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국내 원자력발전소 부지에 대한 설계지진의 확률론적 평가
A Probabilistic Evaluation of Design Earthquakes for Nuclear Power Plant Sites in Korea

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요약 / ABSTRACT

새로운 확률론적 방법을 이용하여 국내 원자력발전소 부지의 설계지진을 평가하였다. 새로운 방법은 소위 지진재해도분해를 통하여 제어지진(또는 최빈지진)을 결정할 수 있다는 점에서 기존의 방법과 다르다. 분석결과, 지진재해도는 적용된 감쇄식에 따라 크게 변하며, 재해도의 표준편차가 매우 큰 것으로 밝혀졌다. 이는 한국의 지진감쇄식과 지진원의 특성 규명에 대하여 많은 연구가 수행되어야 함을 시사한다. 목표초과확률 1.0×10^{-5}/년에서, 4개 원전 부지의 설계지진은 진앙거리 13~26km, 규모 5.7~6.1 사이에 분포하는 것으로 평가되었다. 결정론적인 방법에 의한 설계지진과 확률론적인 방법에 의한 제어지진의 비교 결과 4개 부지 중 3개 부지는 서로 일관성이 있으나 나머지 1개 부지는 상대적으로 일관성이 덜한 것으로 나타났다. 부지별 응답스펙트럼의 변화, 즉 부지고유 응답스펙트럼을 비교하기 위하여 4개 부지 중 대비를 이루는 2개 부지를 선택하였다. 분석결과, 한 부지의 부지고유 응답스펙트럼이 다른 부지에 비하여 약 1.5배정도 높게 나타났다. 마지막으로 2개 부지 중 1개 부지에 대하여 부지고유 응답스펙트럼과 등재해도 스펙트럼을 비교한 결과, 이들 두 스펙트럼은 서로 부합하는 것으로 나타났다.

A new probabilistic method was applied to evaluate the design earthquakes for the nuclear power plant sites in Korea. The new method is different from the current ones in that it can determine the controlling earthquakes (or modal earthquakes) through the so-called seismic hazard deaggregation. It turned out that the seismic hazard is greatly dependent on the attenuation formulas applied and its standard deviation is very large. This implies that intensive efforts should be made to characterize attenuation formulas and seismic sources in Korea. At the target probability of exceedance of 1.0×10^{-5}/yr, the design earthquakes of four nuclear power plant sites are estimated to be 13 to 26km in epicentral distance from the sites and 5.7 to 6.1 in magnitude. Comparison of the design earthquakes by deterministic method with controlling earthquakes by probabilistic method shows that they are consistent at three sites of the four but relatively less consistent at one site. Two contrasting sites among four were chosen to compare the site-dependent variation of response spectra, i.e., site-specific response spectra. The result shows that the site-specific response spectrum of one site is higher by a factor of 1.5 than that of the other. Finally, the comparison of uniform hazard spectrum and site-specific response spectrum at one of the two sites shows that the both spectra are consistent with each other.

Introduction

Design earthquake is a most damaging earthquake of a site. It may be described by either its magnitude and distance, or peak ground acceleration at the site, or response spectrum corresponding to it. Controlling earthquake is slightly different from design earthquake. It is a most frequent earthquake causing damage equal to or greater than a given severity. For this reason, a controlling earthquake is called a modal earthquake too. In other words, a design earthquake is a single biggest hit while a controlling earthquake is accumulated hits to cause a certain damage.

The design earthquake has been evaluated by the deterministic method. However, it is well-known that there are large uncertainties in earthquake mechanism and seismic wave propagation. The uncertainties are the source of many different interpretations of seismic phenomena which, in general, lead to different design earthquakes. This fact has often raised a question on the conservatism of the deterministically evaluated design earthquakes. An alternative approach is the probabilistic method. The probabilistic method is structured to integrate all possible interpretations in a systematic manner. The modern probabilistic method also considers multiple hypotheses on input assumptions and thereby reflects the relative credibilities of competing scientific hypotheses.

