한반도 기록지진의 특성이 원자력발전소 구조물의 지진취약도에 미치는 영향 평가

Effects of the Recorded Earthquake Data on the Seismic Fragilities of Korean Nuclear Power Plant Structures

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요 지

지진취약도분석 기술은 원자력발전소의 구조물 및 기기의 실제 내진성능을 평가하기 위하여 이용된다. 이 논문에서는 원자력발전소를 구성하는 구조물들의 지진취약도를 평가하는 개선된 기법에 대하여 요약하였다. 또한, 최근 몇 년간 한반도에서 발생된 소규모 기록지진의 응답스펙트럼에 대한 공학적 특성을 평가하고, 이러한 기록지진의 응답스펙트럼을 부지의 실제 지반운동으로 사용할 경우, 지진취약도분석에 미치는 영향을 검토하였다. 몇 가지 예제 구조물에 대한 지진취약도분석을 통하여 기록지진의 특성이 한국형 원자력발전소의 내진성능에 미치는 영향을 정량적으로 평가하였다. 평가결과, 현재까지 부지의 실제 지반운동으로 사용되어 오던 Newmark 스펙트럼은 국내 시설물의 내진성능을 과대평가 할 수 있음을 보여주었다.

핵심용어 : 지진취약도분석, 기록지진, 내진성능, 파괴확률

Abstract

Seismic fragility analysis (SFA) has been utilized to evaluate the actual seismic capacity of structure and equipment in nuclear power plants (NPP). This paper briefly introduces an improved method for evaluating seismic fragilities of components of NPP's in Korea. Engineering characteristics of small magnitude earthquake spectra recorded in the Korean peninsula during the last several years are also discussed in this paper. Some significant differences between the Newmark's spectra and the recorded spectra as a site-dependent spectra are assessed. Several comparative SFA's have been performed to evaluate the effects of the recorded earthquakes on the seismic capacities of Korean NPP structures. The results showed that SFA using the Newmark's spectra might over estimate the actual seismic capacities of Korean facilities.

Keywords : *seismic fragility analysis, recorded earthquake, seismic capacity, probability of failure*

1. Introduction

Seismic design is one of the most significant safety issues in NPP engineering. Basic parameters for seismic design of structures and equipments intrinsically include various uncertainties. In particular, the randomness of seismic events does not allow analysts to estimate reasonable structural seismic responses by a deterministic method. Based on this background, the seismic probabilistic risk assessment (SPRA) has been developed to resolve the safety issue and to evaluate the more reasonable seismic capacity of NPP structure.

In 1991, the Nuclear Regulatory Commission (NRC) of the United States (US) issued Generic

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Letter No. 88-20[1] as a policy statement on the severe accidents and also published NUREC-1407[2] to provide a guidance of safety review strategy of NRC SPRA. Thereafter, NPP utilities have been requested to perform an individual plant examination. Accordingly, the SPRA is a regulatory requirement for NPP's under construction as well as in operation. The SPRA is performed by four separate steps, i.e., seismic hazard analysis, seismic fragility analysis (SFA), plant system and accident-sequence analysis, and consequence analysis. The SFA is the most significant and essential process especially for structural or mechanical engineers.

The fragility evaluation methodology which has been developed by foreign countries is described in a number of papers and reports.[3]~[6] Currently, the US Electric Power Research Institute (EPRI) presented a practical guidance for performing SFA for the SPRA of NPP's.[7] For all operating plants in the US, the SPRA has been conducted as an individual plant examination for external events (IPEEE) since 1992.[8] On the contrary, it has not been long to apply the probabilistic concept to the seismic evaluation of major industrial facilities in Korea. The realistic safety assessment of structures under dynamic loadings has yet to be addressed comprehensively.[9] A basic implementation procedure of SFA for NPP structures was first introduced in Korea in 1992.[10] Several research projects by Joe and Cho[11]~[13] about the improved methodology to incorporate the local characteristics have been performed in Korea since 2000.

Because of probabilistic procedure of SFA, the statistical data of design information and ground motions will considerably govern the results of the analysis. A reasonable result of seismic fragility is expected only when the realistic design informations and site-specific data are provided. Therefore, the inherent design information and the site-specific data is required to obtain reasonable results of the SFA. Nevertheless, in the past SFA's performed in Korea, they assumed most basic information arbitrarily and used the methodologies that were provided by some foreign companies without theoretical or practical validation for their applicability to the Korean facilities.

