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EFFECT OF STATISTICAL VARIATION IN SOIL DYNAMIC PROPERTIES ON LOCAL SITE RESPONSE: THE CASE OF LOTUNG

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ABSTRACT

Shear wave velocity profile and dynamic soil properties are the main factors controlling the results of ground response analyses, for a given bedrock input motion. They are known to be spatially variable and adequate consideration of their variability may lead to a better prediction of the site response. This paper aims to investigate the effect of a statistical variation in the initial stiffness profile, stiffness degradation and damping curves on ground response predictions by conducting Monte Carlo simulations. The Large Scale Seismic Test site in Lotung, Taiwan, is back-analysed using a fully-coupled finite element procedure and applying at bedrock level one strong and one weak motion recorded at the site. A kinematic hardening soil model, capable of capturing stiffness degradation and damping data measured from laboratory tests, is adopted in the analysis. The results of the statistical approach indicate that the effect of variability in the elastic and nonlinear soil properties on the site response predictions is very sensitive to the seismic intensity of the input motion. When the level of induced shear strain is higher, i.e. in the case of a strong motion, the variability of the stiffness degradation and damping curves has a more pronounced effect on the predicted site response, whereas the prediction is particularly sensitive to the statistical variation in the initial stiffness profile when a weak motion is considered.

Keywords: Nonlinear site response analysis; Kinematic hardening soil model; Fully-coupled FE scheme; Monte Carlo simulations; Seismic intensity level

1. INTRODUCTION

Ground response analysis is a key tool in the seismic design of earth structures. To predict local site effects, seismic input motions are propagated through the deposit approximating the dynamic characteristics of the soil by means of equivalent linear or nonlinear approaches. The results of the simulations are, then, interpreted mostly in terms of response spectra and amplification factors obtained at surface (Kramer 2014). The free-field seismic response prediction under a single bedrock motion is controlled by the elastic and nonlinear soil properties, i.e. the initial shear wave velocity (V_s) profile, the normalized shear modulus (G/G_0) reduction and damping ratio (D) curves. The V_s profile of a soil deposit is commonly measured by means of in-situ tests, such as cross-hole, down-hole, seismic cone, SASW, suspension logging methods (e.g. EPRI 1993, Kramer 2014). The shear stiffness and associated hysteretic damping can be determined over a range of shear strains through laboratory testing of undisturbed soil samples (e.g. resonant column/torsional shear, cyclic triaxial and cyclic simple shear tests). Although site response analysis usually adopts the deterministic values for the elastic and nonlinear soil properties, their uncertainty and variability, even within a single soil layer, should be taken into account (e.g. Phoon and Kulhawy 1999). In this respect, the effect of soil properties variability on site response predictions is nowadays of great interest for researchers in the geotechnical earthquake engineering field (e.g. Field and Jacob 1993, Idriss 2004, Bazzurro and Cornell 2004a, 2004b, Andrade and Borja 2006, Sarma and Irakleidis 2007, Rota et al. 2011).

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The most common way of including the variability of the soil properties in site response analyses is through Monte Carlo (MC) simulations. As an example, Roblee et.al. (1996) investigated the influence of the variability of soil properties on the site response prediction through MC simulations. They employed a stochastic finite-fault model able to produce a seismic motion with a specific magnitude and distance from the fault. The model was also capable of accounting for soil properties variability within an equivalent linear formulation. The results indicated that i) site effects variability is clearly a function of the distance (and, therefore, of the seismic intensity level); ii) path effects have little impact on response variability near fault, but become more pronounced as fault-to-site distance increases; iii) source effects contribute most to parametric variability at longer periods and are relatively insensitive to both site type and distance. Li and Assimaki (2010) also conducted MC simulations of the site response of three well-investigated down-hole array sites located in the Los Angeles Basin, using the earthquake dataset developed by Assimaki et.al. (2008) based on synthetic records. It was demonstrated that the impact of nonlinear soil properties variability depends strongly on the seismic intensity of the applied input motion, particularly for soft soil profiles. On the contrary, the effects of velocity profile uncertainties are less intensity dependent and more sensitive to the velocity impedance in the near surface that governs the maximum site amplification. Similarly, Rathje et.al (2010) performed MC simulations for equivalent linear site response analysis by including variability coming from the bedrock motions and the elastic and nonlinear soil properties. The statistical model developed by Toro (1995) was used to randomise the shear wave velocity profile and the model of Darendeli and Stokoe (2001) was implemented to vary the nonlinear soil properties. The results pointed out that modelling shear wave velocity variability generally reduces the predicted median surface motions and amplification factors, most significantly at periods less than the site period, while accounting for the variability in nonlinear properties has a slightly smaller effect. Moreover, including the variability in soil properties significantly increases the standard deviation of the amplification factors but has a lesser effect on the standard deviation of the surface motions.

