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Effect of probabilistic variation in soil properties and profile of site response

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Abstract

Site response is a function of the soil profile, and the probable distribution of the soil profile has a significant effect on the seismic site response. In the present study, the influence of random variations in soil characterizations on the site response is investigated using different probabilistic distributions. The important characteristics of the local soil, corresponding to the layering, the shear wave velocity (V_s), the decrease in the nonlinear modulus, and the damping (MRD) curves, are considered when carrying out these random variations. Stochastic processes are generated by using different distribution models and keeping in mind the effect of the coefficients of the variations. In this research, a proposed procedure is developed and coded to perform the variations in soil characterizations. The coding of this new procedure is based on the original SHAKE91 framework. However, instead of using the fixed soil properties and profile, the uncertainties of the MRD curves, the layer thickness, and V_s are generated as the input data. This analysis shows that the use of median V_s, obtained from all the possible inputs under the different stochastic processes, yields good agreements with the baseline profile. Modelling the variabilities in the layering and the V_s profile is seen to have a slight effect on the performance of the site response. Additionally, the results of these analyses indicate that the variabilities in nonlinear soil properties have a significant impact on the median surface response spectrum and the amplification spectrum of the surface motions.

Keywords: Site response analysis; Probabilistic distribution; Nonlinear soil properties; Soil variability

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1. Background

Site response analysis is an important method for simulating the seismic waves from the underlying bedrock motion to the surface ground motion through local soil conditions. The properties of the local soil conditions, such as the layering, the shear wave velocity (V_s), the decrease in the modulus, and the damping (MRD) curves, have a significant influence on ground shaking.

Previous studies have been done to evaluate the response of different characterized local soil. By assuming constant values for both the shear modulus and the damping factor of a soil, Seed and Idriss (1969) provided an appropriate analysis for estimating the surface response during earthquakes. Based on a comparison between the laboratory tests and the experiment, Seed et al. (1986) proposed numerical models for the relationship between the reduction in the nonlinear shear modulus and the increase in the material damping curves for sandy and gravelly soils. The effects of the nonlinear dynamic soil properties have been investigated in some studies (Hardin and Drnevich, 1972; Anderson and Woods, 1975; Darendeli, 2001).

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Moreover, an analytical model of nonlinear soil behavior with shear strain, namely, the hyperbolic model, was developed by Hardin and Drnevich (1972). A modified hyperbolic model, including the published results by Darendeli (2001), was later created to model the relationship between the material damping ratio vs strain and to estimate the MRD curves, using the First-order, Second-moment Bayesian Method – FSBM (Gilbert, 1999). In addition, Anderson and Woods (1975) defined a correlation number for the Ramberg-Osgood curve, which describes the relationship of the shear modulus with shear strain. A few formulas have been proposed to predict the shear modulus and damping ratios of soil properties by reanalyzing the field data on dynamic soil properties, which were developed by Ishibashi and Zhang (1993). Thereafter, Menq (2003) presented the dynamic properties of sandy and gravelly soils using a multi-mode proposed device. Several studies have also been conducted on the dynamic response of soil under multi-directional ground motion loading (Chen et al., 2011; Nie et al., 2017). According to Chen et al. (2011), considering the effects of the variation in the ground water level, the deep soil in Shanghai has been used for a site response. In the work by Nie et al. (2017), the ratio of seismic compression for two horizontal components of earthquake ground motion is proposed.

In practical earthquake engineering, there are usually no data available on the random variables, such as the layer thickness, V_s, density, and shear modulus. Therefore, it is necessary to develop a simulation technique for the uncertainty processes. An essential part of the probabilistic methods is the selection of probability distribution functions to represent the uncertainty of the random variables. The variability of soil was investigated in the work of Bong et al. (2014) by comparing the Monte Carlo simulation results with the stochastic response surface method for a specific site located in Yeonjongdo, South Korea. A statistical model was developed by Toro (1995) to randomize the layering and V_s, for which the V_s variability was described as a log-normal distribution. Likewise, many authors, such as Koutsourelakis et al. (2002), Popescu et al. (2006) and Rathje et al. (2010), also presented probabilistic approaches through several types of research. A non-Gaussian distribution for soil properties and a non-stationary random process for ground motion have been examined by Koutsourelakis et al. (2002) for evaluating the soil-structure system due to liquefaction. The finite element model for a soil profile under seismic excitation, considering the influence of the coefficient of variation (COV), was modelled by Nour et al. (2003) to analyze the behavior of a site, in which V_s was randomized by a non-Gaussian distribution. The effect of the spatial random soil on the amplification between the ground shaking and the bedrock motion was included in the research presented by Bazzurro and Cornell (2004). Two earthquakes in Taiwan and California were reanalyzed by Andrade and Borja (2006) to investigate the soil response by comparing an equivalent linear analysis (Idriss and Sun, 1993) and a time domain nonlinear analysis (Borja et al., 2000). Kwok et al. (2008) evaluated the site-specific soil behavior in Turkey Flat using the nonlinear and equivalent-linear ground-response computer code DEEPSOIL (Hashash et al., 2012) and compared the predictions with the measurement results. Futhermore, Bombasaro and Kasper (2016) conducted an extensive investigation on the soil variability in the Pearl River Estuary based on cone penetration tests with pore pressure measurements (CPTU).

In this study, site response analyses are conducted using a randomized soil deposit (considering the soil profile and nonlinear soil properties) for a specific site due to seismic excitation. The property randomizations include (1) the variation in dynamic soil properties based on the empirical model of Darendeli (2001) and (2) the layering and V_s of the soil deposit from the surface to the bedrock with different stochastic processes using the Toro model or the log-normal distribution. The influence of the COV of the layering and V_s is also introduced in these procedures. In addition, the proposed solution, PSHAKE, is developed, based on the original SHAKE91 framework of the site response analysis. The results of more than 1800 randomized profiles are used to confirm the influence of random fields for soil properties on the site response analyses. The results of the maximum peak ground acceleration (PGA) at each layer, the amplification function (AF), and the spectral acceleration (S_a)of the ground motion at the surface under the current approaches are compared with the results of the equivalent linear ground response software, SHAKE91.

2. Numerical modelling

2.1. Site profile

A realistic site profile, namely, Sylmar County Hospital (SCH) site (Chang, 1996) located in the San Fernando Valley of Southern California is considered in evaluating the site response. The V_s along the depth of the soil is plotted in Fig. 1. The total depth is about 90 m of alluvium above bedrock with V_s ranging from about 250 m/s at the surface and rising to above 700 m/s at 60 m (Gibbs et al., 1996).

