2</td><td>1.2</td><td>1.2</td><td>0.1</td><td>0.2</td></tr>
<tr><td>Building behavior: F3</td><td colspan="5">1.0</td><td>-</td><td>-</td></tr>
<tr><td rowspan="4">Response factor of components</td><td>Model: F4</td><td colspan="5">1.3</td><td>0.1</td><td>0.2</td></tr>
<tr><td>Attenuation rate: F5</td><td colspan="5">1.2</td><td>0.1</td><td>0.1</td></tr>
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<tr><td>Yield stress: F9</td><td colspan="5">1.3</td><td>0.1</td><td>0.1</td></tr>
<tr><td colspan="2">Total</td><td>21.4</td><td>13.0</td><td>8.4</td><td>5.5</td><td>4.1</td><td>0.3</td><td>0.4</td></tr>
</table>

(Ss: Design-basis earthquake)

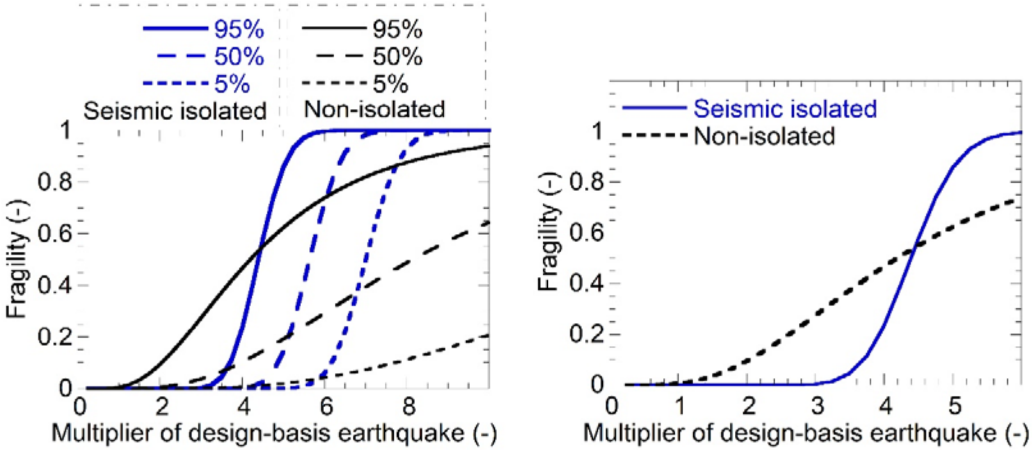
The fragility is calculated by the following equation (AESJ, 2015)

$$p_f\left(Z_m(s)\right)=\varphi\left[\frac{\ln\left(Z_m(s)/A_m\right)+\beta_u\varphi^{-1}(Q)}{\beta_r}\right] \tag{2}$$

where p_f is the fragility, A_m is the median value of response acceleration, β_u is the logarithmic standard deviation which expresses epistemic uncertainty, β_r is the logarithmic standard deviation which expresses aleatory uncertainty, $\phi(-)$ is the standard normal probability distribution function, $\phi^{-1}(-)$ is the inverse function, and Q is the non-exceedance probability considering the epistemic uncertainty.

Figure 2 shows the obtained fragility curves of 95%, 50% and 5% confidence level for the thin-walled RV. The right-side figure shows the comparison between the seismic isolated and non-isolated plants with 95% confidence level. The HCLPF value, which is generally considered to be approximately 95% confidence with less than 5% probability of failure, is used as an index value to compare the seismic response analysis results. The comparison results indicate that the seismic isolation technology is effective to prevent cliff-edge effects: the HCLPF of seismically isolated plant (3.5 Ss) is nearly twice as high as that of non-isolated plant (1.7 Ss). In other words, the seismic margin of the seismically isolated plant is twice larger than that of the non-isolated plant.

On the other hand, if we look at a failure probability of 0.5, there is no considerable difference between the isolated and non-isolated plants. The isolated plant can reduce the response to lower than that of the non-isolated one; therefore, the isolated plant can reduce its failure probability lower than the non-isolated one within the range where no hardening effect of laminated rubber appears in a lower earthquake level. When the earthquake motion exceeds a certain level, however, the failure probability increases because the hardening effect brings increase in the response of the isolated plant. Figure 2 shows the noticeable difference between the fragility curves of the thin-walled RVs of isolated and non-isolated plants on the assumption that isolated one has non-linearity and non-isolated one has simple linearity.