This paper presents a practical methodology for seismic fragility analysis that has been utilized and is being improved in Korea. Particularly, the effects of site-dependent response spectra in Korea on the seismic capacity of NPP are discussed. For this purpose, the response spectrum characteristics of small magnitude earthquake motions recorded in the Korean peninsula during the last several years have been evaluated. The seismic fragilities of several Korean NPP structures have been estimated using the resulting response spectra of recorded earthquakes, and the results are comparatively evaluated.

2. Basic SFA Methodology

2.1 Seismic Capacity for Fragility Analysis

The Korean method for SFA is basically similar to that of EPRI,[7] called "response factor method" or "safety factor method". In this method, the response factor is a measure of conservatism included in seismic design and a ratio of design response to actual response. Using peak ground acceleration as a ground motion parameter, an actual seismic capacity, A is expressed by equation (1).

$$A = \left(\prod_i F_{Ci} \cdot F_{Ri}\right) \times A_{ref} \tag{1}$$

where,

F_{Ci} : safety factors for capacity variables

F_{Ri} : safety factors for response variables

A_{ref} : reference ground acceleration (usually, safe shutdown earthquake level)

Considering the approximate second moment procedure for multiplicative equation, the median capacity, $\breve{A}$, and the logarithmic standard deviations for randomness, β_R, and uncertainty, β_U, are obtained by equation(2) and (3), respectively.

$$\breve{A} = \breve{F}_S \cdot A_{ref} \tag{2}$$

$$\beta = \left(\sum_i \beta_i^2 \right)^{1/2} \tag{3}$$

where,

$\breve{F}_S$: median safety factor

β : representation of either β_R or β_U

The median safety factor in equation(2) is obtained by using median values for safety factors of all the basic variables in the analysis as equation(4).

$$\breve{F}_S = \prod_i \breve{F}_{Ci} \cdot \breve{F}_{Ri} \tag{4}$$

where,

$\breve{F}_{Ci}$: median safety factors for capacity variables

$\breve{F}_{Ri}$: median safety factor for response variables

In equation(3), each of the individual β_i values is obtained from the following equation.[7]

$$\beta_i = \frac{1}{|\phi|} \ln\left(\frac{F_{\phi\sigma,}}{\breve{F}_i} \right) \tag{5}$$

Where, $\breve{F}_i$ is the median safety factor of individual variables. The parameter $F_{\phi\sigma,}$ is the scale factor to reach failure where the i-th variable is set at the ϕ standard deviation, σ level. The parameter ϕ is usually set at 1 on the side of the median that leads to the lowest capacity (i.e., $F_{1\sigma,}$ for capacity variable and $F_{+1\sigma,}$ for demand variable).

2.2 Basic Variables in SFA

The fragility analysis for structures considers both response and capacity variables as basic fragility analysis variables. These variables are represented by safety factors. The response variable is to account for the conservatism of seismic response which may result from the variabilities of design ground motions, damping values, and caused by the techniques of modeling, mode combination, earthquake component combination, soil-structure interaction analysis, and so on. The strength and the inelastic energy absorption capacity of structural members are considered as capacity variables to reflect the actual resistance of structures under the reference earthquake.

Most of the safety factors of the Korean method are adopting the same values as EPRI's. However, for the response spectrum shape factor, the effects of multi-modes is additionally considered to get more reasonable structural responses, while they use only the fundamental modal response in the EPRI method.[7] The response spectrum shape factor reflecting the multi-modes effects can be expressed by equation(6) using the modal contribution factor for base shear which represents modal contributions to the total seismic response of the structure.[12]

$$F_{ss} = \frac{\sum_{n=1}^{N} r_n S_A(\omega_n, \xi)_{ref}}{\sum_{n=1}^{N} r_n S_A(\omega_n, \xi)_{act}} \tag{6}$$

Where, $S_A(\omega_n, \xi)$ is the spectral acceleration of the n-th mode and the subscriptions stand for the reference earthquake and actual earthquake, respectively, and r_n is the n-th modal contribution factor which is a ratio of the n-th modal response to the total response. ω_n is the n-th modal frequency and ξ is the damping value of structure.

