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Research Article

Impact of Randomized Soil Properties and Rock Motion Intensities on Ground Motion

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Seismic site response is inevitably influenced by natural variability of soil properties and anticipated earthquake intensity. This study presents the influence of variability in shear wave velocity (V_s) and amplitude of input rock motion on seismic site response analysis. Monte Carlo simulations were employed to randomize the V_s profile for different scenarios. A series of 1-D equivalent linear (EQL) seismic site response analyses were conducted by combining the randomized V_s profile with different levels of rock motion intensities. The results of the analyses are presented in terms of surface spectral acceleration, amplification factors (AFs), and peak ground acceleration (PGA). The mean and standard deviation of these parameters are thoroughly discussed for a wide range of randomized V_s profile, number of V_s randomizations, and intensities of input rock motions. The results demonstrate that both the median PGA and its standard deviations across different number of V_s profile realization exhibit a slight variation. As few as twenty V_s profile realizations are sufficient to compute reliable response parameters. Both rock motion intensity and standard deviation of V_s variability cause significant variation in computed surface parameters. However, the variability in the number of records used to conduct site response has no significant impact on ground response if the records closely match the target spectrum. Incorporating the multiple sources of variabilities can reduce uncertainty when conducting ground response simulations.

1. Introduction

Understanding the role of local soil characteristics in seismic response assessment is a critical aspect of earthquake engineering. The inherent variability of local soils has a profound impact on various aspects of ground motion, and accurately assessing seismic site response requires accounting for this variability. Shear wave velocity (V_s) profiles, layering, and material nonlinearity all influence the amplitude of ground shaking. Historical data have consistently demonstrated an evident amplification of ground motion when unfavorable local soil conditions are present [1–9]. For example, the M7.8 earthquake that struck Turkey in 2023 resulted in extensive damage to numerous buildings and claimed thousands of lives [6]. The significant damages caused by the earthquake were mainly due to exceptional combination of soft ground, characteristics of rupture propagation, and near-field impact of the earthquake [6]. Similarly, the M7.0 Samos Earthquake on October 30, 2020, resulted in structural damages and the loss of many lives [7]. The local site conditions, characterized by low-plasticity alluvial deposits and unusual stratified nature of rock sublayers, played a significant role in amplifying seismic waves during the Samos earthquake [7].

The role of local soil conditions on the characteristics of ground motion is typically estimated through site response analysis. Often, this analysis is performed using 1-D equivalent linear (EQL) site response analysis, which involves propagating rock motion (rock acceleration time series) through the local soil profile to compute the ground surface parameters [10, 11]. Over the last few decades, the 1-D EQL site response method has gained popularity due to its simplicity and computational efficiency. In this method, the nonlinear properties (modulus reduction and damping) of soils are estimated through an iterative procedure. This involves iteratively estimating the modulus reduction and damping values by updating them based on induced shear strain.

These values are commonly estimated at 65% of maximum shear strain, known as effective shear strain [12]. Nonlinear site response analysis has the capability to accurately characterize soil under seismic loading. However, their practical application has been limited due to poorly documented and ambiguous parameter selection [13]. Few studies have evaluated the effect of soil nonlinearity on site response by comparing response parameters obtained from the EQL and elastic ground response models. For instance, a study conducted by Chen et al. [9] demonstrated that the differences in spectral shape obtained from the EQL and linear model was insignificant. However, the peak spectral period of the EQL model slightly prolonged due to modulus degradation [9].

The site response analysis evaluates a variety of surface parameters, including acceleration response spectra, acceleration–time histories, and amplification factors (AFs) [14]. When conducting site response analysis, it is crucial to minimize the influence of multiple uncertainties associated with V_s profiles, rock motion selections, soil nonlinearity, and the method of analysis on the computed surface parameter [15]. The scope of the current study is limited to the first two sources of uncertainties. There is a great deal of research concerning the effects of these uncertainties in seismic response analysis. For example, Barani et al. [16] used a 1-D numerical simulation to evaluate the influence of variability in the V_s profile and material properties on soil amplification and fundamental frequency. Their findings indicate that the variability associated with the V_s profile is the main contributor to the uncertainty in response parameters. Another study by Stanko et al. [17] investigated the influence of the analysis method (random vibration theory and time series) on the surface amplification factor. Their results indicated that the amplification factor obtained from the time series method was systematically higher than the amplification factor obtained from random vibration theory, indicating the choice of the analysis method can affect computed ground responses. Therefore, it is essential to carefully consider the sources of uncertainty in site response analysis to ensure accurate and reliable assessments of seismic hazard.

Numerous studies have shown that the V_s profile is a critical parameter in site response analysis [14, 16, 18]. This parameter directly influences the amplitude and frequency content of the ground motion. Hence, considering the variability of the V_s profile in site response analysis is crucial. One way to address this variability is through the use of randomization models, such as Monte Carlo simulations (MCs) or the Toro [19] V_s randomization model. However, there has been limited research on determining the number of V_s realizations needed to compute ground response parameters. Some studies show varying number of V_s profile realizations, ranging from 50 to 1,000 to assess the influence of V_s variability on response analysis [18, 20–24]. The influence of the number of V_s profile realizations was rarely subjected to comprehensive statistical investigation. Furthermore, the surface parameters computed from response analysis are affected by the characteristics of input rock motions. To ensure statistically stable median and standard deviation of these parameters, it is recommended to select enough representative rock motions [14]. However, there is no universally accepted standard for the number of rock motion records to be used for ground response analysis. Some researchers (e.g., [25–28]) used seven records for response analysis, while others (e.g., [14, 29]) suggest as few as five to seven records are sufficient. The lack of thorough exploration in these areas highlights the need for further investigations.

This study seeks to quantitatively assess the effects of V_s and input motion variabilities on computed ground response parameters. It seeks to evaluate the influence of number of V_s profile realization and intensity of input rock motion on these parameters. The V_s profiles were randomly generated using a procedure proposed by Toro [19] based on real V_s velocity data collected in Hungary. To determine the optimum number of records required for analyzing ground motion, a wide range of records (5–25) were utilized. The primary objective is to conduct comprehensive statistical evaluation of how these variabilities impact ground response parameters, including peak ground acceleration and spectral acceleration.