This paper investigates the influence of variability in elastic and nonlinear soil properties on the site response prediction of the Large Scale Seismic Test (LSST) site in Lotung, Taiwan. The fully-coupled finite element (FE) code SWANDYNE II (Chan 1995) is adopted and plasticity is introduced in the FE simulations through the advanced elasto-plastic model (RMW) developed by Rouainia and Muir Wood (2000). The performance of the RMW model in fully-coupled dynamic analysis of earth structures has been demonstrated in previous works (e.g. Elia and Rouainia 2012, 2014). In particular, the LSST site has been already studied by Elia et al. (2017), but using a deterministic approach, i.e. adopting a single shear wave velocity profile and one set of G/G_0 and D curves predicted by the RMW model. In this work, the variability of elastic and nonlinear soil properties in Lotung is accounted for through a MC approach. Two input motions recorded at the site, one strong and one weak, are considered to test the sensitivity of the ground response prediction to the seismic intensity level. The results indicate that the inclusion of stiffness variability does not have a considerable impact on the prediction under the strong input motion, whereas the ground response is significantly affected when the nonlinear soil properties are varied. Conversely, the predicted site response is particularly sensitive to the variability of the initial shear wave velocity profile and not to the randomisation of the stiffness degradation and damping curves when the weak motion is applied at bedrock.

2. LOTUNG SITE AND EARTHQUAKE RECORDS

The Lotung accelerometer array is located in the north-east part of Taiwan (Tang et al. 1990). The site geology consists of recent alluvium and Pleistocene materials over a Miocene basement. The upper alluvial layer, 30-40m thick, consists mainly of clayey-silts and silty-clays (Anderson 1993). The water table is located approximately at a depth of 1m. The local geological profile shows a 17m thick silty sand layer above a 6m thick layer of sand with gravel resting on a stratum of silty clay interlayered by an inclusion of sand with gravel between 29m and 36m. The site was instrumented in 1985 with down-hole accelerometers located at different depths. Of particular interest here is the vertical array named DHB, which can be considered representative of the free-field response at Lotung. The bedrock formation is assumed to be at a depth of 47m, where the recordings of the corresponding accelerometer have been used in the numerical simulations as input motions. Within two years from the instrumentation, 18 earthquake events were recorded with low, moderate and high seismic intensity levels at the LSST site. Two input motions, one strong (LSST07) and one weak (LSST11), have been considered in this work. For the sake of simplicity, only the E-W component of the earthquake events has been adopted in the FE simulations. Table 1 gives general information about the two earthquakes.

Table 1. Earthquakes recorded by the LSST array and used in the analyses.

Event	**Date**	**Magnitude (M_L)**	**Epicentral distance (*km*)**	**Focal depth (*km*)**	a_{max} (*g*)
LSST07	20/5/1986	6.2	66.0	15.8	0.16
LSST11	17/7/1986	4.3	6.0	2.0	0.07

