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Y. Guzel, G. Elia, M. Rouainia
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THE EFFECT OF INPUT MOTION SELECTION STRATEGIES ON NONLINEAR GROUND RESPONSE PREDICTIONS

Yusuf Guzel[1], Gaetano Elia[2] and Mohamed Rouainia[3]

[1] Newcastle University
NE1 7RU Newcastle upon Tyne
y.guzel@newcastle.ac.uk

[2] Newcastle University
NE1 7RU Newcastle upon Tyne
gaetano.elia@ncl.ac.uk

[3] Newcastle University
NE1 7RU Newcastle upon Tyne
mohamed.rouainia@ncl.ac.uk

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Abstract. *Ground response prediction is a key tool in the seismic design of earth structures. The prediction is mainly governed by three factors, namely the bedrock motions, the nonlinear characteristics of the soil deposit and the corresponding initial shear wave velocity profile. This study focuses on the first factor by analysing the effect of five different earthquake selection/scaling strategies on the results of nonlinear ground response. The analyses are interpreted in terms of spectral response and engineering demand parameters (EDPs) at ground surface, including the relative horizontal displacement, the peak ground acceleration (PGA) and the spectral acceleration at the first natural period of the soil deposit (Sa(T_1)). An ideal 50 m soft clay deposit is analysed using a kinematic hardening soil constitutive model implemented in a fully coupled finite element procedure. The results of the advanced nonlinear ground response analyses indicate that, for two different seismic intensity levels, all the selection strategies lead to similar spectral responses at around T_1, with the exception of PGA scaling. Furthermore, the spectral matching strategy leads to a smaller variability in the EDP results. It is also found that the design response spectrum proposed by EC8 for a soft soil deposit does not seem to be fully representative of the possible future earthquake events, thus requiring a revision.*

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1 INTRODUCTION

The alteration of the earthquake characteristics from the bedrock to the surface due to local site conditions is of great interest for the engineering communities dealing with seismic design. The common way of predicting local site effects on wave propagation processes is to propagate seismic input motions through horizontally layered soil deposits by means of simple or advanced numerical methods enabling to assess the surface acceleration time histories, response spectra, amplification factors (AFs), soil stiffness degradation and associated hysteretic damping in response to the shear strains induced by a possible earthquake event [1].

Ground response analyses are mainly governed by the bedrock motion, the nonlinear dynamic features of the soil deposit and its initial shear wave velocity profile. These components sustain some uncertainties attributed to, for example, i) the ambiguity in the selection of a probable earthquake event with specific features from a database (i.e. magnitude, distance, fault mechanism), ii) the possible variability in the measurement of the shear wave velocity profile due to the heterogeneity of the soil deposit and iii) the soil disturbance affecting laboratory tests used to determine the material nonlinear dynamic properties [2]. These uncertainties may ultimately cause bias in site response predictions if they are not properly accounted for in the analysis [3].

Several studies have dealt with the above uncertainties to quantify their possible effects on ground response predictions. For this purpose, Monte Carlo simulations have been conducted with linear or nonlinear soil models by varying site properties [1, 3-5]. While these studies explicitly indicate the importance of accounting for the shear wave velocity, stiffness degradation and damping level variabilities in ground response analyses, they also recognise the impact of the bedrock motion selection on the accuracy of the site response results. Different input motion selection and modification methods, such as peak ground acceleration (PGA) scaling, spectral matching and the mean squared error (MSE) approach, have been proposed in the structural engineering literature [6-9], but their application to geotechnical earthquake engineering problems is limited [10].

This paper examines the impact of different earthquake selection and scaling strategies on the free-field ground response of an ideal soft soil deposit. Sets of seven bedrock motions are used for each selection strategy, considering two seismic intensity levels of 0.15 g and 0.35 g. Advanced time-domain nonlinear ground response analyses are performed with SWANDYNE II [11], a fully coupled finite element (FE) code incorporating the kinematic hardening soil model proposed by Rouainia and Muir Wood [12]. The results of the simulations are firstly interpreted in terms of engineering demand parameters (EDPs) at surface, i.e. relative horizontal displacement, PGA and spectral acceleration at the first natural period of the soil deposit ($Sa(T_1)$). The comparison with EC8 in terms of amplification factors is subsequently presented to highlight the inability of the EC8 prescriptions to fully capture site effects occurring in soft soil deposits.

