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Seismic response distribution estimation for isolated structures using stochastic response database

Seung-Hyun Eem[1] and Hyung-Jo Jung*[2]

[1]*Disaster Management HPC Research, Korea Institute of Science and Technology Information, 245 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea*
[2]*Department of Civil and Environmental Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea*

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Abstract. Seismic isolation systems decouple structures from ground motions to protect them from seismic events. Seismic isolation devices have been implemented in many full-scale buildings and bridges because of their simplicity, economic effectiveness, inherent stability, and reliability. It is well known that the most uncertain aspect for obtaining the accurate responses of an isolated structure from seismic events is the seismic loading itself. It is needed to know the seismic response distributions of the isolated structure resulting from the randomness of earthquakes when probabilistic designing or probabilistic evaluating an isolated structure. Earthquake time histories are useful and often an essential element for designing or evaluating isolated structures. However, it is very challenging to gather the design and evaluation information for an isolated structure from many seismic analyses. In order to evaluate the seismic performance of an isolated structure, numerous nonlinear dynamic analyses need to be performed, but this is impractical. In this paper, the concept of the stochastic response database (SRD) is defined to obtain the seismic response distributions of an isolated structure instantaneously, thereby significantly reducing the computational efforts. An equivalent model of the isolated structure is also developed to improve the applicability and practicality of the SRD. The effectiveness of the proposed methodology is numerically verified.

Keywords: isolated structure; seismic response distribution; stochastic response database; equivalent model

1. Introduction

Intense seismic events cause extensive and severe structural damage. To protect structures from seismic events, one of the most-widely accepted control strategies for civil engineering structures such as buildings and bridges is to use a seismic isolation system. In a seismic isolation system, isolation devices are inserted between the ground and the superstructure to protect the structure in the event of an earthquake (Eem *et al*. 2013). The seismic performance of such isolation systems has been verified by the 1994 Northridge earthquake and the 1995 Kobe earthquake (Jun 2010).

*Corresponding author, Professor, E-mail: hjung@kaist.ac.kr

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Many seismic isolation devices (e.g., laminated rubber bearings, lead-rubber bearings, friction bearings) have been implemented in many full-scale buildings and bridges because of their simplicity, inherent stability, and reliability (Spencer and Nagarajaiah 2003).

It is well known that the most uncertain aspect for structural responses resulting from seismic events is the seismic loading itself (Galambos *et al.* 1982). Knowledge of the seismic response distributions of the isolated structure resulting from the randomness of earthquakes is needed when designing or evaluating an isolated structure. The results of time history seismic analyses are useful factors for designing and evaluating the isolated structures. Increasingly, suites of time histories are used as the primary vehicles for analysis and design. The number of different analyses required for this approach and the volume of information generated by such analyses are both excessive, and gathering average design information from many seismic analyses is a monumental task (Naeim and Kelly 1999). Moreover, evaluating the seismic performance of an isolated structure by analytical methods is difficult. Therefore, Monte Carlo simulations are used to obtain the probabilistic seismic performance of isolated structures by seismic distributions. However, a large number of samples must be extracted to obtain reliable results by using Monte Carlo simulations. Numerous nonlinear dynamic analyses need to be performed to evaluate the seismic performance of an isolated structure, and this is impractical.

Obtaining the seismic response distribution is limited by the extensive simulation needed to account for seismic randomness. To shorten the simulation time, a response database can be developed for calculating the seismic response distribution (Jeong and Elnashai 2007). The response database is a collection of pre-run inelastic response analyses of structures with a wide range of response parameters. Because seismic response analyses are performed for single-degree-of-freedom (SDOF) systems, various types of structures can be used. However, the uncertainty will be increased owing to the simplified structure of the SDOF system. Towashiraporn used the "dual response surface" developed by Lin *et al*. (Lin *et al.* 1995) for storing the response data more efficiently in the response database (Towashiraporn 2004). The dual response surface is organized with means and variances of seismic responses. However, the seismic distribution could not be estimated accurately with only the mean and variance. Moreover, this methodology can be used only for specific types of structures.

In this paper, an efficient and reliable methodology is proposed for predicting the seismic response distribution of an isolated structure using a stochastic response database (SRD). An equivalent model of an isolated structure is also developed. This methodology will improve the applicability and practicality of the SRD. The SRD associates the seismic response distributions with the independent input parameters of response surfaces. The input parameters are structural parameters and seismic intensity, and outputs are the seismic response distributions. Therefore, once the fundamental parameters are known, the seismic response distributions of an isolated structure can be directly obtained from the SRD without the need for simulations. Consequently, the SRD can be used to estimate the seismic response distribution of isolated structures with significantly reduced computational effort.

2. Equivalent model of isolated structures

An equivalent isolated structure model may have different mechanical properties, such as mass and radius of gyration, compared with a fully modeled isolated structure; however, the seismic response of the equivalent isolated structure model would be the same as that of the fully modeled isolated structure. This methodology will improve the applicability and practicality of the SRD to be introduced later.

2.1 Construction of the equivalent model

Before describing the equivalent model of an isolated structure, the simplified model of an isolated structure will be introduced briefly. The simplified isolated structure model is composed of fewer masses and isolators compared to the fully modeled isolated structure. However, the seismic responses of those two models are almost identical (Eem and Jung 2013a, 2014). The six parameters are selected which are affecting the seismic response of an isolated structure for the simplified isolated structure devised by Eem and Jung (Eem and Jung 2013a). Three parameters are selected from the superstructure: the mass (M), the radius of gyration (R_m), and the coordinates of the center of mass (CM). The additional three parameters are selected from the isolation layer: the stiffness (K), the radius of disposition (R_k), and the coordinates of the center of rigidity (CR).

In this section, the equivalent model of an isolated structure is introduced by using a simplified model of an isolated structure. Fig. 1 shows the dynamic model of the simplified isolated structure model used to derive the equation of motion for the simplified isolated structure model. In the figure, K is the nonlinear stiffness of the isolator which varies with displacements, e_r is the eccentricity between the center of mass and the center of rigidity, and u_{Gx} and u_{Gy} are the displacements of the center of mass, respectively.

