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ALEATORY VARIABILITY AND SITE EFFECTS: THE PROBLEM OF SOIL CLASSIFICATION

Stefania Viti[1], **Marco Tanganelli**[1]

[1]Department of Architecture (DiDA), University of Florence
Via della Mattonaia 16, 50121 Firenze, Italy
{viti, marco.tanganelli}@unifi.it

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Abstract. *The seismic excitation to consider for buildings assessment requires the preliminary soil classification of the site, based on the uppermost 30 m shear-wave velocity, and the consequent assumption of the Code spectra. In some cases, however, the soil classification is not easy to pursue, due to the variability of the soil within the area of interest. This paper deals with the aleatory variability of the soil with reference to a real site in Tuscany (Italy), whose soil properties have been determined through a detailed investigation, made of four different methods. Indeed, a seismic refraction test, a down-hall test, a multi-channel analysis of surface waves combined to an extended spatial auto-correlation analysis, besides some single station recordings of the horizontal to vertical spectral ratio for ambient vibrations have been made on the area. Despite the large amount of collected information, an unequivocal soil characterization has not been possible, due to the large variation of the soil stratigraphy. Therefore, the evaluation of seismic demand has been made by performing a Site Response Analysis on alternative cross-sections, representing the different soil profiles obtained from the investigation. The seismic input at the bedrock has been represented by seven ground motions, provided by two alternative databases. Furthermore, two alternative convolution analyses, based on different soil modelling, have been applied to find the surface seismic input. The effects of the aleatory uncertainty related to the soil variability has been compared to the ones of the epistemic uncertainty, related to the choices made to perform the seismic site response analysis.*

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1 INTRODUCTION

The seismic input largely affects the seismic response of buildings [1,2]. The main International Technical Codes, such as Eurocode 8 [3], ASCE/SEI 7-10 [4], FEMA regulations [5], as well as the Italian one [6], provide a seismic input defined after a soil classification based on the uppermost 30 m shear-wave velocity ($v_{s,30}$) of the site. The evaluation of $v_{s,30}$, therefore, plays an important role in the seismic assessment of buildings, even if additional parameters [7], would help achieving a more refined description.

An important aspect related to the definition of $v_{s,30}$ is the possible variability of the soil properties even within the observed site. In fact, especially when a large building complex is investigated, the soil can present different features in different parts of the same area.

The work is focused on a real site, in Tuscany (Italy), having a medium seismic hazard, which houses an Hospital Complex, which has been object of a careful investigation both on the buildings [8] and on the foundation soil [9-11]. Indeed, a seismic refraction test, a down-hall test, a multi-channel analysis of surface waves combined to an extended spatial auto-correlation analysis, besides some single station recordings of the horizontal to vertical spectral ratio for ambient vibrations have been made on the area. The collected data presented different soil properties in various parts of the area, corresponding to two different soil-types (A and B, respectively) according to the EC8 classification. This work continues a previous study [11], which presented the results provided by the geological investigation, performing a detailed comparison between the soil properties and the Codes classification. The comparison was extended even to the surface input, found by performing a site response analysis (SRA) made by considering alternative soil profiles, respectively compatible to the results provided by the geological investigation, starting form a ground motions ensemble spectrum-compatible to the bedrock.

