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Seismic fragility assessment of isolated structures by using stochastic response database

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Abstract. The seismic isolation system makes a structure isolated from ground motions to protect the structure from seismic events. Seismic isolation techniques have been implemented in full-scale buildings and bridges because of their simplicity, economic effectiveness, inherent stability and reliability. As for the responses of an isolated structure due to seismic events, it is well known that the most uncertain aspects are the seismic loading itself and structural properties. Due to the randomness of earthquakes and uncertainty of structures, seismic response distributions of an isolated structure are needed when evaluating the seismic fragility assessment (or probabilistic seismic safety assessment) of an isolated structure. Seismic response time histories are useful and often essential elements in its design or evaluation stage. Thus, a large number of non-linear dynamic analyses should be performed to evaluate the seismic performance of an isolated structure. However, it is a monumental task to gather the design or evaluation information of the isolated structure from too many seismic analyses, which is impractical. In this paper, a new methodology that can evaluate the seismic fragility assessment of an isolated structure is proposed by using stochastic response database, which is a device that can estimate the seismic response distributions of an isolated structure without any seismic response analyses. The seismic fragility assessment of the isolated nuclear power plant is performed using the proposed methodology. The proposed methodology is able to evaluate the seismic performance of isolated structures effectively and reduce the computational efforts tremendously.

Keywords: isolated structure; fragility analysis, seismic response distribution; stochastic response database

1. Introduction

In the event of an earthquakes, seismic waves travel rapidly through the earth's crust, creating ground motions (Eem *et al*. 2011). When the waves strike inhabited areas, the earthquakes can cause extensive and severe social and economic loss, including heavy damages to civil engineering structures such as bridges, buildings, roads, railways and dams as well as fires in many areas. One of the most accepted control strategies utilized for such civil engineering structures is a seismic isolation system. The performance of seismic isolation systems was validated from the "Northridge earthquake 1994" and the "Kobe earthquake 1995" (Jun 2010). The seismic isolation system that is inserted between ground and superstructure, can reduce the structural deformation in the event of earthquake (Eem *et al*. 2013). The seismic isolation system usually prolongs the natural period of the structures and reduces the seismic loading. Many base isolation techniques (e.g., laminated rubber bearings, lead-rubber bearings, friction bearings, etc.) have been implemented in full-scale buildings and bridges because of their simplicity, economic effectiveness, inherent stability and reliability (Spencer *et al*. 2003). However, the seismic performance evaluation of the isolated structure should be re-evaluated considering the effect of the seismic isolation system (Eem *et al*. 2013).

There are two approaches for evaluating the seismic performance of structures, i.e., a probabilistic method and a deterministic method. The deterministic seismic performance evaluation method is based on the results of seismic response analyses using the expected value or the design value of structural parameters and seismic loads. As for the structural responses due to seismic events, it is well known that the most uncertain aspect is the loading and the structure itself (Galambos *et al*. 1982). The characteristics of a structure could be different from its initial design for various reasons such as uncertainties in the material properties or construction practice, etc. Furthermore, it is almost impossible to predict the future earthquakes and their characteristics. The deterministic seismic response analysis only provides the structural responses from the specific seismic events (Towashiraporn 2004). Therefore, the deterministic seismic performance evaluation approach might be misleading in some cases.

On the other hand, the probabilistic seismic performance evaluation approach should consider the effect of randomness and uncertainty of the earthquake and structural aspects. It is too difficult to evaluate the probabilistic

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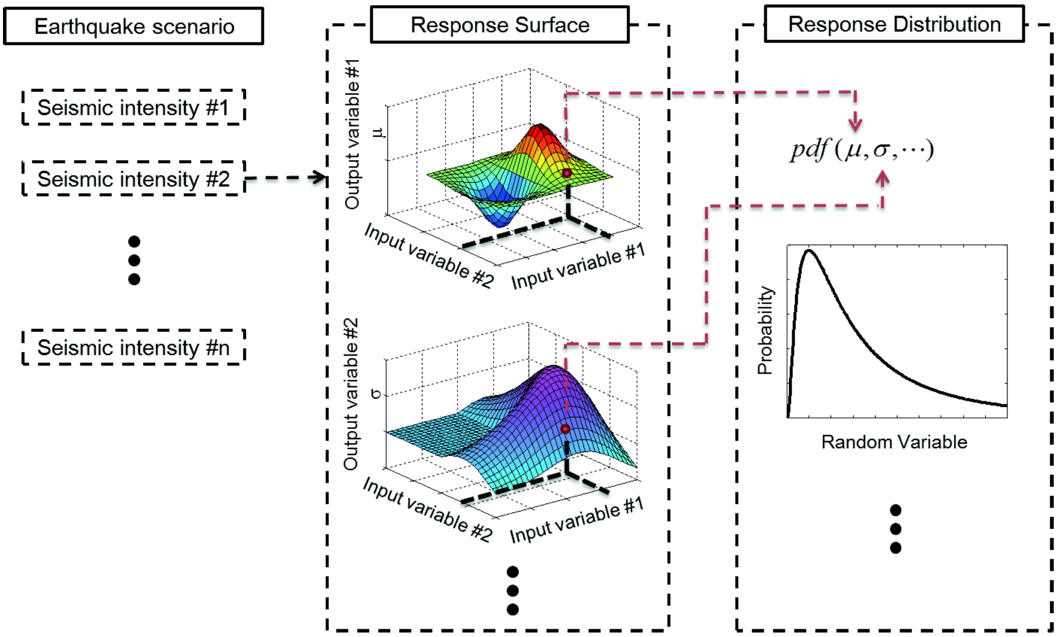


