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Reevaluation of Seismic Fragility Parameters of Nuclear Power Plant Components Considering Uniform Hazard Spectrum

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Abstract

The Seismic probabilistic risk assessment (SPRA) or seismic margin assessment (SMA) have been used for the seismic safety evaluation of nuclear power plant structures and equipments. For the SPRA or SMA, the reference response spectrum should be defined. The site-specific median spectrum has been generally used for the seismic fragility analysis of structures and equipments in a Korean nuclear power plant. Since the site-specific spectrum has been developed based on the peak ground motion parameter, the site-specific response spectrum does not represent the same probability of exceedance over the entire frequency range of interest. The uniform hazard spectrum is more appropriate to be used in seismic probabilistic risk assessment than the site-specific spectrum. A method for modifying the seismic fragility parameters that are calculated based on the site-specific median spectrum is described. This simple method was developed to incorporate the effects of the uniform hazard spectrum. The seismic fragility parameters of typical NPP components are modified using the uniform hazard spectrum. The modification factor is used to modify the original fragility parameters. An example uniform hazard spectrum is developed using the available seismic hazard data for the Korean nuclear power plant (NPP) site. This uniform hazard spectrum is used for the modification of fragility parameters.

Key Words : seismic fragility analysis, uniform hazard spectrum, spectrum shape factor, HCLPF

1. Introduction

The seismic probabilistic risk assessment (PRA) and/or the seismic margin assessment (SMA) studies are performed to estimate and secure the seismic safety of the structures and equipments in nuclear power plants. The reference response spectrum should be defined for the SPRA and SMA. The standard response spectrum proposed by US NRC have been used for the analysis and design of NPP structures and equipments in Korea, since the site specific response spectrum suitable for the Korean nuclear power plant sites is not developed. The US NRC R.G. 1.60 [1] spectrum was developed based on the strong ground motion data recorded from deep soil condition in the high seismicity area. The direct application of this spectrum to Korean NPP can causes the large conservatism in the seismic design.

The reference response spectrum anchored to the ground motion parameter should be selected for the SPRA and SMA. This reference response spectrum is used to define the seismic margin earthquake (SME) or review level earthquake (RLE) in SMA. Several kinds of response spectrum have been used as a reference response spectrum, such as NUREG/CR-0098 [2] spectrum, site-specific response spectrum, R.G. 1.60 spectrum, and uniform hazard spectrum. The NUREG/CR-0098 median curve anchored to a reference PGA has been generally used in past SPRAs. In Korea, the site-specific response spectrum developed for the Kori site has been used in past SPRAs. It is recognized that the site-specific response spectrum does not present the same probability of exceedance over the full frequency range of interest. So the present trend is to develop the spectrum that represents the uniform probability of exceedance over the entire frequency range of interest [3]. This is so-called uniform hazard spectrum (UHS).

In this study, the uniform hazard spectrum for Korean nuclear power plant site is developed using the available probabilistic seismic hazard analysis results. The original fragility parameters based on the site-specific response spectrum is modified by simple method that can incorporate the effects of UHS on the seismic PRA. The modified fragility parameters for the safety related structures and equipments are compared with the original ones.

2. Seismic Fragility Analysis

2.1. Fragility Analysis Method

For the fragility calculation of structures, the realistic seismic capacity is calculated using the factor of safety related with the strength and the design response calculation. The safety factors represent the conservatism in strength and response calculated in the design stage. The median seismic capacity of NPP components can be obtained from the following equation [4].

$$A_m = F \cdot A_{SSE} \tag{1}$$

where A_m and A_{SSE} is the median ground motion capacity and the peak ground acceleration level of safe shutdown earthquake, respectively. The safety factor, F, can be written by using the capacity and response factors of the structures.

$$F = F_S \cdot F_\mu \cdot F_{RS} \tag{2}$$

where F_S, F_μ and F_{RS} is strength factor, inelastic energy absorption factor and structure response conservatism factor, respectively.

