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Seismic performance assessment of reinforced concrete containment vessel considering ground motion recorded in South Korea

Chanyoung Kim[1], Myoungsu Shin[2]

[1] Graduated student, Ulsan National Institute of Science and Technology, Ulsan, South Korea (kcy931208@unist.ac.kr)
[2] Associate professor, Ulsan National Institute of Science and Technology, Ulsan, South Korea (msshin@unist.ac.kr)

ABSTRACT

Fragility analysis is a step of SPRA, that is the process to describe the relation between PGA and probability of failure of target structure, component and system. Current guideline for seismic performance assessment, which based on the Kennedy et al. (1980)'s study, reflect the earthquake characteristic of west region of U.S. In this reason, difference in earthquake characteristics of each region should be considered, when seismic performance assessment was conducted at other region. This paper study about the effects of characteristics of earthquake time histories on fragility curve for containment of nuclear power plant. Several time histories are created by spectral matching between the median response spectrum and the several recorded earthquakes including Kyoungju earthquake data. We conducted certain number of FEM analysis by using these created time histories and developed fragility curves. Resulting fragility curves are compared by their ground motion parameter, and the reliability of ground motion histories measured at South Korea are investigated.

INTRODUCTION

Nuclear power plant is the facility supplying main energy source in modern society, and also required high reliability for expedite action for accident occurrence. Methodology suggested by U.S. NRC, which used widely for seismic performance assessment is based on response spectra that developed through the study about earthquake record from the U.S. west region. Therefore, shape of the response spectra should be modified to fit well with the ground characteristics, when assessment was developed at other countries. Furthermore, appropriate ground motion time histories should be chosen for better assessment. Many previous researches were studied about the effects of earthquake characteristics on probability of collapse of structures. Raghunandan et al. (2013) suggested that significant duration of earthquake has highly affects on ductile buildings. In this reason, the characteristics of ground motion such as shape of response spectrum, and significant duration of corresponding time histories should be considered simultaneously.
In this paper, the ground motion of Kyongju earthquake (2016) observed at Hyodongri was used as material for spectral matching, with the other representative earthquake such as Kobe, Chichi, Northridge & Imperial valley. The effects of time histories generated by spectral matching on fragility curves were analysed by PGA, significant duration, Arias intensity, and maximum displacement. Finally, the reliability and considerations when using ground motion observed at South Korea for seismic performance assessment were discussed.

FEM MODEL & GROUND MOTION

The FEM model used at this research was lumped mass model for OPR-1000, the design applied to Hanul plant 3,4 and Shin-wolsong 1,2, etc. This model is composed of containment structure and internal reinforced concrete structure that were simplified by point mass and beam stick, as it depicted in Fig. 1. Two models that have different point masses were created to analyse for horizontal earthquake and vertical earthquake, respectively. In general, the SSE level ground motion used in seismic performance assessment has a PGA value of 0.2 g, which permit the linear elastic behaviour of model. Therefore, entire model was assigned with linear elastic behaviour. In frequency analysis, the 1st natural frequency of containment structure was investigated as 5.16 Hz, that was different with the value reported before, 4.6 Hz. This lumped mass model not include the massive equipment such as steam generator and heat exchanger, so this can be the reason of slightly higher frequency than reported value.