Additionally, the V_s profile, including the nonlinear soil dynamic of the soil layers, such as the shear modulus reduction and the damping curve, needs to be considered for the site response analysis. The shear modulus reduction defines the variation in the shear modulus with shear strain and the damping curve defines the damping ration with shear strain. In this study, the nonlinear properties are modeled using the Darendeli (2001) model which is a function of the mean effective stress (σ_0'), the over-consolidation ratio (*OCR*), and the plasticity index (*PI*). The variability in the MRD curves for each layer is generated with σ_0' being equal to 0.36 atm, 2.2 atm, 5.6 atm, and 7.7 atm. The *PI* and the *OCR* for all layers in the model are 10 and 1.0, respectively. The soil is split into four layers and the thickness, unit weight, and σ_0' for each layer are shown in Fig. 2.

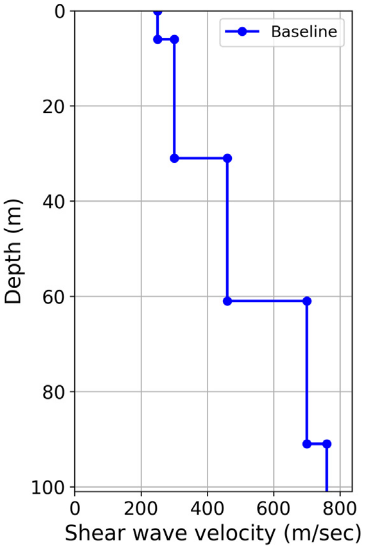


Fig. 1. Shear wave velocity profile.

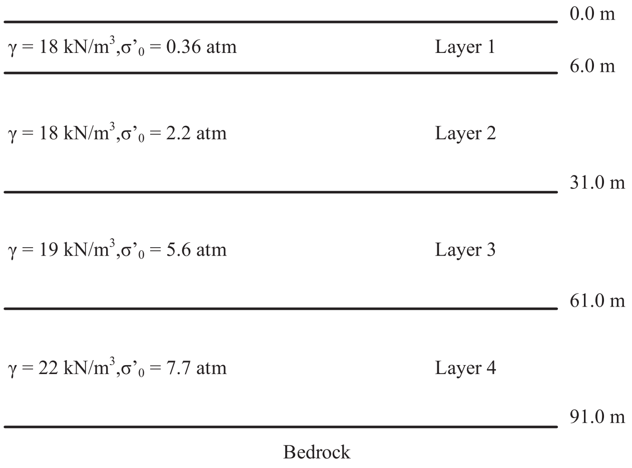


Fig. 2. Soil layers.

The MRD curves of the site at the middle of each layer are plotted in Fig. 3. It can be seen that the MRD curves depend on σ'_0, whereby the shear modulus reduction curve shifts up and the damping curve shifts down when σ'_0 rises.

2.2. Input motion

In order to perform site response analyses, the seismic input as acceleration vs time history data is provided for the procedure and this signal is applied at the bedrock of the site. In the present study, from the PEER strong motion database (Ancheta et al., 2014), an input motion located in Northridge is selected which comes from an earthquake with a magnitude of 6.69 at a distance of 37 km with an average shear wave velocity in the top 30 m ($V_{s,30}$) of about 500 m/s. Fig. 4a represents the time history of the input ground motion applied in this analysis. The PGA and time interval are 0.106 g and 0.02 sec, respectively. The resulting response spectrum of the selected motion is illustrated in Fig. 4b.

3. Probabilistic site response analysis procedure

Many tools have been developed for site response analyses, such as SHAKE91 (Idriss and Sun, 1993) which was modified based on the original SHAKE (Schnabel, 1972), DEEPSOIL (Hashash et al., 2012), STRATA (Kottke and Rathje, 2008), etc. In this paper, a new procedure is developed for a probabilistic site response analysis based on the original SHAKE91 framework. However, instead of fixing the soil profile, an uncertainty of the nonlinear soil properties, layer thickness, and V_s are conducted for the stochastic process, but with different probability distributions. This chapter provides detailed information on the random variation procedure, including the nonlinear soil properties predicted by the Darendeli model, the layering of the profile, and the V_s profile generated by the Toro model, a Gaussian or non-Gaussian distribution. In addition, in order to solve these random variations, a computer code is developed, namely, PSHAKE.

3.1. Variability of nonlinear soil properties

In this work, the effects of nonlinear property parameters are investigated using the empirical model developed by Darendeli. One of the significant aspects of this model is that it estimates not only the mean values of the empirical curves, but also the uncertainty associated with these

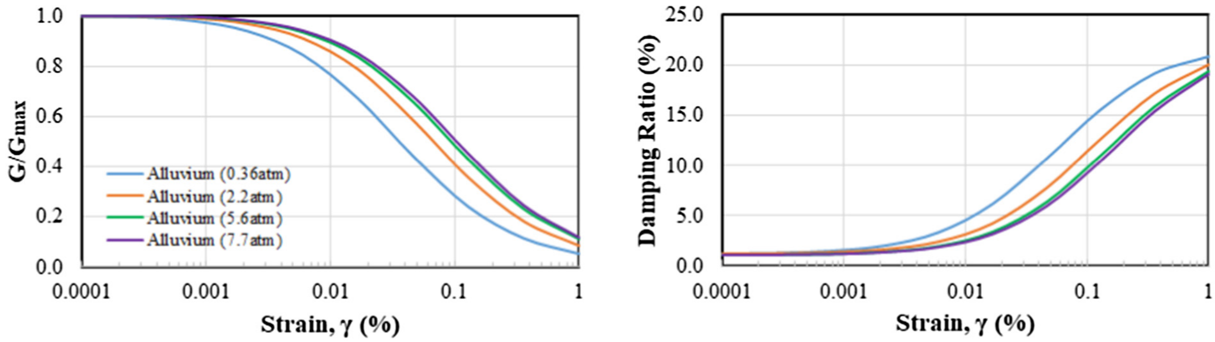


Fig. 3. Nonlinear modulus reduction and damping curves of soil.