2 FINITE ELEMENT MODEL

An ideal 50 m deep soft clay deposit is modelled in SWANDYNE II using a 5 m wide column discretised with 250, 1×1 m isoparametric quadrilateral finite elements with 8 solid nodes and 4 fluid nodes. In the dynamic analyses the bottom of the mesh is assumed to be rigid, while the nodes along the vertical sides are characterized by the same displacements (i.e. tied-nodes lateral boundary conditions). The selected input records are directly applied to the solid nodes at the base of the mesh as prescribed horizontal displacement time histories. The Rouainia and Muir Wood (RMW) advanced soil constitutive model is adopted to simulate the dynamic clay behaviour during the seismic excitation. RMW has been successfully employed to predict the dynamic performance of different earth structures [13, 14], as it has been shown to be able to reproduce the decay of the shear stiffness with strain amplitude, the corresponding increase of hysteretic damping and the related accumulation of excess pore water pressure and structure degradation under undrained conditions. In this work, the model parameters, reported in Table 1, are determined by conducting a series of undrained cyclic simple shear test simulations under controlled strain levels in order to produce normalized shear modulus and damping curves representative of a soft soil material [15].

Parameter/ symbol	Physical contribution/meaning	Value
M	Critical state stress ratio for triaxial compression	1.35
λ^*	Slope of normal compression line in ln v-ln p compression plane	0.252
κ^*	Slope of swelling line in ln v-ln p compression plane	0.0297
R	Ratio of size of bubble and reference surface	0.1
B	Stiffness interpolation parameter	8.0
ψ	Stiffness interpolation exponent	1.0
η_0	Anisotropy of initial structure	**0**
r_0	Initial degree of structure	1.75
A^*	Parameter controlling relative proportion of distorsional and volumetric destructuration	0.494
k	Parameter controlling rate of loss of structure with damage strain	0.5
ν	Poisson's ratio	0.25

Table 1: RMW model parameters.

The initial stiffness profile of the deposit is obtained using the well-known equation proposed by Viggiani and Atkinson [16] for the dependency of the small-strain shear modulus G_0 on the mean effective stress, p', and overconsolidation ratio, OCR:

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

In this work, the dimensionless stiffness parameters A, m and n are set equal to 1050, 0.27 and 0.84, respectively, and p_r is a reference pressure (equal to 1 kPa). In the initialisation phase of the FE model, an overconsolidation ratio of 1.5 is assumed constant with depth. The resulting shear wave velocity profile has an average value in the top 30 m of the column equal to 140 m/s, thus classifying the deposit as a soil class D according to EC8 [9]. The first natural period (T_1), calculated using the elasticity theory, is equal to 1.17 s.

3 SELECTION STRATEGIES

Five different strategies for selecting and modifying bedrock input motions recorded on soil class A are employed in this work. Specifically, PGA scaling, Sa(T_1) scaling, 0.2T_1-2T_1 scaling, spectral matching and mean squared error (MSE) scaling are investigated. PGA scaling focuses only on the compatibility of the bedrock motions, on an average, with the target response spectrum (i.e. the EC8 5% damping design response spectrum for soil class A) at zero period. Sa(T_1) scaling seeks for an average compatibility with the target response spectrum at T_1 only. According to the 0.2T_1-2T_1 scaling strategy proposed by EC8, the average compatibility with the target response spectrum is achieved within the $0.2T_1$-$2T_1$ period range with lower tolerance of 10% and the average PGA is not less than that of the target response spectrum. MSE scaling considers the total difference between the natural logarithmic spectral acceleration of the event and the target response spectrum over a specified period range of interest. Finally, the spectral matching strategy achieves the full matching of the bedrock motions with the target response spectrum by modifying the frequency content of the input motions.