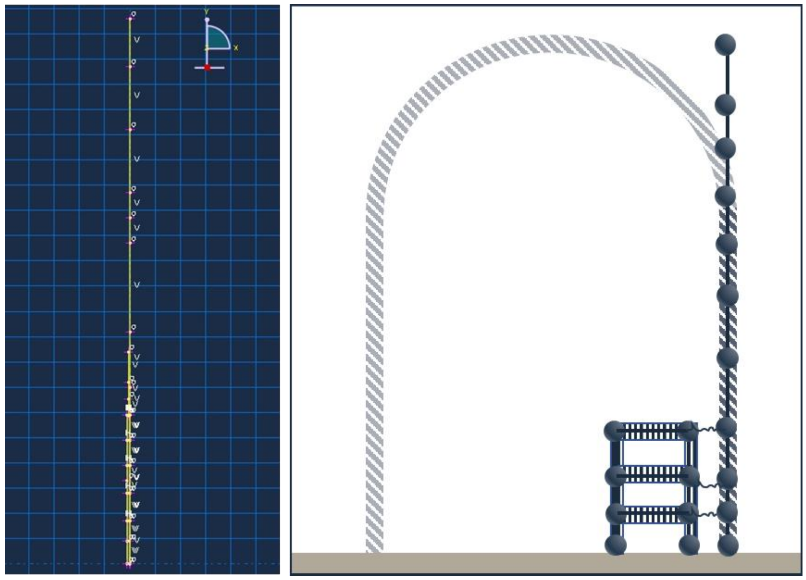

Figure 1. FEM model (left) and terms of simplification (right)

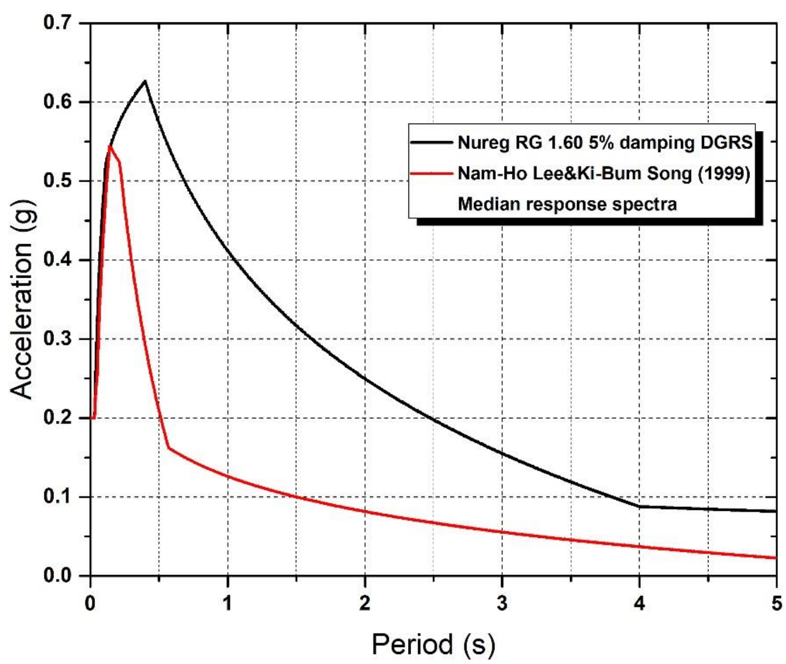

Figure 2. Response spectrum used at spectral matching (red-line)

In case of nuclear power plant design, response spectra suggested at NUREG RG 1.60 guide is generally used. In this paper, used ground motion is generated by spectral matching with the response spectrum obtained from Nam-ho Lee & Ki-bum Song (1999), which reported as a median value. The used response spectrum is depicted in Fig. 2, as compared with the response spectrum of NURG RG 1.60 guide. Resulting ground motions are created by the several data recorded from several earthquakes: Kyoungju, Kobe, Northridge, and Imperial valley. By using SeismoMatch program, spectral matching was conducted with the 80 number of iterations, for enough similarity of response spectrum. Resulting response spectrum of each matched time history conform well with the target response spectrum in the frequency range of 2 Hz -10 Hz, except the matched time history based on Imperial valley data. The response spectrum of this time history has a point that has 1.2 times higher value compared to the target response spectrum at 0.14s but conform well with the target response spectra and anchored well to the target PGA values. Therefore, we use this time history without the further modification. In case of the ground motion data based on Northridge data, the PGA value of response spectra not anchored well to 0.2g of target value. Also, it has other several points in range of 0.62s to 0.94s which over-matched compared to the target response spectrum, yet these points are not in the frequency range recommended matching at TR-103959. But at the points corresponding to other period, the response spectrum of matched time history is well met with the target response spectrum, so we use this ground motion data for structural analysis. Also, we tried another method to anchor the PGA value of this time history closer to target. Because this time history has only one point which over 0.2 g, so at first, we eliminate that one point to fit the target PGA value at first. The time history 'modified' at this stage is well-fitted with target median spectrum, but also has over-matched points in range of 0.62s to 0.94s, like the original time-history. Therefore, we input this 'modified' time history to SeismoMatch program for the elimination of the remaining over-matched points and acquire the resulting 'double-matched time history' from this second spectral matching. The response spectra of Northridge SM&PF (modified to fit the PGA values, right after 1st spectral matching), Northridge SM&PF&SM (spectral matched again after the modification for PGA-fitting), and target response spectrum are described in Fig. 3. Detail characteristics of the time histories created by spectral matching, and their effects on fragility curves will be discussed at later section, in detail.