Fig. 1 Concept of the stochastic response database (Eem *et al.* 2015)

seismic performance, or a seismic fragility curve, of an isolated structure by using analytical methods (Eem *et al*. 2015). The fragility of an isolated structures is defined as the probability of failure at a given value of seismic response parameter as peak ground acceleration, peak ground displacement, spectral acceleration, etc. Therefore, Monte Carlo simulations are used to obtain the probabilistic seismic performance of the seismic isolation system. A Monte Carlo simulation requires numerous nonlinear dynamic analyses, but this is impractical. Hence, the seismic probabilistic performance evaluation has a limitation due to the extensive simulation used to account for the randomness and the uncertainty. The probabilistic models of seismic responses are suggested to reduce the calculation costs (Gardoni and Trejo 2013, Colangelo 2013). Recently, a stochastic response database (SRD), which can immediately estimate the seismic response distribution of isolated structures without any non-linear dynamic analyses, has been developed (Eem *et al*. 2015). To take full advantage of the SRD, an effective methodology that can calculate the seismic fragility curve of an isolated structure should be developed.

The primary goal of this paper is to present a new approach utilizing the SRD to effectively assess the seismic fragility of isolated structures. First, the concept of the SRD is introduced briefly which can be used for estimating the seismic response distributions of an isolated structure. The methodology is proposed for gain the seismic response distribution with the randomness and the uncertainty. This methodology is verified by comparing the results of Monte Carlo simulation. A seismic fragility assessment of an isolated structure will be applied using the SRD. Furthermore, it proposed a seismic fragility assessment methodology is proposed for the isolated structure from the computed seismic response distribution. The approach incorporates randomness and uncertainties in seismic loadings as well as structural parameters. The seismic fragility assessment of the isolated structure requires a lot of seismic response analyses owing to the Monte Carlo simulation. However, the SRD can provide seismic response distributions of the isolated structure without any seismic response analyses. Finally, the seismic fragility assessment of the isolated nuclear power plant is performed using proposed methodology.

2. Seismic response distribution estimation of isolated structures

2.1 Stochastic response database (SRD) and equivalent isolated structure

In this section, the SRD and the equivalent model of an isolated structure is introduced. The detailed information on the SRD and the equivalent model of an isolated structure can refer to “seismic response distribution estimation for isolated structures using stochastic response database” (Eem *et al*. 2015). The SRD is a database for estimating the seismic response distribution of isolated structures instantaneously. The database is constructed with pre-run seismic response analyses of the isolated structures. Fig. 1 illustrates the concept of the SRD.

When the input parameters such as seismic intensity and structural parameters are known, it is possible to estimate the seismic response distribution of isolated structures instantaneously. An equivalent isolated structural model is a seismic model that behaves the same as the original isolated structure, even though its mechanical properties such as mass and radius of the gyration etc. are different from those of the original, when the earthquake occurs. The equivalent model of the seismic isolated structure is transformed by converting the six factors, which affecting most of the seismic behaviors. The six parameters are selected from the superstructure and the isolation layer:

Table 1 Information of selected earthquakes for the SRD

Earthquakes	Station	Year	Earthquake Magnitude	PGA (g)
Parkfield	TMB	1966	6.19	0.2934
San Fernando	PUL	1971	6.61	1.1644
Gazli, USSR	GAZ	1976	6.80	0.6438
Imperial Valley	E05	1979	6.53	0.4481
Imperial Valley	SUP	1979	6.53	0.1598
Livermore	KOD	1980	5.80	0.1066
Victoria, Maxico	CPE	1980	6.33	0.5722
Morgan Hill	CLS	1984	6.19	0.0983
Morgan Hill	G06	1984	6.19	0.2814
Nahanni	S1	1985	6.76	1.0556
Nahanni	S3	1985	6.76	0.1512
Superstition Hills	ICC	1987	6.54	0.2933
Spitak, Armenia	GUK	1988	6.77	0.2071
Loma Prieta	BRN	1989	6.93	0.5263
Loma Prieta	CLS	1989	6.93	0.4975
Loma Prieta	LGPC	1989	6.93	0.7835
Erzican, Turkey	ERZ	1992	6.69	0.4886
Cape Mendocino	CPM	1992	7.01	1.3455
Northridge	CHL	1994	6.69	0.2148
Northridge	PAC	1994	6.69	0.4085
Northridge	PKC	1994	6.69	0.3482
Northridge	RRS	1994	6.69	0.6336
Kobe	KJMA	1995	6.90	0.7105
Kobe	Takatori	1995	6.90	0.6424
Mammoth Lakes	Long Valley	1980	6.06	0.3292
Kocaeli, Turkey	GYN	1999	7.51	0.1387
Kocaeli, Turkey	IZT	1999	7.51	0.2037
Chi-Chi, Taiwan	TCU072	1999	7.62	0.4033
ChiChi, Taiwan	TCU089	1999	7.62	0.2878
Duzce, Turkey	BOL	1999	7.14	0.7662

the mass (M), the radius of gyration (Rm), the coordinates of the center of mass (CM), the stiffness (K), the radius of disposition (Rk), and the coordinates of the center of rigidity (CR).