2. Site Response Analysis

Seismic wave transmission analysis is a complex process divided into four stages, each bearing significant importance for risk assessment and engineering practices. These stages encompass the source of the seismic waves, the propagation of these waves through the geologic layers of rock, their subsequent journey through the near-surface soil and surficial rock layers, and soil structure interaction. While all these stages are integral for a comprehensive risk assessment, the focus of this study will be dedicated to the near-surface path through the soil and surficial rock layers, commonly referred to as site response analysis. In this context, the primary objective centers around the estimation of the input motion at the bedrock and the subsequent computation of the resulting ground motion at the surface. This analysis involves several critical parameters including intensities and duration of rock motion, soil V_s profile, and dynamic properties of the soils including modulus reduction and damping curves.

Geotechnical engineers often employ simplifications in site response analysis, typically using 1-D equivalent linear (EQL) analysis. Several computer programs, including STRATA [10], DEEPSOIL [30], and SHAKE [31], have been developed in recent years to facilitate such analyses. In this study, we utilized STRATA to conduct a series of site response analyses. STRATA allows for the randomization of soil properties based on the Toro randomization model. Additionally, the program provides the flexibility to choose various nonlinear material properties. In this analysis, the modulus reduction and damping curves proposed by Darendeli and Stokoe [32] were employed for the soil profile.

2.1. Cone Penetration Test (CPT). The cone penetration test (CPT) provides valuable information about soil profiles. It is widely used as an in situ exploration technique in Hungary [25–27, 33]. The test is performed by pushing the cone-shaped tool at a constant rate into the ground while recording cone tip resistance (qc) and sleeve frictions (fs). The seismic cone penetration (SCPT) method employs a surface source and two transducers positioned 50 cm apart at depth.

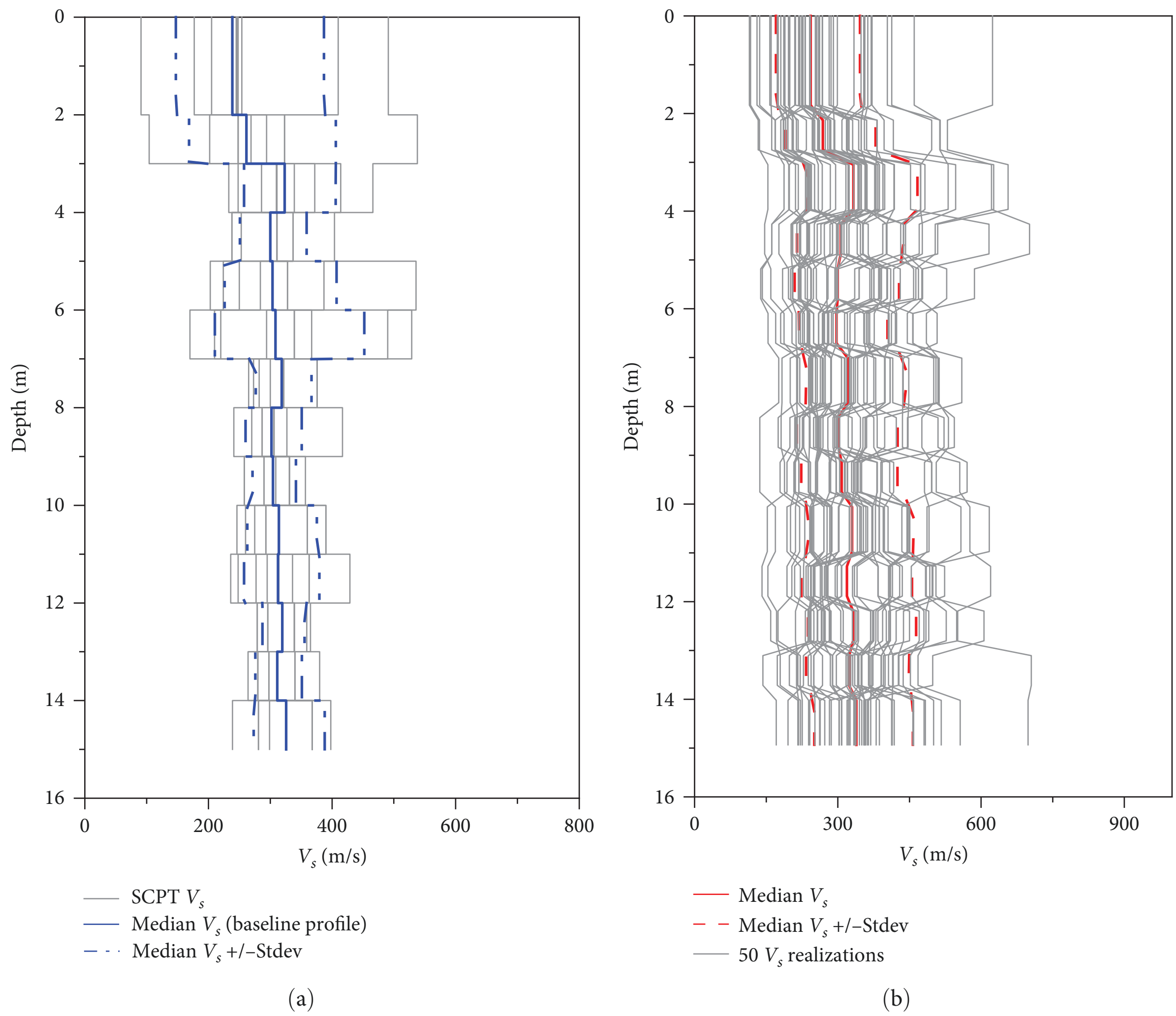


FIGURE 1: (a) SCPT shear wave velocity profiles and (b) generated shear wave velocity profiles employing the Toro randomization model.

This approach allows for the collection of both standard CPT data (qc and fs) and V_s measurements. During the V_s measurements, the CPT cone is paused at a specific depth. Subsequently, the shear wave is generated by striking a beam that is firmly pressed against the ground. V_s is then estimated as the ratio of distance between the two geophones and the difference in propagation time of the wave received by the geophones [26, 34].