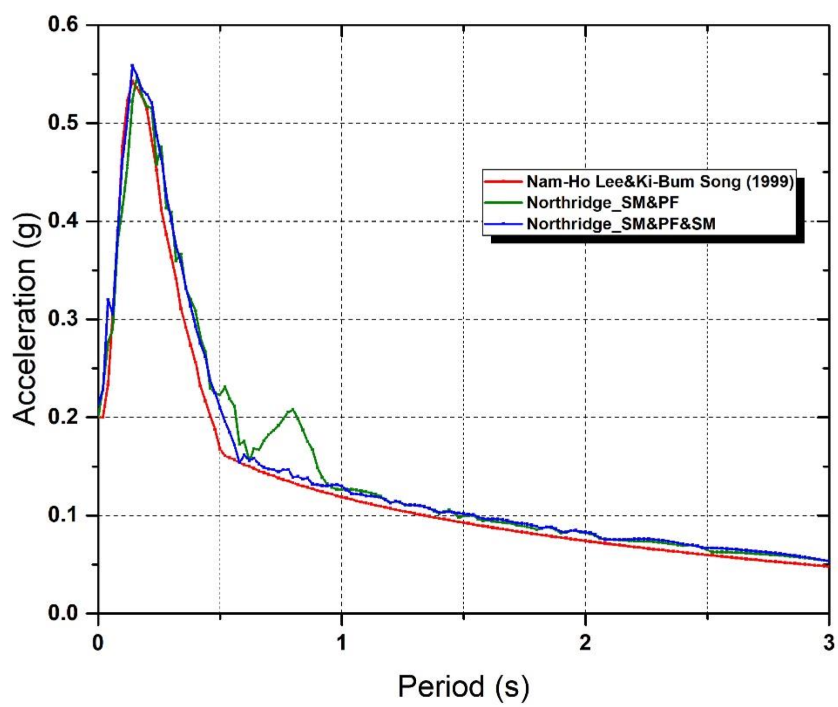

Figure 3. Comparison between target median spectrum, Northridge SM&PF and Northridge SM&PF&SM

FRAGILITY CALCULATION PROCEDURE

Fragility analysis methodology

The fragility analysis developed in this paper is based on methodology suggested at EPRI TR-103959. This methodology composed of calculation of strength factor, calculation of inelastic energy absorption factor, and calculation of uncertainty value. Strength factor is calculated by capacity and demand of structure as it given by equation (1), thereafter, inelastic energy adsorption factor was calculated by effective frequency-effective damping method that described in equation (2). The detail description for several equations are reported in EPRI TR-103959. Pseudo second moment area method or Monte Carlo simulation is the approach for calculation of uncertainty values. In this paper, pseudo second moment area method is used.

