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SEISMIC FRAGILITY PARAMETER THAT MINIMIZE RESPONSE UNCERTAINTY OF SEISMIC ISOLATED NPP

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ABSTRACT

In seismic probabilistic safety assessment (PSA), it is important that one obtains reasonable fragility of components. When a seismic isolation system is installed in a nuclear power plant, it was demonstrated that a good independent variable in fragility (fragility parameter) is required to achieve a less response uncertainty (variation) in the previous studies. In this paper, a quantitative comparison of response variations is carried out to select a good fragility parameter in case of a seismic isolation system. Structural analyses based on a lumped mass model are carried out and response variations are calculated in terms of an independent variable of peak ground velocity (PGV), velocity spectrum which period corresponds to a natural period of a seismic isolation layer ($Sv_{(np)}$) and peak ground acceleration (PGA). In the analyses, a laminated rubber and an oil damper are applied for the isolation system, which is planned to be installed in Japan Sodium-cooled Fast Reactor (JSFR). As a result, it is concluded that there are no large differences of an appropriateness for fragility parameter between PGV and $Sv_{(np)}$, in case of a high damping system. On the other hand, in case of a low damping system, $Sv_{(np)}$ is the most appropriate fragility parameter.

1. INTRODUCTION

Seismic PSA (Probabilistic Safety Assessment) is to assess seismic safety of nuclear facility probabilistically, analyzing core damage frequency. For figuring out core damage frequency accurately, it is important to select a good independent variable in a seismic fragility (fragility parameter) to decrease a response uncertainty (variation). In previous researches, it was proposed that peak ground velocity (PGV) and velocity spectrum which period corresponds to a natural period of a seismic isolation layer ($Sv_{(np)}$) are appropriate fragility parameters for an seismic isolation system. However, a quantitative consideration of a difference among fragility parameters was not discussed well in the previous studies. Accordingly, a quantitative comparison of response variations is carried out in this study. For this purpose, structural analyses based on a lumped mass model are carried out and response variations are calculated in terms of independent variables of PGV, $Sv_{(np)}$ and peak ground acceleration (PGA).

In general, variation of fragility comes from response and capacity of components. Furthermore, response variation is separated into two categories; one stems from physical property of components and the other is seismic wave variation. In this study, the authors focus on a response variation caused by seismic wave variation.

2. STRUCTURAL ANALYSIS MODEL

Response analyses were conducted for a three degree of freedom model as shown in Fig. 1 (Minagawa *et al.*, 2011). The analytical model is composed of two layers of a superstructure and an isolation layer. A combination of a laminated rubber (H=2%) and an oil damper (H=43%) is selected as an isolation system, which is planned to be installed in Japan Sodium-cooled Fast Reactor (JSFR).

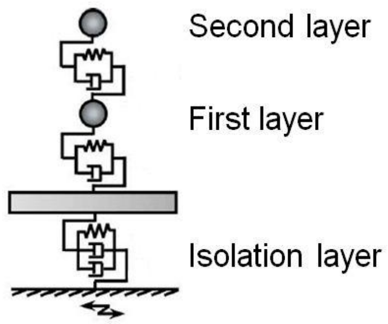

Fig. 1 Analytical model

3. QUANTITATIVE COMPARISON OF RESPONSE VARIATION

The seismic wave variation includes spectral form variation and seismic phase variation. In this evaluation, quantitative comparisons are evaluated by using two kinds of seismic waves. PGA, PGV and $Sv_{(np)}$ are selected as three fragility parameters. $Sv_{(np)}$ is velocity spectrum which period corresponds to a natural period (T=3.41s) of the seismic isolation layer.

3.1 Seismic waves

Firstly, 300 seismic waves are generated by using fixed spectral form and random phase. Then, 300 seismic waves are also generated by using random spectral form and phase. Target spectra consisted of four points which form is defined by using the velocity spectrum of Magnitude 8, Hypocentral distance 25 [km] and Exceedance probability 50% (Hirata *et al.*, 1992) is selected as a base target spectrum.