The kinetic energy of the system is given by

$$T = \frac{1}{2} M \dot{u}_{Gx}^2 + \frac{1}{2} M \dot{u}_{Gy}^2 + \frac{1}{2} I_G \dot{\theta}^2 \tag{1}$$

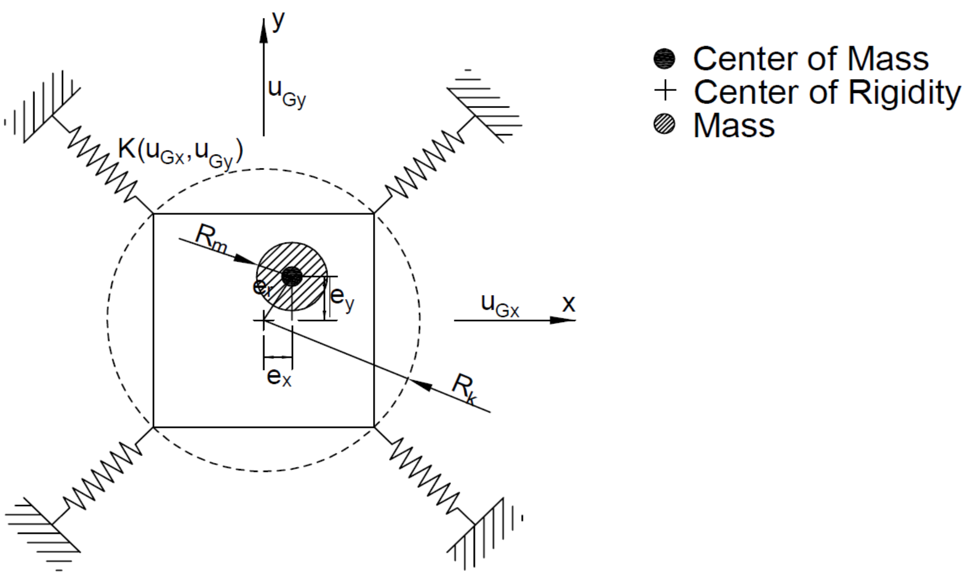


Fig. 1 Simplified isolated structure model

where I_G is the moment of inertia from the center of rigidity and θ is the angular displacement of the center of mass. The potential energy can be expressed as

$$V = 2K(u_{Gx}, u_{Gy})u_{Gx}^2 + 2K(u_{Gx}, u_{Gy})u_{Gy}^2 + \frac{1}{2}K(u_{Gx}, u_{Gy})R_k^2\theta^2(\theta^2 + 4) \tag{2}$$

The equation of motion of the system can be established by Lagrange's equation using Eqs. (1) and (2) as follows

$$M\ddot{u}_{Gx} + 4K(u_{Gx}, u_{Gy})u_{Gx} = -M\ddot{x}_g \tag{3}$$

$$M\ddot{u}_{Gy} + 4K(u_{Gx}, u_{Gy})u_{Gy} = -M\ddot{y}_g \tag{4}$$

$$M(R_m^2 + e_r^2)\ddot{\theta} + 2K(u_{Gx}, u_{Gy})R_k^2\theta(\theta^2 + 2) = -Me_x\ddot{y}_g - Me_y\ddot{x}_g \tag{5}$$

where $\ddot{x}_g$ and $\ddot{y}_g$ are the earthquake inputs (i.e., acceleration time histories) in x and y directions, respectively, e_x and e_y are the eccentricity from the center of mass in x and y directions, respectively.

If it is assumed that the angular displacement is quite small, Eq. (5) can be simplified by treating θ^3=0 and eliminating higher order terms as follows

$$M(R_m^2 + e_r^2)\ddot{\theta} + 4K(u_{Gx}, u_{Gy})R_k^2\theta = -Me_x\ddot{y}_g - Me_y\ddot{x}_g \tag{6}$$

Thus, the equations of motion of the simplified isolated structure model can be expressed as in Eqs. (3), (4) and (6). Let the mass and the radius of gyration both be one for the equivalent isolated structure model. Then, the equations of motion for the equivalent isolated structure model can be revised as

$$\ddot{u}_{Gx} + 4\frac{K(u_{Gx}, u_{Gy})}{M}u_{Gx} = -\ddot{x}_g \tag{7}$$

$$\ddot{u}_{Gy} + 4\frac{K(u_{Gx}, u_{Gy})}{M}u_{Gy} = -\ddot{y}_g \tag{8}$$

Table 1 Equivalent isolated structure model

Equivalent isolated structure model			Value
Mass	*M'*	=	1
Radius of gyration	R_m'	=	1
Center of mass	(CM_x', CM_y')	=	$(e_x/(R_m^2 + e_r^2),\ e_y/(R_m^2 + e_r^2))$
Stiffness	$K(u_{Gx},u_{Gy})$'	=	$K(u_{Gx}, u_{Gy})/M$
Radius of disposition	R_k'	=	$\sqrt{R_k^2/(R_m^2 + e_r^2)}$
Center of rigidity	(CR_x', CR_y')	=	(0, 0)

$$\ddot{\theta} + 4\frac{K(u_{Gx}, u_{Gy})}{M}\frac{R_k^2}{R_m^2 + e_r^2}\theta = -\frac{e_x}{R_m^2 + e_r^2}\ddot{y}_g - \frac{e_y}{R_m^2 + e_r^2}\ddot{x}_g \tag{9}$$

The six parameters for the equivalent isolated structure model are obtained from this simplified isolated structure model as listed in Table 1.

Usually, the mechanical properties of an isolator (nonlinear stiffness) can be represented in bilinear form, as shown in Fig. 2. Each mechanical property of the isolator for the equivalent isolated structure model can be expressed by the following equation

$$K_u' = K_u / M,\;\; K_d' = K_d / M,\;\; Q_d' = Q_d / M \tag{10}$$

2.2 Verification of the equivalent model

Seismic response analyses are performed to verify the validity of the equivalent isolated structure model. The seismic response results of the equivalent model are compared with those of the fully modeled isolated structure model. A building similar to the EOC building of Los Angeles County and the Caltrans San Diego Center, as presented in Naeim and Kelly (1999) and FEMA451, is considered as a verification example. The structural system can be taken as a reinforced-concrete shear wall building with the mass of 1600 tons. As shown in Fig. 3, the building has a regular plan with three rows of columns 10 m apart and spaced at 10 m intervals. The fully isolated structural model is modeled with a total of 15 concentrated masses and 15 collocated base isolators. Also, all the masses are connected to one another with rigid links as shown in Fig. 3.

The base isolation system is designed using a lead rubber bearing (LRB), with a target period of 2.5 s and 15% critical viscous damping (Naeim and Kelly 1999). The parameters for the base isolation system are listed in Table 2.

The equivalent model of the isolated structure consisting of one mass and four isolators is represented in Fig. 1. For the equivalent model, the target mass is 100 tons and the target radius of gyration is 10 m. Details of the parameters for the equivalent model are list in Table 3.

