Probabilistic Site Response Analysis Considering Variability of Soil Properties

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Abstract: It has been revealed from a variety of studies that earthquake ground motions are affected by variability in local soil sites. Therefore, the effects of variability on site responses are studied using a random-vibration-theory based probabilistic site response analysis. The effects of variability of the layer thickness and the low-strain shear-wave velocity at soil sites are considered by Monte Carlo simulations. Soil-amplification functions of generic soil sites are evaluated by the probabilistic approach. The seismic hazard curves of outcropping bedrock motions are combined with the amplification functions to produce seismic hazard curves and uniform hazard response spectra (UHRS) for soil sites. Ground motion response spectra (GMRS) for a seismic design of nuclear facilities are obtained by seismic risk analysis of structures at the sites. The soil-amplification functions and the resulting UHRS and GMRS values for the soil sites are observed to be significantly influenced by the variability in the layer thickness and the low-strain shear-wave velocity influences.

1. INTRODUCTION

Structural engineers have considered the seismic designs of new facilities and the improvements of the seismic performance of existing facilities. In order to ensure the seismic safety of facilities, the effects of seismic excitations on their structural behaviors must be taken into account with the variability of the seismic sources, the propagation paths of seismic waves, and the local soil sites on which the facilities are installed. The (local) soil-structure interaction influences significantly the earthquake responses of structures at soil sites. Therefore, the effects of variability in local soil conditions must be considered to evaluate the seismic safety of facilities.

The frequency contents of seismic waves in layered soil are very different from those of outcropping bedrock motions. The random properties of the seismic sources and the propagation paths from sources to sites affect the frequency contents of outcropping bedrock motions and the resulting ground motions at soil sites. The low-strain shear-wave velocity, the nonlinear dependence of the shear modulus and hysteretic damping on shear strain, and the layer thickness at local sites can influence the earthquake ground motions at local soil sites. Therefore, the corresponding randomness and uncertainty must be considered in the site response analysis when the free-field motions for earthquake response analysis of structures at soil sites are evaluated.

It is described in the ASCE/SEI 4-16 standard how to obtain the seismic input for a soil-structure interaction analysis with the aforementioned randomness and uncertainty taken into consideration [1]. The Monte Carlo simulation technique can be employed to consider the variability at a local soil site. The probabilistic properties for the shear-wave velocity, the nonlinear material properties, and the layer thickness must be described in the simulation.

The response-history (RH) methodology and the random vibration theory (RVT) methodology can be employed to consider randomness in outcropping bedrock motions as described in the ASCE/SEI 4-16 standard [1]. In the first methodology, the time histories of ground motions consistent with design response spectra are input into the soil column as outcropping bedrock motions. A sufficient number of input ground motions are required for a proper consideration of the randomness of outcropping bedrock motion in this approach because the soil responses depend heavily on the characteristics of the input ground motions. On the other hand, the RVT methodology can be employed in a probabilistic site response analysis. In this approach, a design response spectrum can be used instead of the time histories of the input ground motions for the RH methodology. Nguyen and Lee [2], Deng and Ostadan [3, 4], and Rathje and Ozbey [5] performed probabilistic site response analyses based on the RVT methodology. Rathje et al. [6] studied the effects of input motion and site property variabilities by means of a seismic site response analysis.

Seismic actions on structures are usually represented by a design response spectrum. The design response spectrum can be obtained from statistical analysis of actual records of earthquake ground motions in a region. The standard design response spectra, specified in the United States Nuclear Regulatory Commission (USNRC) Regulatory Guide (RG) 1.60 [7], is one example of the spectra obtained from the approach. After the concept of a probabilistic seismic hazard analysis was introduced, a uniform hazard response spectrum (UHRS) and a design response spectrum based on the maximum considered earthquake (MCE) ground motions were employed for the seismic designs of facilities [8]. The level of earthquake ground motion in a UHRS is determined such that the seismic hazard, obtained from a probabilistic seismic hazard analysis, is uniform for all considered frequencies. With the introduction of the concept of performance-based design, a uniform risk response spectrum (URRS) [9], also referred to as the ground motion response spectrum (GMRS), and the design response spectrum based on the risk-targeted maximum considered earthquake ground motions [10, 11] were proposed to have a uniform level of seismic risk at all frequencies.