3. SOIL PROPERTIES VARIABILITY

The shear wave velocity profile along with shear modulus reduction and damping curves are the main soil dynamic properties which have significant impact on the response of a site subjected to an earthquake event. These properties can vary spatially due to aleatory or epistemic uncertainties. The aleatory uncertainty (or randomness) depends strongly on the site geology and cannot be reduced by collection of additional information (Roblee et al. 1996). On the other end, epistemic uncertainty can be caused by man-made errors during laboratory soil testing or deficiencies of current methods in determining the soil properties and can be minimised, for example, by gathering good quality data and developing more rigorous field and laboratory measurement techniques (e.g. Roblee et.al. 1996, Rathje et.al 2010). Most of the soil properties are known to exhibit a high coefficient of variation (CV) that can be represented appropriately using a MC method (e.g. Li and Assimaki 2010). In order to randomise the soil properties in each MC simulation, a specific probabilistic distribution for each property is required. However, since the availability of soil data to constrain the selected probabilistic distribution is usually very limited, it is more practical to formulate such distribution based on data from several well-monitored and investigated sites. In this respect, Toro (1995) has developed a statistical model - based on generic soil profiles retrieved from EPRI database (1993) - to randomise low strain shear wave velocity profiles. The model is able to predict random soil stiffness profiles by considering a baseline V_s profile, the data distribution and the interlayer correlation. Once the average value of V_s at the top 30m of the deposit is known, the stiffness profile can be randomised using the logarithmic standard deviation and the interlayer correlation parameters given by the statistical model. Darendeli and Stokoe (2001) developed an empirical method based on extensive data of G/G_0 and D curves obtained from resonant column and cyclic torsional shear tests on soil samples retrieved from different geotechnical array sites. The dynamic characteristics of these soils were interpreted in terms of confining pressure, overconsolidation ratio, number of loading cycles, loading frequency and site class. The model is based on a first order second-moment Bayesian statistical method and is able to generate correlated G/G_0 and D curves.

In this work, the amount of data from the Lotung site in terms of high quality shear wave velocity measurements and G/G_0 and D laboratory data allows to undertake MC simulations with well-constrained probabilistic distributions. The generation of stiffness variability with depth and G/G_0 and D curves for the LSST site is described in the following sections.

3.1 Initial stiffness variability

The shear wave velocity values obtained at different depths from the results of seismic cross-hole and up-hole tests performed at the LSST site are illustrated in Figure 1. To represent the small-strain shear modulus (G_0) profile of the Lotung site, the well-known equation proposed by Viggiani and Atkinson (1995) is adopted in the FE procedure (Equation 1):

$$\frac{G_0}{p_r} = A\left(\frac{p'}{p_r}\right)^n R^m \tag{1}$$

where p_r is a reference pressure, p′ is mean effective stress, R is overconsolidation ratio and A, m and n are dimensionless stiffness parameters. The details of the FE model and its boundary conditions are presented in Elia et al. 2017. In the initialisation of the FE model, a higher overconsolidation ratio has been assumed for the upper part of the column (from 0 to a depth of 6m), with an average R equal to 4, while a constant overconsolidation ratio of 2 has been imposed for the remaining part of the model. Therefore, the G_0 profile is completely controlled by the parameters A, m and n of Equation 1 and to randomise the small-strain shear modulus profile it is necessary to transfer the variability of G_0 to these parameters. Considering that m and n have relatively less effect on the elastic formulation (due to their small range of values), they are regarded as deterministic input with values of 0.2 and 0.6, respectively. Hence, only the parameter A is subjected to variability when the initial stiffness profile is randomised for the MC simulations. A lognormal distribution can be reasonably fitted through the data points for the different layers, as presented in Figure 1a. In addition, this assumption provides realistic stiffness profiles as it only generates positive values of G_0 (Andrade and Borja 2006). The mean variation of G_0 with depth shown in the figure corresponds to the baseline profile adopted by Elia et al. 2017 in their deterministic simulations. Once the G_0 profile has been randomised, the corresponding V_s variation with depth is obtained for each realisation assuming a total unit weight of the soil equal to $20kN/m^3$ (as proposed by Borja et al. 1999). Figure 1b displays examples of randomised shear wave velocity profiles used in this study. The coefficient of variation of V_s with depth is, instead, presented in Figure 1c.