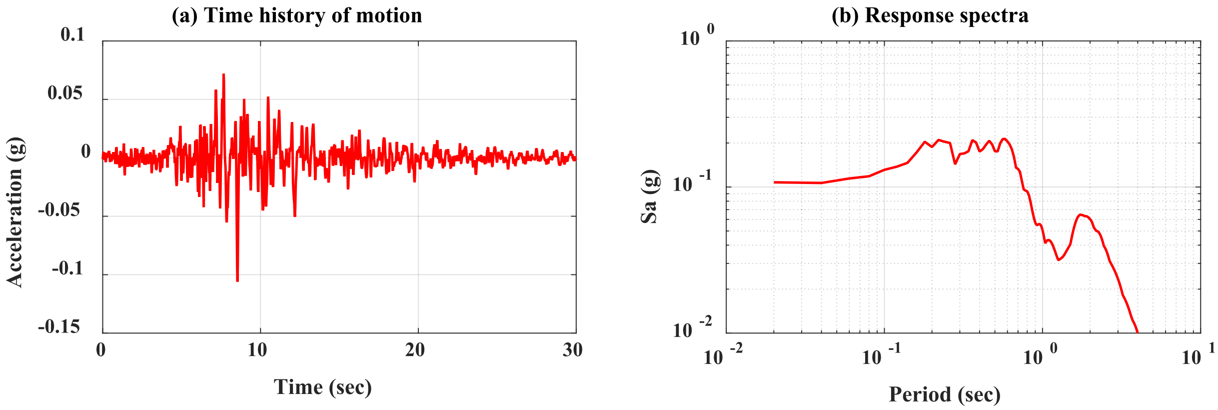


Fig. 4. Ground motion records.

values. In the Darendeli model, the variability of the soil properties is modelled as a normal distribution. G/G_{max} and D are generated from the baseline (mean) curves and the values are computed from Eqs. (1) and (2), respectively.

$$G/G_{max}(\gamma) = [G/G_{max}(\gamma)]_{mean} + \varepsilon_1 \sigma_{NG} \tag{1}$$

$$D(\gamma) = [D(\gamma)]_{mean} + \rho\sigma_D\varepsilon_1 + \sigma_D\sqrt{1-\rho^2}\varepsilon_2 \tag{2}$$

where, ε_1 and ε_2 are uncorrelated random variables with zero mean and unit standard deviation, and (σ_{NG}) and (σ_D) are the standard deviations of the normalized shear modulus and the damping ration, respectively, which are defined as follows:

$$\sigma_{NG} = \exp(-4.23) + \sqrt{\frac{0.25}{\exp(3.62)} - \frac{\left(\frac{G}{G_{max}} - 0.5\right)^2}{\exp(3.62)}} \tag{3}$$

$$\sigma_D = \exp(-5.0) + \exp(-0.25)\sqrt{D(\%)} \tag{4}$$

$[G/G_{max}(\gamma)]_{mean}$ and $[D(\gamma)]_{mean}$ are the mean value of the shear modulus and the damping ratio evaluated at strain level γ, respectively. They present the following relations:

$$\frac{G}{G_{max}} = \frac{1}{1+\beta\left(\frac{\gamma}{\gamma_r}\right)^a} \tag{5}$$

$$D = b\left(\frac{G}{G_{max}}\right)^{0.1} D_{Masing} + D_{min} \tag{6}$$

where β and a are fitting parameters generally taken as 1 and 0.9190, respectively, γ and γ_r are the shear strain and the reference shear strain, respectively, D_{Masing} and D_{min} are the Masing damping and the minimum damping ratio, respectively, and b is defined as a function of the number of cycles of loading (N). An example of the MRD curves for the first layer is also randomized here and is shown in Fig. 5 using the above stochastic process. As described previously, the variation in these properties follows a normal distribution in the Darendeli model, since negative values are not physically possible for either G/G_{max} or D. As a result, the normal distributions need to be truncated and, for correction, the minimum values for G/G_{max} and D are specified. In this research, the maximum for G/G_{max} and D are capped at 1 and 25%, respectively.

3.2. Soil profile

The randomized V_s profiles in this work are generated from the Toro model which is described as a log-normal distribution with the median $\ln(V_{median,i})$ and the standard deviation $\sigma_{\ln V}$ of V_s. The shear wave velocity of layer i (V_i) is calculated as follows:

$$V_i = \exp\{Z_i \cdot \sigma_{\ln V_S} + \ln(V_{median,i})\} \tag{7}$$

where Z_i is a random standard normal variable for layer i and is defined as follows:

$$Z_1 = \varepsilon_1, \quad \text{for the surface layer} \tag{8}$$

$$Z_i = \rho Z_{i-1} + \varepsilon_i\sqrt{1-\rho^2}, \quad \text{for other layers} \tag{9}$$

where, Z_{i-1} is the standard normal variable of the previous layer, ε_1 is a new normal random variable with zero mean and unit standard deviation, and ρ is the interlayer correlation, defined as follows:

$$\rho(d,h) = [1-\rho_d(d)]\rho_h(h) + \rho_d(d) \tag{10}$$

where ρ_h is the thickness-dependent correlation and ρ_d is the depth-dependent correlation. ρ_h and ρ_d are defined as the functions of thickness (h) and depth (d), respectively.

$$\rho_h(h) = \rho_0 e^{(-h/\Delta)} \tag{11}$$

$$\rho_d(d) = \begin{cases} \rho_{200}\left[\frac{d+d_0}{200+d_0}\right]^b, & d \le 200 \\ \rho_{200}, & d > 200 \end{cases} \tag{12}$$

where $\rho_0, \rho_{200}, d_0, b$, and Δ are the fitting parameters of the Toro model.

Fig. 6 shows the sample realizations of the V_s profiles at the SCH site with and without V_s reversals. Five V_s profiles are generated for interlayer correlation (ρ) values of 0.5 and 1.0. 20% COV is required to generate the randomized V_s profiles. From the figure, it can be seen that the spatial V_s profiles are reversals for $\rho < 1.0$, and they are maintained for $\rho = 1.0$.