In this study, the effects of the variability of local soil profiles on UHRS/GMRS at soil sites will be studied by means of a probabilistic site response analysis based on the RVT methodology as described in Nguyen and Lee [2]. In the study, the RVT methodology and the simulation technique were proposed. In this study, the approach is employed and applied to probabilistic site responses analyses of example soil sites for nuclear facilities in Korea. The site responses analyses will be performed with seismic hazard curves which consider the latest seismic events in Korea. The effects of variability of the soil sites on UHRS/GMRS at soil sites will be examined.

2. PROBABILISTIC SITE RESPONSE ANALYSIS BY THE RVT METHODOLOGY

The ASCE/SEI 4-16 standard presents the state-of-the-art for a probabilistic site response analysis [1]. A probabilistic site response analysis can be conducted using an equivalent linear or fully nonlinear ground response analysis of simulated soil profiles. The equivalent linear analysis can be implemented using the RH methodology or the RVT methodology. The RVT methodology requires the acceleration response spectrum as input rather than the acceleration time history. In this study, the approach by Nguyen and Lee [2] and Deng and Ostadan [3, 4] will be employed for a probabilistic site response analysis with the RVT methodology. Based on the RVT methodology, earthquake responses and response spectra of a soil site can be obtained when the site is subjected to an outcropping bedrock motion which is consistent with a design response spectrum. It should be noted that no time history of outcropping bedrock motion is required for the RVT methodology for a probabilistic site response analysis.

3. VARIABILITY OF THE SOIL PROPERTIES

The material properties of soil layers can vary depending on the site. Usually, it is necessary to define the low-strain shear-wave velocity and the relationships between the shear modulus and hysteretic damping and the shear strain levels in terms of their probability distributions [1]. The variability of the layer thickness can be taken into account if appropriate for the site being considered [1]. It was observed that the variability in the layer thickness and the low-strain shear-wave velocity influences the soil-amplification functions and the resulting UHRS and GMRS at soil sites significantly [2]. On the other hand, the effects of the nonlinear dependence of the shear modulus and hysteretic damping on shear strain were observed to have minor effects of the site responses [2]. In this study, the simulation technique by Nguyen and Lee [2] will be employed to consider the variability in the layer thickness and the low-strain shear-wave velocity in soil sites.

4. APPLICATION

In order to obtain a probabilistic site responses of six generic soil sites for nuclear facilities in Figure 1, the approach based on the RVT methodology in Nguyen and Lee [2] is employed in this study. Figure 1 provides the layered structures, the shear-wave velocities and densities of the soil layers and half-spaces, and the nonlinear shear moduli and damping ratios of soil.

Figure 1: Generic soil sites

Soil depth (ft)	Soil site					
	1	2	3	4	5	6
0 ~ 55	P3	P2	P2	P4	P4	P1
55 ~ 100	P3	P3	P3	P4	P4	P2
100 ~ 200	P4	P3	P4	P4	P5	P3
200 ~ 500	P4	P5	P5	P5	P5	P4
500 ~ 1000	P5	P5	P5	P5	P5	P5
1000 ~	P5	P5	P5	P5	P5	P5

Soil layer	S-wave velocity (ft/sec)	Density (lb/ft^3)
P1	1200	125
P2	2000	130
P3	4000	135
P4	6000	145
P5	9200	155