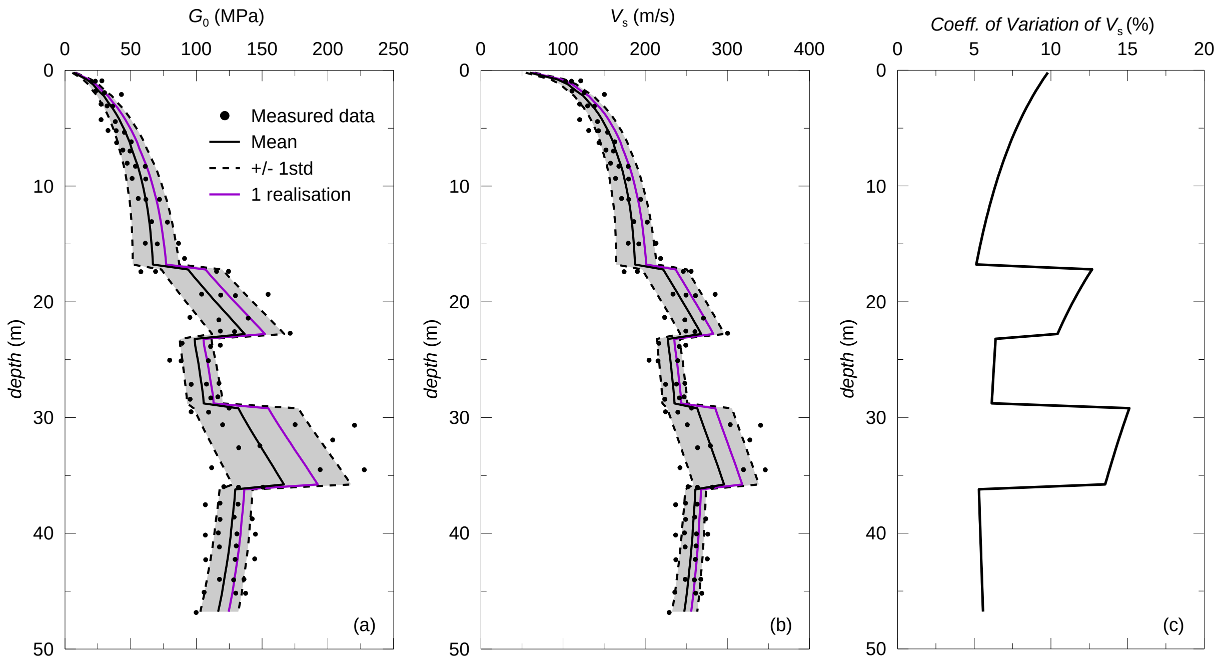

Figure 1. Randomisation of initial stiffness profile and coefficient of variation of V_s

3.2 Normalised shear modulus and damping ratio variability

The randomisation of the stiffness degradation and corresponding damping ratio curve is, in most cases, based on empirical expressions developed considering different soil types and stress conditions (e.g. Darendeli and Stokoe 2001). To randomly generate the nonlinear soil parameters, it is necessary to describe their statistical distribution and define any correlation between them. In this work, the G/G_0 and D curves are the output of the RMW model adopted in the simulations. The constitutive law allows to reproduce some of the key features of the cyclic behaviour of natural soils, such as the destructuration induced by the loading, the decay of the shear stiffness with strain amplitude, the corresponding increase of hysteretic damping and the accumulation of excess pore water pressures under undrained conditions. The plastic modulus H is assumed to depend on the distance between the current stress and the conjugate stress and is given by (Equation 2):

$$H = H_c + \frac{B p_c^3}{(\lambda^* - \kappa^*) R} \left(\frac{b}{b_{\max}} \right)^{\psi} \tag{2}$$

where λ^* and κ^* are the slopes of normal compression and swelling lines in the ln*v* : ln*p* compression plane (being *v* the soil specific volume), *b* is a measure of the distance between the bubble and the structure surface and b_{max} is the nominal maximal value of *b*. The additional soil parameters ψ and *B* control the rate of decay of stiffness with strain and the magnitude of the contribution of the interpolation term, respectively. The hardening modulus H_c is derived from the consistency condition on the structure surface when the bubble and the structure surface are in contact.