A wealth of CPT data is readily available to Hungarian geotechnical engineers and researchers. In this study, we utilized previously recorded nine SCPT data (Figure 1(a)) from the Pak site [26]. V_s was measured at every 1-meter interval along the profile depth. The median value of the measurements (here after referred to as the baseline profile) was subsequently employed to randomize the V_s profiles. The soil deposit at this site is primarily characterized by fluvial sediments from the Danube River. Within these deposits, the predominant soil layers consist of coarse-grained materials, including sand, sandy gravel, and gravelly sand. The average top 30-meter (V_{s30}) profile of the site was 330 m/s, which classifies the site as class C according to Eurocode 8 [35]. Further details regarding in situ tests and geological characteristics can be found elsewhere [26, 33].

2.2. Randomization of Shear Wave Velocity Profile. Seismic site response analysis relies primarily on key soil properties, including the V_s profile and the nonlinear modulus reduction and damping curves. The incorporation of soil property variability into such analyses serves multiple purposes. First, the spatial variation of soil properties within a site arises from natural geological processes, resulting in aleatory variability that is inherently random and beyond control. This variability, though site-specific, can be assessed by conducting multiple V_s profile measurements. Another motivation for integrating soil property variability lies in the epistemic uncertainty associated with measuring these properties. Uncertainties stemming from measurement errors, the reliance on generic soil type, and sample disturbances contribute to epistemic uncertainty [14]. Unlike aleatory variability, epistemic uncertainty can be mitigated by enhancing data quality and quantity. However, distinguishing between aleatory variability and epistemic uncertainty in practice poses challenges, emphasizing the need for careful consideration and comprehensive data collection strategies in seismic analyses.

One way to account for variability in the V_s profile in site response analysis is by using MCs. The randomization of the V_s profile using MCs is determined based on the median base line V_s profile, standard deviation of V_s, and interlayer correlations. In this study, the base line V_s profile was determined based on the SCPT results obtained from the Pak site, where in situ measurement data are available. The Toro randomization model [19], implemented in STRATA [10], was utilized to generate a randomized V_s profile for ranges of standard deviation of V_s ($\sigma_{ln} V_s$) values (0.15, 0.31 (default value), 0.45, and 0.6). These $\sigma_{ln} V_s$ values were selected as part of sensitivity analysis to study site response across a wide range of V_s variability. The resulting V_s profile was then used in the 1-D equivalent linear site response analysis to evaluate the impact of V_s variability on the computed ground motion. Figure 1(a) presents the V_s profile along with the median V_s profile, and the sample V_s profile is generated from the baseline profile using the Toro randomization model (Figure 1(b)). The figure also includes the median ± 1 standard deviation (estimated as the standard deviation of the natural logarithmic of V_s values).

The Toro model assumes that the distribution of the V_s value along the soil depth follows a lognormal distribution. According to this model, the estimation of the layer i^{th} V_s value is expressed as follows [10]:

$$V_{s(i)} = \exp\{Z_i \times \sigma_{ln} V_s + ln[V_{\text{median}}(d_i)]\}, \tag{1}$$

where $V_{s(i)}$ is the V_s of layer i, $\sigma_{ln} V_s$ is the standard deviation of natural logarithmic of V_s, and Z_i is the random variable with 0 mean and standard deviation of 1. Z_i for the surface layer ($i = 1$) is independent of layers below it and computed as follows [10]:

$$Z_1 = \varepsilon_1, \tag{2}$$

where ε_1 is the random variable with 0 mean and standard deviation of 1. Z_i is estimated from layers above it using the following expression [10]:

$$Z_i = \rho Z_{i-1} + \varepsilon_i \sqrt{1 - \rho^2}, \tag{3}$$

where Z_{i-1} is the variable of the previous layer, ε_i is the normal variable with 0 mean and standard deviation of 1, and ρ is the intercorrelation coefficient and is a function of both the depth of the layer (d) and the thickness of the layer (h):

$$\rho(t, h) = [1 - \rho_d(d)]\rho_h(h) + \rho_d(d), \tag{4}$$

where $\rho_d(d)$ is the depth-dependent correlation and $\rho_h(h)$ is the thickness-dependent correlation. The thickness-dependent correlation is defined as follows [10]:

$$\rho_h(h) = \rho_o \exp\left(\frac{-h}{\Delta}\right). \tag{5}$$

The depth-dependent correlation $\rho_d(d)$ is defined as a function of depth (d) [10]:

$$\rho_d(d) = \left\{ \begin{array}{l} \rho_{200}\left[\dfrac{(d + d_o)}{200 + d_o}\right]^b d \leq 200 \\ \rho_{200} d > 200 \end{array} \right\}, \tag{6}$$

where ρ_o is the initial correlation, Δ is the fitting parameter, ρ_{200} is the correlation coefficient at 200 m, and d_o is an initial depth parameter. The values of these correlation parameters can be found in [10]. Readers are encouraged to refer to it for more details.

2.3. Rock Motion Selection. Seismic site response analysis is conducted with the primary goal of acquiring reliable ground response parameters corresponding to anticipated rock motions. The process of selecting input rock motion for site-specific response analysis involves utilizing region-specific real records. However, in cases where region-specific real records are either unavailable or insufficient, it is a common practice to opt for nonregion-specific records. Many previous studies have shown that both region-specific and nonregion-specific real records have been utilized effectively to assess the impact of site soil on ground motion amplifications [5–8, 29, 36]. For instance, Kegyes-Brassai et al. [36] selected seven suites of rock motion from a European Strong Motion Database to assess the impact of local soil effects on ground motion. In contrast, Askan et al. [5], Fiamingo et al. [8], Cetin et al. [7], and Kazaz et al. [6] utilized site-specific records to evaluate the influence of local soil and topography on ground motion. Furthermore, with advancements in computational technology, the practice of simulating region-specific rock motion is prevailing [9, 37–39].

Selecting rock motion records requires specific search criteria, including the target spectrum. Eurocode 8 (EC8) provides most of the necessary criteria for choosing suitable suites of rock motion records from real records databases. Many databases including the European Strong Motion Database [40] and Pacific Earthquake Engineering Research (PEER) strong motion database [41] compile real rock motion records from monitoring stations worldwide. Records from rock or rock-like ground types are preferred to perform response analysis as these ground conditions have minimal impact on the characteristics of motion at seismic bedrock depth. Acquiring an adequate number of records that meet search criteria can be challenging. In many instances, records are modified through relocation and scaling (amplitude increase or decrease) to meet the specified search criteria. It is important to recognize that these scaling and relocation processes influence the final behavior of response analysis.

