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Seismic Fragility Analyses of Nuclear Power Plant Structures Based on the Recorded Earthquake Data in Korea

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ABSTRACT

This paper briefly introduces an improved method for evaluating seismic fragilities of components of nuclear power plants 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. For the purpose of evaluating the effects of the recorded earthquake on the seismic fragilities of Korean nuclear power plant structures, several cases of comparative studies have been performed. The study results show that seismic fragility analysis based on the Newmark's spectra in Korea might over-estimate the seismic capacities of Korean facilities.

KEY WORDS: Seismic Probabilistic Risk Assessment, Seismic Fragility Analysis, Site-dependent Response Spectrum, Modal Contribution Factor

INTRODUCTION

Basic parameters for seismic design of structures and equipments intrinsically include various uncertainties. In particular, the randomness of seismic events does not allow the analysts to estimate reasonable structural seismic responses by a deterministic method. The seismic probabilistic risk assessment (SPRA) is a tool to evaluate the actual safety considering those variabilities and the regulatory requirement for nuclear power plants under construction as well as in operation. In the course of SPRA, seismic fragility analysis (SFA) is the most significant and essential phase especially for structural or mechanical engineers.

In 1991, the Nuclear Regulatory Commission (NRC) of the United States (US) issued Generic Letter No. 88-20 [1] as a policy statement on the severe accidents and also issued NUREC-1407 [2] to provide a guidance of safety review strategy of NRC SPRA. Thereafter, nuclear power plant utilities have been requested to perform an individual plant examination. For all operating plants in the US, the SPRA has been conducted as an individual plant examination for external events (IPEEE) since 1992 [3]. The US Electric Power Research Institute (EPRI) presented a practical methodology of SFA for nuclear power plants.[4]

Whereas, it has not been long to apply the probabilistic concept to the seismic evaluation of major industrial facilities in Korea. Furthermore, past SFA's performed in the Korean nuclear power plant industry arbitrarily assumed most basic information and directly used the methodologies that were provided by some foreign companies without theoretical or practical validation for their applicability to the Korean facilities. However, the inherent and site-specific data is highly significant to obtain the reasonable results of SFA. The rational result is expected only when the realistic information reflecting the unique properties of the object facilities and the sites are provided. Statistical data of design information and ground motions will considerably govern the fragility of structures.

This paper briefly introduces a practical methodology for seismic fragility analysis that has been utilized and is being improved in Korea. For the purpose of constructing the site-specific response spectra, 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 the several Korean nuclear power plant structures have been estimated using the resulted response spectra of recorded earthquakes, and the results are discussed in this paper.

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 [5] were analyzed and the site-specific ground response spectra were presented.

As shown in Table 1, 87 of the earthquakes were analyzed in this study. The magnitudes of the motions vary from 2.7 to 4.8 with 3.7 as the average. Figure 1 shows the stations that are mostly located in the southeast side of the Korean peninsula where most of the nuclear power plant sites in Korea are concentrated.

Table 1 Recorded Earthquake Data Used for the Study

Event	Origin Time		Epicenter		Mag.	No. of Station
	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