2.3 Expression of Seismic Fragility

The seismic fragility is expressed by a set of probability of failure P_f for a given ground level a at any non-exceedance probability level as in equation(7).[4]

$$P_f = \Phi\left[\frac{\ln\left(\frac{a}{\breve{A}}\right) + \beta_U \Phi^{\ 1}(Q)}{\beta_R} \right] \tag{7}$$

where,

$\Phi[\ ]$: cumulative distribution function of normal distribution
Q : non-exceedence probability level (5%, 50%, or 95% level in usual)
$\Phi^{-1}[\ ]$: inverse of normal distribution function
$\check{A}$: median seismic capacity
β_R, β_U : logarithmic standard deviations for randomness and uncertainty of seismic capacity

The median capacity, $\check{A}$ is obtained from equation(2). Adopting the approximate second moment procedure, the median safety factor in equation(2), $\check{F}_S$, and logarithmic standard deviation for the safety factor, β are obtained directly.

$$\check{F}_S = f(\check{X}) \qquad \check{X} = (\check{X}_1, \check{X}_2, \cdots, \check{X}_n) \tag{8}$$

$$\beta = \frac{1}{\check{F}_s} \cdot \sqrt{\sum_i \left(\frac{\partial f}{\partial X_i}\Big|_{\check{X}_i} \beta_i \check{X}_i \right)^2} \tag{9}$$

where,

$\check{X}_i$: median of the basic variables, X_i
β_i : logarithmic standard deviations of the basic variables, X_i
$\frac{\partial f}{\partial X_i}\Big|_{\check{X}_i}$: derivative of $f(X)$ with respect to X_i, evaluated at the median value of $\check{X}_i$

The high confidence low probability of failure (HCLPF) value[14),15)] is used as an index to represent the seismic capacity of the structure. It is the 5% probability of failure point of the 95% confidence curve.

3. Response Spectra of Korean Earthquakes

Recently, statistical and engineering characteristics of earthquake motions recorded in the Korean peninsula during the last several years have been accumulated and analyzed. In this study, small magnitude earthquake records instrumented at rock sites during 1995~1997 in the Kyunsang Basin[16)] were analyzed to construct the site-specific ground response spectra.

As shown in Table 1, 87 earthquake records out of 16 events were analyzed in this study. The magnitudes of the motions vary from 2.7 to 4.8 with 3.7 as the average. As shown in Fig. 1, it is noted that the stations are mostly concentrated in the southeast side of the Korean peninsula where most of the NPP sites in Korea are located.

The horizontal response spectra that are normalized to 1.0g of zero period acceleration are compared in Fig. 2 and Fig. 3. In Figs. 2 and 3, RG1.60(Hor) indicates the horizontal response spectrum of USNRC.[17)] Newmark 50% and Newmark 84% indicate mean and mean + 1 standard deviation response spectra suggested by Newmark,[18)] respectively. The numbers with 'Mag' indicate the averaged magnitudes of the recorded motions. As can be seen, the higher frequency components of the records are dominant and the governing frequencies move to the low frequency side as the magnitudes increase. And the amplifications of the recorded earthquakes are larger than those of the standard response spectra proposed by USNRC[17)] and Newmark[18)] in the frequency