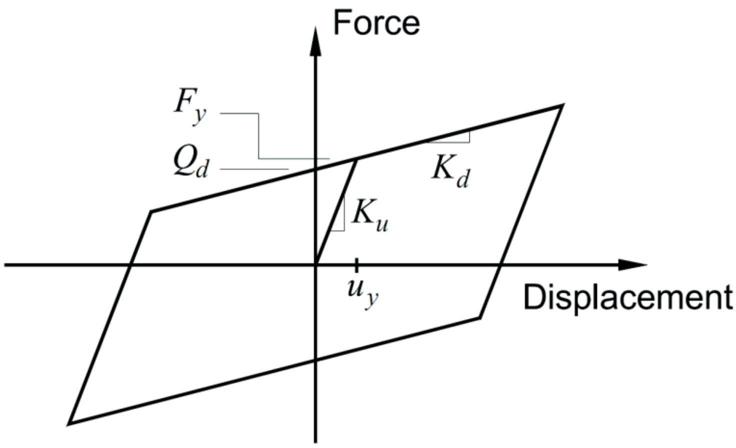


Fig. 2 Mechanical properties of the isolators (Huang *et al.* 2008)

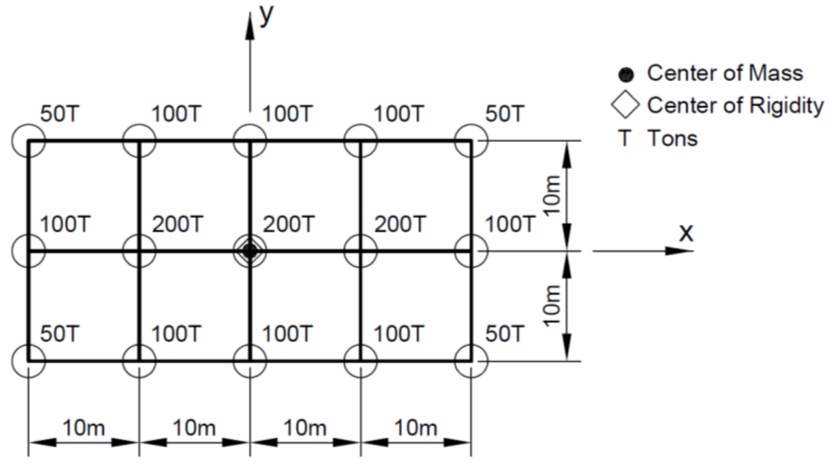


Fig. 3 A verification example structure (Naeim and Kelly 1999)

Table 2 Parameters for the base isolation system (Naeim and Kelly 1999)

Parameters	Values
K_{eff}	10.1 MN/m
K_u	78.49 MN/m
K_d	7.72 MN/m
Q_d	0.637 MN

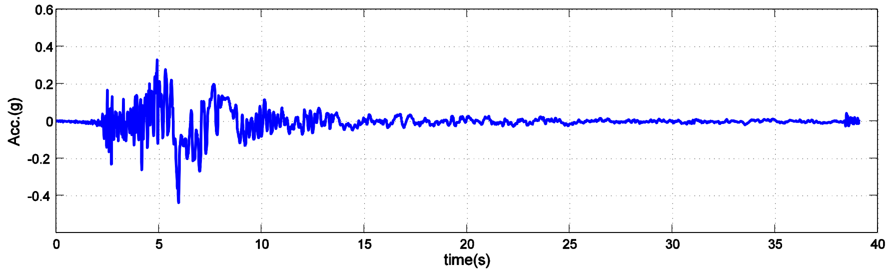
Table 3 Parameters for the equivalent model of the isolated structure

Parameters	Isolated structure	Equivalent model
M	1600 tons	100 tons
R_m	14.1421 m	10 m
CM	(0, 0)	(0, 0)
K_u	78.49 MN/m	4.94 MN/m
K_d	7.72 MN/m	0.48 MN/m
Q_d	0.637 MN	0.040 MN
R_d	16.330 m	11.547 m
CR	(0, 0)	(0, 0)

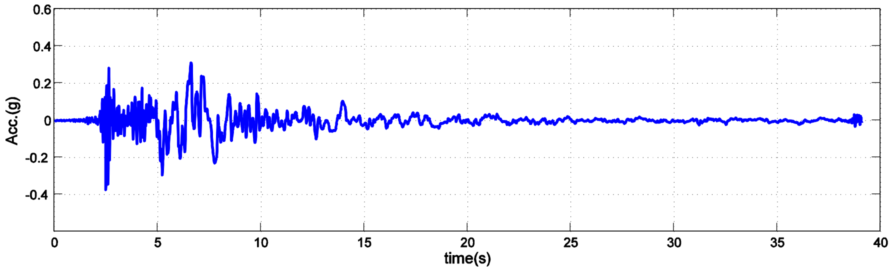
A quantitative study is conducted of the fitness between each seismic response for the full and equivalent models. The fitness between the full model and the equivalent model has been calculated as a fitness value defined as (Eem *et al.* 2012)

$$fitness(\%) = [1 - \frac{norm(D_F - D_E)}{norm(D_F - mean(D_F))}] \tag{11}$$

where norm(·) is the Euclidean norm (2-norm), D_F is the seismic response of the full model and D_E is the seismic response of the proposed model.



(a) Imperial Valley earthquake (Comp. 230° - *x* direction)



(b) Imperial Valley earthquake (Comp. 140° - *y* direction)

Fig. 4 Time histories of the 1979 Imperial Valley earthquake

Table 4 Information on the 1979 Imperial Valley earthquake (Naiem and Kelley 1999)

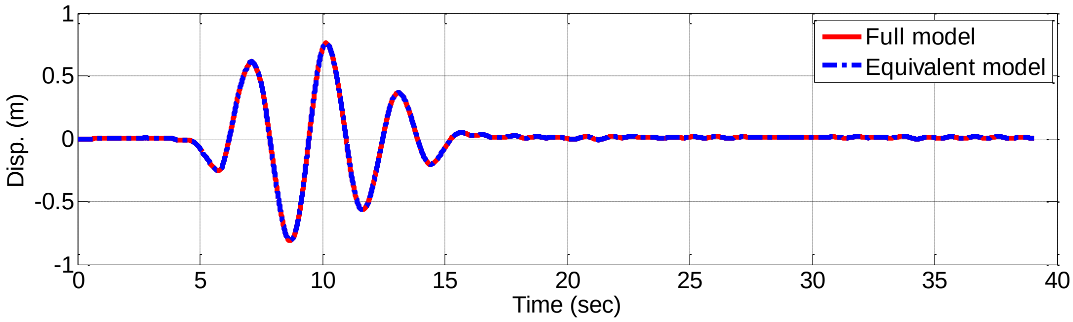
Component	PGA (g)	PGV (cm/s)	PGD (cm)
230°	0.436	100.709	55.165
140°	0.376	63.130	26.942

Table 5 Seismic response fitness values

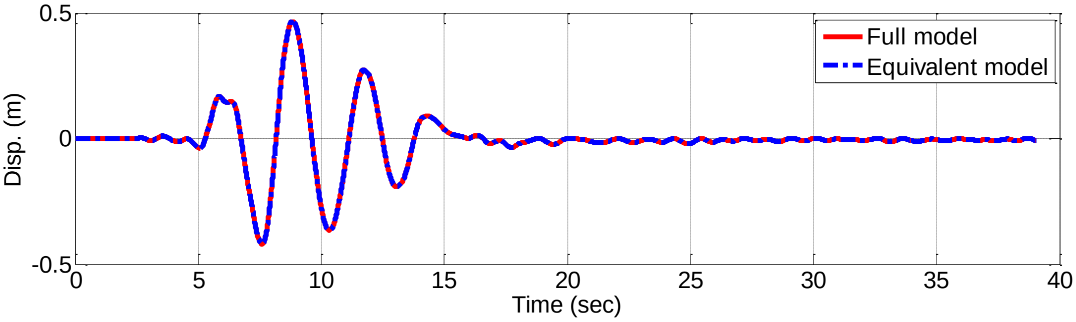
Direction	Fitness value
x (disp.)	99.96 %
y (disp.)	99.96 %
x (acc.)	99.91 %
y (acc.)	99.92 %

A series of seismic response analyses are conducted by using the “1979 Imperial Valley earthquake” excitations. The pairs of time histories are shown in Fig. 4. Other detailed information about the earthquake is given in Table 4.