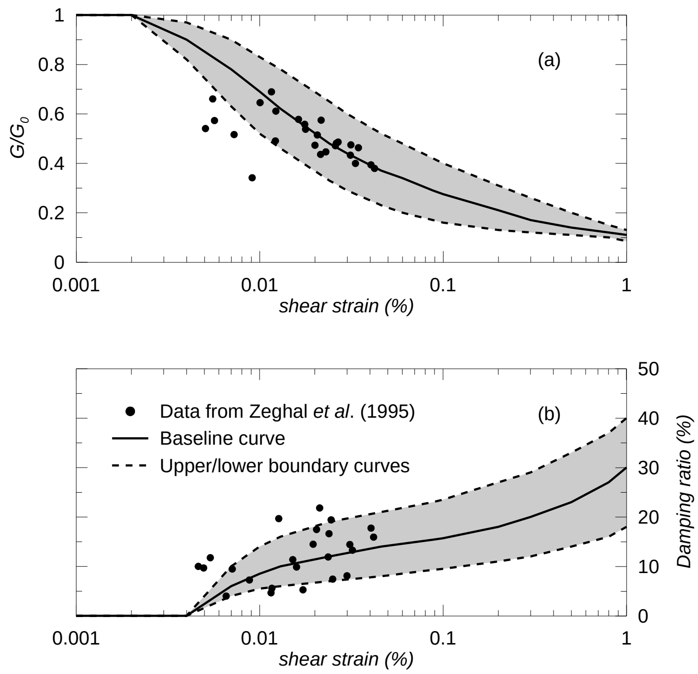

Figure 2. Randomisation of nonlinear property curves

The randomisation of the soil nonlinear parameters can be achieved by varying the RMW parameters which mostly affect the predicted stiffness degradation and damping ratio curves. To identify these parameters, a series of single element simulations of strain-controlled undrained cyclic simple shear (CSS) tests are conducted by applying different shear strain amplitudes. After 500 cycles for each strain level, which is sufficient to achieve a steady-state condition (Elia et al. 2011), the secant shear modulus and damping ratio values are obtained. The use of a lower number of imposed cycles during the CSS simulations would have resulted in the prediction of a stiffer soil response in terms of G/G_0 curves. From an extensive parametric study, it is observed that the G/G_0 and D curves are greatly affected by the interpolation exponent ψ in Equation 2. The remaining RMW parameters are assumed equal to those used by Elia et al. 2017, which were calibrated against the dynamic laboratory tests performed on soil samples retrieved from the Lotung site. The soil parameter ψ is considered as log-normally distributed between a lower value of 0.1 and an upper value of 4. The range of ψ values is determined in order to reasonably capture the experimental data by Zeghal et al. (1995), presented in Figure 2. The mean value of the parameter ψ is set equal to 1.1, as this assumption, along with the remaining soil parameters, gives the baseline nonlinear curve adopted in previous deterministic studies (Elia et al. 2017). The CV of ψ is assumed equal to 0.4, in accordance with the guidance given in the literature (e.g. Phoon and Kulhawy 1999, Chen et al. 2008). Random ψ values are generated such that they are within the lower and upper limit. The corresponding G/G_o and D curves obtained through CSS simulations with the RMW model are shown in Figure 2. The smaller ψ value gives the stiffer G/G_o reduction with shear strain and thus leads to the lower damping ratio curve. In contrast, for the bigger value of ψ the RMW model predicts a more rapid stiffness degradation, resulting in higher hysteretic damping. This inverse trend of the predicted G/G_o and D curves indicates how the RMW model is able to automatically capture the well-known negative correlation between the two curves. Table 2 summarises the CV of both G/G_o and D for different shear strain values.

Table 2. Coefficients of variation of G/G_0 and D for different shear strain values.

Shear strain (%)		0.001	0.004	0.007	0.01	0.024	0.046
CV (%)	G/G_0	0	0	17.31	22.46	33.33	39.19
	D	0	0	50.00	49.00	47.70	46.43

Shear strain (%)		0.088	0.1	0.3	0.5	0.8	1
CV (%)	G/G_0	43.10	43.64	41.18	32.14	20.83	20.45
	D	44.48	44.59	42.50	41.30	38.89	36.67

4. RESULTS AND DISCUSSION

In this section, the results of MC simulations of Lotung nonlinear site response are presented in terms of median response spectrum predicted at ground surface and compared with the actual LSST recorded data and the response spectra computed by Elia et al. (2017) for the best-estimate soil properties (baseline response) using a deterministic approach. All figures show the results obtained using 200 stiffness or, alternatively, 200 nonlinear curves realisations, unless mentioned otherwise. To accurately assess the site response predictions, the standard deviation of the logarithmic spectral accelerations, $\sigma_{\ln Sa}$, is also plotted, as proposed by Li and Assimaki (2010) and Rathje et al. (2010).