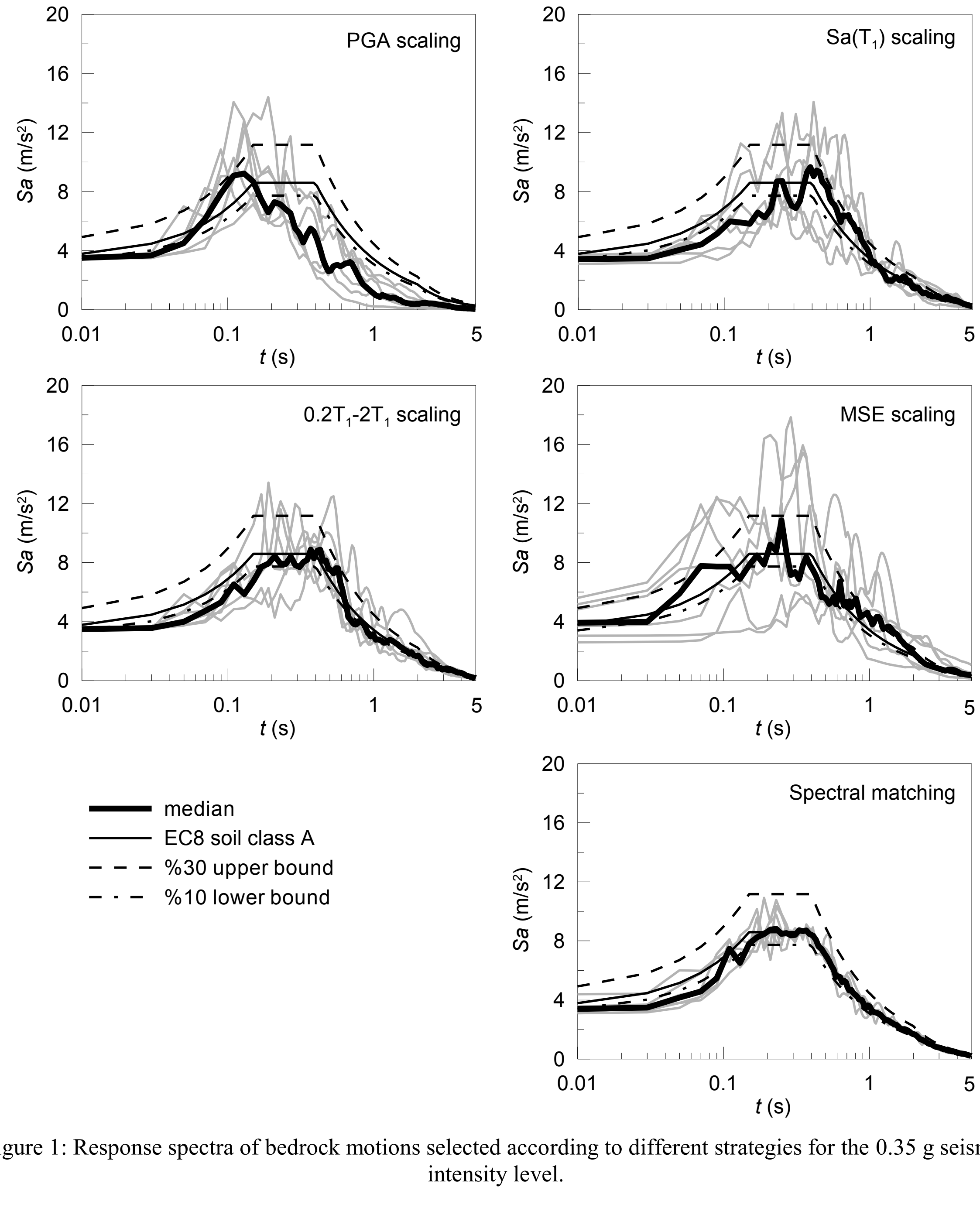

Figure 1: Response spectra of bedrock motions selected according to different strategies for the 0.35 g seismic intensity level.

For each selection strategy, seven motions are chosen from the earthquake database [8, 17] to evaluate the average dynamic response of the FE column in accordance with EC8. In addition, two different seismic intensity levels of 0.15 g and 0.35 g are considered to highlight the effect of soil nonlinearity on the wave propagation process. The selection of the bedrock motions according to the first three strategies is conducted by using the computer program REXEL [17]. SEISMOMATCH [18] is instead used to perform the spectral matching approach, while MSE scaling is obtained using the PEER Ground Motion Database website [8]. Figure 1 presents the response spectra of the five sets of input motions selected according to the different strategies for the stronger intensity level case, together with the comparison between the median and target response spectra for each selection strategy.