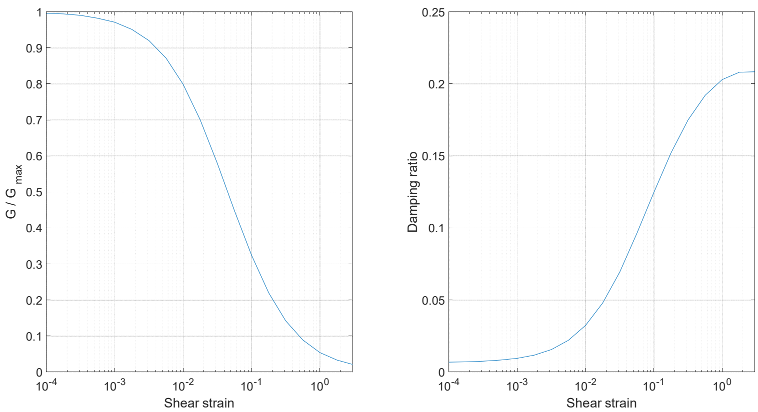
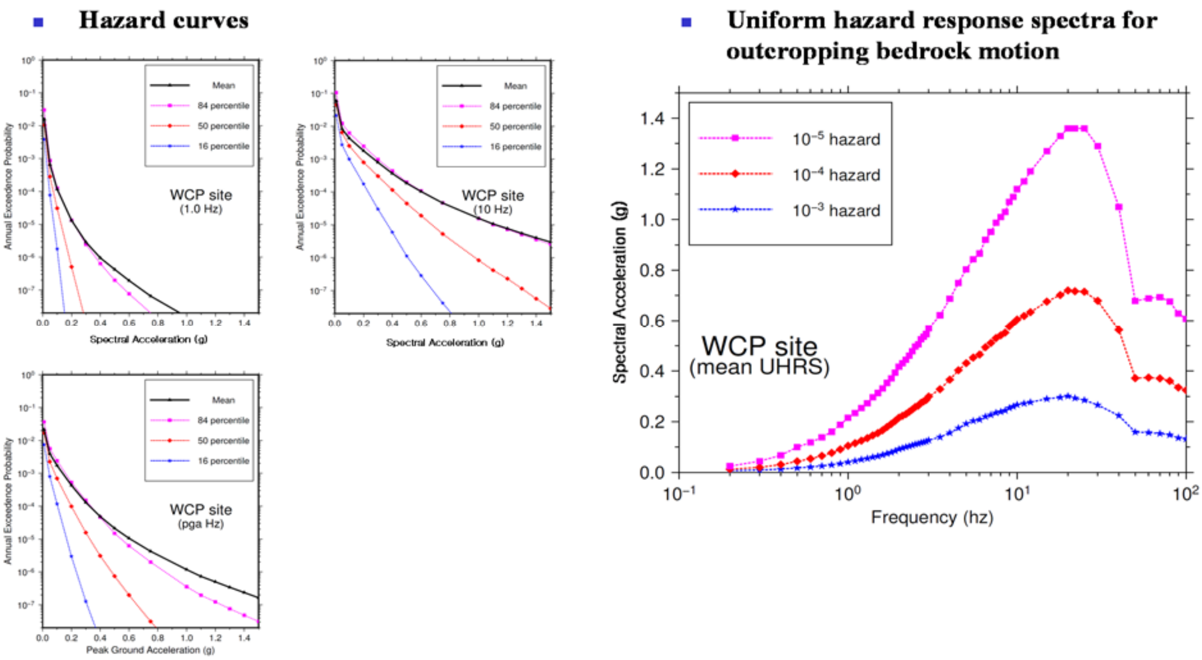


Figure 2: Seismic hazard curves and UHRS for outcropping bedrock motions [12]



The hazard curves and UHRS for the input outcropping bedrock are shown in Figure 2. They were obtained from the probabilistic seismic hazard analysis of a specific site with the latest seismic events in Korea taken into account.

The effects of variability in the layer thickness and the shear-wave velocity are examined. 200 realizations are considered for Monte Carlo simulations.

4.1. Variability in the Layer Thickness

First, the effects of variability of the layer thickness are considered. The layer thickness is realized with Erlang distributions as proposed in Nguyen and Lee [2]. The distributions have three values of 100, 25, and 10 for the parameter k or the coefficients of variation of 0.1, 0.2, and 0.32, respectively. The six soil sites in Figure 1 are realized as shown in Figure 3. Figure 4 presents the median soil-amplification functions for the soil sites. The UHRS at the soil surfaces with annual frequency of exceedance of 10^{-4} can be obtained from the calculated hazard curves as shown in Figure 5 [13, 14]. The GMRS values with the target seismic risk of 10^{-5} are shown in Figure 6 [13, 15]. In the calculation, The fragility curve for a structure is assumed as a cumulative distribution function of a log-normal distribution which satisfies the conservatism requirements in the ASCE/SEI standard [16]. It can be observed that the variability of the layer thickness influences the soil-amplification functions and the resulting UHRS and GMRS for the soil sites significantly.