In this study, outcropping records from rock or rock-like (stiff) ground types that fit EC8 type I target spectrum were selected from the PEER database [41]. The target spectrum corresponds to reference peak ground acceleration (PGA) values ranging from 0.09 to 0.15 g for type A ground (rock). These reference PGA values were determined based on the seismic hazard level of Hungary, which falls within the low to moderate hazard range with a maximum PGA of 0.15 g [42]. Table 1 presents a summary of rock motion records selected for response analysis. We applied the selected records as outcropping motion at the base of the site profile to correct for the free-end wave effect. Figure 2 presents sample rock motion records along with their spectral acceleration utilized in the subsequent response analysis. Figure 2(b) demonstrates an excellent fit between the EC8 target spectrum and median of the scaled motions as evidenced by the lowest mean squared error (MSE) value of 0.037.

3. Results and Discussion

3.1. Influence of Number of Records on Ground Motion. Ground response analyses were carried out using the baseline V_s profile (see Figure 1(a)) to determine the optimum number of rock motion records. A greater number of records, up to 25, were selected from the PEER database [41]. The records were selected to fit EC8 type I target spectrum. The spectrum has a reference peak ground acceleration of 0.15 g on type A ground (rock). Groups of 5, 7, 10, 15, 20, and 25 records were then allowed to propagate through the baseline V_s profile using the STRATA software [10] to compute peak ground acceleration at surface level. Figure 3 shows the STRATA interface and its representative response analysis for determining the optimum number of records.

Figure 4 illustrates the computed PGA for each group of records, along with the standard deviations of PGA (on natural logarithmic scale). As the number of records increased from 5 to 25 (Figure 4(a)), there is a slight variability in the median PGA values. This can be attributed to the scaling process applied to the records to fit the target spectrum. The median PGA computed from 10 records slightly exceeds the corresponding PGA computed from the remaining records. Therefore, for this study, 10 rock motion records are sufficient to conduct a reliable ground response analysis. The variability (standard deviation) associated with the number of records is presented in Figure 4(b). It was observed that as the number of records increased from 5 to 10, the standard deviation of PGA also increased. However, as the number of records increased from 10 to 25, the standard deviation showed a slight decrease. This variability is due to the specific characteristics of individual records within each record group.

3.2. Influence of Number of V_s Profile Realization on Computed Response. A series of site response analyses were performed using a baseline profile (Figure 1(a)) as median V_s, with the varying number of realizations (20–50). The objective was to evaluate the influence of the number of V_s profile realizations on ground response. Ten rock motion records, selected to fit EC8 type I with a reference PGA value of 0.12 g, were applied at the base of the site profile in each analysis. Figure 5 shows lognormally distributed surface PGA for the varying number of V_s profile realizations along with a fitted probability density line and its corresponding coefficient of determination (R^2). Notably, the median surface PGA exhibits a slight variation ($\mu = 0.248$ to $\mu = 0.253$) across different numbers of realizations. Similarly, the uncertainty in surface PGA values also exhibits slight variations as the number of V_s profile realizations increases from 20 to 50. The maximum median PGA and minimum standard deviation were computed from 20 V_s profile realizations, suggesting that 20 V_s profile realizations are sufficient for reliable response analysis.

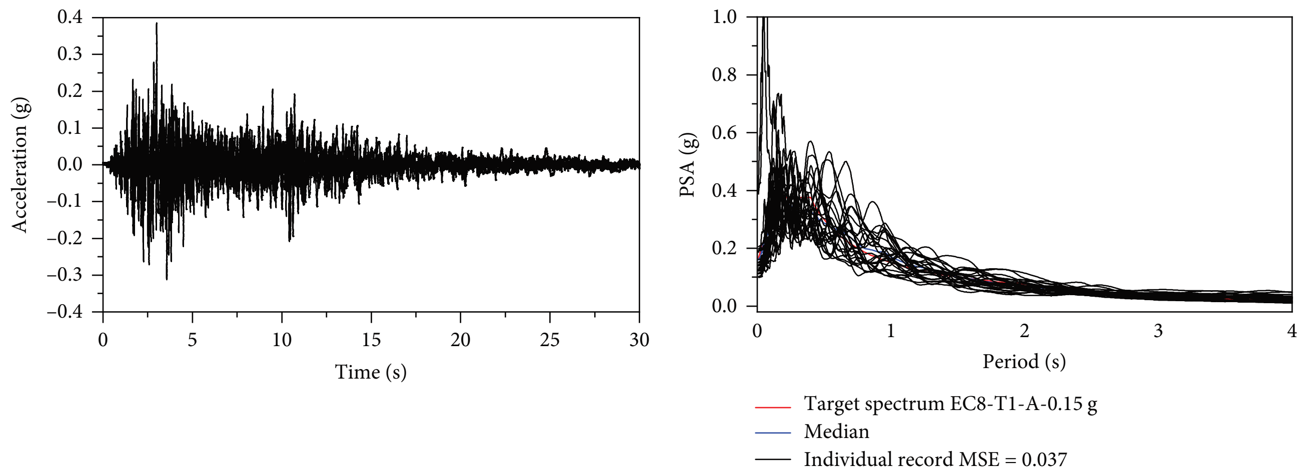
3.3. Effect of Rock Motion Intensity on Ground Response. The effect of varying input rock motion intensity on ground responses was evaluated using the baseline V_s profile (Figure 1(a)). The rock motion records encompass a range of intensities, spanning from PGA values of 0.09–0.15 g. These rock motions were then propagated through a baseline V_s profile to estimate surface response spectra and amplification factors (ratio of surface spectral acceleration to bedrock spectral acceleration). For every set of rock motion, the median amplification factors and surface spectral acceleration along with its natural logarithmic standard deviation (σ_{lnSa}) were calculated at each period. The computed surface spectral accelerations were compared with the EC8 type I design spectra for soil type C (EC8-T1-0.09 g-C, EC8-T1-0.12 g-C, and EC8-T1-0.15 g-C) corresponding to different PGA values.