(a) 95%, 50% and 5% confidence level (b) 95% confidence level

Figure 2. Fragility curves of thin-walled reactor vessels of isolated and non-isolated plants.

Fragility of the Thick-Walled Reactor Vessel

The seismic response of pedestal was analysed by using the point-mass model technique, which simulated a thick-walled RPV and a pedestal as one of its surrounding structures. In the analysis, the natural frequencies of the pedestal were 12 Hz (primary) and 26 Hz (secondary) in the horizontal direction, and 20Hz (primary) and 38 Hz (secondary) in the vertical direction. In contrast to the case of the thin-walled RV that was seismically loaded on the first floor which serves as a support structure, the authors input the seismic load on both the foundation and the first floor which together serve as a support structure for this thick-walled RPV. The same floor response spectra as the thin-walled RV analysis are used in the seismic analyses with and without the seismic isolation system. Since the buckling is unlikely for the pedestal, a stress combining compression, bending and shearing was used for the fragility analysis based on a skirt evaluation method prescribed in JEAC4601-2008 (JEA, 2008).

The strength evaluations of the isolated and non-isolated plants showed the design margins of 1.8 for the isolated one and 0.9 for the non-isolated one. In the same way as the thin-walled RPV, the fragility can be calculated considering the safety factors and uncertainties shown in Tables 3 and 4.

Table 3: Safety factors and uncertainty parameters in the fragility analysis for the thick-walled reactor vessel in the non-isolated plant.

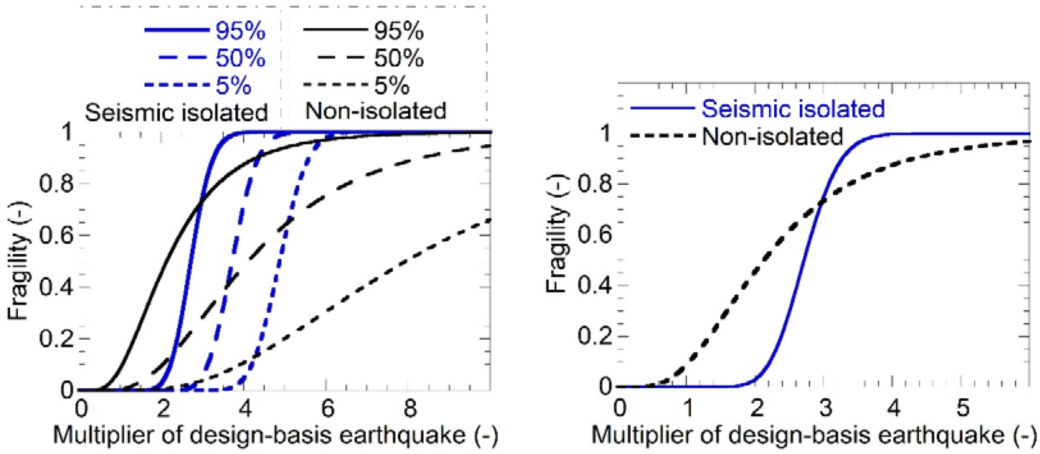
	Safety factor (F)	Aleatory uncertainty (β_r)	Epistemic uncertainty (β_u)
Value	4.4	0.6	0.4

Table 4: Safety factors and uncertainty parameters in the fragility analysis for the thick-walled reactor vessel in the isolated plant.

	Safety factor (F)					Uncertainty (β)	
	Ss	1.5Ss	2Ss	2.5Ss	3Ss	Aleatory uncertainty (β_r)	Epistemic uncertainty (β_u)
Value	4.4	4.0	3.4	2.8	2.5	0.3	0.4

(Ss: Design-basis earthquake)

The fragility curves of 95% confidence level in Figure 3 show HCLPF of 2.1 Ss for the isolated plant, whereas 0.9 Ss for the non-isolated plant. Looking at the fragility of 0.5, the seismic accelerations of the isolated and non-isolated plants are 3.7 Ss and 4.1 Ss, respectively. In the seismic isolated plant, the reduction of the safety factor for the non-linearity could be overestimated when the seismic accelerations are two times or more of Ss because of imprecise extrapolation for which the same reduction of the safety factor as the thin-walled RV was applied. The overestimation of the reduction of the safety factor was also applied to the rigid structure of the RPV. It should be noted that the evaluation could be imprecise if the seismic acceleration exceeds three times Ss because the seismic isolation systems could be damaged.