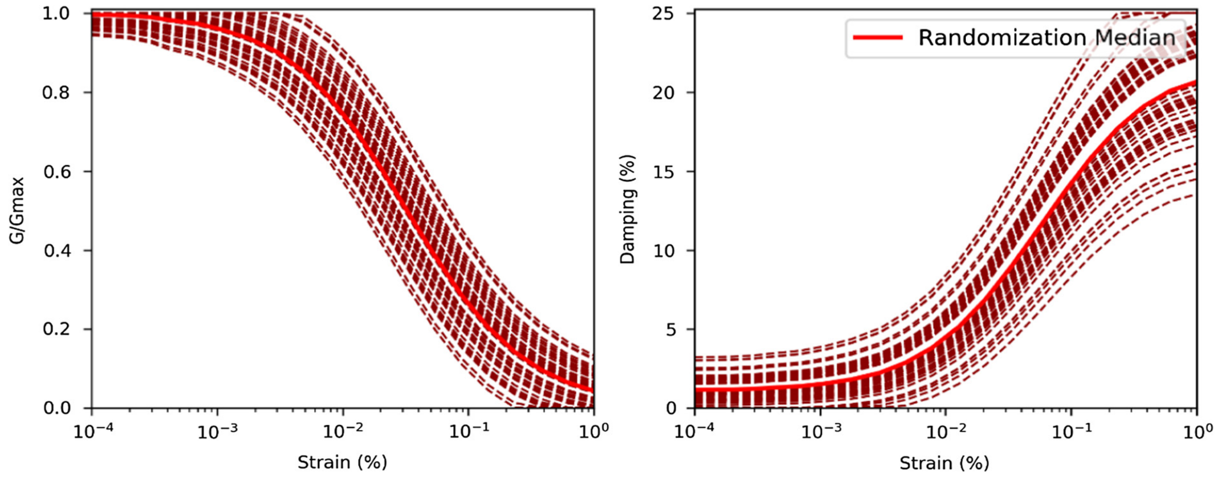
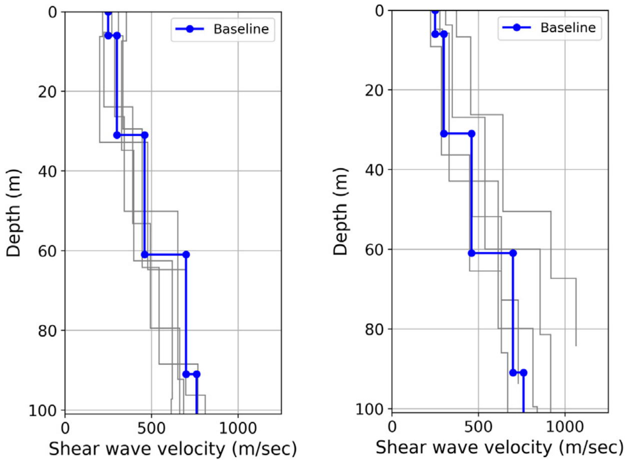


Fig. 5. Variability of shear modulus and damping curves for first layer.



(a) With V_S reversals ($\rho = 0.5$) (b) Without V_S reversals ($\rho = 1.0$)

Fig. 6. Sample realizations of shear wave velocity profiles.

3.3. Algorithm

As per the above-described method, a procedure is coded in the computer program PSHAKE. The step-by-step process is as follow: (1) generate multiple soil profiles based on the baseline profile, (2) run the site response many times considering the variable soil profiles each time, and (3) take the statistical mean value. The parameters and models required for PSHAKE software consist of (1) the control file for PSHAKE (e.g., control.inp) (2) the input file for SHAKE91, and (3) the acceleration data. The control file contains two main options, including soil properties and a soil profile. To describe the probabilistic of the soil profile (e.g., layer thickness V_s), some probabilistic distributions are proposed. The Darendeli model is used for nonlinear soil properties. The layering can be randomized with a uniform, normal or log-normal distribution and the V_s profile can be generated using a normal, log-normal distribution or the Toro model. This paper discusses three cases for conducting a randomization for layering and V_s. A flowchart of the software is shown in Fig. 7. In the first case, “idxModel == 0”, only V_s is randomized using the normal or the log-normal distribution. The second case, “idxModel == 2”, is similar to the first case, but V_s is calculated following the Toro model. In the third case, “idxModel == 1”, both the layering and V_s are randomized. In this procedure, the layer thicknesses are firstly generated and then shear wave velocities are assigned to each layer.

4. Spatial variability in soil profile

The main objective of this work is to investigate the influence of the probabilistic distribution on the site response. All analyses are conducted for specific site SCH with four layers. Details on the input data for the dynamic soil properties and the soil profile are given in Fig. 1 and Fig. 2, respectively. Three cases of random variations in soil profiles, corresponding to the three models shown in Fig. 7, are performed here to understand the effects of the proposed process. They include Case 0, the log-normal distribution model, Case 1, the velocity model (Toro, 1995) and the layering model, and Case 2, only the velocity model. The same processes are repeated for the different COVs, which are varied from 20 to 60%. Considering all the described models, more than 1800 nonlinear site response analyses are conducted in this research. Fig. 8 displays the uncertainty V_s profiles for the COV of 20%. The blue, red, and gray curves represent the baseline, the median, and the simulated soil profiles. Obviously, the median V_s, obtained from different approaches, is in very good agreement with the baseline V_s profile. The results for both Case 0 and Case 2 (only randomized V_s without randomized layering) have similar trends and fitting to the baseline data. For Case 1 (randomized V_s and layering simultaneously), the obtained results are a little bit different between the median profile and the input baseline profile. This bias is due to the variation in layering, and the V_s at the mid-depth of the layer of simulations is calculated by

