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Site-specific Response Spectrum according to Uncertainty Distribution of Site Amplification Factor

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1. Introduction

The seismic design of Nuclear Power Plants (NPPs) is designed using Uniform Hazard Response Spectrum (UHRS or UHS) developed through Probabilistic Seismic Hazard Analysis (PSHA) based on Regulatory Guide 1.165 [1]. Regulatory Guide 1.208 [2] recommended that site seismic hazard characteristics are quantified by the seismic hazard curve from a PSHA and UHS that cover a broad range of natural frequencies. NPPs are generally located on rock site, but site amplification can occur in relatively soft site or in site with a shear wave velocity lower than Ground Motion Prediction Equation (GMPE) used in PSHA. The shear wave velocity at sites of Korean NPPs is approximately 1,000 to 3,000 m/s, but the GMPE in the Central and Eastern United States (CEUS) was considered for sites with the velocity of 2.8 km/s (approximately 2,800 m/s) or higher, so amplification may occur due to the difference in relative shear wave velocity. However, it is difficult to obtain the GMPE for multiple sites, and it is not easy to develop the hazard curve that takes site characteristics into account, especially in Korea where there is not much data of ground motions. To solve this problem, a method of estimating a site-specific hazard curve by applying a site amplification factor derived through site response analysis to an existing hazard curve is widely used. Because this conversion method is highly dependent on the site amplification factor, the results obtained may vary depending on the mean, standard deviation or distribution shape of the site amplification factor. In this study, we attempted to probabilistically calculate and apply the distribution of the site amplification factor by considering the uncertainty that may occur in the site response analysis. Main uncertainties include uncertainty in shear wave velocity and ground motion, but there is the concern that uncertainty of ground motion may overlap because it has already been considered in PSHA. Therefore, in this study, we calculated the probability distribution of site amplification by considering uncertainty in shear wave velocity through a simple example model, and through this, we aimed to use it as a basis for developing the site-specific response spectrum by Approach 3.

2. Approaches of developing site-specific response spectrum

2.1 The standard of developing UHS for soil site

NUREG/CR-6728 and NUREG/CR-6769 [3,4] provides the approaches for developing UHS for soil that take site-specific characteristics into account. This standard presents four approaches. Approach 1 is to apply site amplification as it is by performing a site response analysis for an earthquake representing a specific hazard. Approach is the same as Approach 1 but performs site response analysis for ground motion that have a large impact at 1 Hz and 10 Hz. Approach 2 is again divided into A and B. When only the variability of the site properties is considered, this approach is Approach 2A. And when a ground motion of three or more magnitudes is considered, this approach is Approach 2B that considers the influence of the earthquake magnitude as well as the site properties. Because approaches 1 and 2 apply site amplification as they are, they may be non-conservative for UHS calculating cumulative probability of exceedance for all seismic intensities. Approach 3 is an approach that can solve these problems. The distribution of the site amplification factor derived through the site response analysis is convolved with the UHS of the rock to develop the UHS for the soil. Finally, Approach 4 is an approach to directly develop the hazard using the attenuation equation of the soil site. Although it is the most accurate approach, it has the disadvantage of having to obtain the attenuation for all sites when developing UHS for multiple sites, and it is an approach that is difficult to apply because there is not much attenuation data in Korea.

2.2 UHS according to the method of applying the site amplification factor

In this study, Approach 3 was applied because it was judged the most suitable among the four presented in the NUREG/CR-6728. An approach was used convert the rock UHS to the soil UHS using the mean site amplification factor and standard deviation derived from the site response analysis. To verify the validity of Approach 3, a simple example is shown in Figure 1. When generating a hazard curve, the seismic source and maximum/minimum seismic magnitudes required were arbitrarily set, and a virtual attenuation equation that can be defined as in Equation (1) was used to develop the UHS for an arbitrary rock site.

$$\log(a) = f_1(M) + f_2(R) + sigma \qquad (1)$$

In the above attenuation equation, the functions for magnitude (M) and distance (R) were multiplied by 1.5, and sigma was assumed to be 0.4 for rock and 0.5 for soil, so that the mean site amplification factor (μ_{lnAF}) was 1.5 and the variability (σ_{lnAF}) was 0.3. Figure 1 is a comparison of the hazard curves for rock and soil generated directly using Equation (1) and the hazard curves for soil developed by applying Approach 1 and 3. As can be seen in the figure, Approach 3 showed results that were almost identical to the soil hazard curve developed using the soil attenuation equation. On the other hand, Approach 1 showed large amplification at weak seismic intensity and decreased as the intensity increased, showing results smaller than the soil hazard curve. Therefore, it can be seen that applying Approach 3 is more suitable for developing soil UHS.

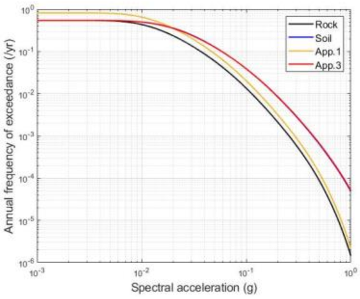

Fig. 1. Hazard curves developed using Approach 1 and Approach 3

2.3 Uncertainty distribution of site amplification factor

The examples performed in the previous section were the results calculated assuming the exceedance probability through a log-normal distribution when the mean site amplification factor and standard deviation are given. In addition, because it was applied with a constant mean value and standard deviation for all seismic intensities, there is a difference from the results applied by performing actual site response analysis. If Approach 3 is applied using the distribution of amplification factors derived from the site response analysis as input values, more accurate results will be obtained. However, because the site amplification is significantly affected by the shear wave velocity, the distribution may vary due to uncertainty in the shear wave velocity, and the distribution shape may not be a log-normal distribution. Therefore, to consider these uncertainties, the probabilistic approach was applied to analyze the probability distribution of the site amplification factor so that it could be applied to Approach 3 in the appropriate distribution shape.