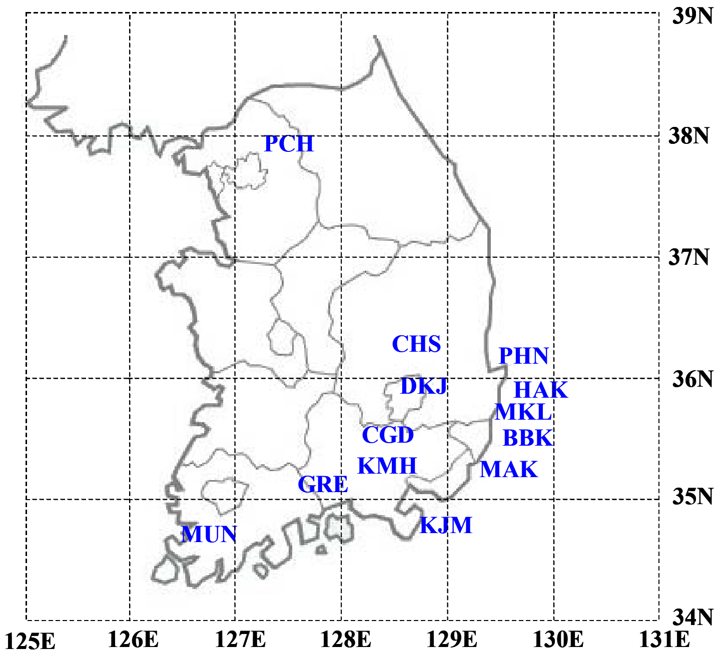
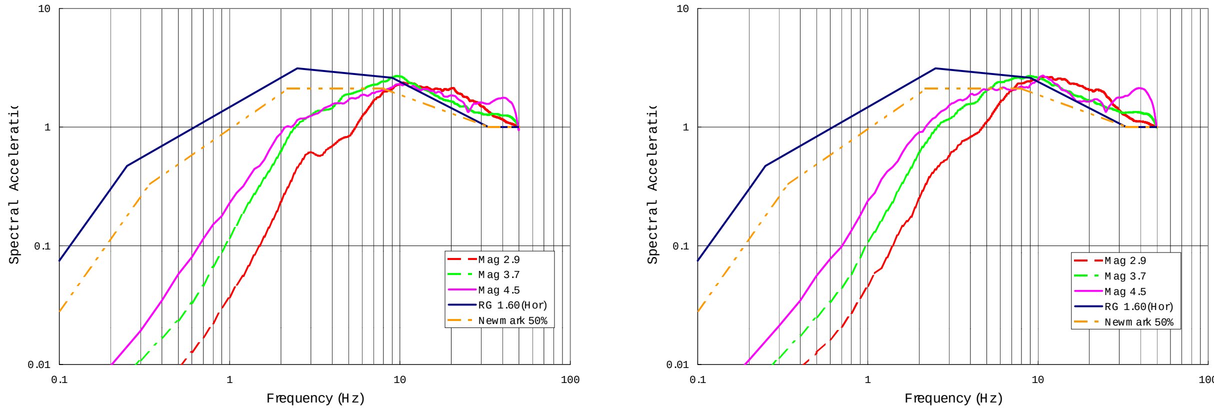


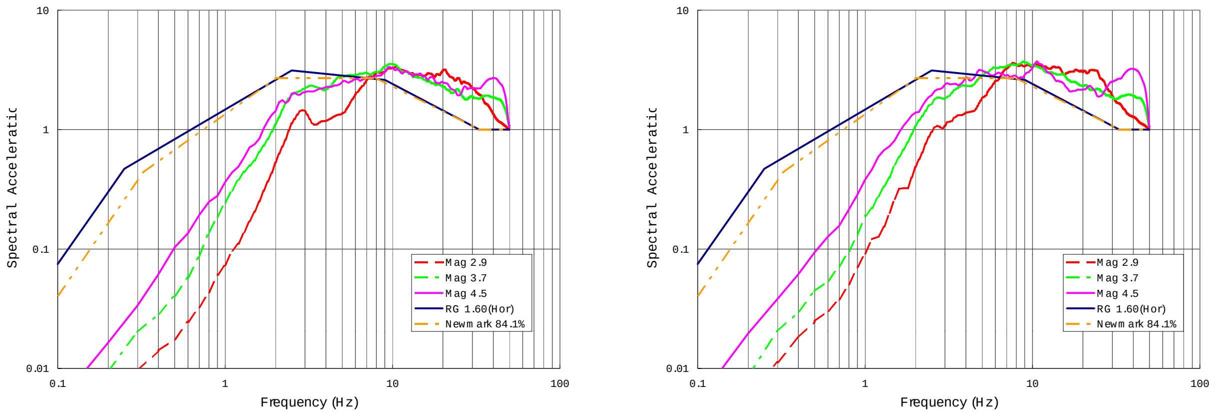
Figure 1 Location of Stations

Figure 2 and Figure 3 compare the horizontal response spectra normalized to 1.0g of zero period acceleration. 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 and Newmark in the frequency 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.



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

Figure 2 Comparisons of Mean Horizontal Response Spectra



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

Figure 3 Comparisons of Mean+1• Horizontal Response Spectra

DESCRIPTION OF BASIC SFA METHODOLOGY

The Korean method for SFA is basically similar to that of EPRI [4], called "response 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).

$$A = \left(\prod_{i=1}^{n} F_{Ci} \cdot F_{Ri} \right) \times A_{ref} \qquad (1)$$

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)

Most of the response factors of the Korean method are the same as EPRI's. However, the Korean method uses the multi-modes response spectrum shape factor to consider the effects of the more reasonable structural responses, while they only use the fundamental modal response in the EPRI method. Some modification of the capacity factor adopting nonlinear static procedures has also been developed, though not discussed in detail in this study.