$$F_{SE} = \frac{C_s - D_{ns}}{D_s + \Delta C_s} \tag{1}$$

Where F_{SE} is the strength factor, C_s is the capacity of structure, D_{ns} is the demand of structure by non-seismic load, D_s is the demand of structure by seismic load, and ΔC_s is the change of capacity by seismic load

$$F_{\mu} = \left(\frac{f_e/f}{f_s/f}\right)^2 \frac{S_A(f,\beta)}{S_A(f_e,\beta_e)} \tag{2}$$

Where F_{μ} is the inelastic energy absorption factor, f_e is the effective frequency, f_s is the secant frequency, f is the 1st natural frequency of structure, β is the median damping value of the structure, and β_e is the effective damping value

The uncertainty and randomness related with strength and response of structure was calculated by using basic beta value suggested in EPRI TR-103959 and material property data reported by Nam-ho Lee & Ki-bum Song (1999). The basic beta value is multiplied to corresponding capacity or demand term, by exponential equation, and thereafter re-evaluated by equation (3). Total β values for randomness and uncertainty are calculated from β_i values by equation (4).

$$\beta_i = \frac{1}{|\phi|} \ln\left(\frac{SF_{\phi\sigma_i}}{\breve{SF}}\right) \tag{3}$$

Where β_i is the re-evaluated beta value, $\breve{SF}$ is the median scaling factor (strength factor × inelastic energy absorption factor), $SF_{\phi\sigma_i}$is the scaling factor which has certain z value of standard deviation, and ϕ is the parameter corresponding to z values of $SF_{\phi\sigma_i}$ (in general, 1).

$$\beta_R = \sqrt{\textstyle\sum_i \beta_{Ri}{}^2}\,, \beta_U = \sqrt{\textstyle\sum_i \beta_{Ui}{}^2} \tag{4}$$

Where β_R is the beta value for total randomness, β_{Ri} is the beta values related with randomness of each variables, β_U is the beta value for total uncertainty, and β_{Ui} is the beta values related with uncertainty of each variables.

Finally, fragility curves can be calculated by following equation:

$$P_f(a) = \frac{1}{2}\left(\frac{1+\mathrm{erf}\left(\ln\frac{a}{A_m} + \beta_U\sqrt{2}\,\mathrm{erf}^{-1}(2*Q-1)\right)}{\sqrt{2}\beta_R}\right) \tag{5}$$

Where $P_f(a)$ is the probability of failure of structure, component or system, a is the value of PGA (g),A_m is the median ground acceleration capacity, and Q is the reliability of fragility curve.

Among these variables, A_m, the median ground acceleration capacity is the value resulting from strength factor and inelastic energy absorption factor. It is calculated by the product of several values calculated from median demand and capacity: median value of strength factor $\breve{F}_{SE}$, median value of inelastic energy absorption factor $\breve{F}_{\mu}$, and the PGA(g) values of reference earthquake (A_{REF}). In this methodology, the A_{REF} is the PGA level of earthquake that causes median demand, and therefore, shape of the fragility curve is sensitive to the PGA values of used ground motion.

Strength equation

Capacity of containment is calculated by using equation (6)-(9), which was suggested at Ogaki et al. (1984)'s study that demonstrated through structural experiment. The coefficient α included in equation (2) and (3) reflect the decrease of effective area by overturning moment.

$$V_U = \frac{v_U \cdot \pi \cdot D_c \cdot t_w}{\alpha} \tag{6}$$

where V_U is the ultimate shear strength, v_U is the ultimate shear stress, D_c is the centerline diameter of containment wall, t_w is the depth of wall, and α: coefficient of conversion.

$$\begin{aligned} &\alpha = 2.0 && \text{for } \frac{M}{VD_0} \leq 0.5 \\ &\alpha = 0.667\left(\frac{M}{VD_0}\right) + 1.67 && \text{for } 0.5 < M/VD_0 < 1.25 \\ &\alpha = 2.5 && \text{for } 1.25 \leq M/VD_0 \end{aligned} \tag{7}$$