For equipments, the factor of safety is made up of three parts consisting of an equipment capacity factor, a structure response factor and an equipment response factor. Thus the safety factor for equipments is given by the following equation.

$$F = F_{EC} \cdot F_{RS} \cdot F_{ES} \tag{3}$$

where F_{EC} is the equipment capacity factor consisting of the strength factor and inelastic energy absorption factor of the equipment. F_{RS} is the response factor of structure where the equipment is installed. The structural response factor is consisting of the variables used to generate floor response spectra for equipments. The structure response factor for equipment fragility analysis is somewhat different from that for structure fragility analysis. F_{ES} is the equipment response factor. The equipment response factor is the ratio of equipment response calculated in the design to the realistic equipment response.

The logarithmic standard deviation of the safety factor for randomness and uncertainty can be obtained by the SRSS (Square Root of the Sum of the Squares) of the individual logarithmic standard deviation of capacity and response factors.

$$\beta_R = [\sum \beta_{r_i}^2]^{1/2} \tag{4}$$

$$\beta_U = [\sum \beta_{u_i}^2]^{1/2} \tag{5}$$

where, subscript i denotes the individual capacity and response factors. β_r and β_u is the logarithmic standard deviation of individual factors for randomness and uncertainty, respectively.

The realistic seismic capacity of structures and equipments in SPRA can be expressed by the fragility curves or HCLPF(High Confidence of Low Probability of Failure) capacity. HCLPF capacity in SPRA is defined mathematically as 95% confidence of less than 5% probability of failure. This HCLPF capacity is generally used as an index to represent the seismic capacity of structures and equipments. The HCLPF capacity may be computed from the following equation.

$$HCLPF = A_m \cdot \exp[-1.65(\beta_R + \beta_U)] \tag{6}$$

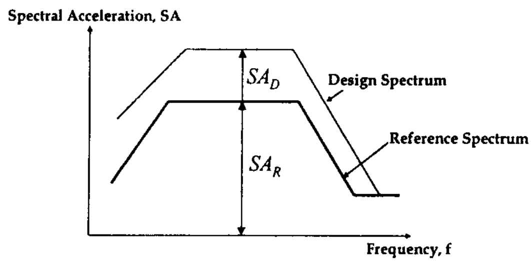


Fig. 1. Spectral Accelerations for Spectrum Shape Factor, F_{ss}

2.2. Spectrum Shape Factor in Fragility Analysis

The spectrum shape factor accounts for the difference between the site-specific ground response spectrum versus the design response spectrum [5]. As shown in Fig. 1, the spectrum shape factor, F_{SS}, can be defined the ratio of the spectral acceleration of the reference response spectrum to that of design spectrum at the fundamental frequency of structure. The spectrum shape factor is one of the dominant factors in structure response factor, F_{RS}. F_{SS} can be obtained from the following equation.

$$F_{SS} = \frac{SA_D}{SA_R} \tag{7}$$

where SA_D and SA_R is the spectral acceleration of the design spectrum and the reference median spectrum at the frequency of interest.

3. Uniform Hazard Spectrum

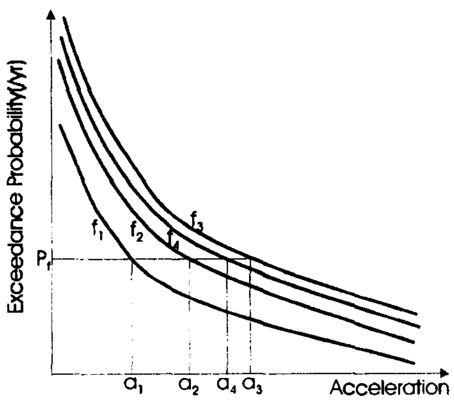
3.1. Probabilistic Seismic Hazard Analysis

The purpose of the seismic hazard analysis is to evaluate the annual probability of exceedance of various earthquake sizes at a given site, and to develop the spectral shapes of the motion from these earthquakes. This is sometimes called as probabilistic seismic hazard analysis to emphasize that its results are intrinsically probabilistic in nature.

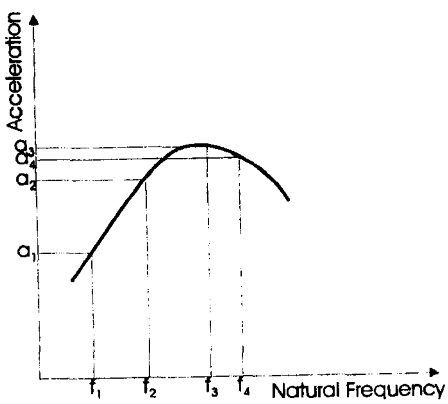
The seismic hazard of a nuclear power plant site is generally described by a series of seismic hazard curves that is a plot of the probability of exceedance vs. the peak ground acceleration.