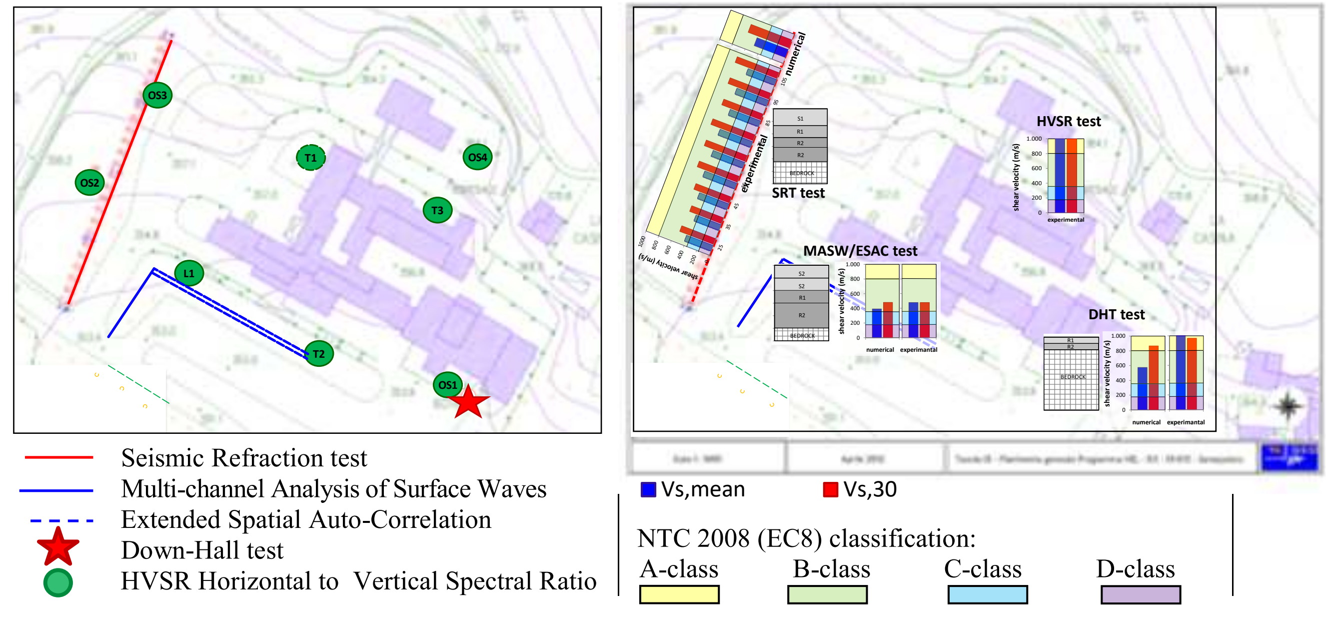
In [11] the soil variability of the area proved to largely affect the seismic input found through the SRA. The results provided by the SRA, however, are affected by several numerical choices, like the model adopted for the convolution, the ensemble of ground motions assumed to represent the bedrock input and the numerical soil representation. In this work the same data have been considered to perform the SRA, but alternative model choices have been considered, in order to compare the variability in results related to the modeling to the one due to the intrinsic soil variability.

Three different soil profiles have been proposed to represent the soil properties provided by the geological investigation, and a SRA has been performed to determine the surface seismic input. The analysis has been made on two different ensembles of seven ground motions, spectrum-compatible to the bed-rock one as provided by NTC 2008.

The considered ensembles have been selected, respectively, by two different databases, based on different criteria: the Italian Accelerometric Archive [12] and ASCONA [13]. The SRA has been performed adopting two different procedures, differing for assumed hypotheses, computational effort and results reliability [14]. The first one [15], working in the frequency domain, performs one-dimension linear-elastic and equivalent-linear (SHAKE type) site response analysis using time series theory ground motions. The second procedure [16,17] still assumes the soil column to be a one-dimensional system, but adopts a nonlinear description of the soil properties. Both procedures adopt the soil relationships provided by experimental tests; the dynamic curves, however, have been arranged through alternative procedure, respectively proposed by Darandeli [18], and Matasovic (masing option MRD, Modulus Reduction and Damping curve [19]). Finally, the scatter found in the seismic input at the surface as a function of the modeling choices has been compared to the one due to the difference in the soil mechanical properties resulted by the geological investigation.

2 SOIL REPRESENTATION

The considered site is located in Sansepolcro, that is one of the most severe seismic areas in Tuscany. The seismic intensity of the area is provided by NTC 2008 [6], which indicates a PGA equal to 0.227g for *RP* equal to 475 years (rock outcrop), i.e. for a probability of occurrence equal to 10% in 50 years [20]. The soil has been object of a comprehensive investigation, including a down-hall test (DHT), a seismic refraction test (SRT), a multi-channel analysis of surface waves combined to an extended spatial auto-correlation analysis (ESAC/MASW), and some single station recordings of the horizontal to vertical spectral ratio for ambient vibrations (HVSR). In Figure 1a the location of each test is indicated, where an accurate description of the investigation and the obtained data can be found in Viti *et al*. [11].



a. Location of the investigations

b. Experimental and analytical shear velocities v_s

Figure 1. Map of the site: performed investigations and consequent soil profiles.

The stratigraphies provided by the three main tests, i.e. DHT, SRT, ESAC/MASW have been reproduce through as much soil profiles, named after the test whose stratigraphy is represented. Figure 2 shows the three soil profiles; four different ground types, i.e. two types of silt (S1, S2) and of altered rock (R1, R2) have been adopted to reproduce the experimental stratigraphies. In the figure the thickness and the shear velocity of each layer are indicated.