3.1.1 Fixed spectral form and random phase

Form of target spectra is fixed and magnitude of the spectra is changed as shown in Fig. 2. The base target spectrum is used for generating a first ground motion. A phase of each wave changes randomly.

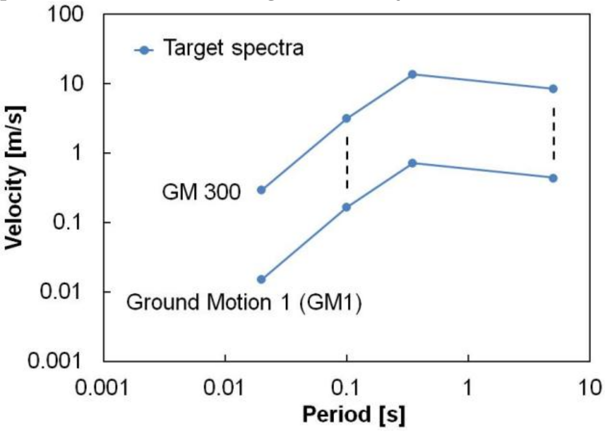

Fig. 2 Schematic of fixed target spectra

3.1.2 Random spectral form and phase

Four points of target spectra are in accordance with lognormal distribution (median: λ, logarithmic standard deviation: ζ). The base target spectrum is defined as a median for generating a first ground motion. A logarithmic standard deviation is defined on the basis of the previous paper (Hirata *et al.*, 1992). Form of median is fixed and magnitude of the median is changed as shown in Fig. 3. A range of probability at four points is 16% < p < 84%. A phase of each wave changes randomly.

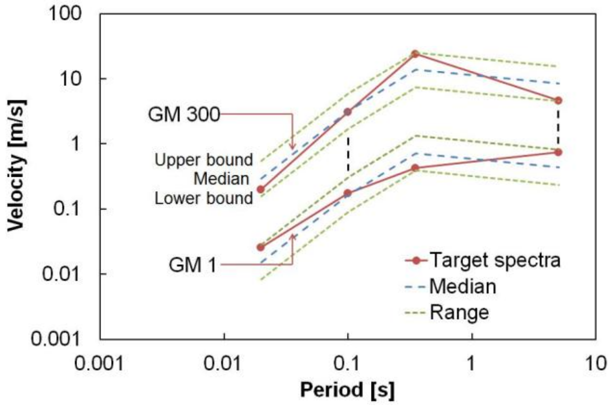

Fig. 3 Schematic of random target spectra

3.2 Analytical Procedure

Response analyses are conducted using two kinds of seismic waves. A relationship between fragility parameters and maximum responses is analyzed. And also, analytical values are separated by whether they are achieved to a hardening. Response variation is calculated as logarithmic standard deviation which is a deviation of analytical values from regression lines. As maximum responses, maximum displacement is selected for the isolation layer and maximum absolute acceleration is selected for two layers of the superstructure. An example of response values and regression lines is shown in Fig. 4 (seismic waves: Fixed target spectra, fragility parameter: PGV, responses: First layer, Maximum absolute acceleration).

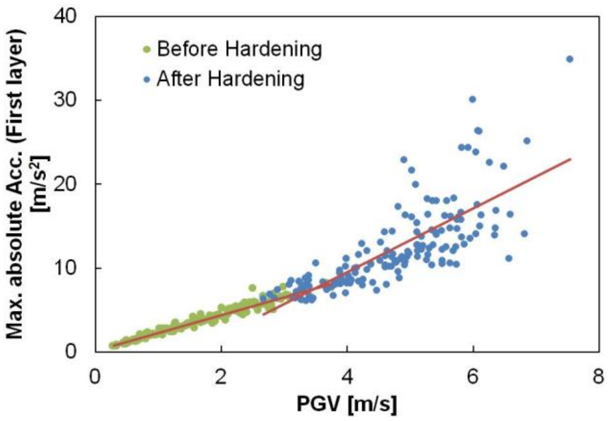

Fig. 4 Analysis result (Fixed target spectra, PGV, First layer, Max. absolute Acc.)