A disadvantage of the current probabilistic method is that the concept of a design earthquake is lost. This disadvantage results directly from the integrative nature of the probabilistic method and can be remedied by introducing the seismic hazard deaggregation. The seismic hazard deaggregation is a process of disintegrating a total seismic hazard into partial seismic hazard for each magnitude and distance bins to get the most contributing magnitude and distance, i.e., the controlling earthquake. A detailed description of deaggregation process can be found, for example, in NRC (1997). McGuire (1995) also proposed a deaggregation process that is basically equivalent to that of NRC. The present study follows the procedure of NRC (1997).

The input data used in this study is composed of seismic sources and attenuation formulas. The present study uses the input data proposed by five Korean experts for the probabilistic seismic hazard analysis of the nuclear power plant sites in Korea (KEPCO, 1992). Attenuation formulas by those experts are specified only for the peak ground acceleration. Because evaluation of response spectra requires the attenuation formulas of spectral acceleration, those attenuation formulas by the experts were not used. We used attenuation formulas developed by Noh and Lee (1995) and Boore and Atkinson (1987). The attenuation formula set by Noh and Lee is the first and only one published work in Korea that predicts peak ground acceleration and spectral acceleration as a function of magnitude. The attenuation formula set of Boore and Atkinson (1987) were developed in the eastern North America which, together with the Korean Peninsula, belongs to the so-called stable continental region (EPRI, 1994). We included the latter attenuation set for comparison.

Target Probability

The target probability is a exceedance probability of the design earthquakes. A higher target probability results in a design earthquake that is closer in distance and/or larger in magnitude. A design earthquake of closer distance or of larger magnitude means a more conservative seismic design of a structure. In other words, the target probability is a reference of conservatism. Under the assumption that the design earthquakes of four existing nuclear power plant sites in Korea is conservative, the target probability is set up in the following way:

Step 1

Read 5% damped spectral accelerations at natural frequencies of 5 Hz and 10 Hz on the response spectrum corresponding to the design earthquake of each nuclear power plant site.

Step 2

Compute median exceeding probabilities of 5 Hz and 10 Hz spectral accelerations(p_5, p_{10}).

Step 3

Compute composite probability($= p_5/2 + p_{10}/2$) for each site.

Step 4

Take the median value of four composite probabilities.

Peak ground accelerations of design earthquakes are 0.2g(=196 gals) for all nuclear power plant sites in Korea and the same design response spectrum of Regulatory Guide 1.60 (NRC, 1973) is used except for one site. For convenience' sake, we assumed the same response spectrum of Regulatory guide 1.60 for all sites. Spectral accelerations on this response spectrum anchored at peak ground acceleration of 0.2g are 556 gals and 473 gals at 5 Hz and 10 Hz, respectively. Since the attenuation formulas by Noh and Lee (1995), and Boore and Atkinson (1987) were derived from simulated seismograms, standard deviations of the formulas were not estimated. A standard deviation of 0.5 is assumed in this study.

Table 1 summarizes the results of composite probability analysis. Also given in the last column are candidate target probabilities which are the median values of four composite probabilities. First of all, we can see that the results are greatly dependent on the attenuation formula applied. Due to the lack of strong ground motion data in the Korean Peninsula, adequate attenuation formulas could not be developed. Therefore, various attenuation formulas of the regions other than the Korean Peninsula has been used in the previous studies on the seismic hazard analysis. Table 1 shows that one should be very careful when borrowing attenuation formulas of other regions even if those regions are considered to have geologic and seismic characteristics similar to those of the Korean Peninsula. The standard deviations are comparable to composite probabilities. This is due to diverse interpretations of earthquake sources. Since the standard deviations are so large that any of the two candidate target probabilities is almost meaningless. For this reason, we tentatively use the target probability of 1.0×10^{-5}/yr which is recommended by NRC for the central and eastern U.S. (NRC, 1997).

Table 1. Composite probabilities of nuclear power plant sites in Korea and candidate target probabilities.