3.2. Development of UHS

The procedure for developing the uniform hazard spectrum is the same as that for developing the seismic hazard curves for the peak ground acceleration (PGA). The uniform hazard spectrum is established by generating first sets of seismic hazard curves, each of which expresses annual frequency of exceedance as a function of an acceleration response spectral value for a specified discrete value of frequency and damping (Fig. 2(a)). Having these sets of spectral hazard curves, the response spectra for a specified probability of exceedance over the entire frequency range of interest are obtained directly (Fig. 2(b)) [6,7].



(a) Spectral Hazard Curves



(b) Uniform Hazard Spectum

Fig. 2. Procedure for Developing the Uniform Hazard Spectrum

Based on the uniform hazard spectrum for the horizontal ground motion, the uniform hazard spectrum for the vertical ground motion can be generated by the following equation proposed by Atkinson [8].

$$\log\frac{H}{V} = 0.0519 + 0.117\log f_n \qquad (8)$$

where, H and V is the spectral acceleration value for the horizontal and vertical ground motion in gal (cm/sec^2), respectively. f_n denotes the frequency of individual spectral hazard curves.

3.3 UHS for Example NPP Site

In this study, example spectral hazard curves are developed using the available results of probabilistic seismic hazard analysis for Korean NPP sites to estimate the effects of the uniform hazard curve on the fragility parameters. Fig. 3 shows the example spectral hazard spectra for a Korean NPP site. Using the spectral hazard curves, the uniform hazard spectra for a Korean NPP site are generated (Fig. 4). The uniform hazard spectrum with a return period of 10^{-4} was used for the modification of original fragility parameters. The ZPA(Zero Period Acceleration) of uniform hazard spectrum was scaled to the safe shutdown earthquake level, 0.2g.