Regarding to the superstructure, before achieving to the hardening, response variation is small. While, after hardening, response variation gets large as shown in Fig. 4. On the other hand, the response variation of isolation layer after hardening gets smaller than that before hardening, because an increasing rate of a maximum displacement is reduced by the hardening.

3.3 Result and Discussion

Response variations of three fragility parameters under given the seismic waves generated from the fixed target spectra are compared as shown in Fig. 5. Response variations of three fragility parameters under given the seismic waves generated from the changed target spectra are compared as shown in Fig. 6.

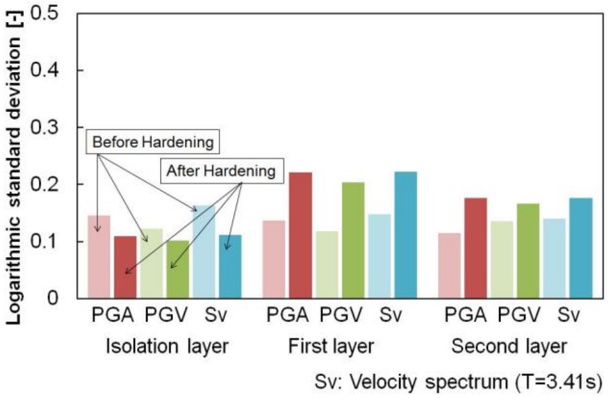

Fig. 5 Comparison of response variation (Fixed target spectra)

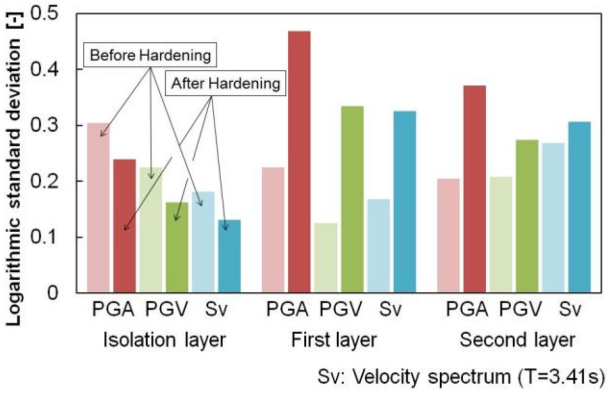

Fig. 6 Comparison of response variation (Random target spectra)

Figure 5 shows that no large differences of the response variations are evaluated regardless of three fragility parameters. On the other hand, Figure 6 shows that the response variations after hardening given by using PGA gets larger than that based on the other fragility parameters in case of the seismic waves with variable target spectra. For this reason, a ratio of short-period intensity to long-period intensity is changed by using seismic waves via the changed target spectra. Therefore, correlation between PGA and a response of an isolation system weaken, because the response has a strong correlation with long-period intensity while PGA has a strong correlation with short-period intensity. Moreover, a hardening is caused by a large displacement of an isolation layer. Hence, the response has a stronger correlation with velocity which is obtained by integrating acceleration than acceleration. In seismic PSA, response variation in which response achieves to strength is used. Therefore, PGV and $Sv_{(np)}$ are more appropriate than PGA as fragility parameter because their response variations after hardening are smaller than PGA. Furthermore, no large differences of the response variations after hardening in terms of $Sv_{(np)}$ and PGV are shown in the both Fig. 5 and Fig. 6.