Where M is the overturning moment, V is the shear force, D_0 is the outer diameter of containment wall.

$$v_U = 0.8\sqrt{f_c} + \left(\rho\sigma_y\right)_{AVER} < 21.1\sqrt{f_c} \tag{8}$$

$$\left(\rho\sigma_y\right)_{AVER} = \frac{(\rho_h + \rho_m)}{2} f_y + \left(\frac{(\rho_{ph} + \rho_{pm})}{2} f_{py}\right) - \frac{(\sigma_h + \sigma_m)}{2} \tag{9}$$

Where f_c is the compressive strength of concrete at 28 days, ρ_h is the re-bar ratio for hoop direction, ρ_m is the re-bar ratio for meridional direction, ρ_{ph} is the prestressing tendon ratio for hoop direction, ρ_{pm} is the prestressing tendon ratio for meridional direction, σ_h is the hoop direction stress by dead load, pressure and seismic load, σ_m is the meridional direction stress by dead load, pressure and seismic load, f_y is the yield strength of re-bar, and f_{py} is the yield strength of prestressing tendon.

Consideration in structural analysis

Almost of beta values related with randomness in spectrum shape, uncertainty in modelling, strength of concrete and steel was calculated by equation (2) and pre-existing values. For example, horizontal spectrum shape is known to have 0.3 of the beta values according to EPRI TR-103959. Then, the 1σ demand related with this parameter, such as shear force and bending moment (except the change of capacity, which is dominated by vertical ground motion) could be calculated simply by following equation (10). Finally, we can calculate the 1σ strength factor with the 1σ demand and equation (1).

$$D_{+1\sigma} = \breve{D} \times e^{\beta} \tag{10}$$

Where $D_{+1\sigma}$ is the demand has 1 z of standard deviation, $\breve{D}$ is the median demand value, and β is the basic beta value suggested by EPRI TR-103959.

However, in case of damping, EPRI TR-103959 suggest the beta value as a form of two damping values: median damping values and 1σ damping value. To calculate the strength factor, scaling factor and re-evaluate the beta value, several structural analyses should be conducted. Therefore, we create 4 model for each damping values and each direction. For the horizontal model, ground motion corresponding to two direction of east-west and north-south are assigned simultaneously. In case of vertical model, ground motion which has same shape but scaled as 0.65 times of horizontal ground motion is assigned by following guidance of NUREG CR-0098.

DISCUSSION

Earthquake characteristics

The ground motion resulting from the spectral matching with the data recorded from several earthquakes are characterized with their PGA, S_a at the natural frequency of containment, significant duration, Arias intensity, and maximum displacement as it depicted in Table 1. All ground motions have very similar spectral acceleration at the period corresponding to the 1st natural frequency of the containment building but have different PGA values. Especially, the ground motion created by spectral matching for the Northridge data has the PGA value farthest from the 0.2g of target PGA. As it discussed before, the methodology used in this paper is very sensitive to PGA value, so we tried several processes to anchor this value to our goal, as it discussed at previous section. As it described in Northridge SM&PF&SM and Northridge SM&PF&SM, PGA values are anchored well with the target, and S_a also confirmed well with the other ground motion. Both have very different maximum displacement with the Northridge SM, but significant duration and Arias intensity of them are similar with that of Northridge SM. Significant duration of almost of time histories are longer than 10 s except the Kyoungju SM data. The Raghunandan et al. (2013) reported about the effects of significant duration on collapse of building, with the 35 s of limit used to distinguish the short duration ground motion and long duration ground motion. Therefore, the difference in significant duration and arias intensity shown in Table 1 expected to have certain effects on fragility curves.