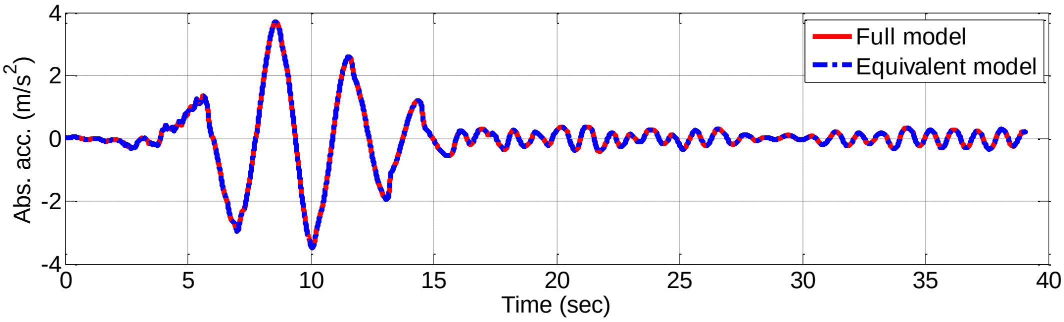
Fig. 5 compares the time histories of the displacement and the absolute acceleration in the *x* and *y* directions at the center of mass. The results show that the equivalent model results correspond quite well with the behavior of fully modeled isolated structure. The resulting fitness values are presented in Table 5. It is observed that the seismic responses of displacements and accelerations in *x* and *y* directions of the equivalent model coincide well with those of the full model results. The high values of the fitness values (>99%) indicate that the equivalent model can be effectively used for estimating the behavior of the fully modeled isolated structure.



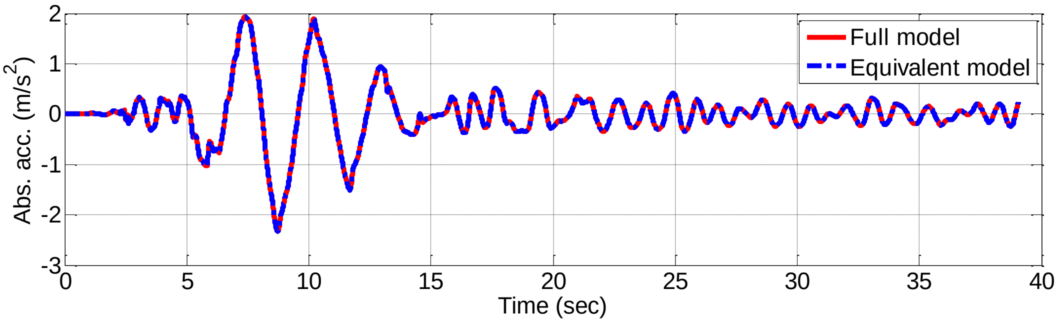
(a) *x* direction displacement



(b) *y* direction displacement



(c) *x* direction acceleration



(d) *y* direction acceleration

Fig. 5 Time history of the seismic response analysis

3. Stochastic response database

The stochastic response database (SRD) is a database for obtaining the distribution of the seismic responses instantaneously. The SRD is also a collection of pre-run dynamic response analyses of an isolated structure with a wide range of response parameters. Once the fundamental parameters are known, the seismic response distributions can be directly obtained without the need for simulation. It is possible to use the equivalent transformation method for an isolated structure, thereby improving the applicability and practicality of seismic analyses of an isolated structure. Thus, the SRD, which is designed for some isolated structure, could be used to estimate seismic response distributions instantaneously of any kind of isolated structures (e.g., buildings, bridges, LNG tanks, and plants).

It is proposed to parameterize the problem in such a manner that a distribution of seismic responses can be derived. The parameters influencing the shape of the distribution of seismic responses are deemed to be (i) earthquake (i.e., seismic intensity, etc.) and (ii) structure (i.e., mass, stiffness, etc.). The SRD will reflect the seismic randomness by considering various types of earthquake scenarios. In the SRD for isolated structures, the structural parameters are the mass (M), the radius of gyration (R_m), the center of mass (CM), the stiffness (K), the radius of disposition (R_k), and the center of rigidity (CR).

Fig. 6 illustrates the concept of the SRD. The SRD is composed of response surfaces that represent the shape of the seismic response distributions. The number of response surfaces with a certain level of seismic intensity depends on which probability model is used for representing the seismic response distribution. Therefore, if the input parameters for the SRD are known, it is possible to obtain the distribution of the seismic response instantaneously.

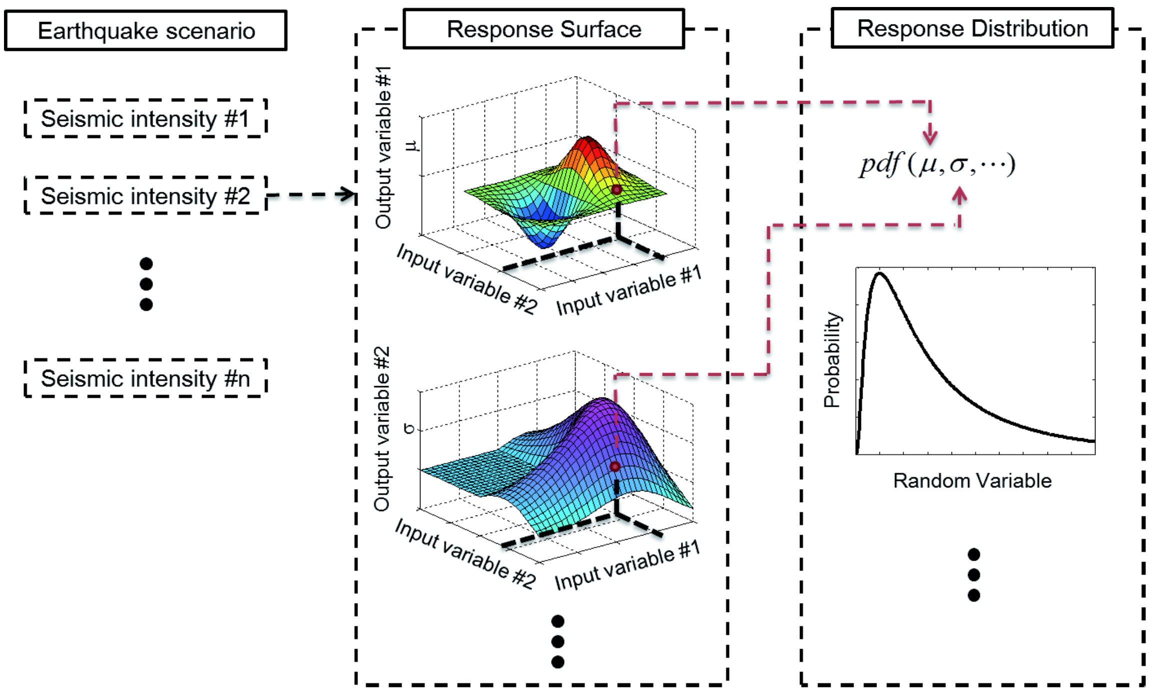


Fig. 6 Concept of the stochastic response database

4. Construction of the stochastic response database

The construction of the SRD can be summarized as follows:

• Select an appropriate seismic intensity parameter (i.e., peak ground acceleration, spectral acceleration, etc.) from the seismic hazard analysis.
• Select or generate an ensemble of earthquake time histories by considering the seismic randomness.
• Identify the structural parameters affecting the seismic responses of the isolated structure.
• Select the ranges of structural parameters.
• Generate isolated structure models using the design of experiments methodology.
• Select the output variables (i.e., displacement, velocity, acceleration etc.).
• Perform seismic response analyses of the isolated structures.
• Select a probability model for the seismic response distribution.
• Extract parameters for the probability model from the seismic response analyses results.
• Generate the response surface to fit the extracted parameters.
• Repeat the process, changing the seismic intensities.

Fig. 7 shows the flowchart for the construction of the SRD.

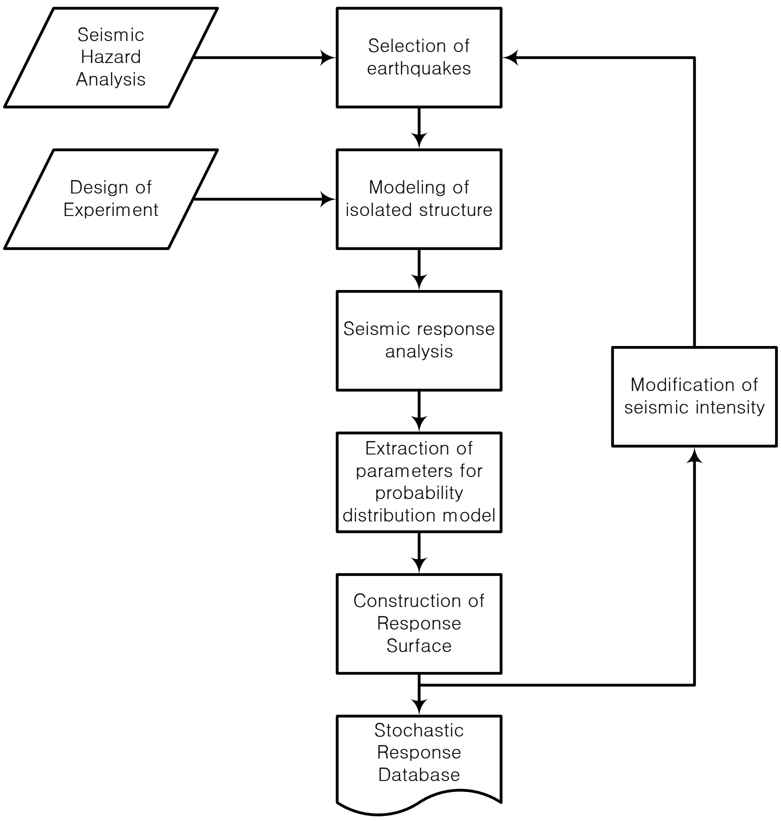


Fig. 7 Flowchart of construction the stochastic response database

4.1 Selection of earthquakes

An appropriate ensemble of earthquakes should be selected for the objectives of the SRD. The selected ensemble of earthquakes defines which sites can be used. For example, if seed earthquakes are selected from a specific site, the SRD can only be used at that specific site. If selected seed earthquakes are revised to match with a certain standard spectrum, the SRD can be used for other sites.

Historical earthquakes or modified historical earthquakes can be used for a nonlinear seismic analysis with ASCE43-05. At least 30 sets of seismic response analyses should be performed to identify the seismic response distribution with ASCE43-05 and SRP 3.7.1 (NRC 2007). In this study, a specific site is not defined, and therefore, 30 seed earthquakes are selected from the Pacific Earthquake Engineering Research Center database. The selected earthquakes are revised to match the design response spectrum as suggested in Regulatory Guide 1.60 (NRC 1973). Selected earthquake information is presented in Table 6.

Table 6 Information for selected earthquakes (30 sets)

Earthquakes	Station	Rock/Soil	Year	Earthquake Magnitude	PGA (g)	PGV (cm/sec)	PGD (cm)
Parkfield	TMB	Rock	1966	6.19	0.2934	17.45	3.61
San Fernando	PUL	Rock	1971	6.61	1.1644	75.55	18.06
Gazli, USSR	GAZ	Rock	1976	6.80	0.6438	61.50	20.80
Imperial Valley	E05	Soil	1979	6.53	0.4481	71.18	49.59
Imperial Valley	SUP	Rock	1979	6.53	0.1598	6.70	2.41
Livermore	KOD	Soil	1980	5.80	0.1066	13.17	4.13
Victoria, Maxico	CPE	Rock	1980	6.33	0.5722	27.06	10.85
Morgan Hill	CLS	Rock	1984	6.19	0.0983	7.92	1.52
Morgan Hill	G06	Rock	1984	6.19	0.2814	23.53	3.85
Nahanni	S1	Rock	1985	6.76	1.0556	43.19	10.20
Nahanni	S3	Rock	1985	6.76	0.1512	4.54	1.95
Superstition Hills	ICC	Soil	1987	6.54	0.2933	45.16	18.07
Spitak, Armenia	GUK	Rock	1988	6.77	0.2071	21.68	8.40
Loma Prieta	BRN	Rock	1989	6.93	0.5263	49.73	10.53
Loma Prieta	CLS	Rock	1989	6.93	0.4975	41.92	10.12
Loma Prieta	LGPC	Rock	1989	6.93	0.7835	77.15	42.67
Erzican, Turkey	ERZ	Soil	1992	6.69	0.4886	72.95	24.79
Cape Mendocino	CPM	Rock	1992	7.01	1.3455	90.38	27.79
Northridge	CHL	Rock	1994	6.69	0.2148	23.13	3.95
Northridge	PAC	Rock	1994	6.69	0.4085	36.76	4.74

Table 6 Continued

Earthquakes	Station	Rock/Soil	Year	Earthquake Magnitude	PGA (g)	PGV (cm/sec)	PGD (cm)
Northridge	PKC	Rock	1994	6.69	0.3482	45.38	11.40
Northridge	RRS	Soil	1994	6.69	0.6336	109.24	28.26
Kobe	KJMA	Rock	1995	6.90	0.7105	77.83	18.87
Kobe	Takatori	Rock	1995	6.9	0.6424	103.197	32.1295
Mammoth Lakes	Long Valley	Rock	1980	6.06	0.3292	19.276	5.1185
Kocaeli, Turkey	GYN	Rock	1999	7.51	0.1387	10.75	2.97
Kocaeli, Turkey	IZT	Rock	1999	7.51	0.2037	27.02	14.61
Chi-Chi, Taiwan	TCU072	Rock	1999	7.62	0.4033	60.08	36.25
ChiChi, Taiwan	TCU089	Rock	1999	7.62	0.2878	30.97	24.38
Duzce, Turkey	BOL	Rock	1999	7.14	0.7662	59.68	17.69