When an oil damper is employed in an isolation system, a high damping factor is achieved at the isolation layer. As a result of this evaluation, no large differences of response variations among fragility parameters (PGA, PGV and $Sv_{(np)}$) are evaluated in case of seismic waves with random phase, when a high damping factor is achieved at an isolation layer. On the other hand, response variation after hardening given by using PGA gets larger than that based on the other fragility parameters in case of the seismic waves with variable target spectra and phase. Consequently, PGV and $Sv_{(np)}$ are more appropriate fragility parameter than PGA.

3.4 Influence of Velocity period on Velocity spectrum

In the previous section, no large differences of response variation after hardening given by using $Sv_{(np)}$ and PGV are investigated. Here, *Sv* is influenced by parameters of period and damping factor. The previous study was conducted for an isolation system with a hysteretic damping device and, 5% damping factor and a natural period of the isolation layer are selected as parameters of *Sv* (Hirata *et al.*, 1992). On the other hand, in this paper, the oil damper (*H*=43%) is employed in the isolation system. A damping factor of the isolation layer is higher than that in the previous study. Therefore, in this evaluation, an appropriateness of *Sv* is evaluated on the basis of a relationship between analytical models and appropriate parameters of *Sv*.

3.5 Evaluation procedure

An evaluation is carried out by figuring out response variations (logarithmic standard deviation) changing period of *Sv* (*h*=5%). Periods are selected nine values including the natural period of the isolation layer.

At first, a comparison of response variation is evaluated by using the original analytical model (damping factor of the isolation layer 45%) and seismic waves generated from the fixed target spectra in previous section. Then, a comparison of response variation is evaluated by using the changed analytical model (damping factor of the isolation layer 2%). And also, seismic waves generated from the fixed target spectra in previous section are scaled down 1/4 in order to divide analytical values between before hardening and after hardening as equally as possible.

3.6 Result and Discussion

At first, a comparison of response variations (Original analytical model, First layer) is given as shown in Fig. 7. A yellow point is plotted as a response variation which period corresponds to the natural period of the isolation layer (*T*=3.41s).

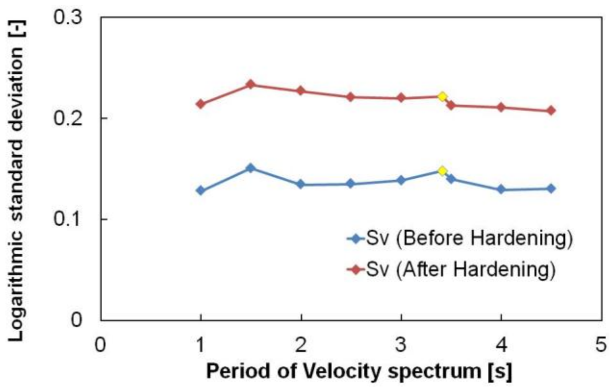

Fig. 7 Comparison of response variations (Isolation layer *H*=45%)

Figure 7 shows that no superiority of the national period of the isolation layer is evaluated in case of the analytical model with high damping system. And also, no difference of the periods is evaluated. Similar results are shown at the other layers as well.

Then, a comparison of response variations (Changed analytical model, First layer) is given as shown in Fig. 8.

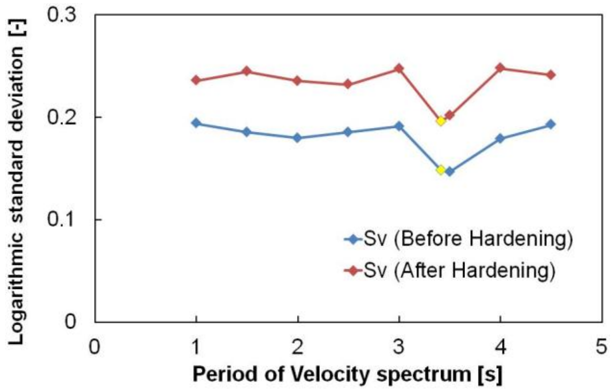

Fig. 8 Comparison of response variations (Isolation layer *H*=2%)

Figure 8 shows that an extreme value around the national period of the isolation layer is evaluated in case of the analytical model with low damping system. Similar results are shown at the other layers as well. Therefore, when a high damping factor is employed at the isolation layer, superiority of the natural period of the isolation layer weakens. In case of a low damping system, the reason of a strong correlation between *Sv* and responses (Maximum acceleration) is as follows.