4 RESULTS AND DISCUSSION

4.1 Response spectra at ground surface

The median site response spectra predictions obtained at surface using the five different sets of bedrock motions are presented in Figure 2 for the two seismic intensity levels. It is clear that, in all cases, the first and the second natural modes of the soil deposit contribute in the seismic oscillation. Moreover, the predictions of site response based on PGA scaling are significantly different from those obtained with the remaining selection strategies, resulting in an average response spectrum positioned well below the EC8 one for both the intensity levels investigated. For the seismic intensity level of 0.15 g, the five selection strategies give similar response spectra at surface, in particular at around T_1, with the exception of PGA scaling. It can be observed, however, that $0.2T_1$-$2T_1$ and $Sa(T_1)$ scaling strategies give slightly higher spectral responses at the second natural period of the deposit. In the case of the higher seismic intensity level (i.e. 0.35 g), $0.2T_1$-$2T_1$ scaling and spectral matching strategies result in higher spectral accelerations at shorter periods. In this case, the MSE scaling strategy produces surface response spectra diverging considerably from the other response predictions at the shorter periods. This might be due to the greater dispersion in the spectral peaks over the entire period range of the individual input motions at bedrock (Figure 1). This issue is not investigated in this research but the reader can refer to the study of Mazzoni *et al*. [19] for more information. Again, the spectral predictions at around T_1 are quite similar, with the exception of PGA scaling.

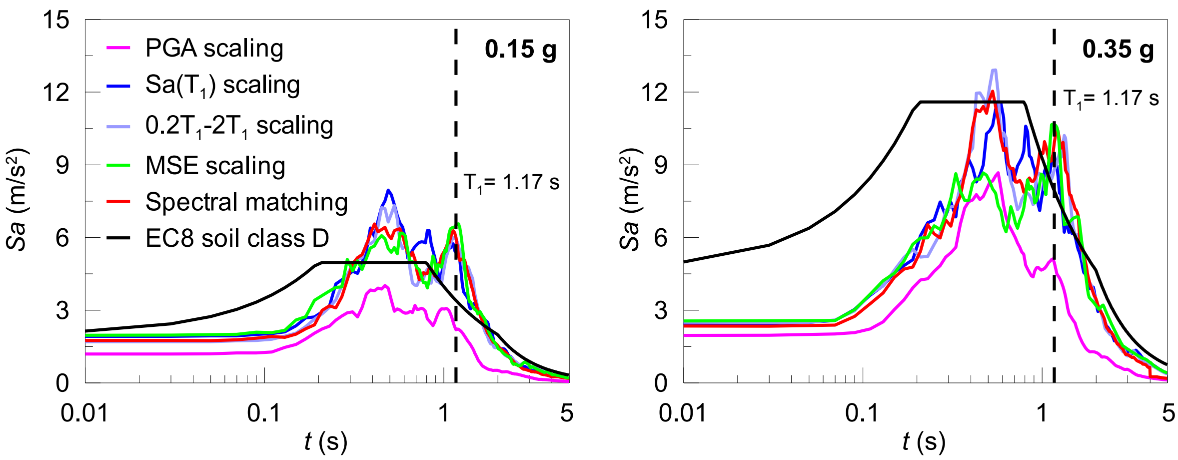

Figure 2: Median site response spectra predictions at surface for the 0.15 g (left) and 0.35 g (right) seismic intensity levels.

4.2 EDPs at ground surface

The impact of the different earthquake selection strategies on the results of the advanced ground response analyses is investigated here with respect to the EDPs obtained at ground surface for both seismic intensity levels. The results are shown in Figure 3 for the individual motions (triangles), together with the mean values (squares) and mean plus/minus one standard deviation (circles) for each selection strategy.

Scaling the input motion records at the same PGA leads to relative horizontal displacements, peak ground accelerations and spectral accelerations at T_1 considerably lower, on average, than those obtained with the other selection strategies. Interestingly, $Sa(T_1)$ scaling introduces similar (or even less) variability in the EDPs at ground surface in comparison with the one obtained with $0.2T_1$-$2T_1$ scaling.