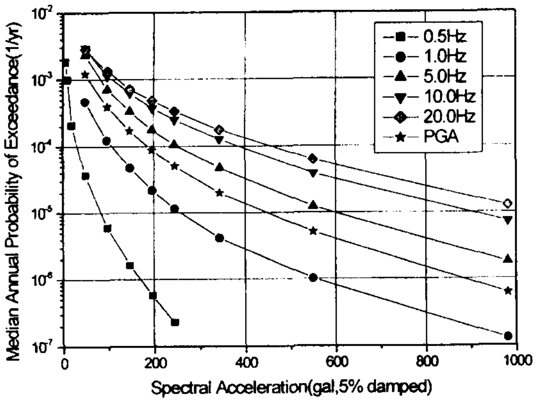


Fig. 3. Example Spectral Hazard Curves for Korean NPP Site

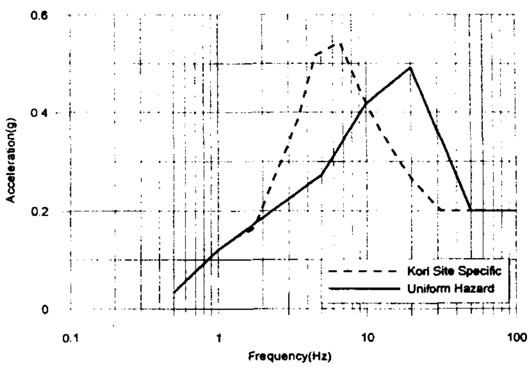


Fig. 5. Comparison the Site-specific Spectrum with UHS

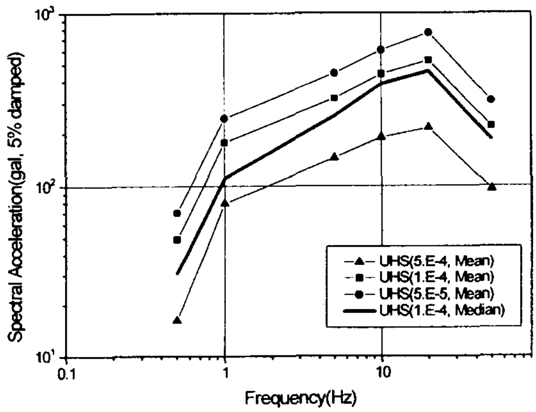


Fig. 4 Uniform Hazard Spectra

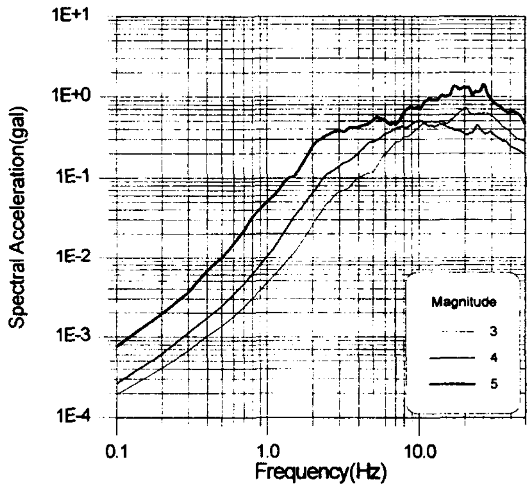


Fig. 6. Mean Response Spectra for Earthquake

Fig. 5 shows the comparison of the site-specific response spectrum that was used for the SPRA of Korean NPP components and the generated uniform hazard spectrum. As shown in Fig. 5, the uniform hazard spectrum has relatively large spectral acceleration contents in high-frequency region and relatively low spectral acceleration contents in the low-frequency region. This implies that the uniform hazard spectrum is less damaging than the design response spectrum or site-specific response spectrum.

Mean ground response spectra obtained from 270 earthquake records with magnitude 3 to 5 which occurred in Korea are shown in Fig. 6 [9]. As shown in the figure, these spectra have relatively large high-frequency spectral acceleration contents. The fluctuation in the spectrum for magnitude 5 earthquakes is due to the very limited number of data. It is noted from Fig. 5 and Fig. 6 that the uniform hazard spectrum shape is very similar to the mean response spectrum developed from the real earthquake data. This results shows that the ground motion attenuation equations used in the seismic probabilistic hazard analysis reflected relative well the ground motion attenuation characteristics and the site soil condition.

4. Fragility Analysis Using UHS

4.1. Safety Factor for UHS

The median seismic capacity of NPP components can be obtained by the equation (1). As mentioned above, the safety factor, F, is composed of several factors related with the capacity and response of components. Equation (1) can be rewritten using the ratio of the local seismic capacity of a component (A_q) and the acceleration level at the location of the component (S_a) due to an input ground motion with peak ground acceleration (A_{SSE}). Equation (1) can then be written as the following equation [10].

$$A_m = \frac{A_q}{S_a} \cdot F_c \cdot A_{SSE} \tag{9}$$

or

$$A_m = F_c \cdot A_q \cdot \left(\frac{S_a}{A_{SSE}} \right)^{-1} \tag{10}$$

Where F_c is a safety factor for taking into account the conservatism in the median ground motion capacity, A_m. This safety factor includes conservatisms inherent in the components response calculations (i.e. F_{RS} and F_{RE}) carried out to obtain A_q and S_a. In Eq. (10), S_a/A_{SSE} is a measure of the spectral amplification of the SSE due to the building response. This spectral amplification is dependent on the shape of the spectrum used as an input in the building analysis. As shown in Fig. 4, the spectral amplification will be quite different for the site-specific spectrum and the uniform hazard spectrum.

In order to incorporate the effects of the UHS in the seismic fragility parameters based on the site-specific response spectrum, the median ground motion capacity should be modified to reflect the difference in the spectral amplification due to the difference of the two spectrum shape. This effect can be incorporated by an additional safety factor, F_{UHS}. The median ground motion capacity of components based on the uniform hazard spectrum, $A_{m,UHS}$, can be obtained by the following equation.

$$A_{m,UHS} = A_m \cdot F_{UHS} \tag{11}$$

F_{UHS} in Eq. (11) which is a factor to incorporate the difference of the two spectral amplification can be obtained by [8]

$$F_{UHS} = \frac{AF_{SSS}}{AF_{UHS}} \tag{12}$$

Here, AF_{SSS} and AF_{UHS} is the spectral amplification of the site-specific spectrum and the uniform hazard spectrum, respectively. Since the spectral amplification is the ratio between the spectral acceleration and the peak ground acceleration. Eq. (12) can be rewritten as the following equation.

$$F_{UHS} = \frac{SA_{SSS}}{SA_{UHS}} \tag{13}$$

Here, SA_{SSS} and SA_{UHS} is the spectral acceleration of the site-specific response spectrum and the uniform hazard spectrum, respectively.