3. Modeling and analysis

3.1 Model of site and input motions

The site model for the site response analysis was modeled as a simple model with two layers of 10 m thickness, as shown in Figure 2, using DEEPSOIL software [5]. Because the domestic bedrock is not deep, it was assumed to be 20 m, and the site properties and nonlinear characteristics were applied with reference to representative models [6], and equivalent linear analysis was performed. The bedrock was assumed to be approximately 3,000 m/s, referring to 2.8 km/s applied when developing the GMPE of the CEUS, and the uncertainties in the shear wave velocity was applied using the variability of 0.5 in the shear wave velocity presented in ASCE 4-16 [7]. In this study, because uncertainty of ground motion was not applied, artificial ground motions corresponding to UHS with the annual frequency exceedance of 1.0E-04 were generated and the analysis was performed by scaling them so that the PGA was 0.2g.

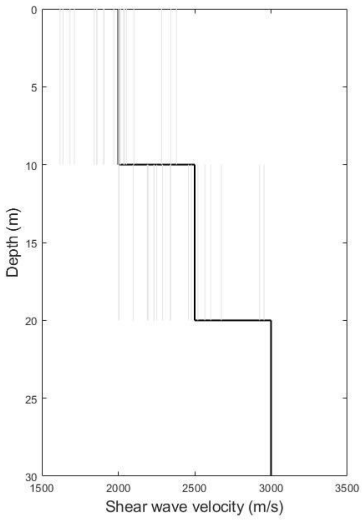

Fig. 2. Shear wave velocity profile considering uncertainties

3.2 Results of analysis

Figure 3 is a response spectrum at the site surface considering the variability of shear wave velocity. When the period is longer than 0.1 seconds, there is little amplification, but amplification occurs in the high-frequency range of 0.01 to 0.1 seconds. Because the natural period of the modeled site was approximately 0.03 to 0.04 seconds, it appears that the amplification occurred more significantly due to resonance. Figure is a graph showing the site amplification, which is the spectral acceleration at the surface divided by the it at the bedrock ($SA_{surface}/SA_{bedrock}$). In the 0.01 second period corresponding to PGA, the amplification was not significant at the mean of 1.13, but in the natural period band of the site, it was amplified by about 1.4 times, and in the case of +1 sigma, it was amplified by up to 1.6 times. That is, the probability distribution may be different for each period, and it may not be appropriate to apply the same probability distribution when applying Approach 3 to the UHS considered for all periods. In addition, the shear wave velocity of domestic NPPs sites was located in bedrock with a range of approximately 1,000 m/s to 3,000 m/s. However, because amplification may occur due to relative differences in the shear wave velocity applied to GMPE, this should be taken into consideration even though it is bedrock.

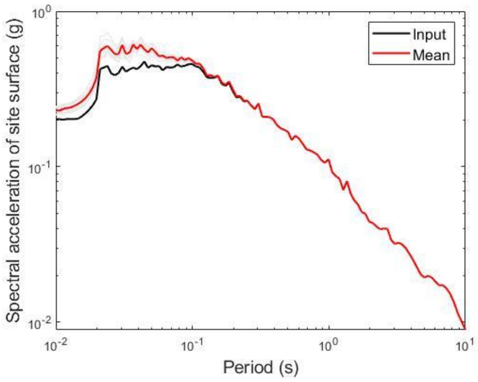

Fig. 3. Response spectrum of site surface considering shear wave velocity variability

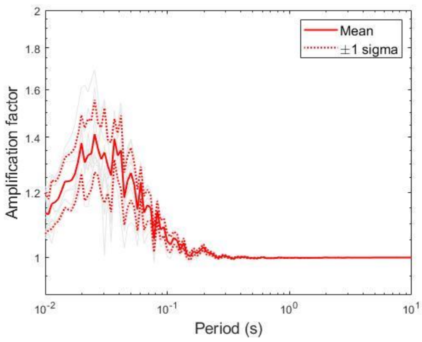

Fig. 4. Amplification factor considering shear wave velocity variability

4. Conclusions

This study aimed to estimate the probability distribution by probabilistically approaching the amplification caused by uncertainty in shear wave velocity. It was confirmed that the variability of the shear wave velocity can cause amplification due to the difference in shear wave velocity with the bedrock, and this has a different probability distribution for each period. If the probability distribution in each period is the same regardless of the seismic intensity, the previously applied Approach 3 can be used, but it is important to consider that the probability distribution may differ depending on the seismic intensity. In addition, it is necessary to consider how to apply the uncertainty of ground motions, which was not considered in this study, without overlapping with PSHA. Based on these follow-up studies, it is expected that the hazard curve for a site-specific can be efficiently developed using only the hazard curve for the rock and site response analysis results without using the GMPE for the specific site. Furthermore, if the uncertainty of the site and ground motions, are considered together for analysis, it is expected that it will be possible to identify the input motions that should be selected when conducting site response analysis.

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