Figure 3: Realizations of the random layer thickness

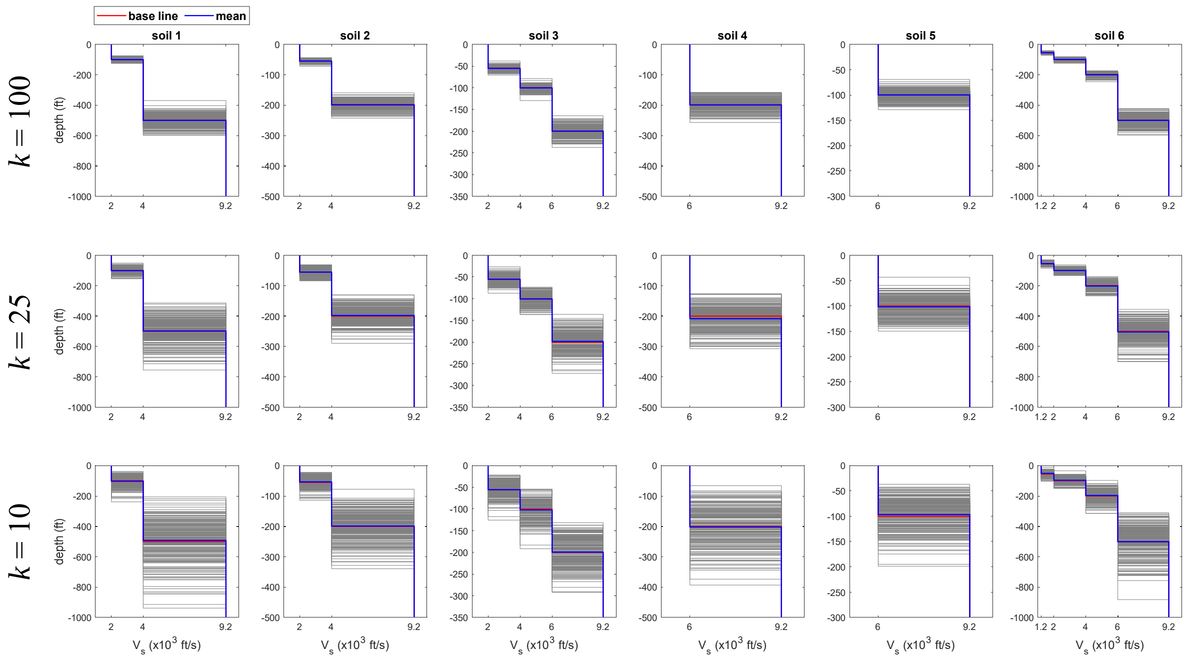


Figure 4: Soil-amplification functions with the variability of the layer thickness

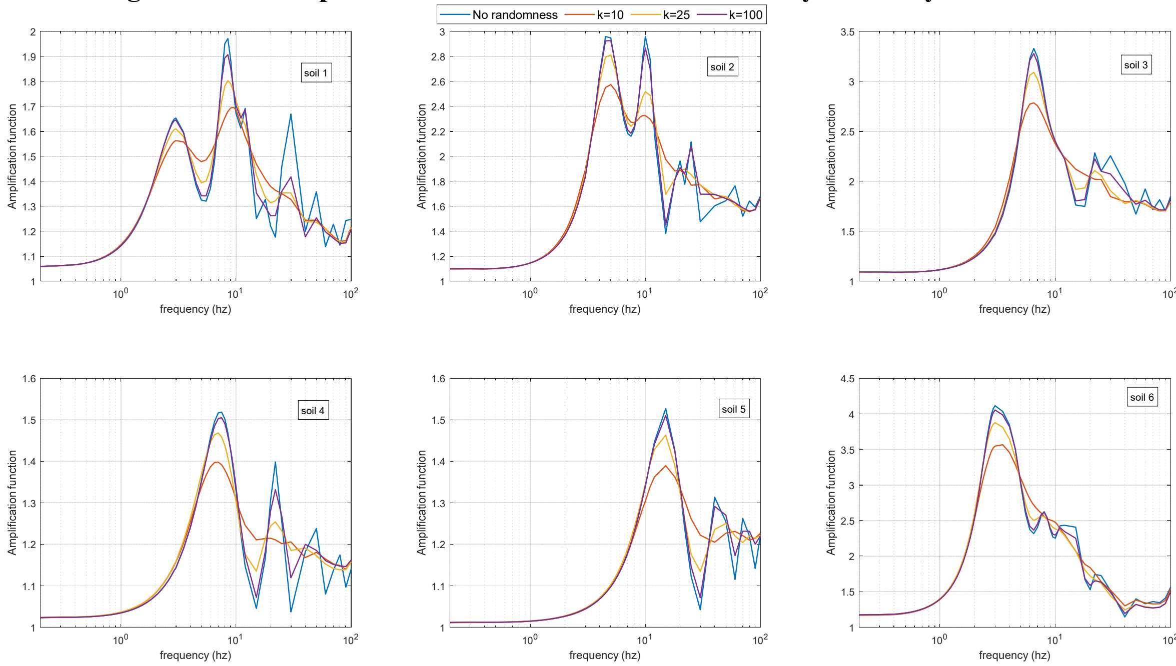


Figure 5: Uniform hazard response spectra with the variability of the layer thickness