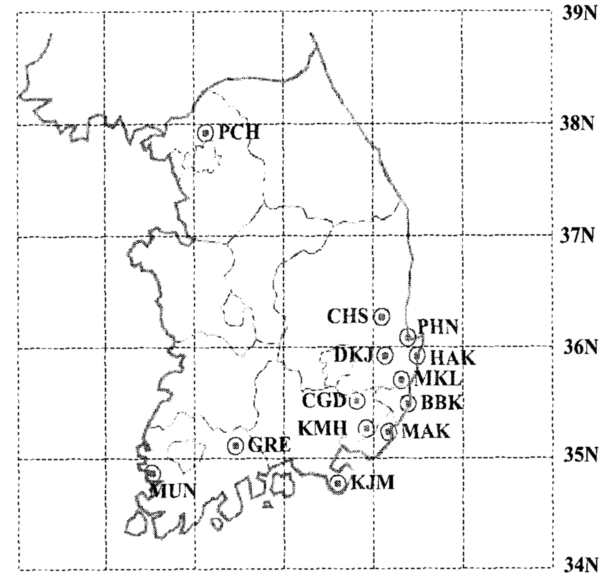
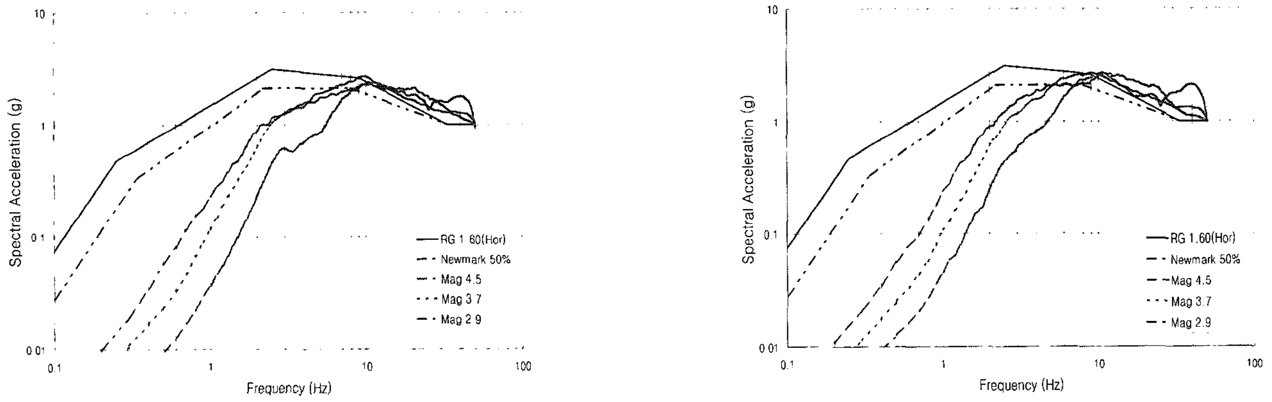


Fig. 1 Location of Stations

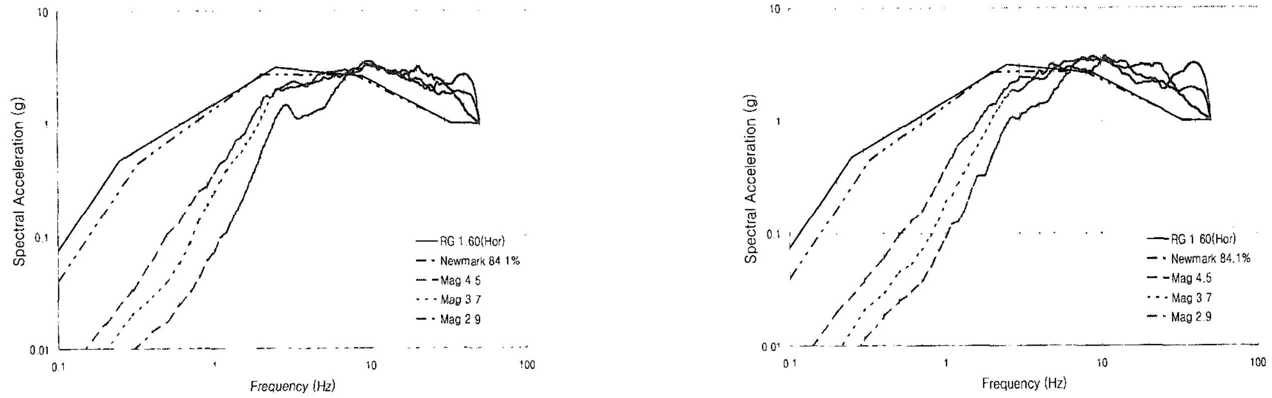
Table 1 Recorded Earthquake Data Used for the Study