This equivalent isolated structural model will improve the applicability and practicality of the SRD. The equivalent model enables the application of the SRD to other isolated structures although the SRD is configured based on a specific isolated structure. The SRD can estimate the seismic response distributions of isolated structures considering the randomness of earthquakes. However, it does not represent the uncertainties of the isolated structures. The methodology of estimation of the seismic response distributions considering the randomness and uncertainty will be introduced in the next section.

2.2 Configuration of the stochastic response database

The SRD is composed in the same manner as the "seismic response distribution estimation for isolated structures using stochastic response database" (Eem *et al.* 2015) for evaluating the seismic performance (i.e., fragility curve) of isolated structures. The 30 seed earthquakes are selected from PEER (Pacific Earthquake Engineering Research Center) database for the construction of the SRD considering the various characteristics of the earthquakes. The selected earthquakes are revised to match with the design response spectrum, as suggested in Regulatory Guide 1.60 (US NRC 2014). The Regulatory Guide 1.60 "Design Response Spectra for Seismic Design of Nuclear Power Plants" is the response spectrum used to meet safety requirements in the seismic design of nuclear power plants. The information on the selected earthquakes is shown in Table 1.

The mass (M) and radius of gyration (Rm) of generated isolated structures models are 1000 ton and 10 m, respectively. Input variables of the response surface are selected, which are T_d, Q_p, e_r, α and R_p. The selected parameters are related to M, CM, R_m, K, CR, and R_k which are affecting the seismic response of the isolated structure. The input parameters, for the response surface, are represented in

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

where T_d (2~3 sec) is the period calculated by the second stiffness (K_d), Q_p (0.003~0.09) is the ratio between characteristic strength (Q_d) and weight (W) of the isolated structure, α (10~50) is the ratio between K_u and K_d. In addition, R_p (0.85~1.15) is the ratio between the radius of gyration (R_m) and radius of disposition (R_k), and e_r (0~0.05) is the ratio between the eccentricity (e) (center of mass and center of rigidity) and the radius of gyration (R_m).

Thirty seismic analyses were performed for one isolated structure model with a certain level of seismic intensity. These results are used to extract the parameters for seismic response distributions. There are two parameters (μ_{ln}, and σ_{ln}) to determine the shape of the log-normal probability distribution. Therefore, 486 parameters will be extracted for each seismic response (translational and rotational displacements). In this research, PGA levels of 0.3 g, 0.5 g, 0.75 g, 0.835 g, 1 g, 1.5 g and 2 g are performed to establish the SRD.

2.3 Seismic response distribution considering the uncertainty

In this section, the procedure to gain the seismic response distribution is proposed to take the uncertainty and the randomness into account. The seismic response distributions, in which randomness and uncertainty are considered, are required to calculate the seismic fragility curve of isolated structures. The SRD can estimate the seismic response distribution of isolated structures, considering only the effect of the randomness of earthquakes. Additionally, the uncertainty of structure should be considered for calculating the seismic fragility curve. Therefore, the application of the SRD is useful to obtain the seismic response distributions for taking randomness and uncertainty into account.

To calculate the seismic response distributions of

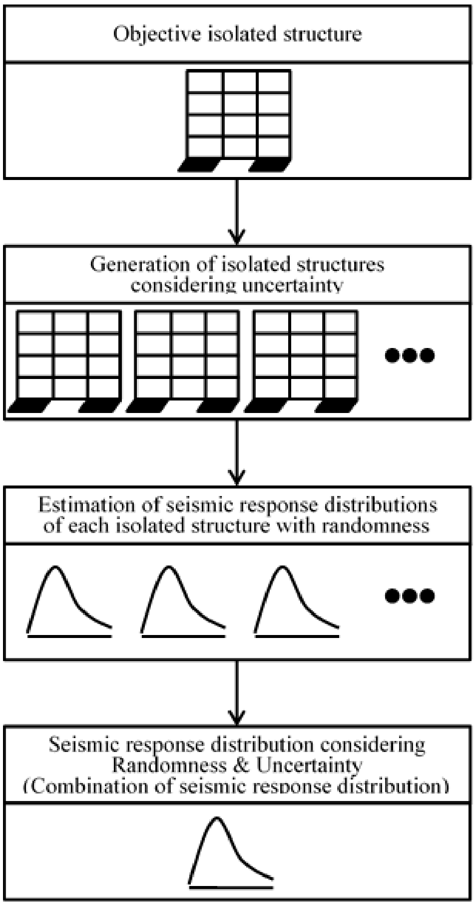
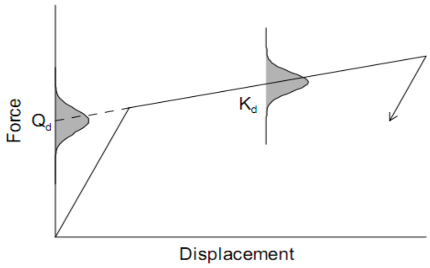