Figure 6 shows the median surface spectral accelerations and their corresponding σ_{lnSa} for different rock motion intensities. The results consistently indicate higher spectral acceleration amplification at a short period (0.42 s) for each rock motion intensity. The spectral accelerations exceed the corresponding EC8 design spectra significantly. The maximum value in spectral acceleration was about 73% larger than that of EC8 design spectra (see Figure 6(a)). Figure 6(b) shows the σ_{lnSa} of surface spectra for each set of rock motion intensities. The variability in σ_{lnSa} is notably higher at lower periods for each analysis, attributed to the increased level of ground shaking experienced at lower periods. Figure 7 illustrates the variations of amplification factors and surface spectral acceleration with rock motion intensities. Amplification factors decrease with an increase in rock motions intensities, while spectral acceleration increases with an increase in rock motion intensities.

3.4. Influence of Randomized V_s Profile on Ground Response. Randomizations of V_s profiles were performed to evaluate the impact of variability in V_s on computed response parameters. The primary objective of the analyses was to evaluate how the variability in soil layers' V_s affects computed surface spectral accelerations and amplification factors. The V_s profiles were created from baseline profile (Figure 1(a)) using the Toro randomization model, with a standard deviation of $V_s(\sigma_{ln} V_s)$ ranging from 0.15 to 0.6. Ten suites of rock motion records that were selected to fit EC8 type I with a PGA of 0.12 g target spectrum were propagated through each randomized soil profile. Twenty realizations of the V_s profile for each $\sigma_{ln} V_s$ value were coupled with ten input rock motions to compute median surface spectral acceleration and amplification factors. Therefore, the results represent the median

Table 1: Rock motion records considered for response analysis.

Group	Record no.	Earthquake name	Year	Station name	Magnitude	Mechanism	Scale factor	Scaled PGA
Group-1 PGA = 0.09 g	1	San Fernando	1971	Pacoima Dam (upper left abut)	6.61	Reverse	0.099	0.12
	2	Tabas_ Iran	1978	Tabas	7.35	Reverse	0.093	0.08
	3	Irpinia_ Italy-01	1980	Arienzo	6.9	Normal	2.887	0.08
	4	Nahanni_ Canada	1985	Site 2	6.76	Reverse	0.446	0.23
	5	Loma Prieta	1989	Gilroy Array #6	6.93	Reverse oblique	0.608	0.08
	6	Loma Prieta	1989	So. San Francisco_ Sierra Pt.	6.93	Reverse oblique	1.251	0.07
	7	Northridge-01	1994	LA—Chalon Rd	6.69	Reverse	0.414	0.09
	8	Northridge-01	1994	LA—Wonderland Ave	6.69	Reverse	0.986	0.1
	9	Northridge-01	1994	Santa Susana Ground	6.69	Reverse	0.38	0.09
	10	Northridge-01	1994	Vasquez Rocks Park	6.69	Reverse	0.57	0.09
Group-2 PGA = 0.12 g	11	San Fernando	1971	Pacoima Dam (upper left abut)	6.61	Reverse	0.132	0.16
	12	Tabas_ Iran	1978	Tabas	7.35	Reverse	0.125	0.1
	13	Irpinia_ Italy-01	1980	Arienzo	6.9	Normal	3.856	0.1
	14	Nahanni_ Canada	1985	Site 2	6.76	Reverse	0.595	0.31
	15	Loma Prieta	1989	Gilroy Array #6	6.93	Reverse oblique	0.812	0.1
	16	Loma Prieta	1989	So. San Francisco_ Sierra Pt.	6.93	Reverse oblique	1.67	0.09
	17	Northridge-01	1994	LA—Chalon Rd	6.69	Reverse	0.553	0.12
	18	Northridge-01	1994	LA—Wonderland Ave	6.69	Reverse	1.317	0.14
	19	Northridge-01	1994	Santa Susana Ground	6.69	Reverse	0.507	0.12
	20	Northridge-01	1994	Vasquez Rocks Park	6.69	Reverse	0.761	0.11
Group-3 PGA = 0.15 g	21	Irpinia_ Italy-01	1980	Arienzo	6.9	Normal	4.776	0.13
	22	Irpinia_ Italy-01	1980	Rionero in Vulture	6.9	Normal	1.451	0.14
	23	Irpinia_ Italy-01	1980	Torre del Greco	6.9	Normal	2.313	0.14
	24	Irpinia_ Italy-02	1980	Bagnoli Irpino	6.2	Normal	3.411	0.19
	25	Irpinia_ Italy-02	1980	Brienza	6.2	Normal	3.592	0.14
	26	Irpinia_ Italy-02	1980	Rionero in Vulture	6.2	Normal	1.023	0.1
	27	Coalinga-01	1983	Parkfield—Stone Corral 3E	6.36	Reverse	1.299	0.2
	28	Coalinga-01	1983	Slack Canyon	6.36	Reverse	0.83	0.14
	29	Nahanni_ Canada	1985	Site 2	6.76	Reverse	0.737	0.38
	30	Chalfant Valley-03	1986	Bishop—Paradise Lodge	5.65	Strike slip	8.993	0.39



(a) (b)

FIGURE 2: (a) Selected rock motion records and (b) corresponding spectral accelerations for response analysis.