Table 1: Ground motion parameters of time histories matched with design response spectrum

	PGA (g)	S_a (g)*	significant duration (s)	Arias intensity	Maximum displacement (m)
Kyoungju_SM**	0.198	0.533	1.6	0.159	0.0604
Kobe_SM	0.173	0.529	18.07	0.676	0.2706
Northridge_SM	0.255	0.530	19.58	0.593	0.1308
Northridge_SM&PF ***	0.2	0.523	19.60	0.587	0.3022
Northridge_SM&PF&SM ****	0.212	0.531	19.59	0.576	0.3076
Imperial valley_SM	0.198	0.529	14.56	0.542	0.1275

*Spectral acceleration at 1st natural frequency of containment building, 5.16 Hz

**SM: spectral matched

***Created by following step: spectral matching → eliminate over-matched point to fit the PGA value

****Created by following step: spectral matching → eliminate over-matched point to fit the PGA value → 2nd spectral matching

Fragility curve

To draw the fragility curve, median capacity A_m and beta values corresponding to randomness and uncertainty, β_R and β_U are required. As it explained at previous section, A_m is calculated as product of PGA described in Table 1, F_{SE} and F_μ described in Table 2. Also, β_R and β_U is calculated by using methodology described in equation (3). In table 1, ground motion parameters of Kyoungju SM, especially the significant duration are very different with other ground motion. Considering the result studied by Raghunandan et al. (2013), the ground motion duration has short period could induce the smaller response compared to that of long period, which results in large F_{SE} in fragility analysis. That might be the main reason that median ground motion capacity and HCLPF resulting from Kyoungju SM has the largest value among all fragility analysis. Imperial valley SM is the other one which has short significant duration than others, so it also has large strength value than others. However, Northridge SM has the highest PGA, so it results in higher median capacity and HCLPF than those of Imperial valley SM. High variance in A_m and HCLPF resulting from different ground motion data is not the desirable results in fragility analysis, despite the fact that difference between PGA and S_a at certain frequency reflects the spectral shape which is the origin characteristic of earthquake. This is the reason that we discussed several modification processes to anchor PGA values between spectral matched spectrum and target response spectrum at previous section. As it can see, SM&PF&SM (additional PGA-fitting & spectral matching) result in the more reasonable median capacity and HCLPF compared to those of analysis based on Northridge SM. However, the result coming from Northridge SM&PF is similar with the result calculated by Kobe SM has large difference with the median also like the Northridge SM data.

Considering that the spectral matching mechanism of SeismoMatch program is based on Al Atik, L. and Abrahamson, N. (2010), the only difference between Northridge SM&PF and Northridge SM&PF&SM is the little difference in their shape of response spectrum, while their maximum displacement, significant duration and Arias intensity are very similar.

Table 2: Variables for fragility curves based on analysis with several spectral matched ground motion

	F_{SE}	F_{μ}	A_m (g)	β_R	β_U	HCLPF (g)
Kyoungju SM*	18.30	1.498	5.427	0.2279	0.3485	2.096
Kobe SM	9.308	1.534	2.600	0.2266	0.2775	1.131
Northridge SM	11.13	1.481	4.205	0.2272	0.2912	1.788
Northridge SM&PF **	10.31	1.506	2.686	0.2277	0.3038	1.117
Northridge SM&PF&SM ***	10.94	1.507	3.495	0.2269	0.2926	1.483
Imperial valley SM	12.28	1.494	3.632	0.2266	0.2787	1.578
median	11.035	1.502	3.5635	0.2271	0.2919	1.5305

*SM: spectral matched

**Created by following step: spectral matching → eliminate over-matched point to fit the PGA value

*** Created by following step: spectral matching → eliminate over-matched point to fit the PGA value → 2nd spectral matching