In order to obtain the seismic fragility of complex or irregular structures having more than one effective mode, it is necessary to consider the modal contributions including all the effective higher modes. The response spectrum shape factor reflecting the multi-modes effects can be expressed by equation (2) using the modal contribution factor for base shear which represents modal contributions to the total seismic response of the structure.

$$F_{ss} = \frac{\sum_{n=1}^{N} r_n S_A(\omega_n, \xi)_{ref}}{\sum_{n=1}^{N} r_n S_A(\omega_n, \xi)_{act}} \tag{2}$$

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. The n-th modal contribution factor [6], r_n which is a ratio of the n-th modal response to the total response is expressed by equation (3).

$$r_n = \frac{R_n(t)}{\sum_{n=1}^{N} R_n(t)} \tag{3}$$

where, $R_n(t)$: n-th modal response

N : total number of modes

The logarithmic standard deviation of the response spectrum shape factor resulted from the randomness of the earthquake is calculated by equation (4).

$$\beta_R = \ln\left\{ \frac{\sum_{n=1}^{N} r_n S_A(\omega_n, \xi_n)_{84\%}}{\sum_{n=1}^{N} r_n S_A(\omega_n, \xi_n)_{Mean}} \right\} \tag{4}$$

STRUCTURAL MODELS

This study selected two representative nuclear power plant structures to evaluate the effects of the Korean site response spectra on the fragility results. As shown in Figure 4 and Figure 5, the models are a containment building and a component cooling water (CCW) building of Korean standard plant. The containment building is a prestressed concrete structure and the CCW building is a two-story concrete-steel composite structure. The first story of the CCW building is a reinforced concrete shear wall structure and the 2nd story is a steel structure with bracings.

The vibrational properties of the models are summarized in Table 2. In this study, the modal properties of the shell and dome excluding the internal structures were considered in SFA of the containment building. Because of the composite structure, two different modal dampings were considered in SFA of the CCW building. Referring to Table 2, the modal contributions of the dominant modes of two models are above 70%. As indicated in the previous study [7], when considering a single mode, the seismic capacities of two models might be under-estimated by about 5% or over-estimated by about 18%, respectively.

In this study, SFA's were performed using the Newmark spectra of NUREG/CR-0098[8] and the recorded earthquake spectra as an actual earthquake, and the results were compared. The Newmark spectra have been used as an actual earthquake in the SPRA up to now for all the nuclear power plant in Korea. The site-independent response spectra of the RG 1.60[9] were adopted as the reference response spectra. Figure 6 shows the response spectra applied in this study. The mean curve in Figure 6 is an average of all the recorded earthquakes having the magnitudes of 2.7 to 4.5, and the 84.1% curve represents a mean plus one standard deviation of all the recorded earthquakes.

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. For the containment building, the 5% and 7% damping factors were used for the 1/2 yield stress level and for the yield stress level, respectively. For the CCW building that is a composite structure, 4% for the steel structure and 7% for the concrete structure, respectively, were used for the 1/2 yield stress level damping factor and 10% for the yield stress level.