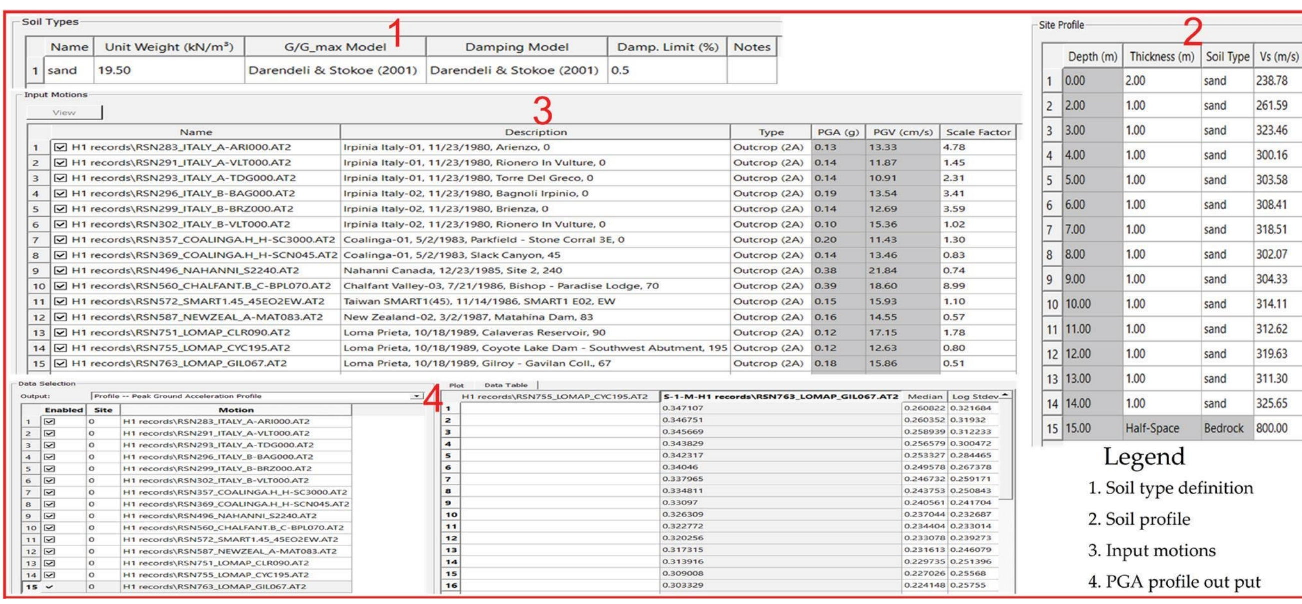
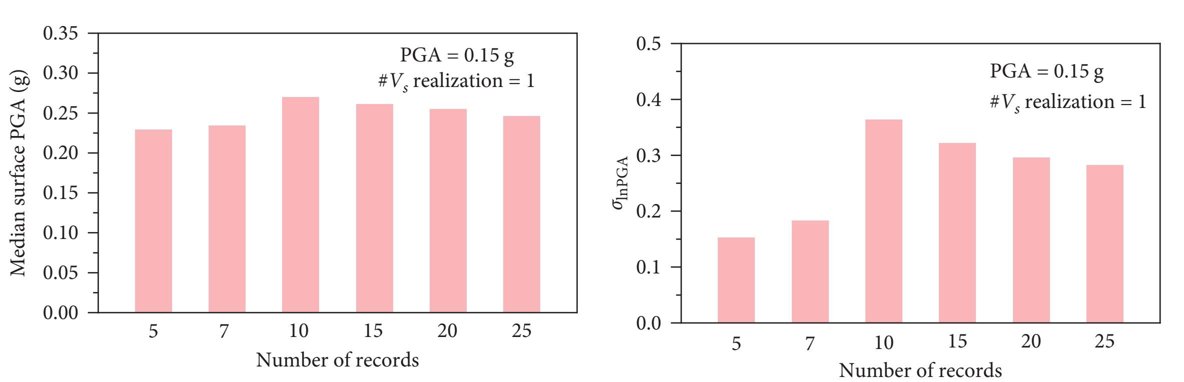


FIGURE 3: STRATA interface illustrating sample user input and output results.



(a) (b)

FIGURE 4: Influence of the number of records on (a) median surface PGA, and (b) standard deviation of PGA.

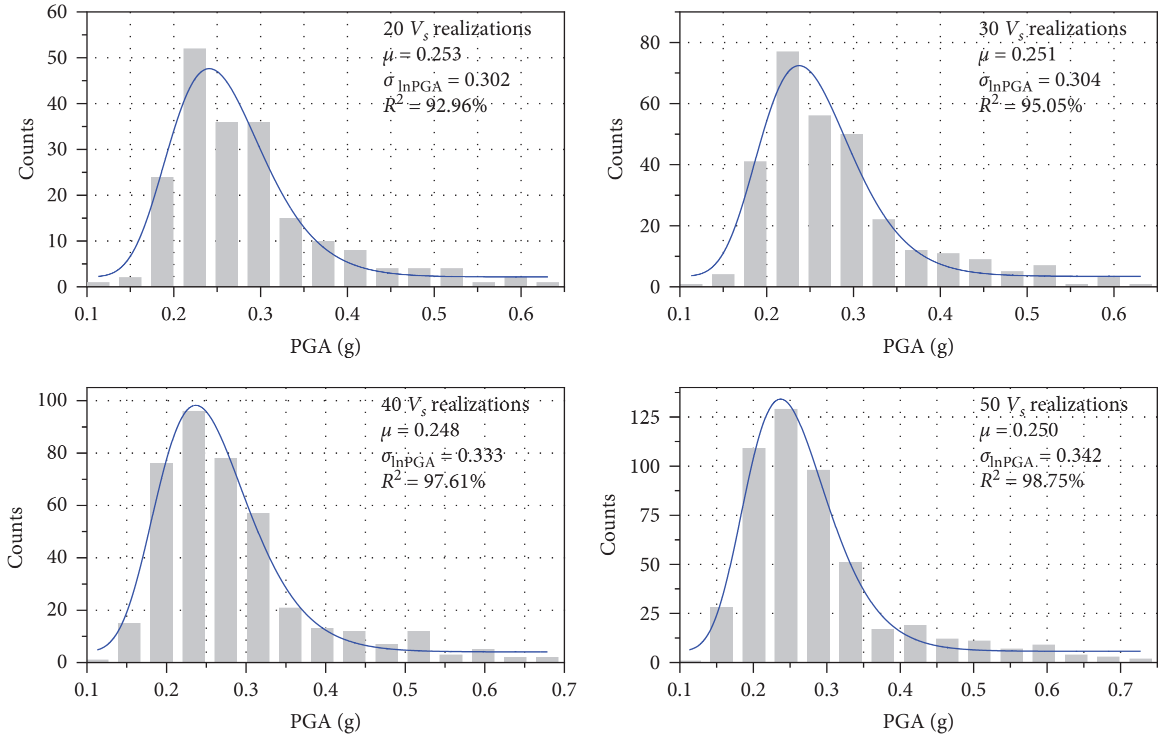


FIGURE 5: Lognormally distributed surface PGA for different numbers of V_s profile realizations.