Attenuation Formula	Composite Probability (Standard Deviation)				Candidate Target Probability
	Site A	Site B	Site C	Site D	
Noh and Lee (1995)	6.434E-07 (5.305E-07)	4.698E-06 (3.723E-06)	4.359E-06 (3.648E-06)	1.784E-06 (1.483E-06)	3.072E-06
Boore and Atkinson (1987)	2.745E-05 (1.324E-05)	9.431E-05 (5.762E-05)	7.930E-05 (5.580E-05)	6.489E-05 (4.103E-05)	7.210E-05

Target Ground Motion and Controlling Earthquake

Target ground motion is a spectral acceleration corresponding to target probability. It is also called a safe shutdown earthquake by NRC (1997). The target ground motion is the design earthquake in the present study. To calculate target ground motion, first perform probabilistic seismic hazard analysis to obtain seismic hazard curves for 5 Hz and 10 Hz spectral accelerations (5% damped). A seismic hazard curve is a smooth curve connecting series of points that represent accelerations and exceeding probabilities of those accelerations. Second, make composite hazard curve from the two and read an acceleration corresponding to the target probability. These values are used later to scale the response spectrum shapes calculated from controlling earthquakes.

The controlling earthquake is calculated from deaggregation of the total seismic hazard at target probability into partial seismic hazards for each magnitude and distance bins. This is done for 5 Hz and 10 Hz spectral accelerations. Deaggregated hazards at Site A are given in Table 2. The contribution of earthquakes greater than M=7.0 is zero irrespective of distance because there are no seismic sources to generate such large earthquakes. Magnitude of all seismic sources by experts ranges 5.0 to 7.0. Zeros for magnitude of 6.5 to 7.0 mean that such earthquakes are too far from the site or have extremely low probabilities of occurrence. If the contribution of distant earthquakes, say farther than 100km, is significant, one should take into account of the effects of these earthquakes because distant earthquakes affect the shape of response spectrum at low frequencies. However, the contribution of distant earthquakes turned out to be less than 5% at all sites.

Table 2. Deaggregated seismic hazards of Site A.

Distance bin (km)	Magnitude bin				
	5 - 5.5	5.5 - 6	6 - 6.5	6.5 - 7	> 7
0 - 15	7.049E-02	1.904E-02	6.800E-02	0.000	0.000
15 - 25	4.390E-02	7.856E-02	3.948E-01	0.000	0.000
25 - 50	1.930E-02	4.881E-02	2.552E-01	0.000	0.000
50 - 100	6.308E-05	1.408E-03	4.209E-04	0.000	0.000
100 - 200	0.000	1.918E-07	8.118E-06	0.000	0.000
200 - 300	0.000	0.000	0.000	0.000	0.000
> 300	0.000	0.000	0.000	0.000	0.000

Target ground motions are given in Table 3. The target ground motion is smallest at Site A and large at Site B. It can be said that Site A has a larger seismic safety margin than the other sites because a same design earthquake of 0.2g (in peak ground acceleration) had been assigned to all Korea nuclear power plant sites. Table 3 shows also controlling earthquakes evaluated in this study and design earthquakes evaluated by deterministic method. They are consistent at three sites(B, C, and D) of the four but relatively less consistent at one site(A).

Table 3. Target ground motions, controlling earthquakes, and design earthquakes of four sites. Controlling earthquakes are evaluated in this study by the probabilistic method while design earthquakes were evaluated by the deterministic method.

Site	Target ground motion (gal)	Controlling earthquake by this study	Design earthquake by deterministic method
A	274.8	M=5.74, D=22.8 km	M=6.75, D=90 km
B	408.5	M=5.99, D=14.0 km	M=5.00, D=0 km
C	399.1	M=5.96, D=13.2 km	M=5.00, D=0 km
D	338.4	M=6.05, D=25.5 km	M=5.00, D=0 km

Development of Site-Specific Response Spectra

Once the target ground motion and controlling earthquake are evaluated, development of site specific response spectrum (SSRS) is straightforward. The first step is to collect a suite of time histories recorded from those earthquakes of which magnitudes and distances are close to those of controlling earthquake. But in practice, rare are the cases that, even in seismically active regions, such earthquake records are sufficient enough to develop a statistically meaningful SSRS. It should also be studied how much close the magnitude and distance shall be chosen. In the present study, we used the attenuation formulas of spectral accelerations by