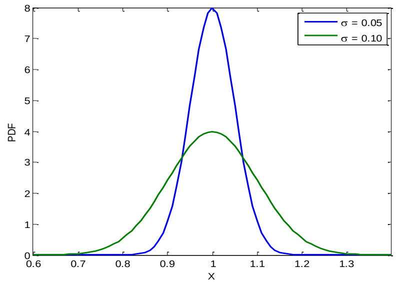
Fig. 2 Flowchart of calculating the seismic response distribution

isolated structures in consideration of the uncertainty of structures and the randomness of earthquakes, the SRD can be utilized as follows: First, a large number of isolated structural models should be generated to reflect the uncertainty of an isolated structure. The number of models generated should be sufficient to represent the structure uncertainty distribution. However, the required time for this process is similar to the only random number generation time. The seismic response distributions, which takes into account the randomness of earthquakes, of each isolated structural model can be obtained through a SRD. Seismic response distributions of each isolated structural model can be obtained through a transformation of an equivalent isolated model and SRD. The seismic response distribution of the isolated structure, in which randomness and uncertainty are considered, can be produced by combining the estimated seismic response distribution of each generated structural model. Fig. 2 shows the flowchart of the calculating process of the seismic response distribution considering the effect of the uncertainty and the randomness for an isolated structure.

The proposed methodology for gaining the seismic response distributions with the randomness and the uncertainty is verified by comparing the results of seismic response distributions with those calculated by the SRD and the direct Monte Carlo simulation. As a verification example, the selected isolated structure is the

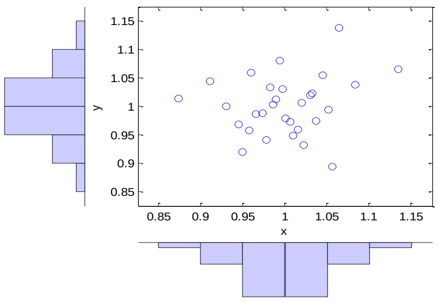


(a) Mechanical properties of the isolation system (Haung *et al*. 2009)

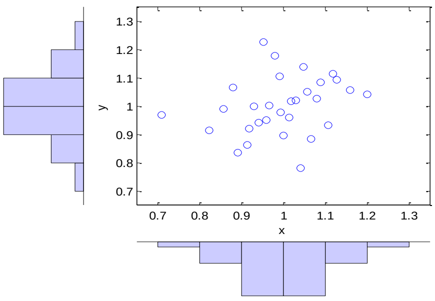


(b) Normal distribution

Fig. 3 Mechanical properties of the isolation system with uncertainty



(a) Case of coefficient of variation (CV) of 0.05



(b) Case of coefficient of variation (CV) of 0.1

Fig. 4 Mechanical properties of the isolation system with uncertainty

Korean Standard Nuclear Power Plant (i.e., Advanced Power Reactor 1400 (APR1400)). The total mass of the APR1400 is 464,500 *tons* and the size of APR1400 is 140 m×103 m. The mechanical properties of an isolation system are idealized to a bi-linear model as shown in Fig. 3(a). The detailed information of the APR1400 is discussed in the next chapter.

A base isolation system is designed with a period of 4 sec by the second stiffness (K_d), the characteristic strength

Table 2 Information of selected earthquakes for the SRD

ZPA	Case	Number of earthquakes	Number of models	Coef. of Variation	Number of Analyses
0.5g	RA05	30	30	0.05	900
	RA10	30	30	0.10	900
1.0g	RA05	30	30	0.05	900
	RA10	30	30	0.10	900

Table 3 Estimation log-normal probability distribution parameters of maximum seismic responses

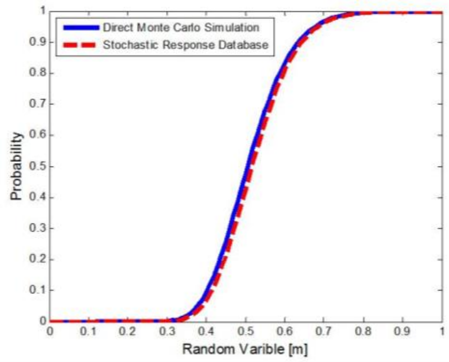
ZPA	Case	Direct Monte Carlo Simulation		Stochastic Response Database	
		μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}
0.5g	RA05	-0.6828	0.1778	-0.6718	0.1701
	RA10	-0.6825	0.1868	-0.6629	0.1855
1.0g	RA05	0.4129	0.1550	0.4193	0.1751
	RA10	0.4126	0.1666	0.4157	0.1774

(Q_d) is 6% of the total weight, and the ratio between the first stiffness (K_u) and the second stiffness (K_d) is 10. The seismic isolation characteristics of the isolated structure are distributed by uncertainty. It is assumed that characteristic strength (Q_d) and the second stiffness (K_d) has uncertainty in this study. Fig. 3(b) describes that two parameters are following normal probability distribution with the coefficients of variation of 0.05 and 0.10. The coefficient of variation (CV) is defined as the ratio of the standard deviation to the mean.