F_{UHS} depends on the dynamic characteristics of the building and the equipment item. For the equipments, F_{UHS} depends on its location whether it is located in a building or on the ground, since the response amplification at the ground level and in a building is different.

F_{UHS} of a building and a flexible equipment installed on the ground become simply the ratio of the spectral acceleration at the natural frequency of the buildings and equipments. In case of the rigid equipment on the ground, F_{UHS} becomes unity.

For equipments in a building, F_{UHS} is the ratio of the spectral acceleration at the natural frequency of equipments obtained from the floor response spectrum derived using the site-specific spectrum and the uniform hazard spectrum respectively. The floor response spectrum derived using the uniform hazard spectrum can be obtained by the additional analysis of the building. This work needs much time and effort. F_{UHS} of the equipments located in a building can be approximated by the ratio of the spectral acceleration at the natural frequency of the building, since the seismic motion at the location of the particular item in a building is dominated by the response of the building at its fundamental frequency.

4.2. Randomness and Uncertainty Estimation of UHS

In general, real earthquakes would be different from the reference input used in the fragility analysis. The response spectrum of a real earthquake has peaks and valleys, which are either higher or lower than the reference spectrum. This peak and valley variability is considered as randomness. In addition it is impossible to predict the real earthquake exactly. This is reflected in the uncertainty in the response spectrum shape.

In this study, the logarithmic standard deviations for the randomness and uncertainty of the uniform hazard spectrum were obtained by the second moment procedures and the empirical relationship between the two logarithmic standard deviations. The logarithmic standard deviations for randomness, β_r, and uncertainty, β_u, can be obtained from the following equations.

$$\beta_r = \ln\left(\frac{SA_{M+1\sigma}}{SA_M}\right) \tag{14}$$

$$\beta_U \approx \frac{2}{3}\beta_r \tag{15}$$

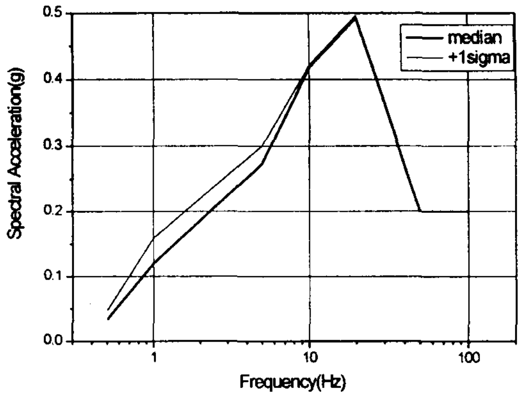


Fig. 7 Median and +1σ UHS

Here, SA_M and $SA_{M+1\sigma}$ is the spectral acceleration of the uniform hazard spectrum at median and median plus 1 standard deviation level (Fig. 7), respectively.

5. Example Fragility Analysis

In this study, the fragility analyses of the typical safety related structure and equipments were performed to estimate the effect of UHS on fragility parameters. The structure and equipments that have relatively low seismic capacity (HCLPF) were selected for reassessment. Table 1 shows the original fragility parameters based on the site-specific spectrum as the reference spectrum. The location and failure mode of components and their fundamental frequencies are also shown in Table 1. As shown in this table, most of the equipments are located in the auxiliary building. The condensate storage tank is located on the ground. The fundamental frequency of the auxiliary building and the condensate storage tank is 7.20Hz and 9.72Hz, respectively.