The selected earthquakes are modified in the time domain by using wavelets to maintain non-stationary properties of the earthquake signals which will be more similar to natural earthquakes (Ashtari and Ghasemi 2013). The program used is RspMatch, which was developed by Hancock *et al.* (2006). This program modifies the earthquake signal by adding a wavelet function (f)

$$f_j(t) = \cos[\omega_j(t - t_j + \Delta t_j)]\exp[-(\frac{t - t_j + \Delta t_j}{\gamma_j})^2] \tag{12}$$

where ω_j is the corresponding circular frequency, γ_j is calculated by using

$$\gamma_j = 1.178 f^{-0.93} \tag{13}$$

and Δt_j is the interval between the maximum response time t_j and the wavelet.

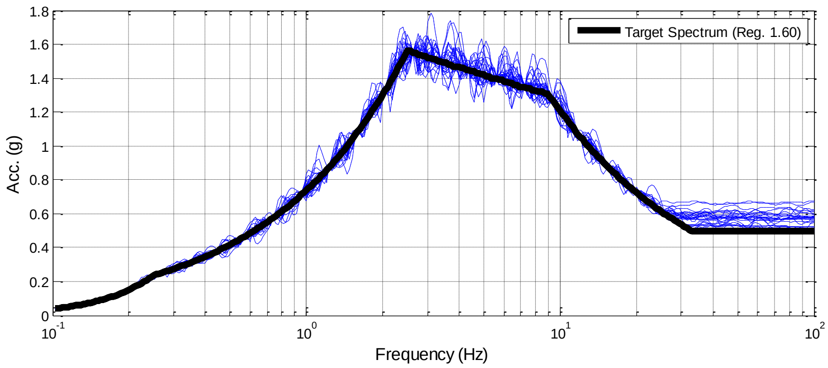


Fig. 8 Response spectra of the modified earthquakes

Table 7 Range of parameters

Parameters	Range
T_d	2 ~ 3
Q_p	0.03 ~ 0.09
e_r	0 ~ 0.05
α	10 ~ 50
R_p	0.85 ~ 1.15

Therefore, modifying the earthquake signal using the wavelet minimizes the distortion of the original earthquake signal. Fig. 8 shows the response spectra of modified earthquakes matched to the zero-period acceleration (ZPA) level of 0.5 g and a damping ratio of 5%. As shown in the figure, the modified earthquakes slightly exceed 0.5 g ZPA. However, this occurs at over 30 Hz; therefore, long-period structures such as isolated structures do not significantly affect the seismic response of the structure (Kim *et al.* 2013).

4.2 Generation of isolated structure models

Kinematic hardening of an isolation system is idealized by using a bilinear model, as shown in Fig. 2. The mass (M) and radius of gyration (R_m) of the generated isolated structures models are 1000 tons and 10 m, respectively. The input parameters selected for the response surface are represented as

$$T_d = \frac{1}{2\pi}\sqrt{\frac{K_d}{M}},\ Q_p = \frac{Q_d}{W},\ \ \alpha = \frac{K_u}{K_d},\ \ R_p = \frac{R_k}{R_m},\ \ e_r = \frac{e}{R_m} \tag{14}$$

where T_d is the period calculated by the second stiffness (K_d), Q_p is the ratio between characteristic strength (Q_d) and weight (W) of the isolated structure, α is the ratio between K_u and K_d, R_p is the ratio between the radius of gyration (R_m) and the radius of disposition (R_k), and e_r is the ratio between the eccentricity (e) of the center of mass and the center of rigidity and the radius of gyration (R_m). The selected parameters are related to M, CM, R_m, K, CR, and R_k, which affects the seismic response of the isolated structures. Table 7 lists the range of each parameter.

The 3-factorial design is used to generate the isolated structure models. The total number of isolated structure models is 243 (i.e., with five input variables for the response surface, one gets 3^5=243). The isolated structure model is generated with one mass and four isolators, as shown in Fig. 1.

4.3 Construction of response surface

The 30 sets of earthquakes and 243 isolated structure models are established for the SRD. A total of 7290 seismic analyses should be performed for a certain level of seismic intensity. Input variables for the SRD are seismic intensity (PGA), T_d, Q_p, e_r, α and R_p. Output variables for the SRD are selected as parameters that define the shape of the seismic response distributions of the translational displacements at the center of mass. The log-normal probability distribution is selected for the shape of the seismic response distributions. Usually, the log-normal probability distribution is used to represent a maximum seismic response distribution (Shinozuka *et al.* 2000). Also, realizations in a seismic analysis set of isolated structures are compared with log-normal distribution which shows that it is acceptable to assume the seismic response distributions follows the log-normal distributions (Huang *et al.* 2009). In addition, a Chi-square goodness-of-fit test is performed to verify that the maximum seismic response distributions of isolated structures follow the log-normal probability distribution (Eem and Jung 2013b). It is observed from the Fig. 13 that the probability distributions of the maximum seismic response follow the log-normal probability distribution.

The 30 seismic analyses will be performed for one isolated structure model with a certain level of seismic intensity. These results will then be used to extract parameters for the seismic response distributions. Two parameters (μ_{ln}, and σ_{ln}) are needed to determine the shape of the log-normal probability distribution. Therefore, two parameters will be extracted for each isolated structure model. In this research, PGA levels of 0.5 g, and 1.0 g are used to establish the SRD.

The response surface is established for a certain level of seismic intensity for the SRD. Input variables for the response surface are $T_d(x_1)$, $Q_p(x_2)$, $e_r(x_3)$, $\alpha(x_4)$, and $R_p(x_5)$. Output variables are statistical parameters (μ_{ln}, and σ_{ln}) that can describe the seismic response distribution. A second-order response surface can be established because of the 3-factorial design method. Two response surfaces will be established for a certain level of seismic intensity to represent the translational displacements of the seismic response distributions. The MATLAB program is used for regression to construct the response surfaces. The second-order response surface is defined by

$$
\begin{aligned}
y = {} & C_0 + C_1x_1 + C_2x_2 + C_3x_3 + C_4x_4 + C_5x_5 \cdots \\
& C_{12}x_1x_2 + C_{13}x_1x_3 + C_{14}x_1x_4 + C_{15}x_1x_5 + C_{23}x_2x_3 \cdots \\
& C_{24}x_2x_4 + C_{25}x_2x_5 + C_{34}x_3x_4 + C_{35}x_3x_5 + C_{45}x_4x_5 \cdots \\
& C_{11}x_1^2 + C_{22}x_2^2 + C_{33}x_3^2 + C_{44}x_4^2 + C_{55}x_5^2
\end{aligned} \tag{15}
$$