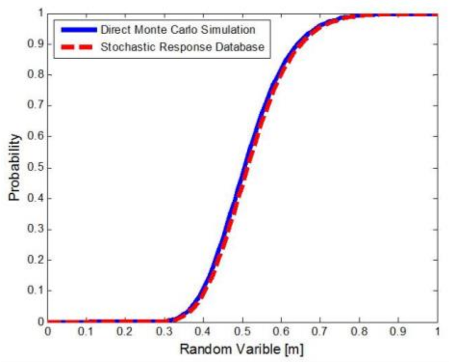
The Latin hypercube sampling method is used to model an isolated structure with certain mechanical properties. A total of 30 sets of the isolated structure are modeled for each case. The selected two parameters are uncorrected with each other as shown in Fig. 4.

In order to validate the proposed methodology, a series of response analyses are conducted with the earthquakes that are described in Table 1 with ZPA levels of 0.5 g and 1.0 g. The bi-axial interaction is considered in response analyses. All cases of the Direct Monte Carlo simulation are represented in Table 2. Similar to the Direct Monte Carlo simulation cases, maximum seismic response distributions of an isolated structure are estimated from 900 sets of the maximum seismic responses with 30 isolated structural models for the SRD cases.

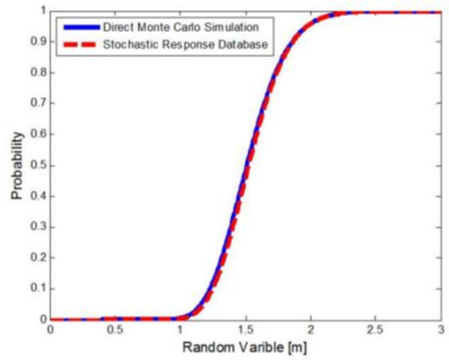
Seismic response distributions of the Direct Monte Carlo simulation and the SRD are represented in Fig. 5 and Table 3. It was observed that seismic response distributions by the two methodologies coincide well witheach other.



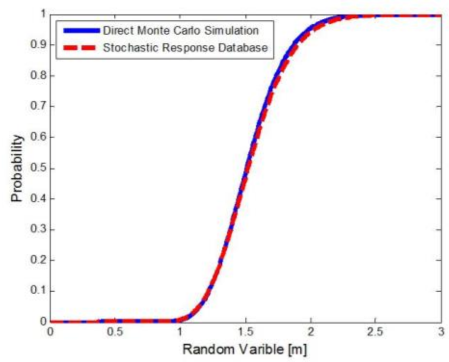
(a) RA05 case with 0.5 g



(b) RA10 case with 0.5 g



(c) RA05 case with 1.0 g



(d) RA10 case with 1.0 g

Fig. 5 Estimation of probability distribution of maximum seismic response

3. Application of stochastic response database for the fragility assessment

The seismic fragility assessment of an isolated structure is performed by using the SRD in this chapter. To identify the seismic response distribution, the SRD can be used for various types of isolated structures such as buildings, bridges, LNG tanks and plants. As an application of the SRD, a selected isolated structure is the Korean Standard Nuclear Power Plant (Advanced Power Reactor 1400 (APR1400)). This nuclear power plant is a typical structure implementing a probabilistic safety assessment (Park *et al*. 2003). Also, a number of studies have been made on the

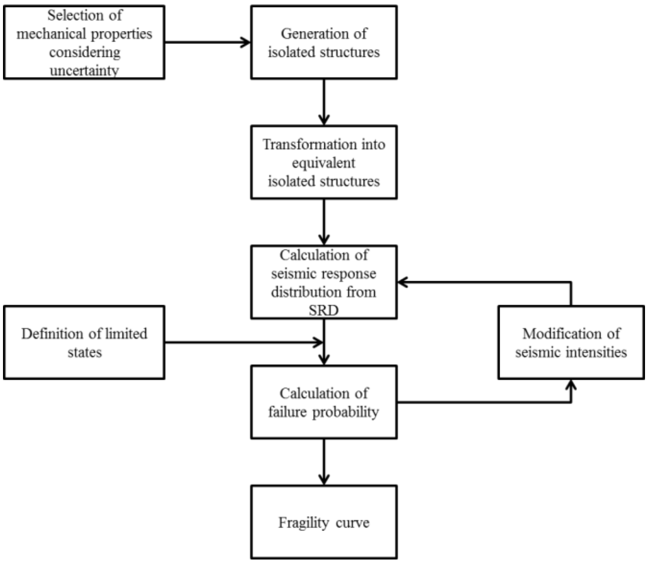


Fig. 6 Flowchart of fragility assessment for isolated structures using the SRD

Fig. 7 Advanced Power Reactor 1400 (KEPCO Nuclear Energy Solution 2011)