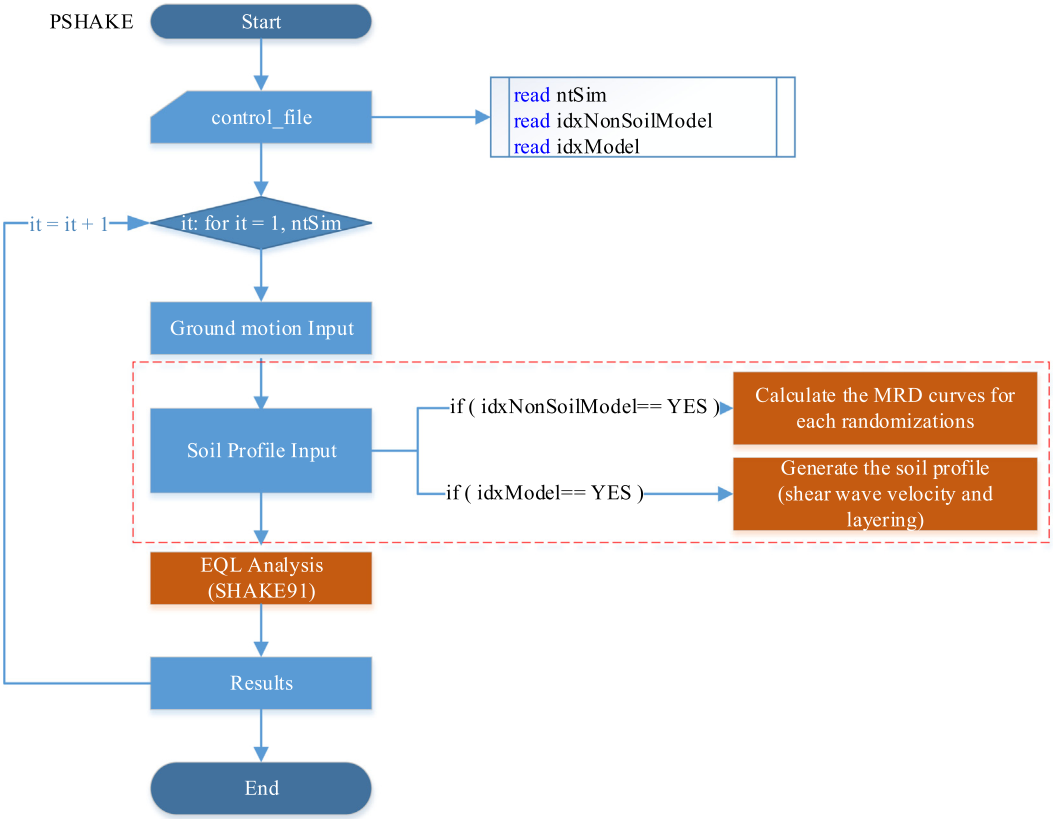
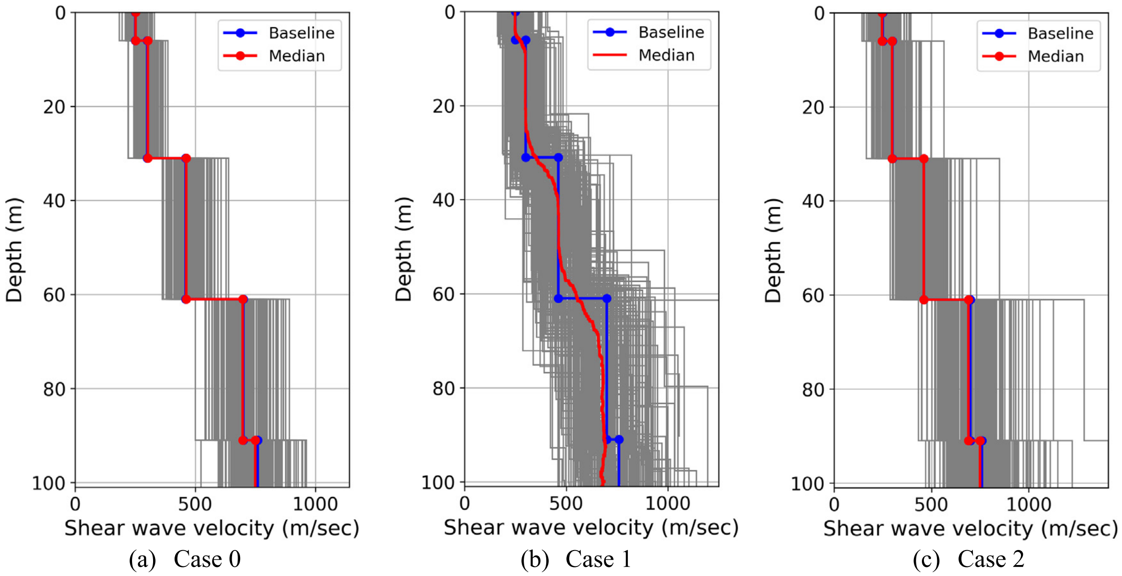


Fig. 7. Schematic flow chart of stochastic process.

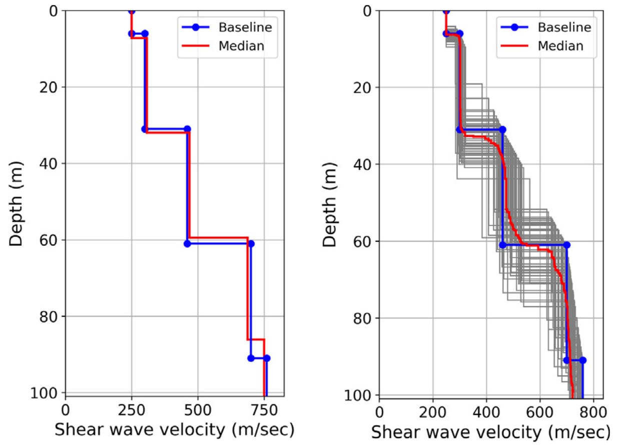


(a) Case 0 (b) Case 1 (c) Case 2

Fig. 8. Simulated probabilistic shear wave velocity profiles (COV = 20%).

interpolating the V_s of the baseline profile, so that median V_s deviates from the baseline data.

For an elaborated clarification of the influence of the variation in layer thickness, samples of one simulation and fifty simulations are generated by varying solely the layering, as shown in Fig. 9. From the yielded graph, it is seen that albeit the randomized V_s has not been thought of, the V_s of every layer is also thicker or diluent than the baseline profile. Therefore, the median V_s profile is additionally biased with the baseline profile. Therefore, the median V_s profile is also biased with the baseline profile. This observation leads to the conclusion that the soil



(a) One simulation (b) Fifty simulations

Fig. 9. Shear wave velocity profiles considering only variation in thickness of layers.

profiles obtained with different approach models are satisfactory for the probabilistic site response analysis as the first condition.

5. Results and discussions

In the seismic site response analysis, each layer is characterized by its thickness, mass density, shear wave velocity, and nonlinear soil properties. Based on this proposed procedure for the variability of the input parameters, a site response analysis is performed in this research for the specific site subjected to the ground motion. The influence of uncertainty in layering, V_s, and the MRD curves are investigated. Three COVs that vary from 20 to 60% are also applied to evaluate the effects of their random variations on the site response analysis. The results of the maximum PGA at each layer of the soil are recorded. Moreover, the AF and S_a at the surface are also calculated. The results of two hundred simulations for each case, generated by the PSHAKE software, are compared with the results of the base input data generated by SHAKE91.