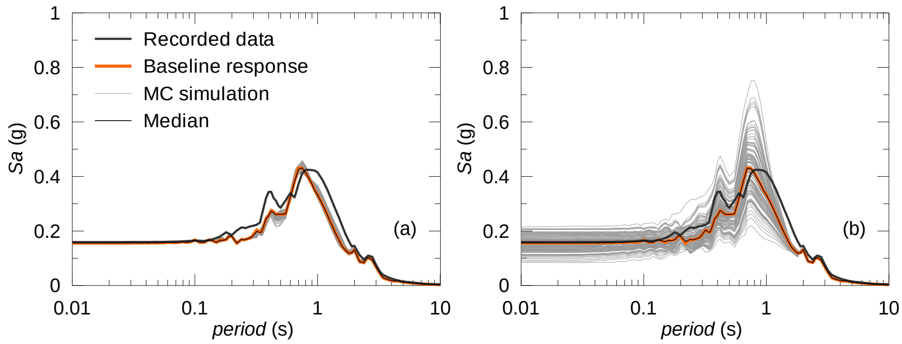

Figure 3. Influence of (a) stiffness profile and (b) nonlinear curves variability on the site response prediction for the LSST07 event

The surface response spectra of the nonlinear site response analyses are shown in Figure 3 when the strong input motion (LSST07) is applied at bedrock. The results are obtained with the V_s profile and G/G_o and D curves being randomised around the baseline corresponding values within plus and minus one standard deviation. By statistically changing the V_s profile, the MC simulations clearly exhibit only a modest variation in the response spectra at surface over the engineering period of interest (Figure 3a). Moreover, the median is remarkably similar to the baseline response prediction. In contrast, a significant variation in the response spectra can be observed by randomising the G/G_o and D curves (Figure 3b). The median, in this case, also closely matches the baseline response, thus indicating that the variation of nonlinear soil properties does not necessarily lead to a different or improved surface response prediction with respect to a deterministic approach.

To estimate the number of MC simulations required to achieve a stable site response prediction when the G/G_o and D curves are varied, five suites of 10, 20 and 50 realisations are considered. Each suite represents a reasonable realisation of nonlinear curves, such that comparing the results from different suites provides an evaluation of the statistical stability of the computed response. This analysis is not performed for the shear wave velocity profile, as the MC simulation results presented in Figure 3a show that the spectral response at surface of 200 different realisations of V_s exhibit inconsiderable level of dispersion around the baseline prediction. The median surface response spectrum and the standard deviation of the surface response spectra (σ_{lnSa}) at each period are computed for each suite of G/G_o and D curves and plotted in Figure 4. It is clear how 10 and 20 realisations do not produce a consistent median response at surface. In contrast, using 50 (or more) realisations allows to predict a stable response, very close to the baseline prediction (Figure 4c). This is also evident in Figure 4d, where the reduction of the standard deviation as the number of realisations increases from 10 to 50 is presented. At the lower periods, sets of 10 and 20 realisations have similar but higher values of standard deviation with respect to the suite composed by 50 realisations, while the difference become evident at around 0.85s, representing the first natural period of the soil deposit, T_1. This may be explained by the tendency of the system to oscillate around its fundamental period, leading to substantial spectral amplifications at that period. Therefore, the spectral response predictions become more sensitive to the variability of the soil properties at around T_1, causing great deviations in the results. At the higher periods (greater than 2s), the standard deviations of the suites composed by 20 and 50 realisations are very similar and approaching zero.