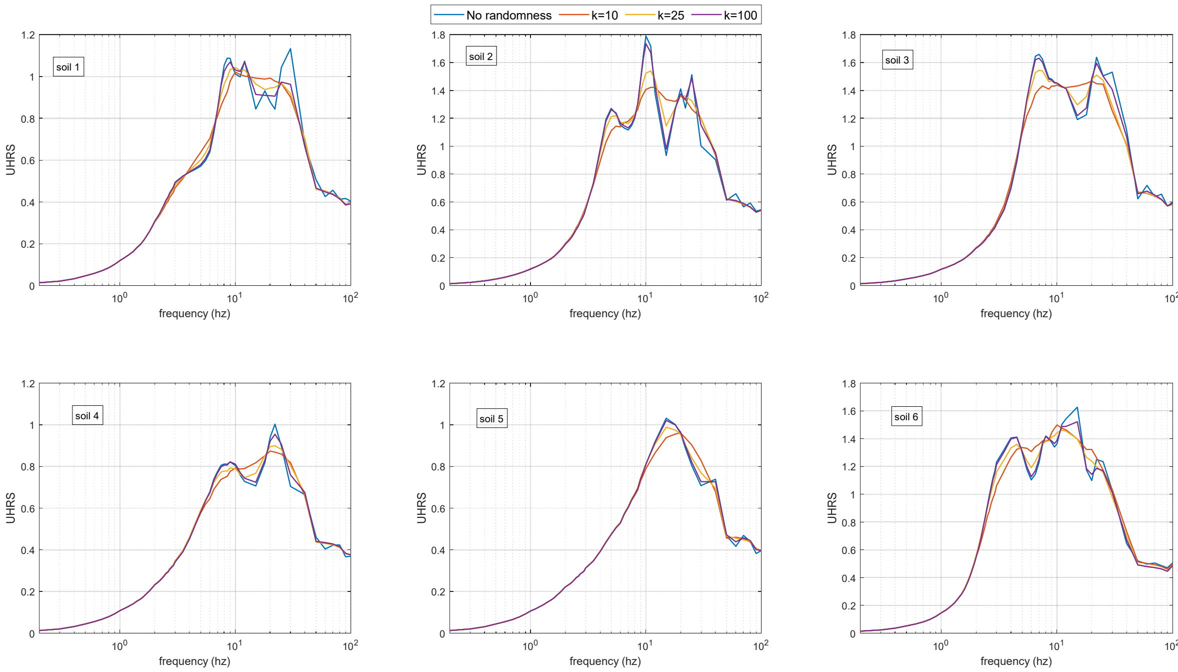
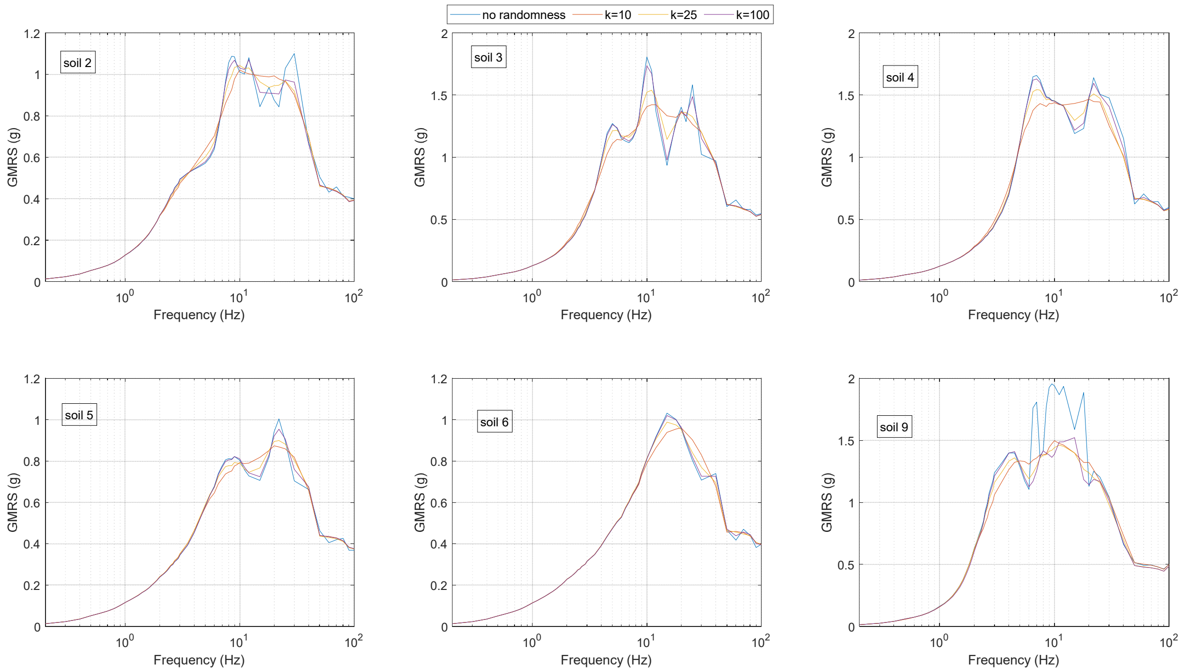