5.1. Influence of soil profile variation

The variability of the soil profile with the 20% COV, considering the MRD curves, is discussed herein. The variation in the PGA at each layer, with and without the variation in the nonlinear soil properties, together with the baseline value subjected to ground motion are listed in Table 1. Fig. 10 shows that, for all cases, the median PGA generally increases with the increasing distance from the bedrock. The median PGA values for Case 0, Case 1, and Case 2 (in case of the fixed nonlinear soil) are 0.154 g, 0.149 g, and 0.151 g, respectively, at the surface, while they are 0.049 g, 0.052 g, and 0.050 g, respectively, at the bedrock. However, in the randomized nonlinear soil, the expected responses at the surface are evaluated at higher values of 0.168 g, 0.171 g, and 0.157 g for the same cases, while they are 0.054 g, 0.052 g, and 0.049 g at the bedrock. Based on the results, it is known that the uncertainties in the soil properties play an essential role in the assessment of the site response. As shown here, there are slight decreases in the median PGA at the surface when only the variability in the soil profile (V_s and layering) is applied. These reductions are 2.02%, 5.02%, and 3.43% for Case 0, Case 1, and Case 2, respectively. When both the soil profile and the nonlinear soil property are considered, the increase in median PGA is inconsiderable. Nevertheless, these changes are in the opposite direction to the changes in soil profile caused only. The increment reaches a maximum of about 3.32–11.58%, 3.49–16.23%, and 4.56–10.49% for Case 0, Case 1, and Case 2, respectively. These increments appear due to soil damping, which affects the higher frequencies. Therefore, taking into account the variabilities in both the soil profile and the nonlinear soil properties leads to an increase in the median PGA at the surface, while considering the soil profile with constant nonlinear properties leads to a decrease in the median PGA.

The spectral acceleration and the amplification spectrum at the surface of the ground motion, considering the nonlinear soil properties, are also presented. Fig. 11 shows a comparison of the median surface response spectra in three cases of the uncertainty of the soil profile. It is noted that the median obtained spectral accelerations for Case 0 are the largest among all the cases when both considering and ignoring the nonlinear soil properties. In addition, the maximum spectral accelerations lie in the range of 1.5 Hz and 2 Hz. Without the randomization of the nonlinear soil, the median surface spectral accelerations in all cases have a good match with the S_a of the baseline data. When the MRD curves are included, the median spectral accelerations are very similar to the baseline at low

Table 1
Variation in PGA(g) with depth.

Depth (m)	Without Nonlinear Soil			With Nonlinear Soil			Baseline
	Case 0	Case 1	Case 2	Case 0	Case 1	Case 2	
0	0.154	0.149	0.151	0.175	0.168	0.171	0.157
6	0.129	0.123	0.125	0.145	0.138	0.140	0.134
31	0.075	0.075	0.076	0.080	0.080	0.082	0.077
61	0.053	0.059	0.058	0.055	0.061	0.058	0.053
Bedrock	0.049	0.052	0.050	0.053	0.054	0.052	0.049

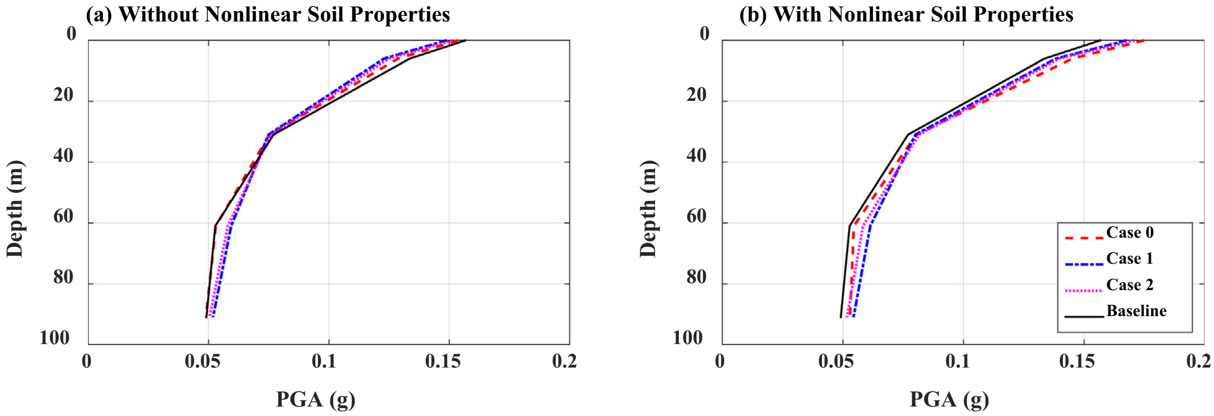


Fig. 10. Median of peak ground accelerations.

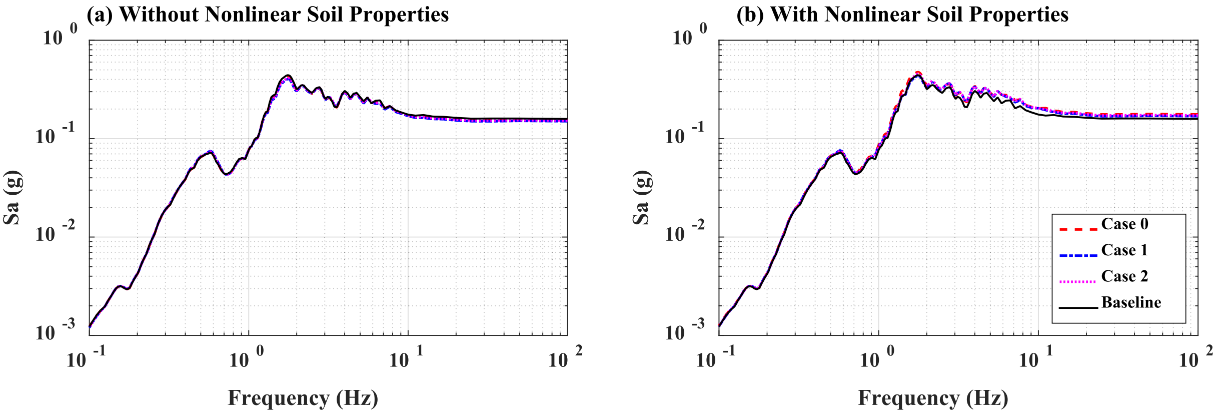


Fig. 11. Median spectral accelerations with (a) fixed and (b) randomized nonlinear soil.

frequencies, but their estimations are slightly higher than the S_a of the baseline at high frequencies.