Event	Origin Time		Epicenter		Richter Magnitude	No. of Stations
	Y/M/D	H/M/S	Lat.	Long.		
1	95-06-19	18/09/25.54	36-14.49	128-15.07	3.8	4
2	95-10-06	21/07/28.70	37-44.65	129-38.11	4.3	3
3	96-01-24	05/09/51.07	38-05.00	129-33.65	4.8	7
4	96-02-27	04/39/33.98	35-57.00	129-29.55	3.0	6
5	96-04-14	05/22/11.05	35-51.90	127-53.58	3.9	7
6	96-05-13	00/49/27.12	35-50.00	130-21.90	3.9	4
7	96-05-16	11/05/43.27	35-18.50	129-06.91	3.0	4
8	96-08-14	18/10/03.06	36-41.00	128-01.75	3.5	8
9	96-10-16	04/45/30.40	36-12.43	128-18.83	3.8	2
10	96-11-10	21/33/19.17	36-47.16	125-24.00	4.2	3
11	97-01-15	05/34/04.61	38-50.16	128-25.93	3.6	10
12	97-05-09	21/40/07.11	35-17.64	126-19.45	3.8	4
13	97-05-22	07/52/37.52	36-04.12	127-06.30	3.9	8
14	97-06-26	03/50/23.19	35-48.09	129-14.20	4.3	3
15	97-10-11	19/50/28.76	35-55.05	128-50.69	2.7	8
16	97-10-18	19/35/31.31	37-13.11	128-41.35	3.0	6
Total	-					87



(a) EW-Direction (b) NS-Direction

Fig. 2 Comparisons of Mean Horizontal Response Spectra



(a) EW-Direction (b) NS-Direction

Fig. 3 Comparisons of Mean+1σ Horizontal Response Spectra bands above 10Hz in the mean spectra and 6Hz in the 84th percentile spectra of Newmark's, respectively. Though not shown in this paper, the vertical components of the spectra also showed similar characteristics of the shape.

4. Comparative Evaluation of Seismic Fragility

In order to evaluate the variation of seismic capacity of structure due to the different site-dependent earthquake motions (response spectra), SFA's have been performed for the several structures which were selected from the typical NPP structures in Korea. In addition, the multi-modes effects have also been evaluated for each case. As indicated in the previous study,[12] when using the response spectrum shape factor considering a single mode only, the seismic capacity might be under-estimated or over-estimated depending on structural types or spectral shapes. Therefore, the four following different cases are considered in this study in accordance with the spectral shapes and number of effective modes. And five different types of structures are adopted for the comparative analyses.

(1) Case A : Newmark's spectra considering single mode
(2) Case B : recorded spectra considering single mode
(3) Case C : Newmark's spectra considering multi-modes
(4) Case D : recorded spectra considering multi-modes

4.1 Structural Models

The selected models are five representative structures of YGN 3&4[19,20] which are prototype models of Korean standard NPP. They are a containment building, an auxiliary building, a component cooling water (CCW) building, a refueling water storage tank (RWST), and an essential service water intake (ESW) structure. The containment building consists of a right cylindrical wall closed on top by a hemispherical dome. The containment is constructed of concrete and prestressed by horizontal and vertical post-tensioned tendons in the cylindrical wall and dome. Other structures are all rectangular reinforced concrete

Table 2 Structural Properties of the Structures

Structure	Size (meter)[a]	Damping[b]	
		About 1/2 Yield	Near Yield
Containment Bldg.	43.9(D)×66.8(H)	5%	7%
Aux. Bldg.	66.4(W)×98.8(L)×37.8(H)	7%	10%
CCW Bldg.	17.4(W)×31.1(L)×17.7(H)	7%	10%
RWST	11.3(W)×31.7(L)×12.6(H)	7%	10%
ESW Structure	14.3(W)×14.1(L)×11.3(H)	7%	7%

Notes. a) D: diameter, W: width, L: length, and H: Height
b) percentage of critical damping value

Table 3 Modal Properties of the Structures

Prop. / Mode	Containment Structure		Aux. Building		CCW Building		RWST		ESW Structure	
	Freq.(Hz)	γ (%)	Freq.(Hz)	γ (%)	Freq.(Hz)	γ (%)	Freq.(Hz)	γ (%)	Freq.(Hz)	γ (%)
1st	4.6	71.7	2.02	6.8	14.33	85.0	0.23	4.7	20.61	86.0
2nd	13.4	19.5	2.06	5.8	27.69	15.0	9.56	22.7	≥31.0	14.0
3rd	24.1	2.5	7.06	60.4	≥33.0	0.0	13.25	59.7	-	-
4th	27.6	2.3	15.99	4.1	-	-	23.73	11.0	-	-
5th	≥33.0	2.1	18.68	13.3	-	-	≥33.0	1.9	-	-
6th	-	-	≥33.0	9.6	-	-	-	-	-	-

Note. γ : modal contribution factor structures of shear wall type.