Figure 6: Ground motion response spectra with the variability of the layer thickness



4.2. Variability in the Low-strain Shear-wave Velocity

Second, the effects of variations in the shear-wave velocity are considered. Three values of 0.1, 0.2, and 0.3 are considered for the standard deviation of logarithmic value of shear-wave velocity in this example. The six soil sites in Figure 1 are realized as shown in Figure 7. Figures 8 to 10 present the soil-amplification functions and the resulting UHRS and GMRS for the soil sites, respectively. It can be observed that the soil-amplification functions, UHRS, and GMRS for soil sites are significantly influences by the variability of the shear-wave velocity.

Figure 7: Realizations of the random low-strain shear-wave velocity

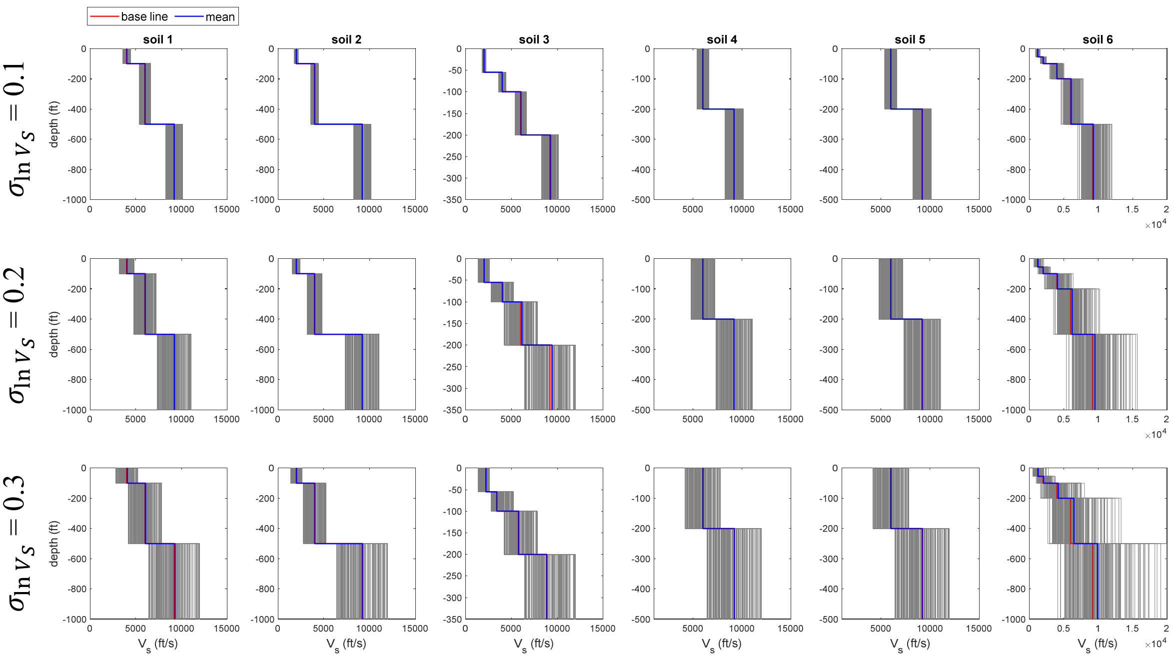


Figure 8: Soil-amplification functions with the variability of the low-strain shear-wave velocity