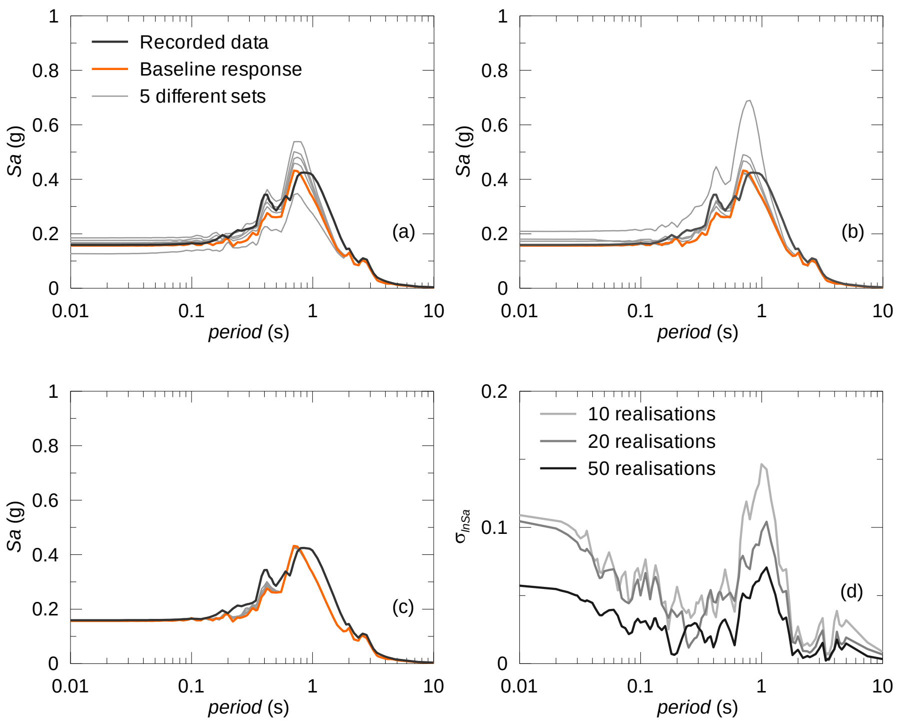

Figure 4. Median surface response for suites of (a) 10, (b) 20, (c) 50 realizations of nonlinear curves and (d) standard deviation of the surface response spectra

An analogous statistical analysis is conducted applying the weak motion LSST11 at bedrock. Figure 5 describes the influence of stiffness profile and nonlinear curves variability on the site response prediction in this case. The variation of the V_s profile has now a significant impact on the site response prediction at the surface (Figure 5a). The median response spectrum obtained from MC simulations is greater than the baseline result between 0.1s and 0.35s and closer to the actual recorded data, thus indicating that an improved prediction can be obtained in the weak motion case if the shear wave velocity profile variability is accounted for. In contrast, there is almost no influence of the variability of G/G_o and D curves on the response at surface, as seen in Figure 5b showing an exact match between each MC simulation and the baseline spectral prediction.

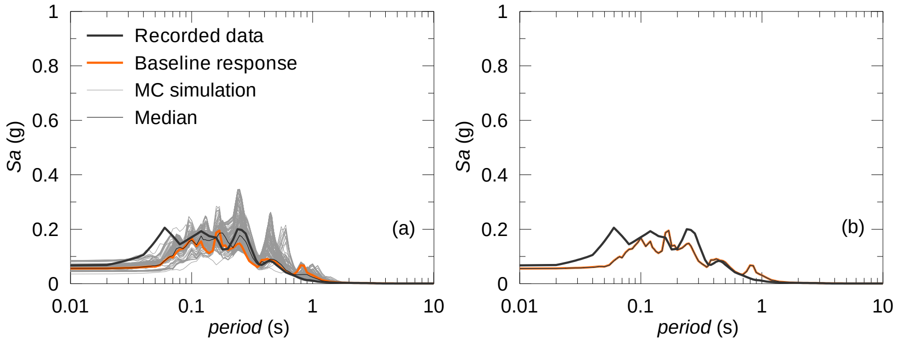

Figure 5. Influence of (a) stiffness profile and (b) nonlinear curves variability on the site response prediction for the LSST11 event

Since the V_s profile is the only factor controlling the predicted spectral accelerations when the weak input motion is applied, the adequate number of initial stiffness profile realisations required to get a stable response at the surface is investigated. Figure 6 presents the median response spectra for five sets of 10, 20 and 50 realisations of V_s and their standard deviations. The suites of 10 or 20 realisations produce a significant variation in the median responses (Figures 6a and 6b). Conversely, the sets of 50 realisations reduce the variability of the median responses, particularly in the period range between 0.3s and 2s, as shown in Figure 6c. This ensures a more stable response at the surface. When suites of 50 realisations are considered, discrepancies between the median spectral values can be still observed, but the level of standard deviation is considerably reduced (Figure 6d).