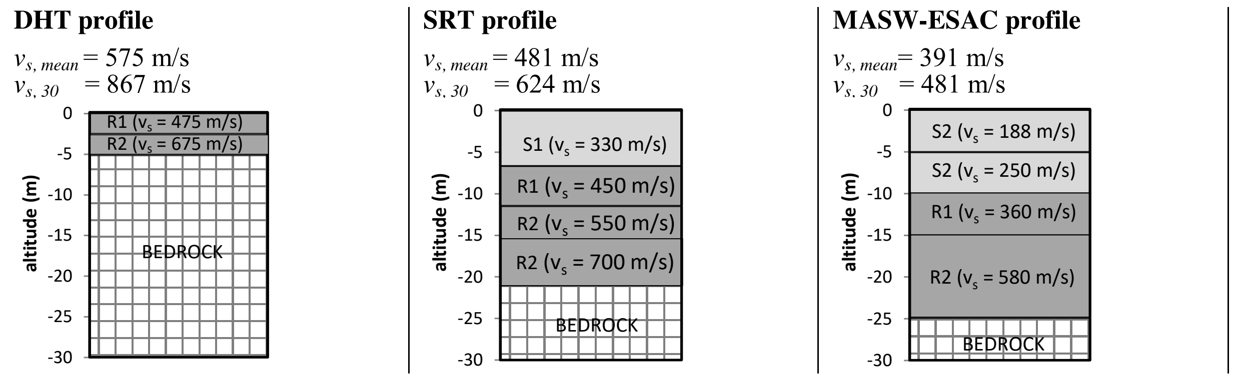


Figure 2. Assumed Geological Profiles.

Two different v_s values are shown for each profile, found respectively on the effective thickness checked in each investigation, $v_{s,mean}$, which is different for each test, and for the upper 30 meters ($v_{s,30}$) as required by the Code. In the latter case the missing layers have been assumed compatible to the properties of the deepest available soil. Figure 1b shows the values of the shear velocities found for the soil profiles, compared to the same quantities provided by the experimental investigations and to the $v_{s,30}$ ranges of values provided by EC8 (and NTC 2008) for the different soil classes. As should be noted, the DHT has evidenced $v_{s,30}$ compatible to the A-soil, whilst the other two tests have provided shear velocities belonging to the B-soil type.

3 THE SITE RESPONSE ANALYSIS (SRA)

3.1 The seismic input at the bedrock

In order to perform the analysis, a selection of ground motions representative of the seismic input at the bedrock must be made. In this work three different seismic intensities, respectively corresponding to *RP* equal to 101, 949 and 1950 years, have been considered. The selected ground motions should be spectrum-compatible to one at the bedrock, represented, in this work, through the elastic spectrum provided by NTC 2008 for the A-soil. This selection is not simple, since not for all sites there are A-soil ground motions available for all the required intensities. The optimal criterion for ground motions selection would consist of limiting the choice to local unscaled records only. For the investigated area, however, there were no availability of real local records. For this reason, two different ensembles of ground motions have been considered, selected according different criteria.

Table 1. The Assumed Ground Motions by Scalcona [13,21]

File name	Epic. Distance	Magnitude	Scale Factors for each RP		
	Km	Mw	years		
			101	949	1950
ESM EU.HRZ..HNE.D.19790524.172317	29.90	6.20	1.61	2.82	
ESM IT.ATN..HNN.D.19840507.174943	10.10	5.90	1.23		
NGA-West2 RSN1091_NORTHR_VAS000	38.07	6.69	0.81	2.02	2.19
NGA-West2 RSN2989_CHICHI.05_CHY102N	78.79	6.20	2.14		
NGA-West2 RSN8167_SANSIMEO_DCPP247	57.74	6.50	2.64		
KiK-net SAGH050503201053	62.00	6.60	0.87		
ESM IT.AQP..HNE.D.20090407.174737	13.20	5.40	1.30		
NGA-West2 RSN146_COYOTELK_G01320	12.57	5.74		3.00	3.94
NGA-West2 RSN804_LOMAP_SSF115	83.53	6.93		4.84	
KiK-net SMNH100010061330	31.00	6.60		0.99	1.39
NGA-West2 RSN5685_IWATE_MYGH11NS	70.13	6.90		3.61	
ESM IT.AQP..HNN.D.20090409.005259	11.80	5.20		3.89	
ESM EU.HRZ..HNE.D.19790415.061941	62.90	6.90			1.24
NGA-West2 RSN789_LOMAP_PTB207	103.91	6.93			3.81
KiK-net FKOH060503201053	90.00	6.60			5.62
KiK-net MYGH041103280724	97.00	6.10			3.94

The first one, described in Table 1, has been selected through the software SCALCONA 2.0 [21], from the data-base ASCONA [13]. All the considered ground motions are compatible to the required criteria, even if not all them are local and they have been scaled by proper scale factors. The second ensemble, described in Table 2, has been selected within the Italian Accelerometric Archive [12] through the adoption of the software REXEL [22,23]. In this case all the records are unscaled, but some of them do not belong to the A-soil class, even if their mean spectrum complies all the requirement of the fitting. In Figures 3 the elastic spectra of the two considered ensembles have been compared to the Code one, whilst Figure 4 shows the percentage difference between the spectral acceleration of the ensembles and the ones of reference bedrock (A soil, NTC 2008). As can be noted, both the ensembles comply the required features.