Fig. 8 Concept of base-isolated Advanced Power Reactor 1400 (KEPCO E&C 2012)

application of a seismic isolation system to nuclear power plants. Developed countries have done various activities in order to adopt the seismic isolation system for commercial nuclear power plants. U.S. NRC (Nuclear Regulatory Commission) constituted a research team to establish technical standards of the isolation system for nuclear power plants (Bozidar 2011), Italy MSE (Economic Development Ministry) and ENEA conducted studies for applying the seismic isolation system to nuclear power plants (Martelli *et al*. 1991). During the period of 1987-2000, Japan Atomic Energy Research Institute (JAERI) conducted research on seismic isolation devices, and the Japanese Nuclear Energy Safety Organization (JNES) has been researched on the application of the seismic isolation system to nuclear power plants (Japan Electric Association 2000). In additions, in Korea, research of application of a seismic isolation system to the Korean Standard Nuclear Power Plant APR1400 is on-going (Eem *et al.* 2013). In addition, several researches have been focused on calculating the seismic fragility of isolated nuclear power plants (Huang *et al.* 2013, Perotti *et al.* 2013, Jeon *et al.* 2015).

3.1 Seismic fragility assessment calculation utilitzing stochastic response database

The SRD is a database for obtaining the seismic response distribution of the isolated structure instantaneously. This methodology can be used for where the seismic response distributions are needed such as a design or a seismic performance evaluation of an isolated structure. It especially can be used for the seismic fragility assessment of an isolated structure. In addition, it is useful because the seismic fragility assessment requires a lot of seismic response analyses for calculating the seismic response distributions.

Obtaining the fragility curves of isolated structures by using the SRD is similar to the general procedure. However, the way that calculating seismic response distribution of isolated structures is different. A general way to obtain the seismic response distributions of the isolated structure needs a lot of seismic response analyses from generated earthquakes and structure models considering their randomness and uncertainty. The fragility curve of a structure can be calculated using results of seismic response analyses in general way. However, a seismic fragility assessment using the SRD can skip the time-consuming seismic response analyses. Instead, the seismic responses can be obtained from seismic response distributions which are provided from the SRD. The procedure of a seismic fragility assessment for an isolated structure is introduced using the SRD. The flowchart of the fragility assessment process using the SRD is shown in the Fig. 6.

3.2 Isolated nuclear power plant

The Advanced Power Reactor 1400 MWe (APR1400) is a standard evolutionary advanced light water reactor (ALWR) in Korea developed in 2002. Fig. 7 shows the nuclear power plant, APR1400. “The design is based on the experience that has been accumulated through the development, construction, and operation of OPR1000, the Optimum Power Reactor 1000MWe, the first standard pressurized water reactor (PWR) plant in Korea. Also, the APR1400 utilizes the state-of-the-art proven technology and incorporates a number of advanced design features to meet the utility’s needs for enhanced economic goals and to address the new licensing safety issues and requirements for an improved plant safety”. (KEPCO Nuclear Energy Solution 2011). The APR1400 was designed to endure 0.3 g (Safe Shutdown Earthquake) with a 60-year design life.

Fig. 8 shows a concept of the Isolated APR 1400. As shown in the figure, the application range of an isolation

Table 4 Parameters for the isolation system (Eem *et al.* 2015)

Parameters	Values
K_{eff}	2939.72 MN/m
K_u	19620.51 MN/m
K_d	1962.05 MN/m
Q_d	329.43 MN

Table 5 Allowable variations of mechanical properties

Criteria	Allowable variations	Note
ISO	±30%	15% for fatigue
BS	±20%	Type test
ASCE	±20%	Long-term variation
ENEA	±15%	For nuclear power plant

system is Nuclear Island (NI), i.e., the reactor containment building and the auxiliary building.

Three types of isolators for a nuclear power plant, an RB (Rubber Bearing), LRB (Lead Rubber Bearing), and friction type are recommended by the NRC (Nuclear Regulatory Commission). In this study, LRB type isolators are used for the isolation system. The isolation system for APR1400 is designed by ASCE 7-13 and FEMA 451. In the preliminary design, seismic displacement of the isolation system can be calculated using Eq. (2) when assuming an effective period (T) and an equivalent damping ratio (β).

$$D = \frac{g}{4\pi^2}\frac{S_1 T}{B} \tag{2}$$

where g is gravity acceleration, S_1 is the spectral acceleration (SA) with 1 sec of period and a 5% of damping ratio. T is the effective period of the isolation system, and B is the damping coefficient which is calculated using Eq. (3).

$$B = (\frac{\beta}{0.05})^3 \tag{3}$$

The design response spectrum of APR1400 is referenced by the response spectrum from Reg. Guide 1.60 with ZPA 0.5 g. It is reinforced in the high frequency range compared to Reg. Guide 1.60 response spectrum. S1 is 0.73 g with ZPA level 0.5 g; therefore; the design displacement is approximately 35 cm. The effective period is recommended around 2-3 sec by design codes. An isolation system for APR1400 is designed with an effective period of 2.5 sec and a damping ratio of 20%. Disposition of isolators is referenced from drawing by KEPCO E&C which is represented in Fig. 10. The details of parameters for base isolation system are shown in Table 4.