The relationship between several ground motion parameter and resulting HCLPF are investigated by using linear regression analysis. Take account for the R^2 values, the variable which has the largest degree of relationship with the HCLPF is maximum displacement, followed by Arias intensity, S_a at 1st natural frequency of containment, significant duration and PGA. In case of β_R, it has too less relationship with other ground motion data, but β_U is highly related with Arias intensity of ground motion. The R^2 values between HCLPF of containment building and maximum displacement of ground motion is about 0.697, while the R^2 values between β_U and Arias intensity of ground motion is about 0.82, as they described in Fig. 4. Finally, resulting fragility curves drawn based on Table 2 is described in Fig.5. Considering that the resulting fragility curve has the highest uncertainty, median capacity and HCLPF, Kyoungju SM makes too different with values with the other earthquake, while it has the best correspondence with the target response spectrum suggested by Nam-ho Lee & Ki-bum Song (1999). Take accounts for this fact, the difference in fragility curves of the Kyoungju SM with those of calculated by other ground motion is due to the site characteristics of Korea. In other words, this result seems justifying its use at seismic performance assessment in only specific local area.

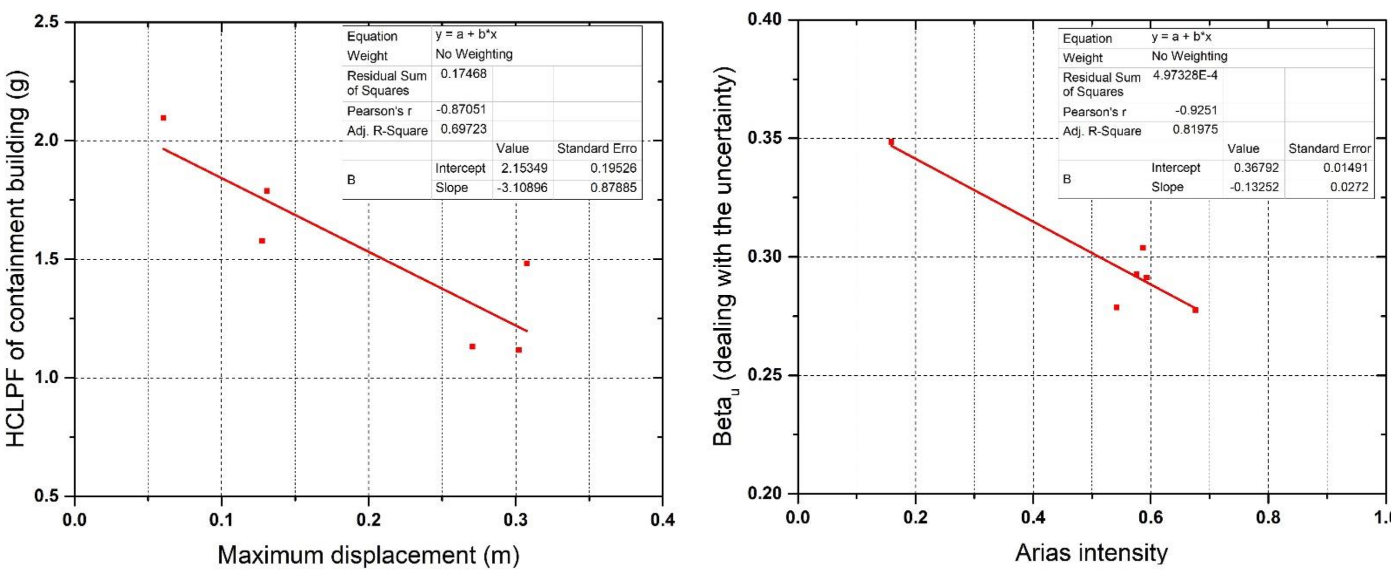

Figure 4. Regression analysis result for HCLPF vs maximum displacement (left) and $\boldsymbol{\beta_U}$ vs Arias intensity (right)