The size and design damping values of the structures are shown in Table 2, and their modal properties are summarized in Table 3. It is noted that the modal properties of the containment building were recalculated in this study just to consider the modes of the shell and dome excluding the internal structures. Other properties in Table 3 are directly cited from the project design report.[19] The two different damping values according to the stress levels (1/2 yield level for the reference earthquake and yield level for the actual earthquake) are considered in SFA.

4.2 Response Spectra

The Newmark's spectra of NUREG/CR-0098[18] have been used as an actual earthquake in all the past SPRA's up to now in Korea. In this study, both of Newmark's spectra and the recorded earthquake spectra were used as an actual earthquake and their characteristics were compared. The site-independent response spectra of the RG 1.60[17] were adopted as the reference response spectra.

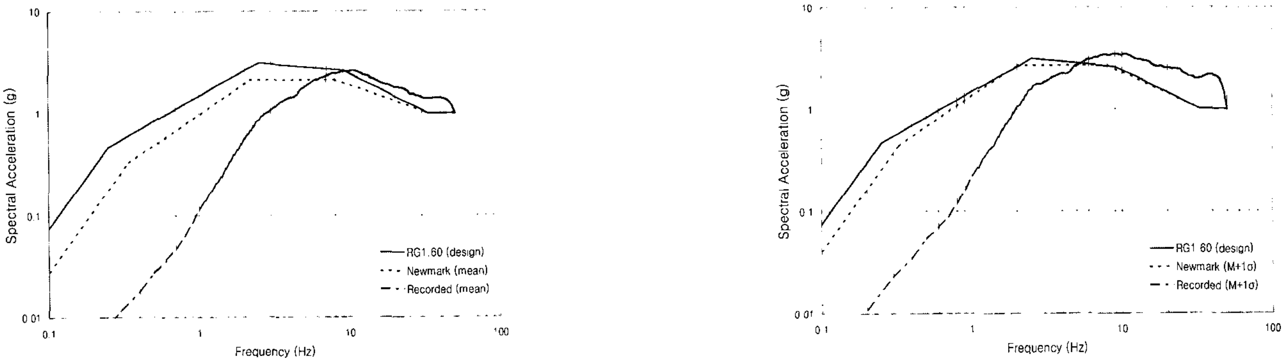
The response spectrum curves of 5% damping used in this study are shown in Fig. 4. Recorded spectra were originally instrumented for the 5% damping factor, so curves of damping factors other than 5% were generated from 5% damping curve by applying the Newmark's scale factors.[18]

From Fig. 4, it is expected that for the lower frequency structures with the fundamental frequency of less than 10Hz, the larger seismic capacity might be estimated when using the recorded spectrum as an actual earthquake in SFA compared to the case in use of the Newmark's spectrum, and vice versa for the case of the higher frequency structures.

4.3 Fragility Variables

Table 4 shows the median response spectrum shape factors, and its logarithmic standard deviations for randomness which are calculated by using the two different response spectra, i.e., Newmark's and the recorded spectra. Logarithmic standard deviations for uncertainty of the response spectrum shape factor, β_U are assumed to be the same as the design value of 0.05 for all the cases.