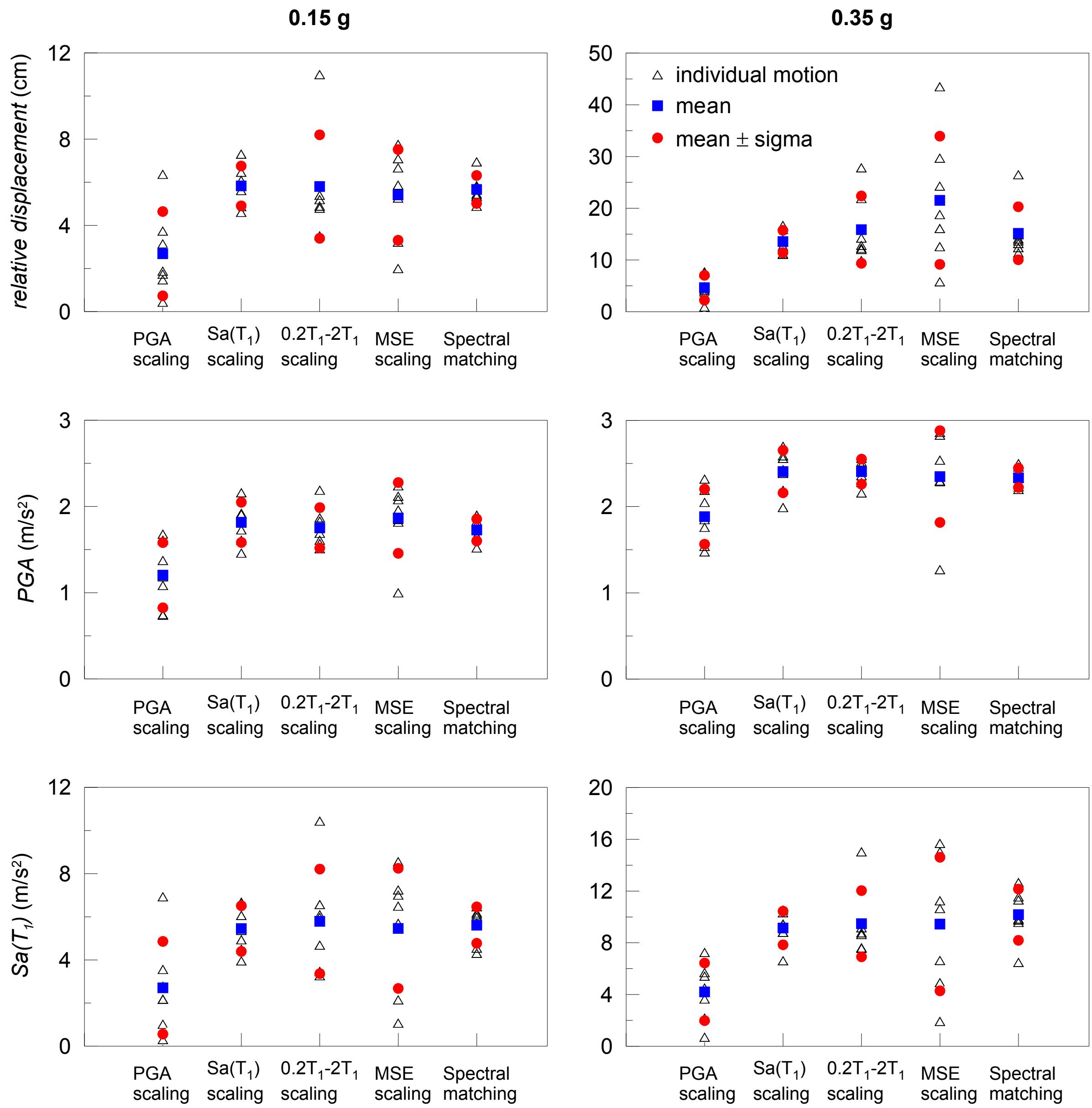

Figure 3: EDPs obtained for the 0.15 g (left) and 0.35 g (right) seismic intensity levels, including mean and mean plus/minus one standard deviation.

The MSE scaling strategy is characterised by the higher dispersion of values around the mean (i.e. the higher standard deviation), especially at the higher intensity level. The cause of this level of dispersion, as explained earlier, can be attributed to the greater scattering of the spectral peaks of the individual bedrock input motions. On the contrary, the EDPs obtained with the spectral matching strategy are the least scattered at both seismic intensity levels. This is due to the fact that, in this case, the bedrock motions are fully matched with the target response spectrum, thus producing more stable and robust results at ground surface.