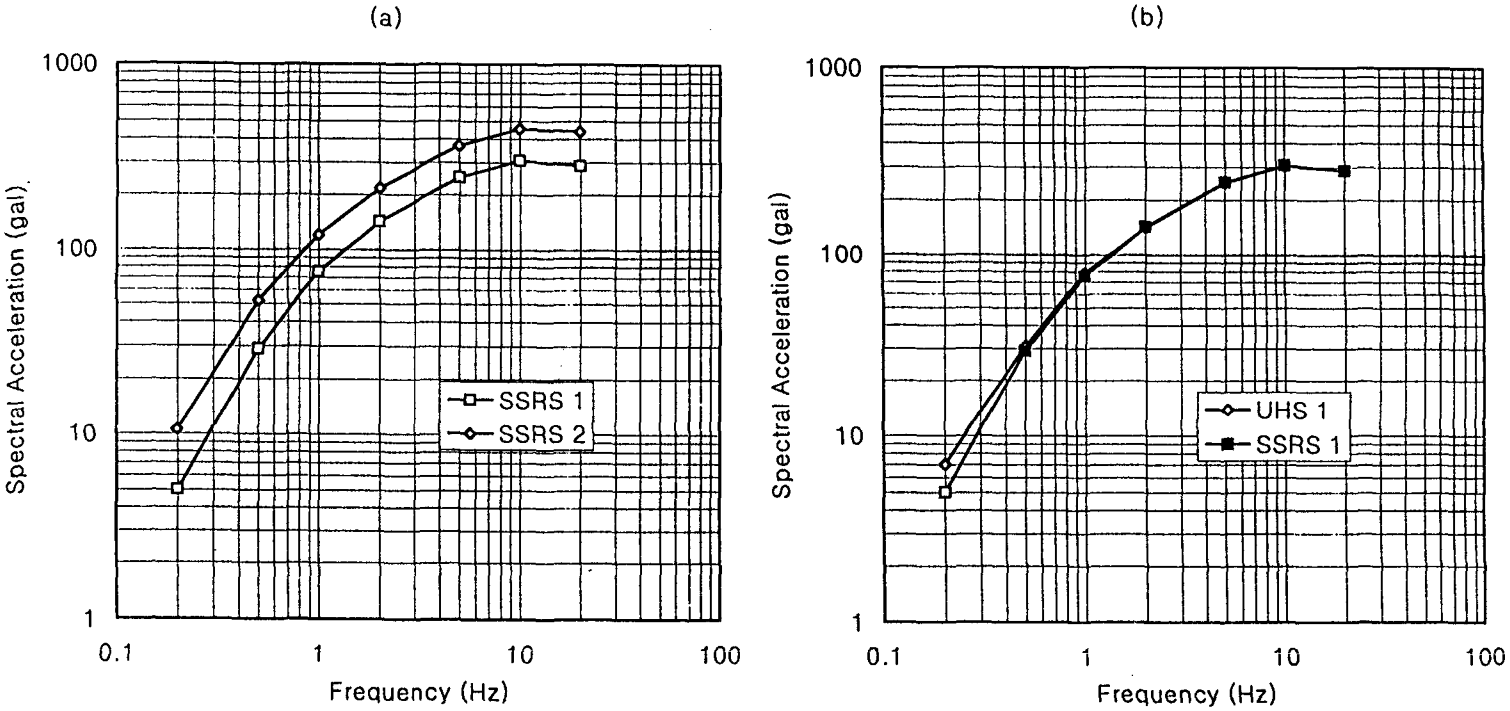

Figure 1. Comparison of site-specific response spectrum (SSRS). SSRS 1 and SSRS 2 are SSRS's of Site A and Site B, respectively. UHS 1 is the uniform hazard spectrum of Site A that corresponds to the target probability of 10^{-5}/yr.

Noh and Lee (1995).