Table 8 Response surface coefficients at 0.5 g and 1.0 g

PGA	Par.	C_0 / C_{13} / C_{35}	C_1 / C_{14} / C_{45}	C_2 / C_{15} / C_{11}	C_3 / C_{23} / C_{22}	C_4 / C_{24} / C_{33}	C_5 / C_{25} / C_{44}	C_{12} / C_{34} / C_{55}
0.5 g	μ_{ln}	-1.58E+0	7.53E-1	8.24E-4	-1.15E+1	-9.75E-3	-2.47E-1	-9.17E-4
		-1.46E+0	-5.47E-4	2.26E-2	-5.05E-2	-9.46E-6	1.34E-4	-5.54E-2
		1.18E+0	1.04E-1	-7.38E-2	5.70E-5	5.40E+1	7.28E-3	-7.90E-1
	σ_{ln}	3.08E-2	4.24E-2	-5.96E-4	1.99E+0	-1.16E-3	-5.11E-3	7.94E-5
		-2.90E-1	-1.70E-4	5.53E-3	2.07E-2	7.63E-6	-1.42E-4	1.06E-2
		-1.88E-2	-6.50E-3	-4.60E-3	-7.59E-6	-4.00E+0	4.27E-4	1.40E-3
1.0 g	μ_{ln}	-9.88E-1	8.56E-1	1.72E-4	-5.80E+0	-6.75E-2	-7.02E-1	-1.60E-4
		-1.68E+0	-4.30E-3	4.24E-2	-7.64E-3	-1.51E-6	4.84E-5	-2.30E-1
		2.92E+0	3.87E-1	-8.18E-2	8.90E-6	2.94E+1	4.64E-2	-2.00E+0
	σ_{ln}	1.61E-1	-7.52E-2	6.56E-5	1.91E+0	-2.16E-2	8.08E-2	-2.92E-5
		-3.41E-1	1.22E-3	8.67E-3	7.26E-4	1.81E-6	-1.02E-4	6.20E-2
		-1.87E-1	-9.74E-2	1.74E-2	-2.55E-7	-2.35E+0	7.33E-3	2.58E-1

Table 9 Response surface R^2 values

PGA	Par.	SST	SSR	SSE	R^2
0.5 g	μ_{ln}	24.521	24.415	0.106	0.996
	σ_{ln}	0.305	0.263	0.042	0.862
1.0 g	μ_{ln}	19.969	19.956	0.012	0.999
	σ_{ln}	0.117	0.112	0.005	0.954

The response surface coefficients are listed in Table 8.

Response surface R^2 values are listed in Table 9. When R^2 is close to 1, the response surface is well fitted. The R^2 value can be calculated by using the following

$$\begin{aligned} &SST: total\,sum\,of\ squares = \sum\sum (y_i - \bar{y})^2 \\ &SSR: regression\,sum\,of\ squares = \sum\sum (y_i^* - \bar{y})^2 \\ &SSE: residual\,sum\,of\ squares = SST - SSR \\ &R^2 = SSR / SST = 1 - SSE / SST \end{aligned} \tag{16}$$

where y is the real value, $\bar{y}$ is the average value, and y^* represents the estimation value from the response surface.

As shown in Table 9, R^2 values of μ_{ln} are >0.99 and R^2 values of σ_{ln} are >0.85, which means that the established response surfaces are well fitted.

5. Verification of the stochastic response database

Seismic response distributions of an isolated structure will be estimated by using the SRD. The SRD is verified by comparing the results of seismic response distributions calculated by using the SRD to those of obtained by direct Monte Carlo simulation. The selected isolated structure is the Korean Standard Nuclear Power Plant (Advanced Power Reactor 1400). The Advanced Power Reactor 1400 (APR1400) is a standard evolutionary advanced light water reactor developed in Korea in 2002, capable of producing 1400 MWe. The total mass of the APR1400 is 464,500 tons and its size is 140 m×103 m. The APR1400 nuclear island consists of the reactor containment building, containment internal structures, and an auxiliary building. The nuclear island structures share one common basemat, as shown in Fig. 9. Fig. 10 shows a disposition of isolators.

In order to validate the equivalent model of the isolated nuclear power plant structure, seismic response analysis is performed, which is used for Monte Carlo simulation. The base isolation system is designed for the structural model with the target period of 1.5 sec. The finite element model of the isolated nuclear power plant structure is shown in Fig. 11.

The equivalent model consists of 1 mass and 4 isolators as shown in Fig. 1. The modified historical earthquake input (Spitak, Armenia earthquake), which is revised to match with target spectrum (Reg. 1.60), is used for both models to compare the seismic response results. Fig. 12 compares the seismic response of the x and y displacement at the center of mass. The results show that the results of an equivalent model of the isolated structure corresponds quit well with those of the isolated nuclear power plant.

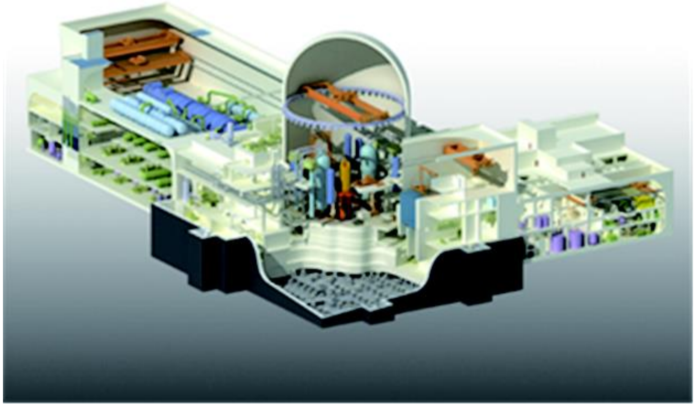


Fig. 9 Advanced Power Reactor 1400 (KEPCO E&C 2012)