(a) 95%, 50% and 5% confidence level (b) 95% confidence level

Figure 3. Fragility curves of the thick-walled reactor vessel of the isolated and non-isolated plants.

EVALUATION OF RESPONSE REDUCTION EFFECTS

This section describes quantitative evaluations of the response reduction effects of the seismic isolated system focusing on uncertainties for the response factors of components, which are emphasized in case that various components are installed in the RV and around. This study considers potential cliff-edge effects in areas beyond existing knowledge, called "knowledge-oriented cliff-edge". In other words, this study attempts to identify the appearance of cliff-edge effects under very severe conditions in the physically possible range.

In this study, we introduce a factor for the uncertainty for the response factor of components, as listed in Table 5. The response factor of components was multiplied by factors from 0.5 to 2. The values of aleatory and epistemic uncertainties are calculated as root mean squares of all values. Using these uncertainty values, the fragility analyses are conducted for thin- and thick-walled RVs with and without the seismic isolated system.

Table 5: Uncertainty values introducing factor of uncertainty parameter.

Factor	Total values of uncertainty for response factor of components		Non-isolated plant		Seismic isolated plant			
					Thin-walled		Thick-walled	
α	$\beta_{r,C}$	$\beta_{u,C}$	β_r	β_u	β_r	β_u	β_r	β_u
0.5	0.1	0.2	0.5	0.3	0.2	0.3	0.2	0.3
1.0	0.2	0.3	0.6	0.4	0.3	0.4	0.3	0.4
1.5	0.3	0.5	0.6	0.5	0.4	0.5	0.4	0.5
2.0	0.4	0.6	0.7	0.7	0.5	0.7	0.5	0.6

Response Reduction Effects on the Thin-Walled Reactor Vessel

Figure 4 shows fragility curves with 95% confidence level considering uncertainties of the response factors of components. Figure 5 compares HCLPF acceleration of the thin-walled RV between the isolated and non-isolated plants. If the uncertainty of the response factors is doubled, the HCLPF acceleration of the isolated plant is 2.4 Ss, whereas that of non-isolated plant is 0.9 Ss. If the HCLPF is regarded as the strength limit with high confidence, the HCLPF value of the horizontally isolated plant is about twice more than that of the non-isolated plant regardless of uncertainties of the response factors of components. This study revealed that the isolation technology has notable effects on reducing the seismic response, even with uncertainty.

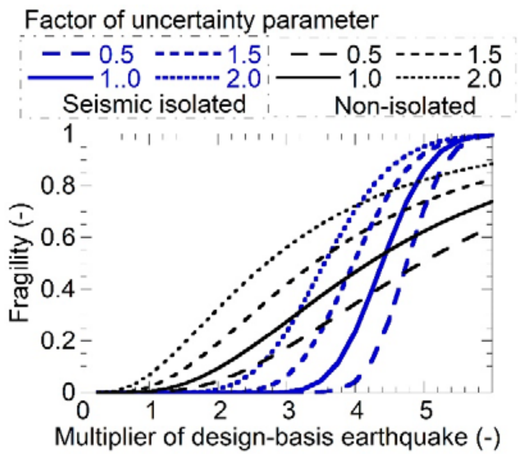


Figure 4. Fragility curves of the thin-walled reactor vessel considering uncertainty parameters.

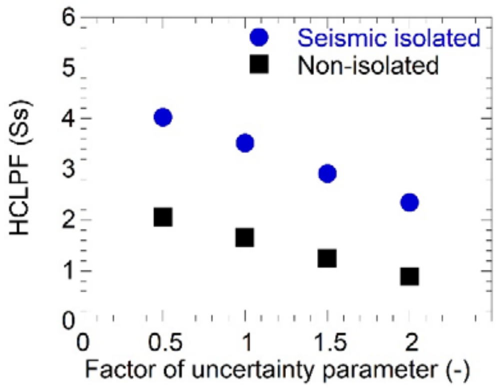


Figure 5. Response reduction effects on the thin-walled reactor vessels.
(Ss: Design-basis earthquake)

Response Reduction Effects on the Thick-Walled Reactor Vessel

In the same manner as the thin-walled RV, fragility curves with 95% confidence level and HCLPF acceleration of the thick-walled RV are plotted in Figures 6 and 7, respectively. If the uncertainty of the response factors is doubled, the HCLPF value of isolated plant is 1.3 Ss, whereas that of non-isolated plant is 0.5 Ss. This implies that a cliff edge might appear in the non-isolated plant if the uncertainty is taken into account. That is to say, the knowledge-oriented cliff edge might appear in the non-isolated plant. On the other hand, the seismic isolation technology has a large effect on the structural response reduction effect, for which the HCLPF value is nearly twice as much as that of the non-isolated plant even if the uncertainty is considered. One can say that the seismic isolated plant has no cliff edge effect in the uncertainty range considered in this study. This analysis concluded that the seismic isolation technology has a significant effect on reducing the response and is effective to avoid cliff-edge effects.