In the second step, a shape of response spectrum corresponding to the controlling earthquake is developed by using a suite of time histories, attenuation formulas, or others. For convenience' sake, we call the ground motions on this response spectrum the modal ground motions after the meaning of the controlling earthquake. The modal ground motions are generally smaller than target ground motions. Chapman (1995) showed that this is entirely due to the uncertainty in the attenuation formula. Only the shape of the SSRS is developed in the second step.

Naturally, the last step is to match the modal ground motion to the target ground motion, at a selected frequency. In the procedure of NRC (1997), this is achieved simply by multiplying the whole spectrum by a constant. This constant is the ratio of the target ground motion to the modal ground motion at 7.5 Hz (average of 5 and 10 Hz). On the other hand, McGuire (1995) developed a different matching procedure. In his procedure, the ground-motion uncertainty, ε is adjusted until the modal ground motion at the given frequency replicates the target ground motion at the same frequency. Then the adjusted ε is applied to all the attenuation formulas of natural frequencies being considered. Though McGuire's procedure seems quite different from that of NRC, the results are same as long as attenuation model takes a logarithmic form. The present study revealed that the scaling factors for four sites range 2.2~3.1 which, in terms of ε in common logarithms, amounts to 0.35~3.1.

We sampled Sites A and B to see the site-dependent variation of SSRS's. These are most contrasting sites (see Table 3). Figure 1 (a) compares the SSRS's of 5% critical damping. The SSRS of Site B is higher than that of Site A by the factor of about 1.5 at frequencies considered, due to the lower target ground motion. Again, this proves that Sites A has a larger seismic safety margin than Site B. Figure 1 (b) shows the comparison of the SSRS and the UHS (uniform hazard spectrum) of Site A. The UHS of the Figure 1 (b) corresponds to the same critical damping (5%) and target probability (10-5/yr). The difference between the SSRS and the UHS increases as decreasing frequencies because the SSRS was adjusted at 7.5 Hz to replicate the target ground motion. In case that the difference at low frequencies is significant, additional controlling earthquake should be evaluated to modify the shape of SSRS at low frequencies. We consider that this is not such a case.

Discussion

The low and well-understood seismicity is essential to site selection for critical structures such as nuclear power plants, radioactive waste disposal facilities, and underground gas storage facilities. However, it is practically impossible to find out such sites because earthquake characteristics of a low seismicity region cannot be fully understood due to the lack of earthquake data. Large uncertainties in earthquake mechanism and wave propagation is inherent in the low seismicity region. Large uncertainties result in diverse models for earthquakes activity. The deterministic method selects a single most reasonable model for a given site and discards the other models. However, a more hazardous but probably less reasonable model cannot always be neglected, if uncertainties are large. For this reason, the deterministic method tends to take a conservative design earthquake rather than a realistic one. On the other hand, the probabilistic method is structured to integrates all possible models in a systematic manner. The modern probabilistic method also considers multiple hypotheses on input assumptions and thereby reflects the relative credibilities of competing scientific hypotheses. Thus the probabilistic method is expected to be more adequate method to evaluate the realistic design earthquake, especially in the low seismicity regions such as the Korean Peninsula and the eastern North America.

The response spectra of Regulatory Guide 1.60 (NRC, 1973) have been widely used in the design of nuclear facilities, especially in Korea and U.S.A.. With Regulatory Guide 1.60 response spectra, one can easily construct design response spectra of a site. The required parameter is only one : the peak ground acceleration (PGA) at the site. Design response spectra of the site is constructed simply by scaling Regulatory Guide 1.60 response spectra with the PGA at that site. This procedure does not discriminate the distances and magnitudes of the earthquakes which produce that value of PGA. Both a large earthquake at large distance and a small earthquake at small distance can cause the same PGA at a site. In this case, however, the frequency contents of seismic energy transported to the site are not same due to the characteristics of source spectra and crustal attenuation. The small earthquake occurred at small distance from the site is richer in the high-frequency energy than the large earthquake at large distance. This fact necessitates the development of site-specific response spectrum (SSRS).

In this study, the design earthquake and corresponding SSRS are evaluated by a single procedure. Design earthquake and SSRS obtained in this way is more consistent than those by ofher multiple procedure.

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