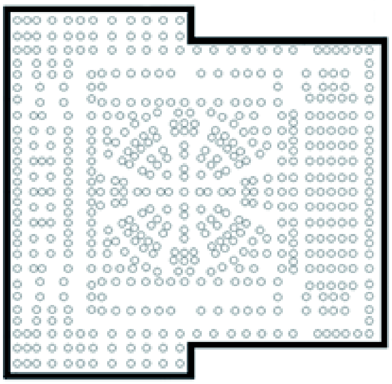


Fig. 10 Disposition of isolators

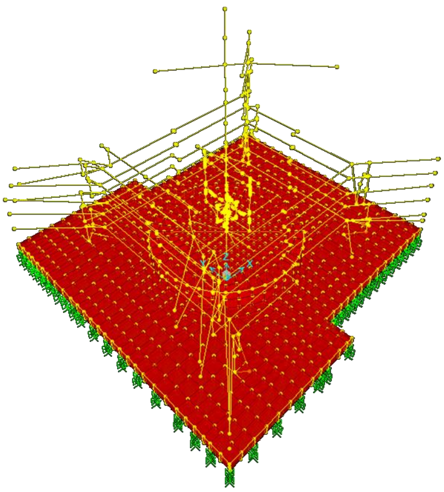
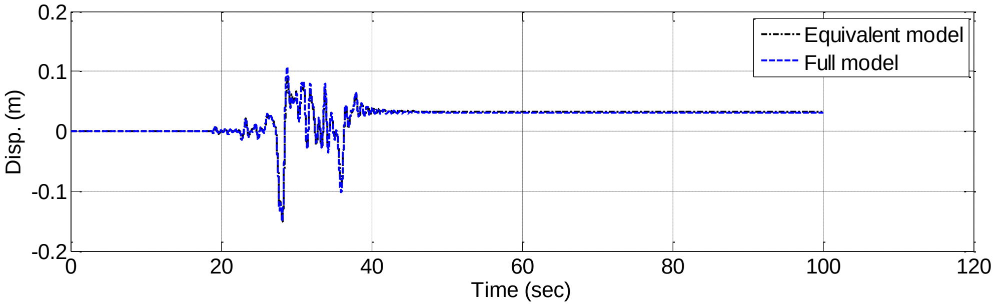
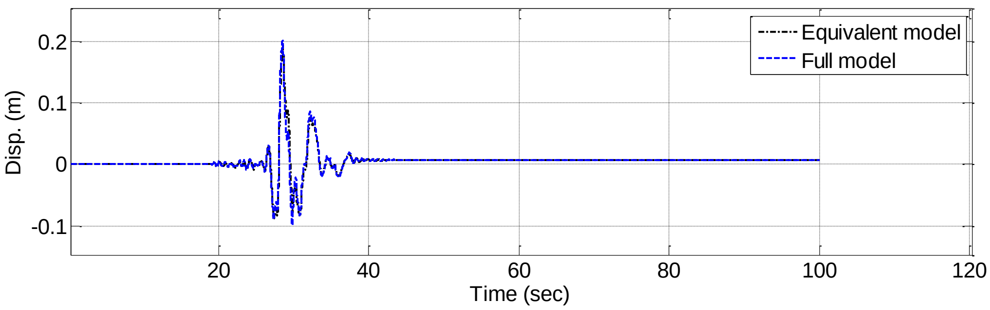


Fig. 11 Isolated nuclear power plant (Eem and Jung 2013a)



(a) *x* direction

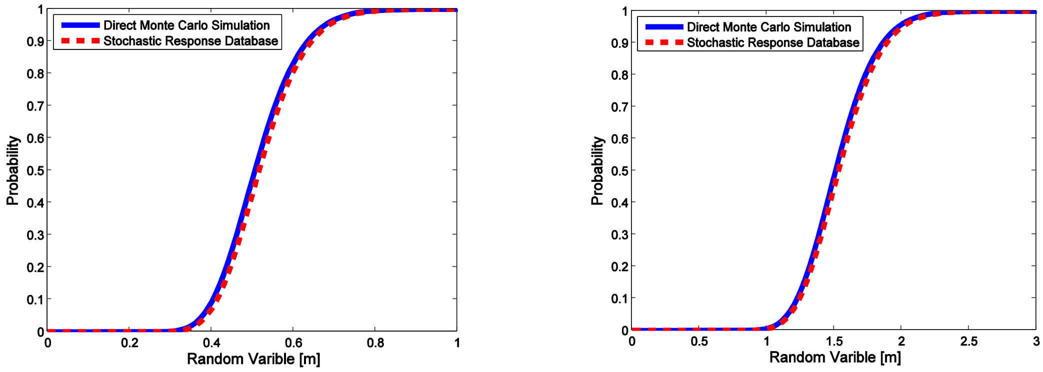


(b) *y* direction

Fig. 12 Displacement history of the seismic response analysis

To verify the effectiveness of the proposed SRD, maximum seismic responses (i.e., the displacement at the center of mass) are compared with outcomes of the Monte Carlo simulation and the SRD. The mechanical properties of the isolation system are idealized as a bilinear model, as shown in Fig. 2, and each isolator is positioned as shown in Fig. 10. The base isolation system is designed with a period of 4 sec as determined by second stiffness (K_d), a characteristic strength (Q_d) of 6% of the total weight, and a ratio between first stiffness (K_u) and second stiffness (K_d) of 10. For direct Monte Carlo simulation, a series of seismic response analyses are conducted with the earthquakes described in section 4.1 with ZPA levels of 0.5 g and 1.0 g. Total 30 seismic response analyses are performed for each case (0.5 g and 1.0 g). All realization in seismic response analyses set are assumed to have distributions of log-normal distribution (Eem and Jung 2013b).

The maximum seismic response distributions of the direct Monte Carlo simulation and the SRD are represented in Fig. 13 and listed in Table 10. It is clearly observed from the figures and table that the probability distributions of the seismic response obtained by using the two methods coincide well with each other, confirming that the SRD can estimate the seismic response distribution of an isolated structure with significantly reduced computational effort. Thus, it is expected from the results that the proposed SRD can be effectively used in the process of design or evaluation of isolated structures, and the equivalent model for an isolated structure, which is developed in this study, can be also utilized to obtain the seismic responses of various isolated structures easily. Moreover, the proposed SRD can be effectively applied for figuring out the change in the seismic response distribution when the mechanical properties of an isolator vary due to thermal variation (Kalpakidis *et al.* 2008, Constantinou *et al.* 1999) and aging effect (Itoh *et al.* 2006, Kim *et al.* 2014).



(a) Seismic intensity of 0.5 g (b) Seismic intensity of 1.0 g

Fig. 13 Estimation of probability distribution of maximum seismic responses

Table 10 Estimated log-normal probability distribution parameters of maximum seismic responses

Case	Direct Monte Carlo simulation		Stochastic response database	
	μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}
0.5 g	-0.6825	0.1769	-0.6626	0.1731
1.0 g	0.4114	0.1629	0.4261	0.1634

6. Conclusions

In this paper, the concept of the SRD is established to obtain the seismic response distributions of an isolated structure instantaneously due to the randomness of earthquakes. And the distribution of seismic responses are needed to perform the probabilistic analysis of structures. The SRD is a collection of pre-run dynamic response analyses of an isolated structure. The SRD associates the seismic response distributions with independent input parameters for the construction of response surfaces. Therefore, the seismic response distributions of the isolated structure can be directly obtained from the SRD without the need for simulation, which can significantly reduce the computational effort. An equivalent model of an isolated structure is also developed to improve the applicability and practicality of the SRD. Thus, the SRD, which is designed for an isolated structure, could be used to readily estimate seismic response distributions. This methodology exhibits the outstanding effectiveness in calculating the seismic response distribution of isolated structures. The suitability of the SRD is verified by comparing its results with those of the direct Monte Carlo simulation. It is clearly observed that the seismic response distributions obtained by using the two methods coincide well with each other. Therefore, it is concluded that the proposed SRD can be used to estimate the probability distribution of the seismic response for an isolated structure with the significantly reduced computational effort. In order to obtain the more reliable results, the uncertainty of a structure should be also taken into account. Thus, the additional numerical study is underway by simultaneously considering the uncertainty of a structure as well as the randomness of an earthquake input.

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