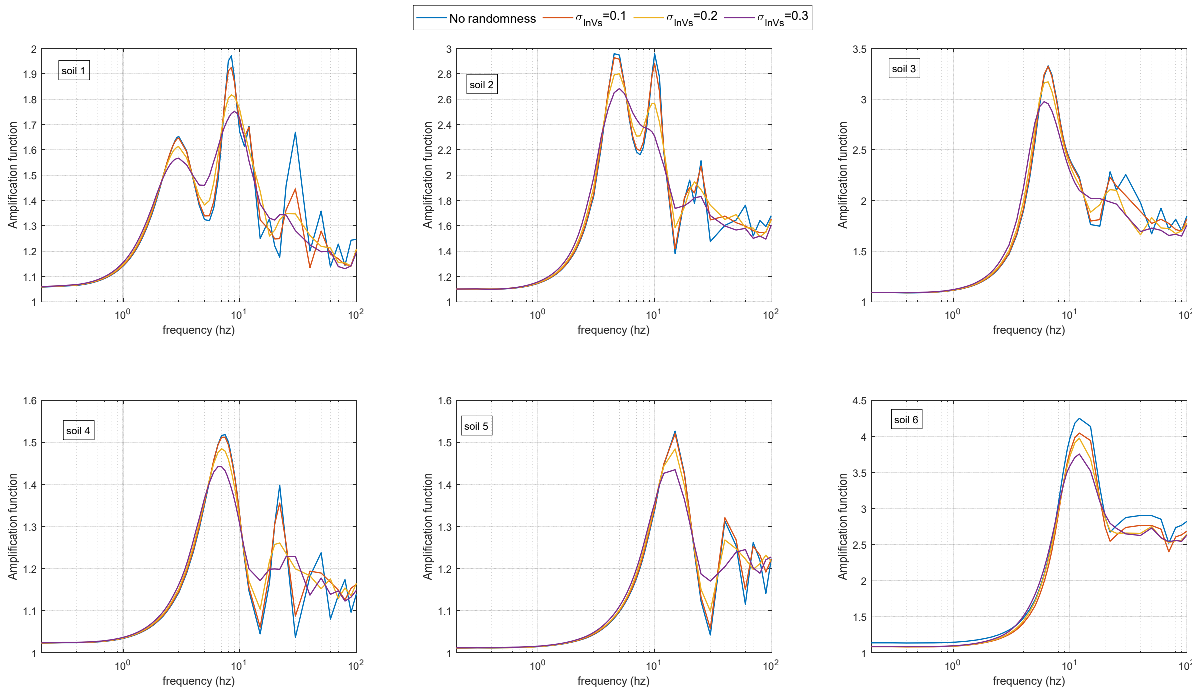


Figure 9: Uniform hazard response spectra with the variability of the low-strain shear-wave velocity