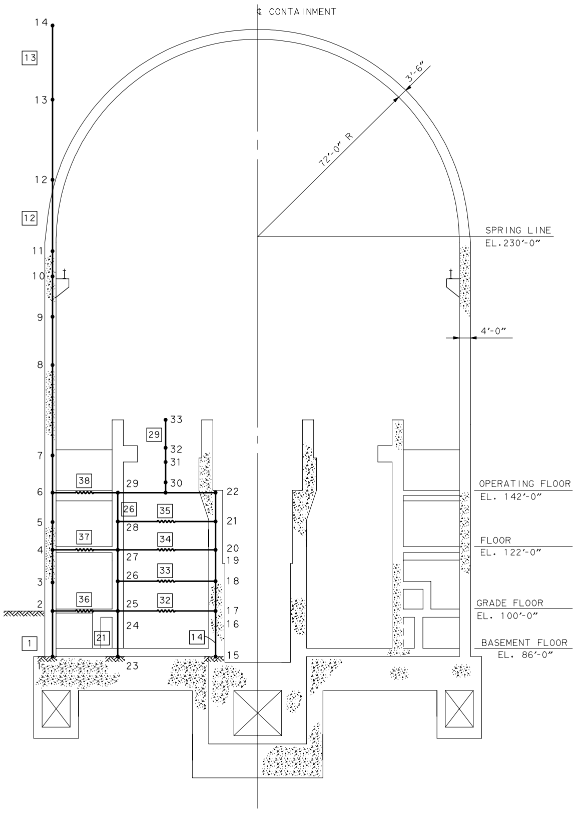


Figure 4 Analytical Model of Containment Building

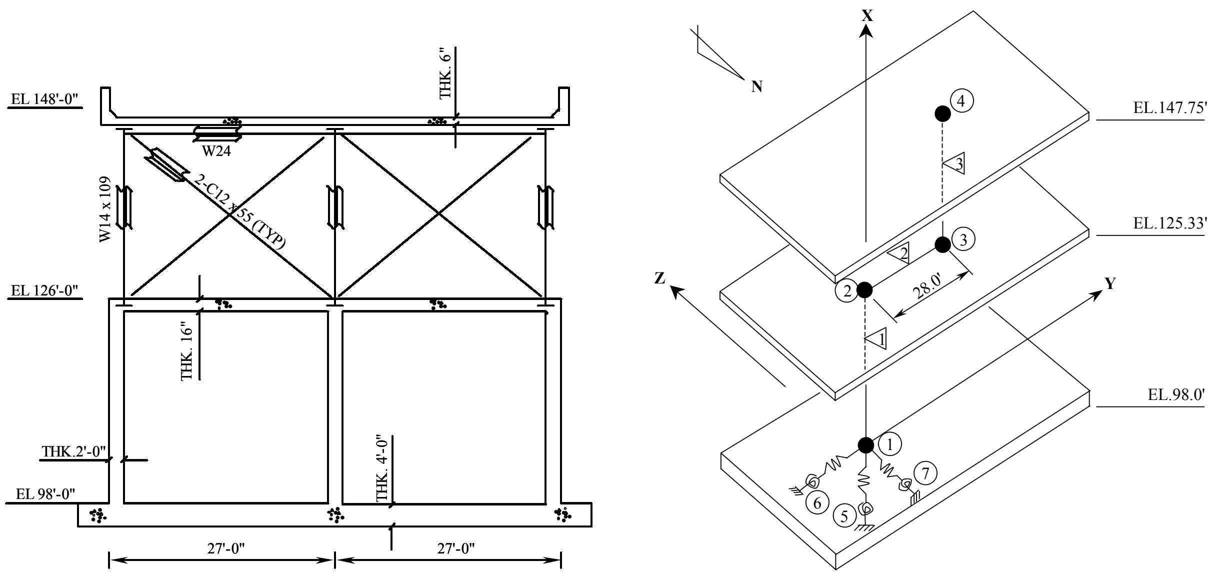


Figure 5 Analytical Model of CCW Building

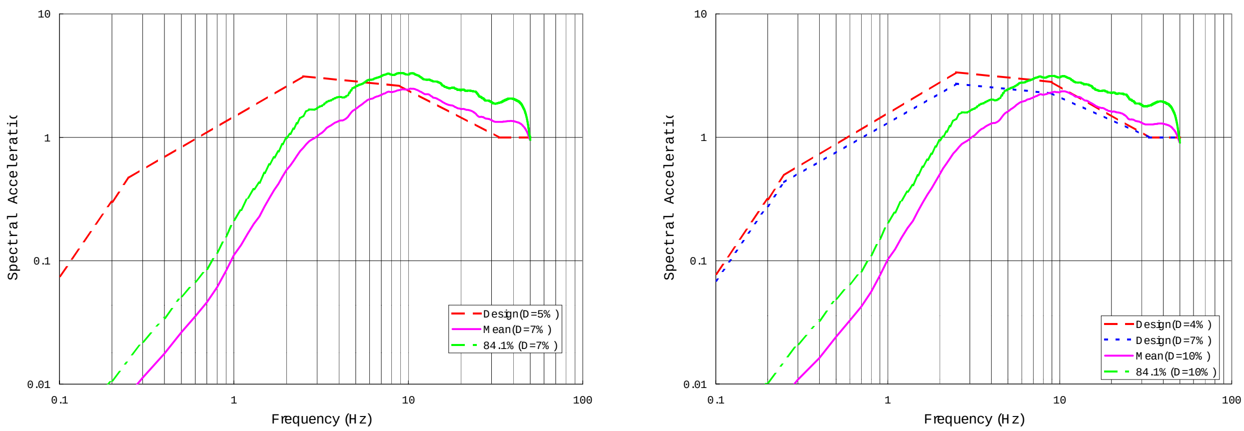
Table 2 Modal Properties of Models

(a) Containment Bldg.