As shown in Table 4, the cases using Newmark's spectra over-estimate the factors comparing to the cases of the recorded spectra for most of models except the containment building. This has been caused by the fact that the spectral values of the recorded spectra are much smaller than the reference spectra values[17] in the lower frequency range of the containment building (4.6Hz) and the opposite is true in the higher frequency range of the other buildings (above 10Hz), while the Newmark's spectral values have no significant difference along all frequency ranges. This phenomenon implies that the seismic capacity of the



(a) Mean

(b) Mean+1σ

Fig 4 Response Spectra (5% damping) for Seismic Fragility Analyses

Table 4 Comparison of Response Spectrum Shape Factors

Parameter / Model	Newmark's Spectra				Recorded Spectra			
	Single Mode		Multi-modes		Single Mode		Multi-modes	
	$\check{F}_{ss}$ a)	β_R b)	$\check{F}_{ss}$ a)	β_R b)	$\check{F}_{ss}$ a)	β_R b)	$\check{F}_{ss}$ a)	β_R b)
Containment Bldg.	1.52	0.22	1.46	0.20	1.88	0.41	1.54	0.38
Aux. Bldg.	1.15	0.19	1.20	0.18	0.89	0.35	1.03	0.34
CCW Bldg.	1.26	0.11	1.24	0.10	0.86	0.31	0.85	0.31
RWST	1.29	0.12	1.26	0.12	0.84	0.28	0.88	0.30
ESW Structure	1.09	0.07	1.08	0.07	0.79	0.36	0.81	0.34

Notes. a) $\check{F}_{ss}$: median response spectrum shape factor

b) β_R : logarithmic standard deviation of response spectrum shape factor

Table 5 Comparison of Seismic Capacities

Parameter / Model	Newmark's Spectra				Recorded Spectra			
	Single Mode		Multi-modes		Single Mode		Multi-modes	
	$\check{A}$ a)	HCLPF b)	$\check{A}$ a)	HCLPF b)	$\check{A}$ a)	HCLPF b)	$\check{A}$ a)	HCLPF b)
Containment Building	4.93	1.35	4.73	1.32	6.08	1.31	4.98	1.12
Aux. Building	2.03	0.59	2.12	0.62	1.58	0.39	1.82	0.45
CCW Building	2.37	0.84	2.32	0.83	1.60	0.47	1.60	0.47
RWST	2.68	0.93	2.62	0.91	1.84	0.53	1.84	0.53
ESW Structure	0.63	0.23	0.62	0.23	0.47	0.13	0.47	0.13

Notes. a) median acceleration capacity (0.2g of reference earthquake level)

b) HCLPF = $\check{A} \cdot \exp[-1.645(\beta_R + \beta_U)]$

structures in the higher frequency range might be overestimated when using the Newmark's spectra instead of recorded spectra.

Besides, the logarithmic standard deviations for randomness of recorded spectra are larger than those of the Newmark's spectra. This might have been caused by the fact that most of the recorded data used in this study are from the small or medium amplitude earthquakes and in consequence, have the larger relative variation compared with strong-motion earthquakes. This fact would result in the lower seismic capacities of structures.

4.4 Comparison of Seismic Capacities

As final results, the median acceleration capacity and HCLPF values are summarized in Table 5. When calculating the fragility results in Table 5, other basic variables except response spectrum shape factor are directly cited from the project report.[20] From Table 5, it is found that in the case of using the Newmark's spectra, the HCLPF values obtained by considering a single mode are similar to those of considering multi-modes, while there are some differences in case of the recorded spectra.

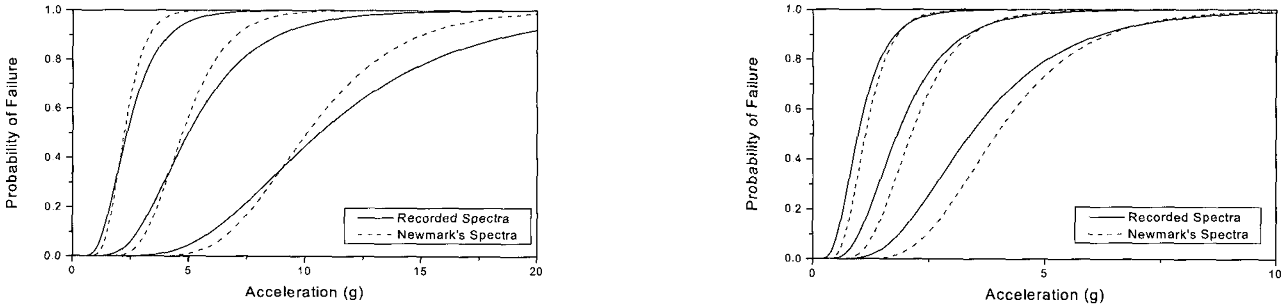
In Table 6, the HCLPF value ratios are compared to show the impact by the spectral shapes and multi-modes. As can be seen, Newmark's spectra case always gives much higher HCLPF values by up to 80% than the recorded spectra case. On the other hand, the effects by the number of modes to be considered vary from case to case and the differences in amplitude are less than 20%.