Firstly, a correlation coefficient between maximum acceleration (first layer) and maximum relative story displacement (isolation layer – first layer) is shown in the following table.

Table 1 Max acceleration (first layer) and Max relative story displacement (isolation layer – first layer)

Damping factor of the isolation layer	45%	2%
correlation coefficient	0.99	1.00

Table 1 shows that regardless of the damping factor, the correlation coefficient between maximum acceleration and maximum relative story displacement is high. In a next paragraph, a relationship between *Sv* and maximum displacement is evaluated in detail.

A maximum relative displacement of each layer is given as (Ohsaki, 1996)

$$\left|x_i(t)\right|_{\max} \simeq \sqrt{\sum_{j=1}^{n}\left|x_i^{(j)}\right|^2} \simeq \sqrt{\sum_{j=1}^{n}\left[\beta^{(j)}u_i^{(j)}Sd_{\left(h^{(j)},T^{(j)}\right)}\right]^2} \qquad (1)$$

where $\beta^{(j)}u_i^{(j)}$ is a participation vector and $Sd_{\left(h^{(j)},T^{(j)}\right)}$ is a value of a displacement spectrum of each mode.

Participation vectors of both analytical models are given as shown in Fig. 9. A stiffness of the isolation layer before hardening is used in calculating the participation vectors.

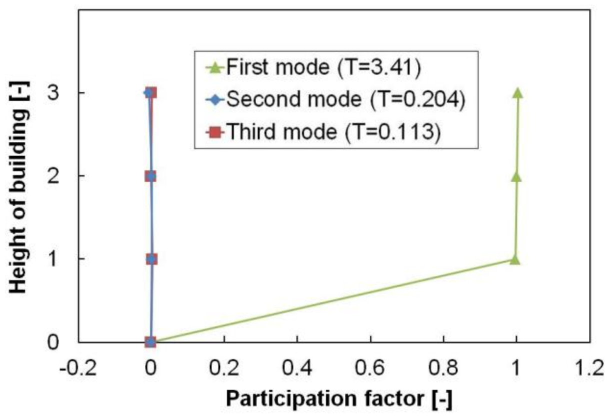

Fig. 9 Participation vector of each mode

Figure 9 shows that an influence of first mode is strong and a difference between second mode and third mode is a little. Therefore, the superstructure on the isolation system behaves like a rigid body. However, in case of a high damping system, there is a difference of time when each mass point achieves to a maximum displacement point and a neutral axis.

Here, in case of the low damping system (*H*=2%), displacement spectra of each mode are evaluated as shown in Table 2. And also, a case of the 45% damping factor is shown in Table 3.

Table 2 Displacement spectra of each mode (Damping factor *H*=2%)

	First mode	Second mode	Third mode
$Sd_{\left(h^{(j)},T^{(j)}\right)}$ [m]	h=2%, T=3.41s	h=5%, T=0.204s	h=9%, T=0.113s
	0.34	0.012	0.003

Table 3 Displacement spectra of each mode (Damping factor *H*=45%)

	First mode	Second mode	Third mode
$Sd_{\left(h^{(j)},T^{(j)}\right)}$ [m]	h=45%, T=3.41s	h=6%, T=0.204s	h=13%, T=0.113s
	0.083	0.012	0.002

The displacement spectrum of the first mode is larger than other modes, regardless of the damping factor of the isolation layer as shown in Table 2 and Table 3. And also, strong influence of the first mode is evaluated in case of the low damping system.