4.3 Comparison with the EC8 design response spectrum

From Figure 2 it is clear that the EC8 spectral shape does not capture well the amplification, which takes place at the first natural period of the soil deposit for the lower seismic intensity level. Nevertheless, in the case of earthquake events with higher intensity level, the EC8 design spectrum becomes a better proxy of the predicted surface response spectra, even though the amplification at around T_1 is still not fully captured. This observation is consistent with the results presented by Pitilakis *et al.* [20] and Rey *et al.* [21]. The same trend is observed when presenting the results of the ground response analyses in terms of amplification factors (Figure 4). Although the scope of this research is not to recommend new soil factors or a new spectral shape in the design code prescriptions, nonetheless the work highlights the necessity of revisiting the EC8 design response spectrum for soft soil deposits.

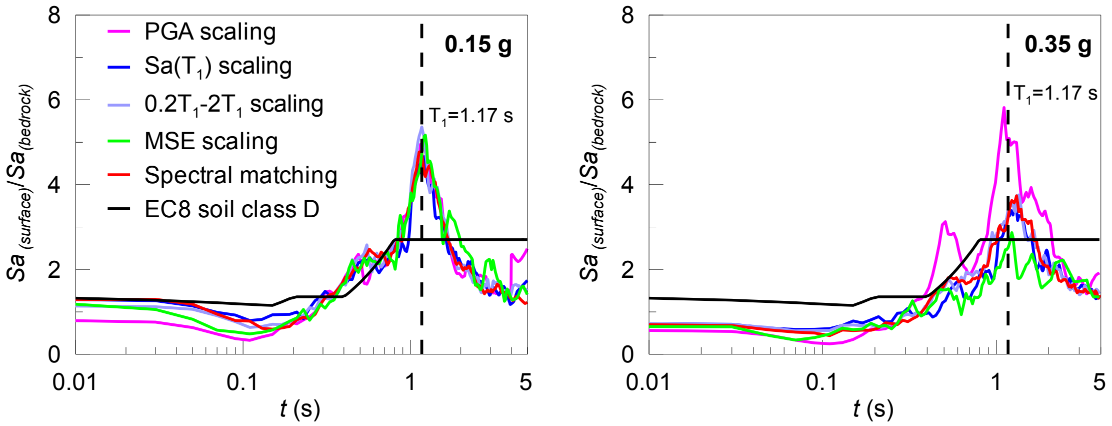

Figure 4: Amplification factors obtained from each selection strategy at 0.15 g and 0.35 g seismic intensity levels.

In the case of a low seismic intensity level, the five selection strategies give similar amplification factors between 0.3 s and 5 s, with PGA scaling producing an overall de-amplification of the peak ground acceleration at surface. For the higher intensity level, instead, the PGA scaling strategy gives considerably high amplification factors between 0.4 s and 2 s, i.e. in the range corresponding to the first two natural periods of the deposit.

5 CONCLUSIONS

Five different earthquake selection and scaling strategies are chosen in this study to analyse the effect of the input motion characteristics on the results of free-field ground response analyses of an ideal soft clay deposit. A fully coupled effective stress based FE code is employed in the dynamic simulations in conjunction with an advanced soil constitutive model. For each selection strategy, sets of seven bedrock motions for two different seismic intensity levels are generated using freely available computer programs (i.e. REXEL, SEISMOMATCH and PEER Ground Motion Database). The principal findings of this work are that:

- Simply scaling the ground motion records at the same PGA does return EDP results that are not consistent with those obtained with more advanced scaling strategies. This is due to the importance of the spectral shape in nonlinear response, as PGA is not a good indicator of the strength and frequency content of the ground motion.

- The level of variability of the site response in the form of standard deviation of the resultant EDPs at ground surface is significantly reduced when using the spectral matching strategy. A robust and stable mean value of the EDPs can be estimated by using spectrally matched accelerograms.
- The spectral shape proposed by EC8 for soft soils does not seem to capture well the predicted surface response spectra for the lower seismic intensity levels, while it becomes a better proxy at higher intensity levels. Although the aim of this research is not to propose a new spectral shape for design prescriptions, the work highlights the necessity of revisiting the EC8 design response spectrum for soft soils.

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