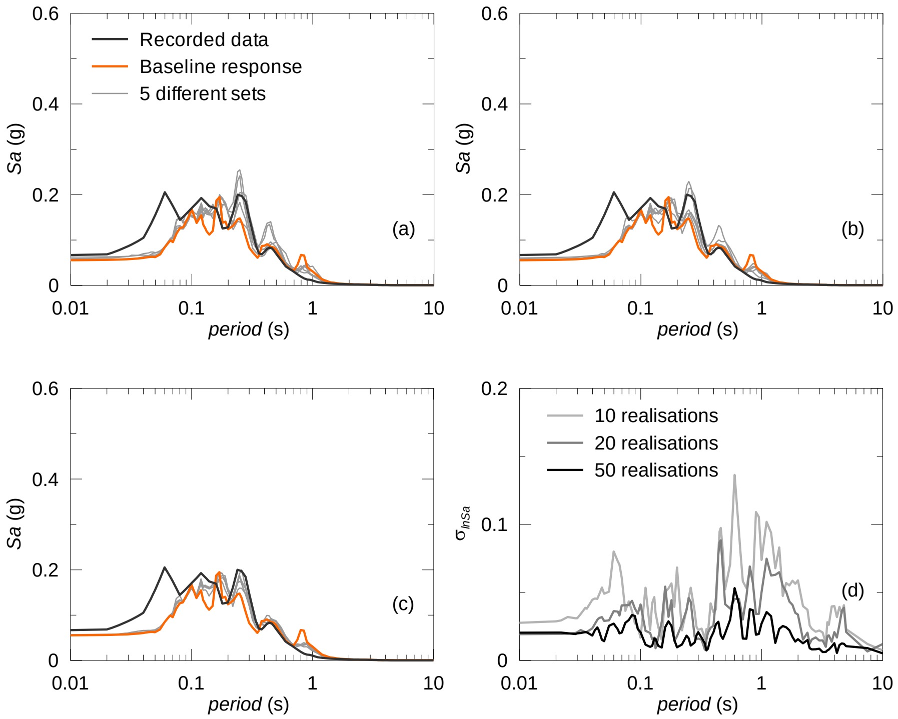

Figure 6. Median surface response for suites of (a) 10, (b) 20, (c) 50 realizations of V_S profile and (d) standard deviation of the surface response spectra

5. CONCLUSIONS

This study investigates the influence of variability of elastic and nonlinear soil properties (i.e. shear wave velocity profile, shear modulus reduction and damping curves) on site response predictions through a Monte Carlo approach. For this purpose, the Large Scale Seismic Test site in Lotung is back-analysed using a fully-coupled finite element code and plasticity is introduced in the simulations through a kinematic hardening soil model. Two different input motions recorded at the site, one weak and one strong, are applied at bedrock to investigate the sensitivity of the statistical results to the seismic intensity level. The output of the MC simulations are interpreted in terms of spectral responses at surface and standard deviation of the logarithmic spectral accelerations. They are also compared to the recorded array data available at the site and to the baseline predictions of deterministic FE analyses performed adopting best-estimate soil properties.

Overall, the results of the statistical approach indicate that the effect of variability in the elastic and nonlinear soil properties on the site response predictions shows a great dependency on the seismic intensity level of the input motion. In the case of a strong motion, the variability of the stiffness degradation and damping curves has a more pronounced effect on the predicted site response, as nonlinearity is triggered by the high level of induced shear strain. Nevertheless, the median response spectrum of the MC simulations is remarkably similar to the baseline prediction. On the contrary, the MC results at surface are particularly sensitive to the statistical variation in the initial stiffness profile when the weak motion is considered, being nonlinear effects almost negligible. Additionally, accounting for the variability of the V_s profile in the case of a weak earthquake event can lead to an improved surface response prediction with respect to the deterministic approach.

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