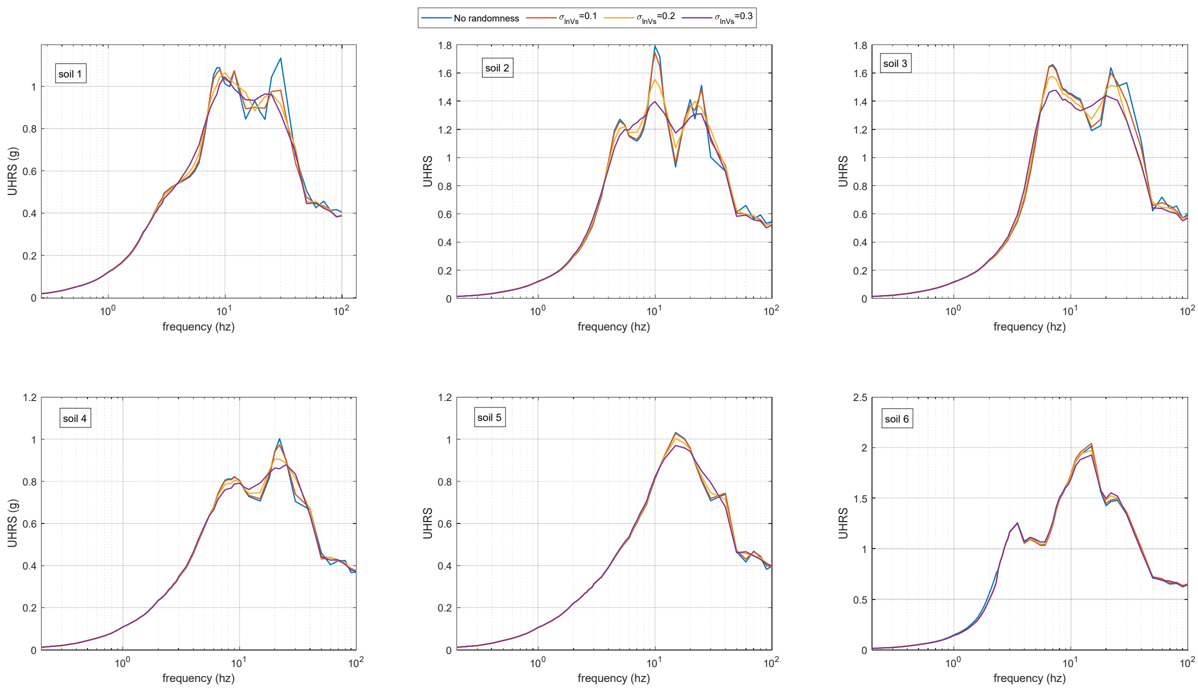
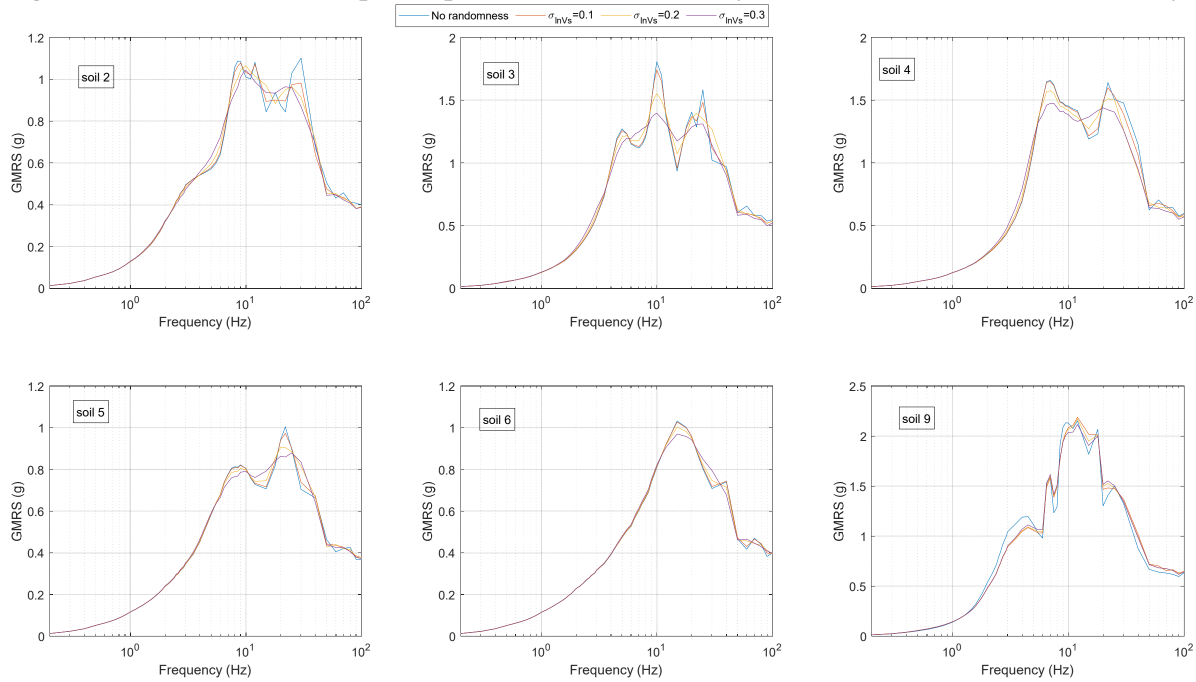


Figure 10: Ground motion response spectra with the variability of the low-strain shear-wave velocity



5. CONCLUSION

The seismic designs of new facilities and the improvements of the seismic performance of existing facilities can be considered using site-specific UHRS/GMRS. Because earthquake ground motions are influenced by the variability at local soil sites, it must be considered in the site-specific UHRS/GMRS to ensure the seismic safety of facilities. The probabilistic site response analysis based on the RVT methodology can be employed to reveal the effects of variability in local soil profiles on UHRS/GMRS. The variabilities of the layer thickness and the shear-wave velocity were considered in this study by employing the Monte Carlo simulation technique.

The site response analysis of generic soil sites was performed by the probabilistic approach. In the analysis, the seismic hazard curves at a specific site for nuclear facilities were considered with the latest seismic events in Korea taken into account. The corresponding soil-amplification functions and the resulting UHRS and GMRS were obtained. It was observed that the calculated results were affected significantly by the variability in the layer thickness and low-strain shear-wave velocity. The peaks in the soil responses at the natural frequencies of the sites were reduced due to the variability and the valleys in the responses were raised. The effects were observed to be more significant for higher coefficient-of-variation values. The variability must be considered for site-specific UHRS/GMRS in order to prove the seismic safety of new and existing facilities at soil sites.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20201510100020 and No.20181510102410). This research was also supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2020R1I1A3068424 and 2019R1I1A3A01058812).

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