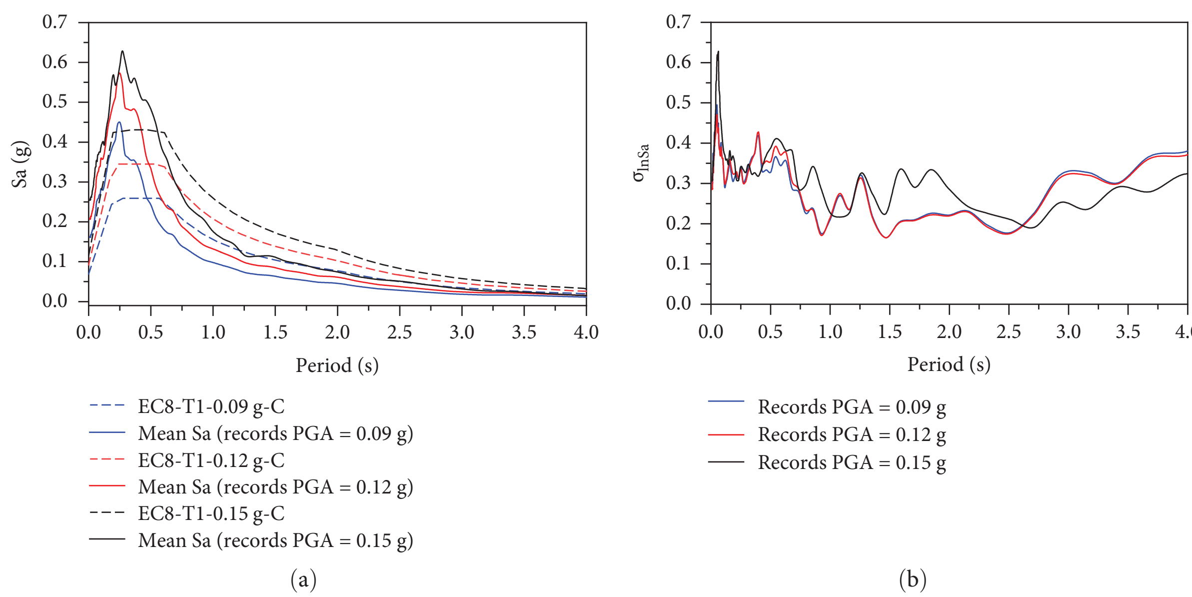


FIGURE 6: Effect of input rock motion variabilities on (a) spectral acceleration and (b) σ_{lnSa}.

surface spectral acceleration and amplification factors derived from 200 (10×20) analyses.

Figures 8 and 9 present the median amplification factors and surface spectral accelerations, respectively, obtained from randomized profiles with different values of $\sigma_{ln} V_s$. As the values of $\sigma_{ln} V_s$ increase, the median amplification factors exhibit a decrease (Figure 8(a)). The decrease in median amplification factors is most prominent at a period less than 0.4 s. Similarly, with an increase in $\sigma_{ln} V_s$, median spectral accelerations decrease (Figure 9(a)). The decrease in spectral acceleration is more noticeable at a period less than 0.4 s. It is important to note that the decrease in surface parameters, resulting from the randomized V_s profile, can vary depending on site-specific conditions [14]. With increasing values of

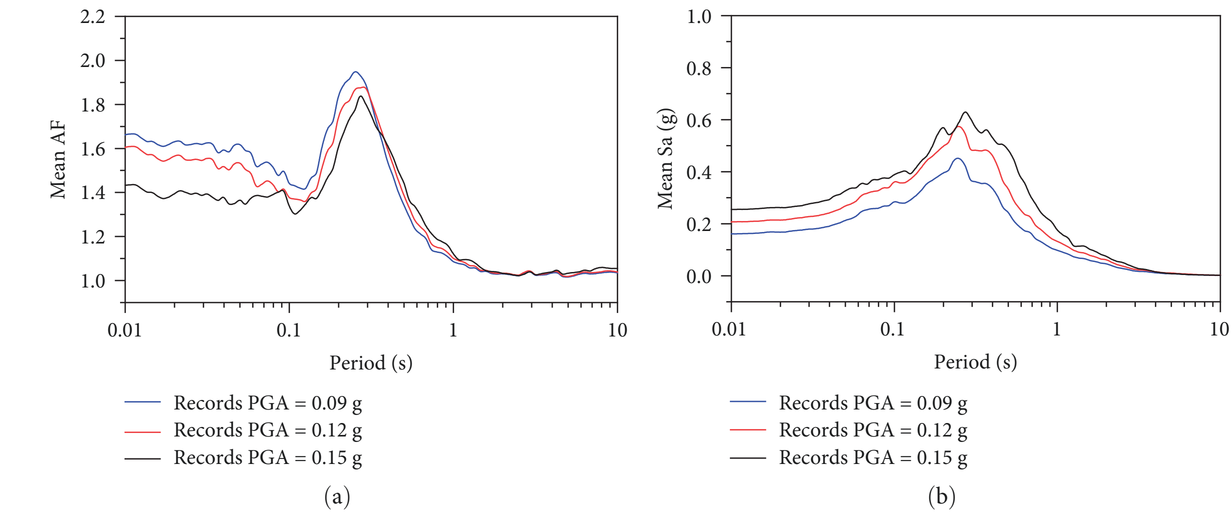


FIGURE 7: Effect of input rock motion variabilities on (a) mean amplification factor and (b) mean spectral accelerations.