A maximum relative displacement of each layer is given by Eq. (2) because of Eq. (1), Table 2 and Table 3.

$$\begin{aligned}\left|x_i(t)\right|_{\max} &\simeq \beta^{(1)} u_i^{(1)} Sd_{\left(h^{(1)},T^{(1)}\right)} \\ &\propto Sd_{\left(h^{(1)},T^{(1)}\right)}\end{aligned} \tag{2}$$

Here, a maximum relative story displacement is closely related to a difference of each maximum relative displacement because of superiority of the first mode.

A maximum relative story displacement is given as

$$\begin{aligned}X_{iso} &= \left|x_1(t)\right|_{\max} \\ X_{21} &= \left|x_2(t)\right|_{\max} - \left|x_1(t)\right|_{\max} \\ X_{32} &= \left|x_3(t)\right|_{\max} - \left|x_2(t)\right|_{\max}\end{aligned} \tag{3}$$

where X_{iso} is a maximum relative story displacement between ground and isolation layer, X_{21} is a maximum relative story displacement between the isolation layer and first layer and X_{32} is a maximum relative story displacement between the first layer and the second layer. However, it is not appropriate to use Eq. (3) for a high damping system because of time difference to achieve to each maximum displacement point.

Here, a validation of Eq. (3) is shown in Table 4 and Table 5. Firstly, in Table 4, a validation in case of the low damping system (*H*=2%) is evaluated. Then, in Table 5, a validation in case of the high damping system (*H*=45%) is evaluated.

Table 4 Displacement spectra of each mode (Damping factor *H*=2%)

	Analytical value	Estimate value	
		Estimate maximum relative story displacement	Estimate maximum relative story displacement (only first mode)
X_{32} [m]	1.45E-03	1.43E-03	1.43E-03
X_{21} [m]	1.59E-03	1.54E-03	1.54E-03
X_{iso} [m]	3.73E-01	3.66E-01	3.66E-01

Table 5 Displacement spectra of each mode (Damping factor *H*=45%)

	Analytical value	Estimate value	
		Estimate maximum relative story displacement	Estimate maximum relative story displacement (only first mode)
X_{32} [m]	1.33E-03	3.49E-04	3.49E-04
X_{21} [m]	8.45E-04	3.76E-04	3.76E-04
X_{iso} [m]	8.94E-02	8.91E-02	8.91E-02

Table 4 shows that it is appropriate to use Eq. (3) for the low damping system because an analytical value and an estimate value of each layer are similar. And also, a strong influence of the first mode is shown. Table 5 shows that it is not appropriate to use Eq. (3) for the high damping system. This result shows that there is time difference to achieve to each maximum displacement point. Hence, in case of a low damping system, a maximum relative story displacement is estimated by a displacement spectrum which parameters correspond to a first mode (natural period and damping factor of an isolation layer) and a participation vector.

A relationship between a maximum relative story displacement and a displacement spectrum is given as

$$X_i \propto Sd_{\left(h^{(1)},T^{(1)}\right)} \tag{4}$$

Here, when a damping factor is low, a relationship between a displacement spectrum and velocity spectrum is given by Eq. (4). (Ohsaki, 1996)

$$Sd_{(h,T)} \simeq \frac{T}{2\pi} Sv_{(h,T)} \qquad (h \ll 1) \tag{5}$$

Substituting Eq. (5) into Eq. (4), a relationship between a maximum relative story displacement X_i and a velocity spectrum is given as

$$X_i \propto Sv_{\left(h^{(1)},T^{(1)}\right)} \qquad (h \ll 1) \tag{6}$$

Here, a maximum relative story displacement is closely related to a maximum acceleration A_i as shown in Table 1. A relationship between response (maximum acceleration) and fragility parameter (*Sv*) is given as

$$A_i \propto Sv_{\left(h^{(1)},T^{(1)}\right)} \qquad (h \ll 1) \tag{7}$$

In the Eq. (7), when a damping factor of an isolation layer is low, velocity spectrum which parameters correspond to a natural period and a damping factor of a seismic isolation layer shows strong correlation with response (maximum acceleration). Similarly, fragility parameter (velocity spectrum which period corresponds to a natural period of a seismic isolation layer) shows a strong correlation with response.