The results say that the SFA using site- independent spectra like Newmark's can highly overestimate the seismic capacity of structures and the present SFA procedure in Korea based on the site-independent spectra should be improved to reflect the local site effects. The results also imply that consideration of multi-modes in SFA might have some significant effects particularly for some irregular types of structures.

The fragility curves of the containment building

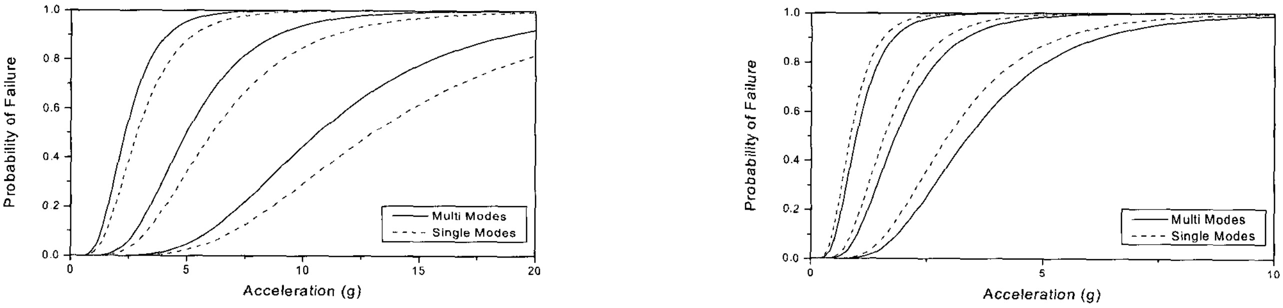
Table 6 Comparison of HCLPF Value Ratios

Parameter / Model	Spectral Type Effects (Newmark's / Recorded)		Multi-modes Effects (Single Mode / Multi-modes)	
	Single Mode	Multi-modes	Newmark's	Recorded
Containment Building	1.03	1.18	1.02	1.17
Aux. Building	1.51	1.38	0.95	0.87
CCW Building	1.79	1.77	1.01	1.0
RWST	1.75	1.72	1.02	1.0
ESW Structure	1.77	1.77	1.0	1.0



Aux. Building (a) Containment Building

Fig. 5 Comparison of Seismic Fragility Curves for Spectral Type Effects (Multi-modes Case)



Aux. Building (a) Containment Building

Fig. 6 Comparison of Seismic Fragility Curves for Number of Mode Effects (Recorded Spectrum Case)

and the auxiliary building corresponding to the 95%, 50% and 5% confidence values are shown in Fig. 5 and Fig. 6. From Fig. 5 and Fig. 6, we can find some significant differences in shapes of fragility curves in accordance with spectral types and number of modes considered. For the buildings not shown in this paper, the results also show a similar trend.

5. Conclusions

This paper introduces an SFA procedure based on the improved response spectrum shape factor considering the multi-modes effects and also discusses the characteristics of the local earthquake data recorded in Korea over several years and its impact on the SFA result. Applying the procedure to several typical NPP structures in Korea, practical applicability of the proposed procedure was validated. From the comparative study results, the following conclusions have been drawn.

(1) The shape and variation of the response spectra of the actual earthquake in SFA has a significant impact on the result.

(2) The seismic capacity of structures in Korea can be highly overestimated when using Newmark's spectra instead of the recorded spe-

ctra as an actual earthquake. Therefore, the present SPRA procedure in Korea should be improved to incorporate the characteristics of the recorded local earthquake data.

(3) The effect of modal properties of structure in SFA is not negligible. Therefore, multi-modes effects on response spectrum shape factor should be adopted in SFA for some irregular typed structures.

(4) Some extended studies should be continued using the updated characteristics of local earthquakes based on the larger number of earthquake data accumulated in Korea, because the recorded data in this study is not completely satisfactory due to the smaller magnitudes of the earthquake and the limited number of earthquakes.

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