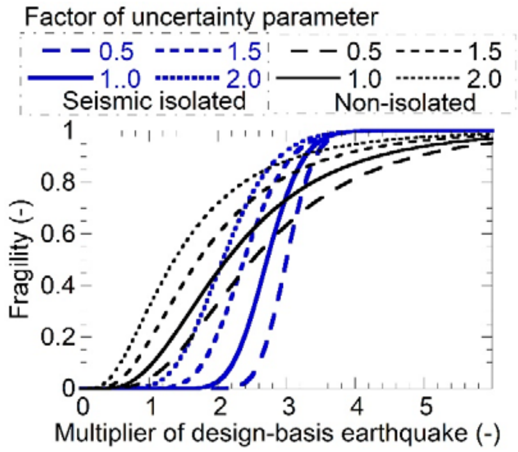


Figure 6. Fragility curves for thick-walled reactor vessel considering uncertainty parameters.

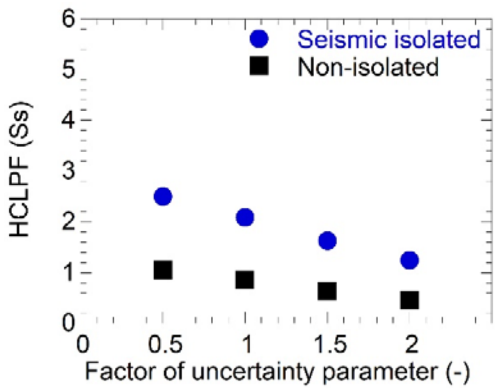


Figure 7. Response reduction effects on thick-walled reactor vessel.
(Ss: Design-basis earthquake)

SEISMIC COUNTERMEASURES AGAINST CLIFF-EDGE EFFECTS

According to past seismic risk assessment studies, cliff-edge effects could be caused by the loss of function of the auxiliary cooling system or power supply system important for decay heat removal in non-isolated LWRs, whereas it can be caused by the loss of components boundary in SFRs. Countermeasures against cliff-edge effects, therefore, are required to seismically reinforce components or to introduce the seismic isolation system so as to withstand greater earthquakes.

When a seismic acceleration exceeds the limit of linear behavior of the laminated rubber, the hardening behaviour could occur in the horizontal direction and softening could occur in the vertical direction. Significant hardening and softening effects increase remarkably loads on the systems and components and tend to increase these fragilities in the seismic isolated plant. However, such a coupled behavior has not been fully figured out yet, and therefore it can be one of knowledge-oriented cliff-edge effects. For countermeasures against the cliff-edge effect, this study suggests mitigation of the hardening and softening effects and mitigation of the deformation of laminated rubber.

For the mitigation of the hardening and softening; these phenomena should be understood correctly at first, and the findings should be reflected to seismic response analyses. As mentioned previously, active researchers have been conducting fracture and aging tests which provide experimental findings for the hardening and softening behaviours. The mitigation of hardening and softening was observed in the rather thick laminated rubber developed for SFRs.

For the mitigation of the deformation of laminated rubber, one of the solutions is to strengthen a damping function in the horizontal direction in order to suppress the horizontal deformation of laminated rubber, namely hardening. The other one is a vertical isolation technology to mitigate significant vertical deformation, namely softening.

CONCLUSIONS

The results of the fragility analysis showed that the seismic isolation technology is effective to prevent cliff-edge effects since the technology largely reduced the structural response effects nearly twice as much as that of the non-isolated plant even with the uncertainty focusing on response factors of components. This study concluded that the isolation is notably effective to avoid the cliff-edge effects. The seismic countermeasures against the cliff edge effect of the seismic isolation technology were also proposed to be the mitigation of the hardening and softening effects and the mitigation of the deformation of laminated rubber. To reduce these potential cliff edge effect, further research and development efforts are necessary in future.

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