Similar results are also presented for AF. As seen in Fig. 12, the calculated median AF expresses the COV of 20%. It can be explained that the AF has little effect at low frequencies, but it has a large effect at high frequencies in both constant and randomized nonlinear soil. A clear distinction in the site amplification spectrum has been visualized for considering the nonlinear soil properties, especially at high frequencies. For the fixed nonlinear soil, the AF for Case 0 is similar to the baseline profile, while the other cases have more bias than the baseline profile. Although the randomized nonlinear soils are applied, all cases have a greater effect on the AF. The observed results indicate that the uncertainties in the soil properties should be considered conservatively for the site response analysis. The MRD curve is one of the sensitive parameters that contributes to the uncertainties of the soil properties on

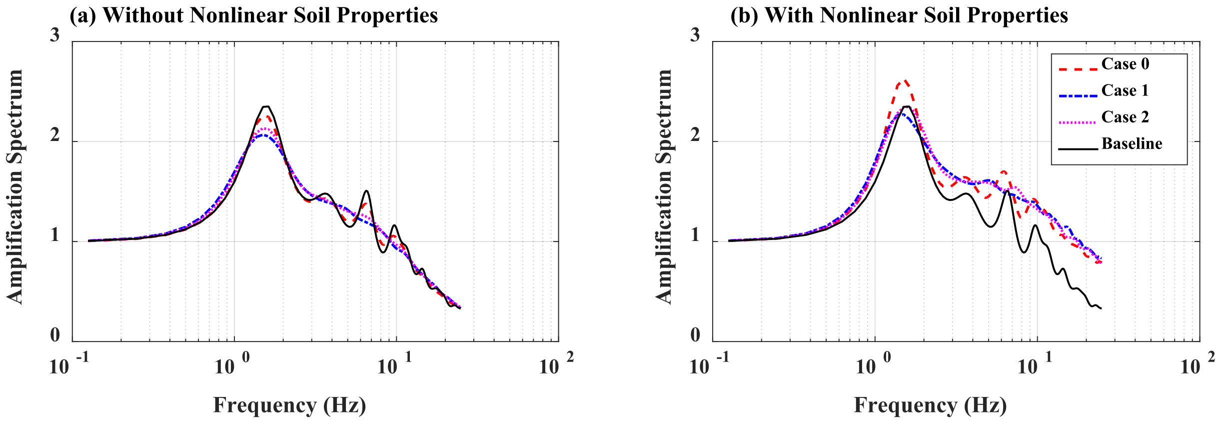


Fig. 12. Median amplification functions with (a) fixed and (b) randomized nonlinear soil.

the AF. The changes in AF occur predominantly at frequencies greater than 1.5 Hz. However, when the randomized nonlinear soil properties are applied, these changes are more obvious. The increases in AF at second predominant frequencies are about 20% for Case 0, 24% for Case 1, and 31% for Case 2, while the results are much better for the constant nonlinear soil with small changes ranging around 2% for all cases in the same frequency. In general, the uncertainties of the MRD curves of the soil properties have large variations in the site amplification spectra. This observation reflects the same conclusion found in the work by Rathje et al. (2010), namely, that the AF generally increases in variability when adding variability to the soil profiles (V_s and MRD curves). The cause of this phenomenon can be explained by the material damping represented by an MRD curve capped at a damping ratio of 25%. For practical engineering, it is significant to note how to control these parameters for reflecting the dispersion of the expected results.

5.2. Influence of coefficient of variation on site response analysis

The coefficient of variation also has an important effect on the seismic site response analysis. In the work by Moss (2008), the COV values depended on the different testing methods of the thirty-meter shear-wave velocity ($V_{s,30}$). The COV values, varying from 20 to 60% with an interval of 20%, are investigated in this section. The effect of the COV is investigated by assuming similar soil parameters (i.e., layering, V_s). No randomization is done for the nonlinear soil properties; only variabilities of the layering and V_s are conducted. Figs. 13 and 14 show the median surface spectral acceleration and the amplification spectra for Case 0 and Case 1 with different level of COVs. As seen in Fig. 13, when increasing the COV of the soil properties, there are large variations in the median S_a in each case, as expected. The median spectrum accelerations contain many fluctuations in the frequency band of 1.0–10 Hz and they are flat from 10 Hz to the end with the amplitude below 0.18 g. It is also shown that the median S_a for the COV of 20% in both cases stays in close comparison to the baseline values, while larger variations are obtained for COVs of 40% and 60%. As previously discussed, when the nonlinear soil properties are constant, the results indicate that the median spectral acceleration at the surface from the different probabilistic are smaller than those computed from the baseline shear-wave velocity profile. The reduction in S_a for Case 0 ranges from about 4% for a COV of 20% to about 10% for a COV of 60%. For Case 1, those reductions are about 5% and 15% for COVs of 20% and 40%, respectively.

Fig. 14 compares the median AF observed from the site response analyses for the site with the differences in COVs. In general, when the COV values change from 40 to 60%, the median AFs increase in large variations, as expected. In all cases, the observed results to be amplified by increasing the COV and its intensities are wider at high frequencies. On the other hand, all the amplification curves in both cases are almost above 1.0 for the entire frequency range. The behaviors of amplification in Case 0 are better than in Case 1, although both of them have a larger bias at high frequencies. The behaviors of amplification of the spectral acceleration for a COV of 20% by a factor of 2.270 to 1.483 for Case 0 occur in a frequency band of 1.5–2.5 Hz, while they range from 2.014 to 1.630 for Case 1 in the same frequencies. For the COV of 60%, the amplification factors for Case 0 are from 2.291 to 1.510 and for Case 1 are 1.911 to 1.791 when the frequencies range between 1.5 and 2.5 Hz. The reductions in median AF are exactly the same as those for S_a at the surface, the changes in the predominant frequency are most obvious in the representation of the results. Additionally, the higher coefficients of variation lead to a lower median AF and the bias is wider. It also causes more amplification at high vibration modes of the site. This observation reflects the conclusion that, the choice of COV ought to be done fastidiously, as within the work by Moss (2008). For practical cases, the COV values associated with the different methods of $V_{s,30}$ are estimated to be about 1–3% for the downhole, suspension logging, and seismic cone penetration testing, 5–6% for the spectral analysis of the surface waves,