	Frequency	Contribution Factor
1st Mode	4.6Hz	71.7%
5th Mode	13.4Hz	19.5%
7th Mode	24.1Hz	2.5%
10th Mode	27.6Hz	2.3%
13th Mode	39.1Hz	2.1%

(b) CCW Bldg.

	Frequency	Contribution Factor
1st Mode	3.64Hz	22.0%(4% Damp.)
2nd Mode	16.0Hz	78.0%(7% Damp.)



(a) Containment Bldg.

(b) CCW Bldg.

Figure 6 Response Spectra for Seismic Fragility Analyses

Table 3 Calculated Response Spectrum Shape Factors

	Newmark Spectra			Recorded Earthquake Spectra		
	$\breve{F}_s$	β_R	β_U	$\breve{F}_s$	β_R	β_U
Containment Bldg.	1.459	0.199	0.200	1.545	0.373	0.200
CCW Bldg.	1.415	0.144	0.150	1.153	0.333	0.150

The median response spectrum shape factors, $\breve{F}_s$ and its logarithmic standard deviation, β_R calculated for the two different response spectra are shown in Table 3. Same logarithmic standard deviations of uncertainty, β_U were assumed for the two cases. Other basic fragility variables are summarized in Table 4 referring to the values of reference 7.

As final results, the median acceleration capacity, A_m and its logarithmic standard deviations are summarized in Table 5. It can be seen in Table 5 that the HLCPF (high confidence of low probability of failure) value for the CCW building based on the recorded earthquake is larger by 55% than the case of the Newmark spectra, while smaller by 17% in the case of the containment building. These results say that fragility values from the SFA using the site-independent spectra can give us quite unreliable results. Specifically, the overestimation of the fragility by 55% in the CCW building implies that existing procedures based on the site-independent response spectra should be improved to reflect the effect of the characteristics of recorded local earthquake data.

Table 4 Basic Fragility Variables for Objective Models

	Containment Bldg.			CCW Bldg.		
	$\breve{F}_s$	β_R	β_U	$\breve{F}_s$	β_R	β_U
Strength	7.42	0.0	0.21	4.63	0.0	0.22
Inelastic Energy Absorption	2.1	0.22	0.17	1.75	0.14	0.11
Damping	1.0	0.06	0.06	1.0	0.03	0.10
Modeling	1.0	0.0	0.17	1.0	0.0	0.19
Mode Combination	1.0	0.05	0.0	1.0	0.05	0.0
Earthquake Component Combination	1.0	0.05	0.0	1.0	0.05	0.0
Foundation-Structure Interaction	1.0	0.0	0.0	1.0	0.0	0.0
Horizontal Direction Peak	0.9	0.0	0.0	1.0	0.15	0.0

Table 5 Seismic Fragility Analysis Results

	Newmark Spectra				Recorded Earthquake Spectra			
	A_m	β_R	β_U	HCLPF	A_m	β_R	β_U	HCLPF
Containment Bldg.	4.09g	0.311	0.381	1.31g	4.33g	0.443	0.381	1.12g
CCW Bldg.	2.29g	0.262	0.359	0.83g	1.87g	0.399	0.359	0.54g

CONCLUDING REMARKS

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 effect on the SFA result.

Applying the procedure to several typical nuclear power plant structures in Korea, practical applicability of the proposed procedure was validated. And from the application results, it has been concluded that seismic fragility analysis based on the site-independent spectra might over-estimate the seismic capacities of Korean facilities. However, because the recorded data is not completely satisfactory due to the smaller magnitudes of the earthquake and the limited number of earthquakes, some extended studies should be continued based on the larger number of earthquake data accumulated in Korea using the updated characteristics of local earthquakes.

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