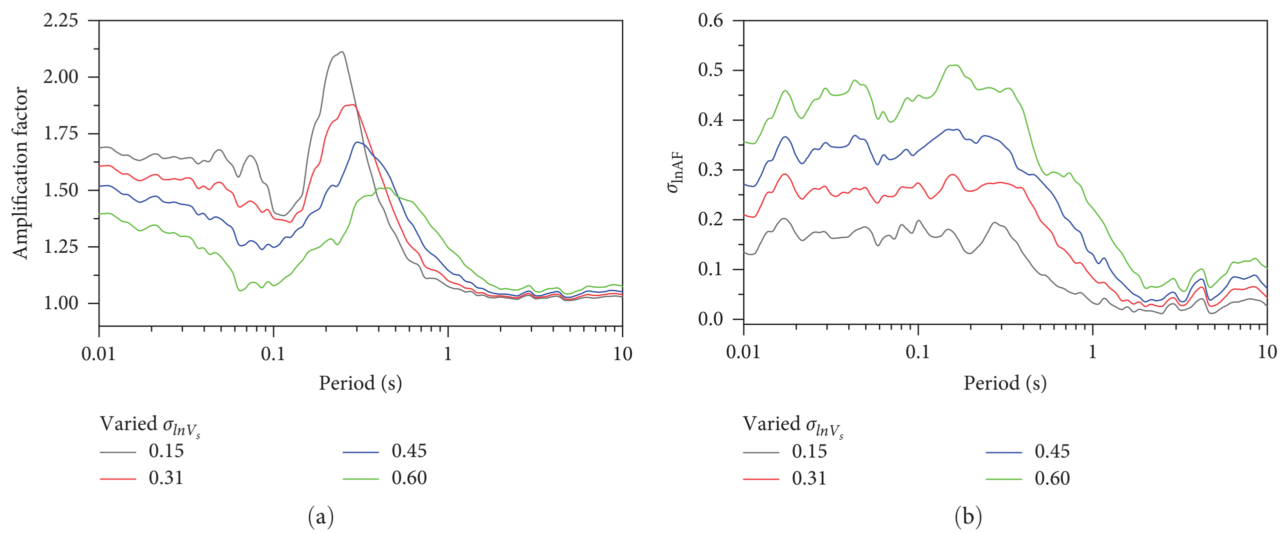


FIGURE 8: Influence of V_s randomization on (a) amplification factors and (b) σ_{lnAF}.

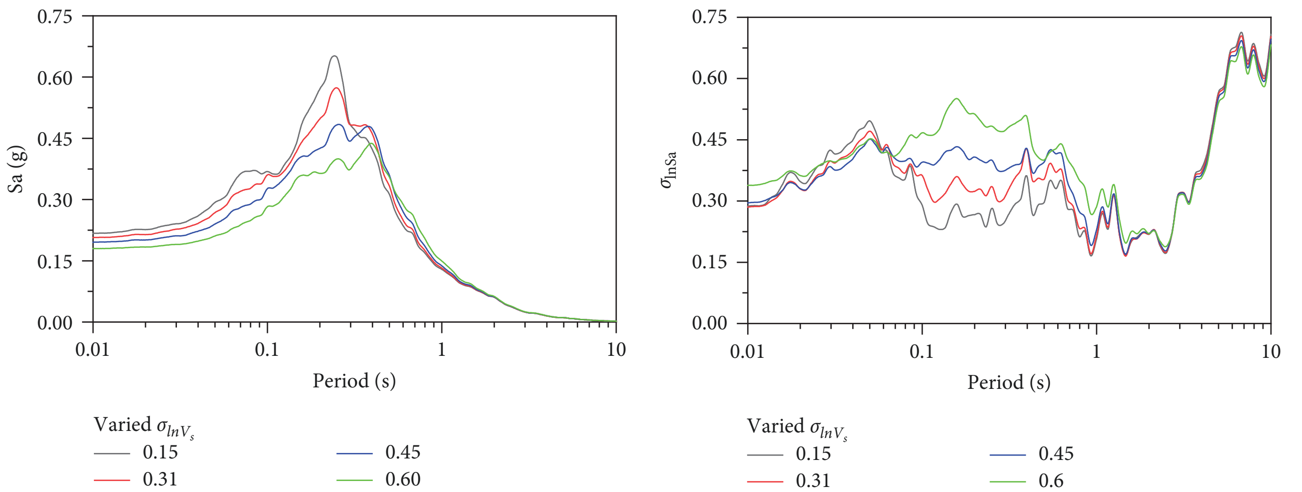
$\sigma_{ln} V_s$, the standard deviation of the amplification factor (σ_{lnAF}) increases across all periods (Figure 8(b)). Similarly, the standard deviation of surface spectral acceleration (σ_{lnSa}) increases at periods between 0.06 and 1 s (see Figure 9(b)).

4. Conclusions

This research presents the impact of V_s profile variabilities on site response analysis. The variabilities associated with the V_s profile was modeled using the Toro (1995) randomization model by varying values of $\sigma_{ln} V_s$ while keeping other model parameters to default values. Furthermore, the influence of the number of V_s profile realizations on computed ground parameters was statistically analyzed. In addition, rock motion records with a range of PGA values (0.09–0.15 g) were considered to assess the impact of varying rock motion intensities on ground responses. The results of the analyses were thoroughly evaluated in terms of amplification factors, surface spectral acceleration, and PGA. The following conclusions can be drawn from this study:

(1) A series of site response analyses were performed with a varying number of V_s profile realizations (20–50) to investigate the effect on ground response. The results showed only a slight variation in median surface PGA as the number of V_s profile realizations increased from 20 to 50. This suggests that as few as 20 realizations are adequate to account for V_s profile variability in ground response analysis.

(2) The impact of V_s variability on ground response was assessed by varying the standard deviations of V_s values (0.15–0.6). The results of the variations revealed a significant influence on both median amplification factors and surface spectral accelerations. Furthermore, it was observed that as the variability in V_s increased, so did the



(a) (b)

Figure 9: Influence of V_s randomization on (a) spectral acceleration and (b) σ_{lnSa}.

variability of both amplification factors and surface spectral acceleration.

(3) Ground response analyses were performed with a varying number of input motion records (5–25) to determine the optimal number of records needed for response analysis. It was found that using 7 –10 records yield satisfactory results, indicating that 7–10 records are sufficient for conducting reliable response analysis if the records reasonably match the target spectrum.

(4) The impact of varying rock motion intensities on ground response was evaluated across a range of input motion intensities from 0.09 to 0.15 g. It was observed that surface spectral acceleration increased with increased rock motion intensities, while the amplification factor decreased with increased rock motion intensities. Furthermore, the local soil deposit consistently amplified the input motions, irrespective of its intensity.

(5) This study systematically assessed the influence of variability associated with the V_s profile and rock motion intensity on site responses, shedding light on an essential aspect of response analysis. However, it also underscores the pressing need for further investigation into how the soil property variabilities influence the ground response. Furthermore, the current study utilized outcropping rock motion records from a different region due to the unavailability of site-specific motion records. Additionally, the selected outcropping motions from rock and/or rock-like ground type may not accurately characterize the within motion at seismic bedrock depth. These situations introduce unavoidable uncertainties and impact the reliability of ground response assessments. Future research should prioritize the development of region-specific ground motion models by accounting for input parameter uncertainty.

Data Availability

The SCPT datasets and analyzed data during the current study are available from the corresponding author on reasonable request.

Disclosure

The authors confirm that they are not associated with any organization or entity that has financial or nonfinancial interests in the topic or materials covered in this article.

Conflicts of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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