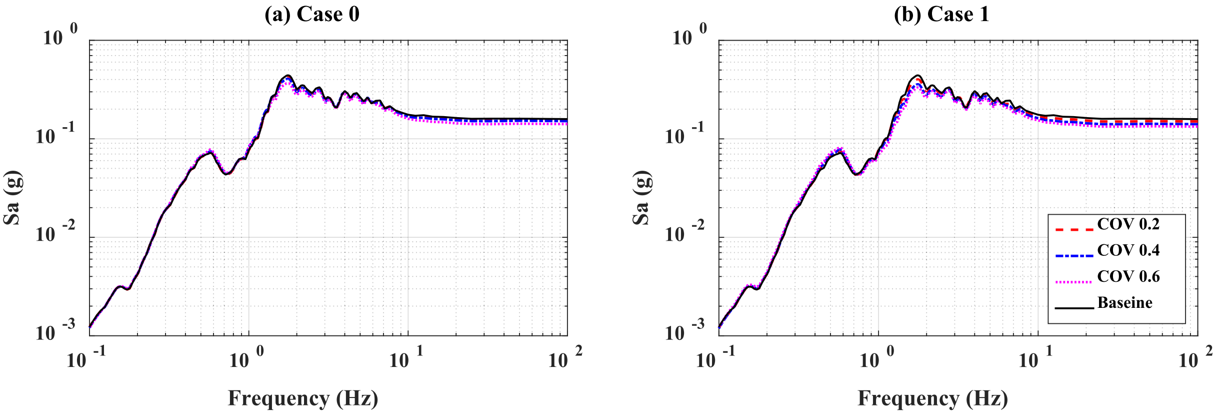


Fig. 13. Median response spectra for (a) Case 0 and (b) Case 1 with different COVs.

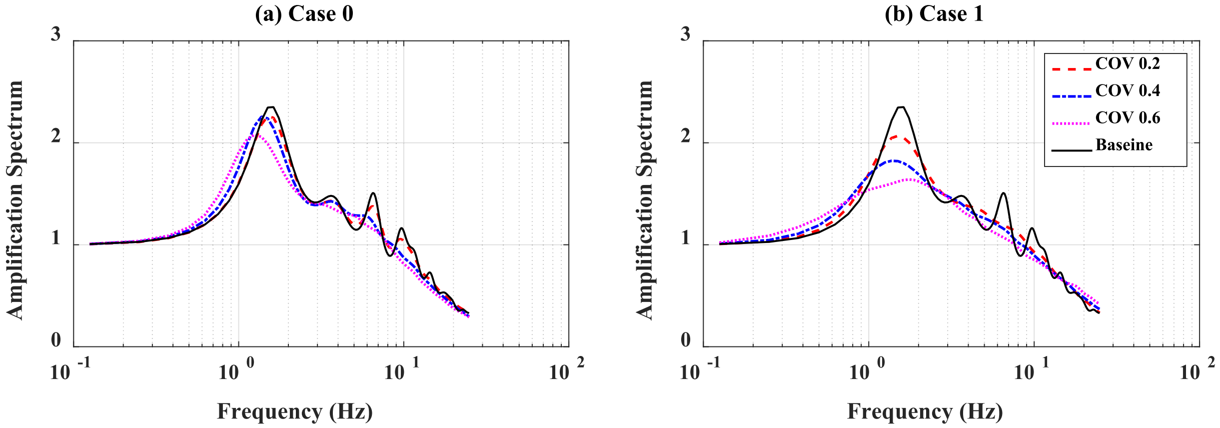


Fig. 14. Median amplification functions for (a) Case 0 and (b) Case 1 with different COVs.

and 20–35% for the V_s-correlated geologic units. The results in this study are obtained based on a similar assumption for the COVs for all parameters (i.e., 20% for shear wave velocity, damping, and layering).

6. Conclusion

In this study, the behavior of a site-specific SCH under real ground motion has been examined. The soil characterizations, including the nonlinear soil properties, the layer thickness, and the V_s were modeled as spatially random fields considering the different probabilistic distributions. The nonlinear soil properties were modeled using the Darendeli model, while the uncertainties of the layering and the V_s profile were conducted using the Toro model or a non-Gaussian distribution. To determine the influence of the probabilistic distributions on the evaluations of the site response, two hundred simulations of soil profiles were generated using the proposed solution. By employing them, this work has compared the response of the site considering the variability of the soil properties, when (1) only V_s is randomized using the log-normal distribution, (2) the layer thickness and V_s using the Toro model are randomized simultaneously, and (3) only V_s using the Toro model is randomized. The results for the maximum peak ground acceleration at each layer, the amplification, and the surface response spectrum were observed in this research. Based on the obtained results, the major conclusions are drawn as follows:

- The probabilistic distributions of the random nonlinear soil properties, layering, and V_s have a significant effect on the evaluations of the site response. It is obvious that the variations in the site characteristics should be considered as conservative in the performances of the site response. The proposed model for the probabilistic site response, based on the available information, can provide a broad view of the effect of the soil properties and offer a better understanding of the amplification factors for the soil.
- Based on the simulations of layering and the V_s profile under different approaches of probabilistic distributions, the values of median V_s corresponding to the layering almost matched the baseline profile. Additionally, the median surface spectral acceleration and the amplification spectrum of all cases have a good agreement with the baseline values when the randomized nonlinear soil properties are not included. In addition, taking into account the variabilities in both the soil profile and the nonlinear soil properties leads to an increase in the median PGA at the surface, while considering the soil profile with constant nonlinear properties leads to a decrease in the median PGA.
- It also shows that the variability in the nonlinear soil properties (modulus reduction and damping curves) plays an important role in the predicted surface response. When considering the nonlinear soil properties, the estimations of the median spectral accelerations and the amplification spectra for all cases are more considerable than with the baseline results. The material damping represented by an MRD curve is significant in the assessment of the soil response.
- The research also indicates that the coefficient of variation must be chosen carefully when the randomization of the soil profile is considered for the seismic site response. The randomness for each parameter of the soil profile may have the most or least effect on the amplification function.
- For solving the proposed procedure of this research, a new program, namely, PSHAKE is developed. The purpose of this program is to be a flexible tool for estimating probabilistic site response analyses.

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