3.3 Seismic fragility assessment of isolated nuclear power plant

A variation of the seismic responses is caused by an uncertainty of the structure's mechanical properties and the randomness of earthquakes. The randomness of earthquakes is considered by selecting the ensemble of earthquakes during constructing the SRD. The uncertainty of structure's mechanical properties is considered by generating the isolated structural models. Therefore, the uncertainty of structure's properties should be considered while generating the isolated structural models. The major uncertainty of the structure's mechanical properties is the isolation system's mechanical properties which cause variation of seismic responses.

The characteristics of a structure can be different from the initial design due to construction practice. The properties of the isolation system possess uncertainty from the manufacturing processes or inherent unpredictability within materials themselves. In addition, the mechanical properties of an isolator vary due to the temperature (Kalpakidis *et al*. 2008; Constantinou *et al*. 1999). In addition, it changes most significantly and keeps changing over the time (Itoh 2006). Thus, the mechanical properties of the isolation system have uncertainties. Table 5 shows the allowable variation of the mechanical properties of the isolation system within each criterion. For the seismic fragility assessment of an isolated nuclear power plant, it is assumed that the mechanical properties of the isolation system, i.e., K_u, K_d and Q_d, have uncertainty. K_u, K_d and Q_d follow the normal distribution with a coefficient of variation of 10% and 20%, respectively.

The failure criteria of an isolated nuclear power plant are needed for performing a seismic fragility assessment. The performance expectation of ASCE43-05 is defined as follows:

1) 1% probability of unacceptable performance for 100% DBE (Design Basis Earthquake) shaking

2) 10% probability of unacceptable performance for 150% DBE (Design Basis Earthquake)
shaking

The four performance statements for achieving the two performance objectives of ASCE43-05 were assumed in the writing of Section 7.7, namely,

1) Individual isolators should suffer no damage in DBE shaking

2) The probability of the isolated nuclear power structure impacting surrounding structure or the
moat wall for 100% (150%) DBE shaking should be 1% (10%) or less

3) Individual isolators should sustain gravity and earthquake-induced axial loads at 90th percentile
lateral displacements consistent with 150% DBE shaking

4) The probability of unacceptable performance in the isolated superstructure for 100% (150%)
DBE shaking should be 1% (10%) or less

To perform the seismic fragility assessment of the isolated nuclear power plant, the failure criteria is defined as following with reference to statements:

1) Impacting the isolated nuclear power structure and the moat wall

2) The interface failure between isolated structure and un-isolated structure

Fig. 9 shows the location of the edges of the isolated structure (A) and main pipelines (B) where the failure might occur. The allowable maximum displacement is assumed as 70 cm and 105 cm, respectively, which is two and three

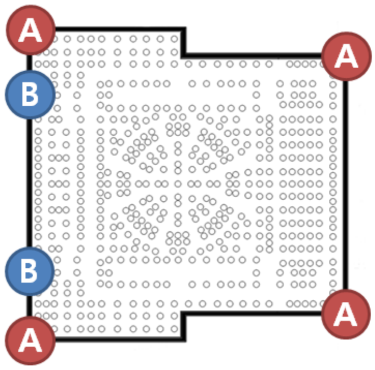


Fig. 9 Location of the edge of the isolated structure (A) and main pipelines (B) and dispositions of isolators

times of the design displacement.

The seismic fragility curve of the Korean Standard Nuclear Power Plant APR1400 with the seismic isolation system was developed using the proposed method under various conditions. A total of six seismic fragility curves were developed with two different failure criteria and three different uncertainty conditions. The process of a seismic fragility assessment (section 3.1) for a nuclear power plant is listed below:

○ Generation of 500 isolated structural models with uncertainty

○ Transformation of isolated structural models into the equivalent isolated structural models

○ Calculation of input variables for the stochastic response database

○ Extraction of seismic response distributions from the stochastic response database

Table 6 The values of fragility curve parameters of the isolated nuclear power plant

Allow. Max. disp.	Parameters	Values		
	CV	0%	10%	20%
70 cm	μ (g)	0.7123	0.7025	0.6980
	σ	0.0701	0.0852	0.1006
105 cm	μ (g)	0.9217	0.9209	0.9203
	σ	0.0908	0.0983	0.1188

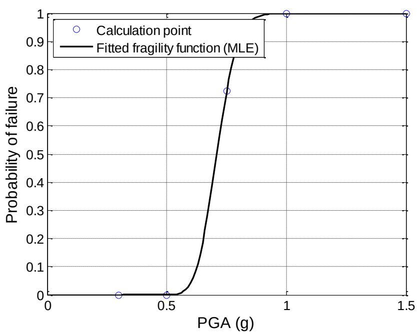
○ Extraction of 100 maximum seismic responses from each isolated nuclear power plant model

○ Calculation of failure probability from the failure modes

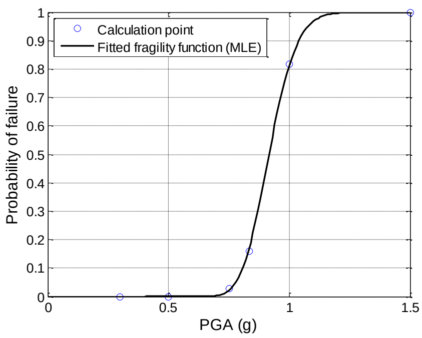
○ Repetition of the process with changing the seismic intensities