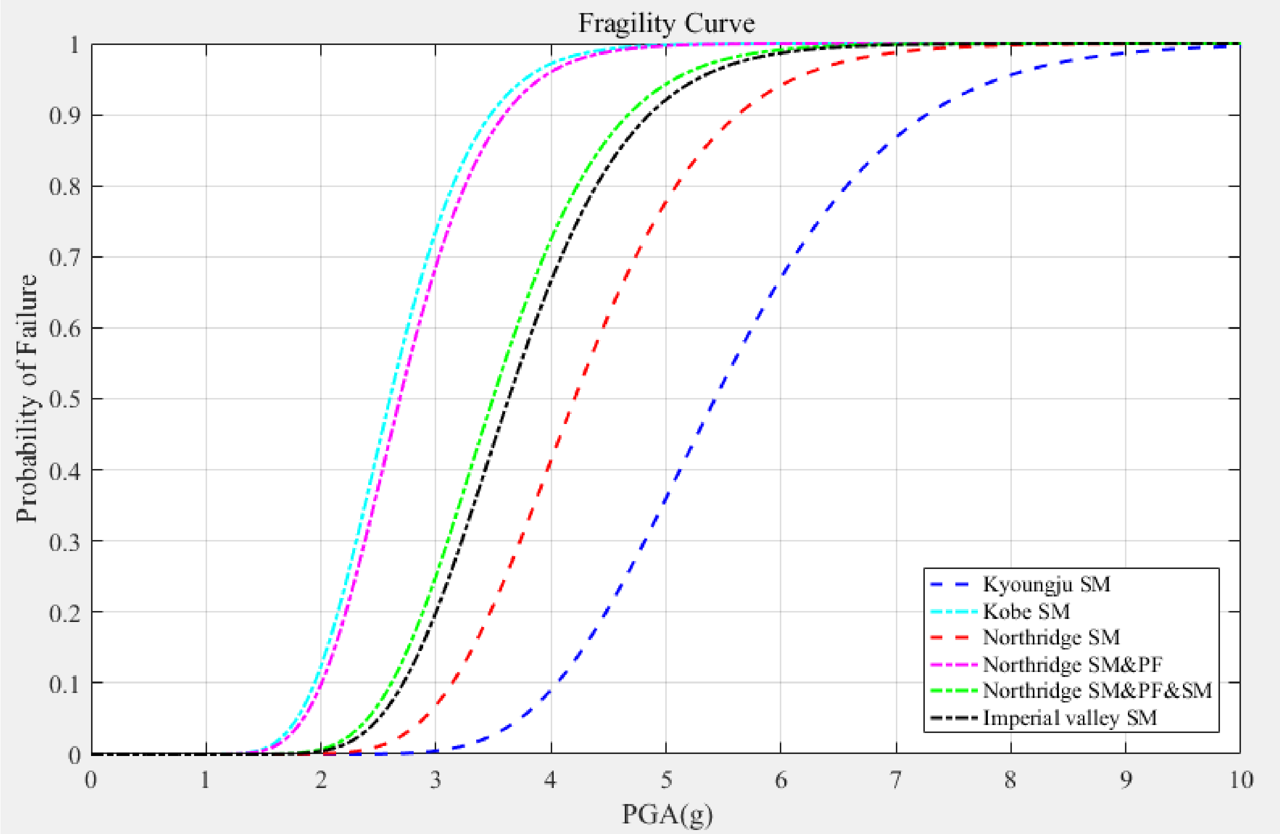

Figure 5. Fragility curves based on several ground motion data

CONCLUSION

In this paper, we use the several ground motion data: Kyoungju, Kobe, Imperial valley and Northridge earthquake to make several fragility curves. The spectral matched ground motion based on Kyoungju earthquake makes lower response of containment building, which estimated to be the result of too short significant duration, low Arias intensity or maximum displacement. The median value for HCLPF of all fragility curves is about 1.531, so the results from Imperial valley_SM and Northridge_SM&PF&SM are the closest value to this median value. Considering the resulting fragility curve, Kyoungju earthquake is the time history that should be permitted only to seismic performance assessment at certain area of Korea. Furthermore, Arias intensity and maximum displacement investigated to be the key factor for uncertainty and HCLPF, so we conclude that consideration about these factors are important when using ground motion for seismic performance assessment.

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