Using both the site-specific spectrum and the uniform hazard spectrum, the safety factor was calculated. F_{UHS} for the auxiliary building and condensate storage tank was 1.486 and 1.0,

Table 1. Original Fragility Parameters for Safety Related Components

Components	Location	Nat. Freq. (Hz)	Failure Mode	A_m (g)	β_R	β_U	HCLPF (g)
Aux. Building		7.20	Wall Shear Failure	2.14	0.29	0.36	0.73
Condensate Storage Tank	Ground	9.72	Sliding	1.04	0.25	0.24	0.46
CCW Surge Tank	PAB 165'	17.6	Concrete Coning	2.00	0.41	0.47	0.47
ECW Pump	PAB 77'	37.2	Pump H.D bolt	1.85	0.36	0.27	0.65
ECW Compression Tank	PAB 77'	>33	Anchorage	1.00	0.35	0.20	0.40
4.16kV Switchgear	PAB 100'-6"	6	Functional	1.33	0.33	0.29	0.48
			Structural	1.99	0.33	0.32	0.68
480V MCC	PAB 165'	11	Functional	1.33	0.33	0.29	0.48
			Structural	1.99	0.33	0.33	0.67

Table 2. Modified Fragility Parameters for Safety Related Components

Components	Frequency (Hz)	F_{UHS}	Failure Mode	A_m (g)	β_R	β_U	HCLPF (g)
Aux. Building	7.20	1.486	Wall Shear Failure	3.18	0.30	0.36	1.07
Condensate Storage Tank	9.72	1.0	Sliding	1.04	0.25	0.24	0.46
CCW Surge Tank	7.20	1.486	Concrete Coning	2.97	0.42	0.47	0.68
ECW Pump	7.20	1.486	Pump H.D bolt	2.75	0.37	0.27	0.96
ECW Compression Tank	7.20	1.486	Anchorage	1.49	0.36	0.20	0.59
4.16kV Switchgear	7.20	1.486	Functional	1.97	0.34	0.29	0.70
			Structural	2.96	0.34	0.32	0.99
480V MCC	7.20	1.486	Functional	1.98	0.34	0.29	0.70
			Structural	2.95	0.34	0.33	0.98

respectively. F_{UHS} for other equipments were 1.486 because those equipments are located in the auxiliary building. The logarithmic standard deviations for randomness and uncertainty were modified by considering the additional logarithmic standard deviations inherent in F_{UHS}. Table 2 shows the modified fragility parameters and HCLPFs with F_{UHS}.

As shown in Table 2, the realistic seismic capacity of the components is increased due to the effect of the uniform hazard spectrum. However the logarithmic standard deviations for randomness were increase due to the additional randomness of F_{UHS}. The additional consideration of uncertainty did not affect the final logarithmic standard deviation for uncertainty, since the logarithmic standard deviation for uncertainty inherent in F_{UHS} is small.

In seismic PRA, the seismically rugged structures and equipments can be screened out from detailed fragility analysis. The components whose median ground motion capacity greater than 1.5g were screened out in the past SPRAs for Korean NPP. Most of the selected components in this study can be screened out. By using the uniform hazard spectrum, it is possible to estimate the realistic seismic capacity and the realistic seismic risk of NPP.

5. Conclusions

In this study, the original fragility parameters based on the site-specific response spectrum were modified using the uniform hazard spectrum. The probabilistic seismic hazard analysis for most of the Korean NPP sites had been completed. It is possible to develop the uniform hazard spectrum using the results of PSHA. So it is desirable to use the uniform hazard spectrum in the seismic PRA.

The uniform hazard spectrum was developed for example Korean NPP sites using the available PSHA results. It is shown that the uniform hazard spectrum has large spectral acceleration above approximately 10Hz. However it has a significantly lower spectral amplification below approximately 10Hz. It means that the uniform hazard spectrum is less damaging than the design response spectrum or site-specific response spectrum, since the fundamental frequencies of the NPP structures are less than 10Hz.

It is shown that the simple method for modifying the fragility parameters is very effective to incorporate the effects of the uniform hazard spectrum. The results of this study show that the realistic HCLPF capacity of NPP components is increased due to the low amplification of spectral acceleration at the fundamental frequencies of NPP structures. This can reduce the number of structures and equipments that should be analyzed in detail, since the number of components that can be screened out is increased.

More detailed estimation of the high frequency seismic effects on the components sensitive to the high frequency motion should be performed. Because the functional failure of the electrical equipment is cause by the failure of active electrical components such as relay chattering.

Acknowledgements

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