○ Drawing a fragility curve of an isolated nuclear power plant structure from the failure probability

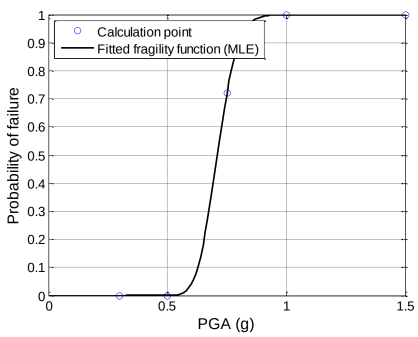
Fig. 10 shows the fragility curves of the isolated nuclear power plant. The parameters of the fragility curve are listed in Table 6. As shown in Fig. 10, the fragility curves are calculated by changing the allowable maximum displacements and the coefficient of variation (CV). The calculation point is the failure probability calculated from the seismic intensity of the SRD constructed in Section 2.2. The seismic fragility curves were developed using the Maximum Likelihood Estimation method at the calculation points, assuming a log normal distribution. The case of CV of 0% means that the randomness of earthquakes is only considered. In addition, these cases are performed to compare with other cases. It is shown that the standard deviation of the fragility curve was increased when



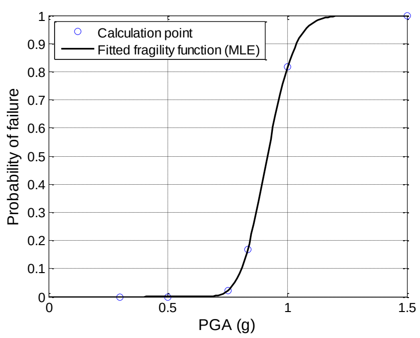
(a) Allow. 70 cm , CV 0%



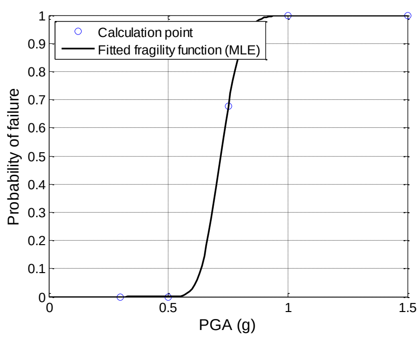
(b) Allow. 105 cm, CV 0%



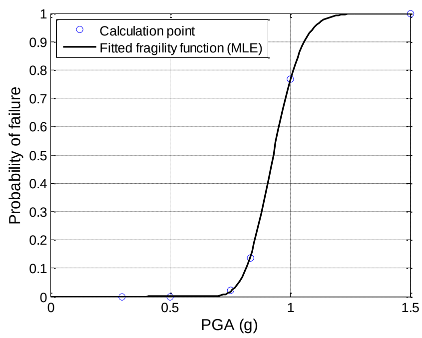
(c) Allow. 70 cm, CV 10%



(d) Allow. 105 cm, CV 10%



(e) Allow. 70 cm, CV 20%



(f) Allow. 105 cm, CV 20%

Fig. 10 The fragility curve of isolated nuclear power plant uncertainties of the structural parameters are increased. It is obviously demonstrated that the means and standard deviations were increased when the allowable maximum displacements were increased. It was confirmed that calculation of the fragility curves by using the SRD is feasible to take into account the randomness and the uncertainties.

4. Conclusions

This paper proposes an alternative approach for the seismic fragility assessment of isolated structures by using the stochastic response database (SRD). The seismic responses of an isolated structure vary with the randomness and the uncertainty. It is well known that the most uncertain aspects are the earthquake and the structure itself. Therefore, the probabilistic seismic performance (or seismic fragility assessment) of isolated structures should be performed. However, the probabilistic seismic performance of isolated structures brings a large number of non-linear dynamic analysis which is impractical.

A new methodology is proposed for calculating the seismic response distributions considering the randomness and the uncertainty by utilizing the SRD and the equivalent model of isolated structures. First, the concept of the SRD is introduced, which can obtain the seismic response distributions of the isolated structure instantaneously. In addition, an equivalent model of the isolated structure is introduced for improvements of the applicability and practicality. The proposed methodology shows outstanding effectiveness to calculate the seismic response distribution of the isolated structure. The suitability of the SRD is verified by comparing the results obtained by the SRD with those obtained by the direct Monte Carlo simulation. It was observed that seismic response distributions by the two methodologies coincide well each other, while the proposed method shows tremendous reduction of the computational efforts.

Finally, an alternative methodology for the seismic fragility assessment of the isolated structure is proposed using the SRD. The approach incorporates uncertainties in seismic loadings as well as structural parameters. The proposed methodology is applied to the isolated nuclear power plant (i.e., APR1400). The seismic fragility curve of the isolated nuclear power plant is successfully evaluated considering the uncertainty of the isolation system. Moreover, the computational efforts are significantly reduced through the use of the SRD.

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