A comparison of response variation is shown in Fig. 10 (First building, before hardening, damping factor of the isolation layer 2%). Two damping factors, 2% and 5% are selected, and nine periods including the natural period of the isolation layer are selected.

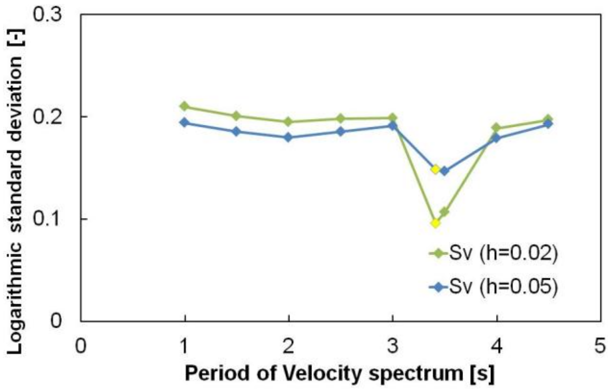

Fig. 10 Comparison of response variations (Isolation layer *H*=2%, Before hardening)

Figure 10 shows that an extreme value is evaluated around the national period in case of the isolation system with the low damping factor, regardless of the damping factors of the isolation layer. And also, a response variation given by the velocity spectrum which parameters correspond the damping factor and the national period of the isolation layer shows an extreme value. Similar results are shown after hardening. Accordingly, in case of the isolation system with low damping factor, when the damping factor and the national period of the isolation layer are used as parameters of *Sv*, the *Sv* has the strongest correlation with response. On the other hand, a correlation between fragility parameter and response weaken, in case of the isolation system with high damping factor, because of a low superiority of a first mode and a weakness of a relationship between *Sv* and *Sd*.

As a result, when a high damping factor is achieved at an isolation layer, a superiority of velocity spectrum with a natural period of the seismic isolation layer is not investigated. On the other hand, in case of a low damping system, local minimization of the response variation is achieved around a natural period of the seismic isolation layer.

4. CONCLUSIONS

The selection of a good fragility parameter to lower response variation is proposed, and conclusions of this paper are summarized as follows.

No large differences of response variations among fragility parameters (PGA, PGV and $Sv_{(np)}$) are evaluated in case of seismic waves with random phase, when a high damping factor is achieved at an isolation layer. On the other hand, response variation after hardening given by using PGA gets larger than that based on the other fragility parameters in case of the seismic waves with variable target spectra and phase. Consequently, PGV and $Sv_{(np)}$ are more appropriate fragility parameter than PGA.

When a high damping factor is achieved at an isolation layer, a superiority of the velocity spectrum with a natural period of the seismic isolation layer is not investigated. On the other hand, in case of a low damping system, local minimization of response variation is achieved around a natural period of the seismic isolation layer.

As a result, when a high damping mechanism is installed in a seismic isolation system, no large differences of response variations between PGV and $Sv_{(np)}$ are evaluated. On the other hand, in case of a low damping system, it is concluded that velocity spectrum with a natural period of a seismic isolation layer is the most appropriate fragility parameter.

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NOMENCLATURE

PGA	peak ground acceleration	[m/s^2]
PGV	peak ground velocity	[m/s]
Sv	velocity spectrum	[m/s]
H	damping factor of an isolation layer	
T	period	[s]
p	probability value	
h	damping factor of velocity spectrum	
x_i	relative displacement	[m]
Sd	displacement spectrum	[m]
u	eigenvector	
X_i	maximum relative story displacement	[m]
A_i	maximum acceleration	[m/s^2]

Greek Letters

λ	median
ζ	logarithmic standard deviation
β	participation factor

Subscripts

np	natural period of a seismic isolation layer	[s]
i	*i*-th material point	
j	*j*-th mode	

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