Table 2. The Assumed Ground Motions by Rexel [22,23].

File name	Epicentral Distance	Magnitude	Scale Factors for each RP		
	Km	Mw	years		
			101	949	1950
E.BUI..HNE.D.19760915.092118	10.8	6.0	1		
IT.CRP..HNN.D.20120529.070002	16.8	6.0	1		
IV.MI03..HNE.D.20090407.174737	2.8	5.5	1		
IV.T0803..HNN.D.20120529.070002	24.0	6.0	1		
IV.T0823..HNE.D.20120529.070002	24.1	6.0	1		
IV.T0824..HNE.D.20120529.105556	12.5	5.5	1		
IV.T0824..HNN.D.20120529.070002	14.2	6.0	1		
BA.MIRE..HLE.D.20120529.070002	4.1	6.0		1	
E.SRC0..HNE.D.19760915.092118	15.8	6.0		1	
IT.AQG..HNE.D.20090406.013240	5.0	6.3		1	
IT.TLM1..HNN.D.19760506.200012	27.7	6.4		1	1
IV.T0802..HNE.D.20120529.070002	9.9	6.0		1	
TV.MIR05..HNN.D.20120529.070002	15.8	6.0		1	
TV.MIR08..HNE.D.20120529.070002	8.6	5.8		1	
IT.MRN..HNE.D.20120520.020350	16.1	6.1			1
IT.STR..HNE.D.19801123.183453	33.3	6.9			1
IV.T0814..HNE.D.20120529.070002	9.3	6.0			1
IV.T0814..HNN.D.20120529.070002	9.3	6.0			1
IV.T0819..HNE.D.20120529.105556	6.8	5.5			1
TV.MIR01..HNE.D.20120529.070002	0.5	6.0			1

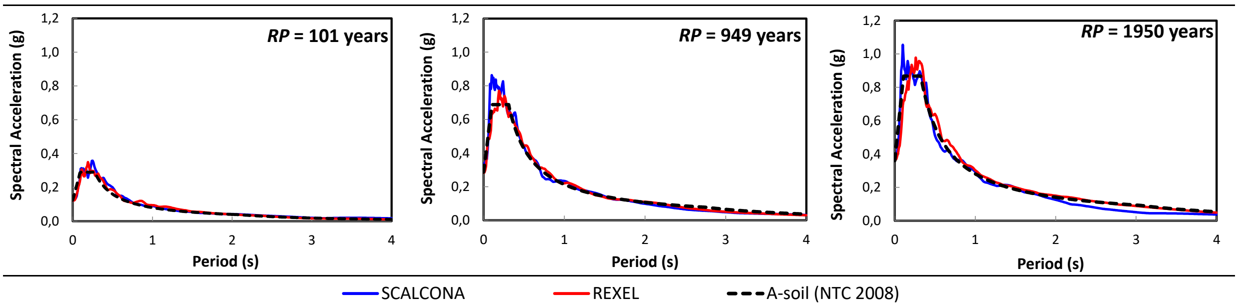


Figure 3. Spectra of The Assumed Seismic Ensembles Compared to the Corresponding A-Soil Spectrum.

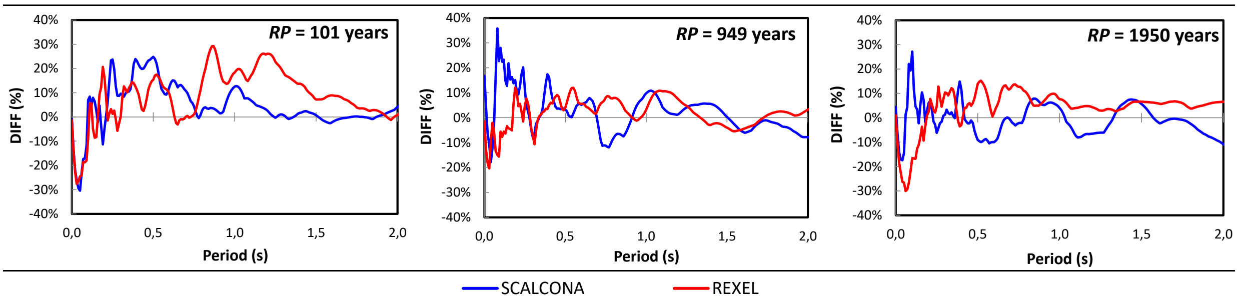


Figure 4. Percentage difference between spectral accelerations of the considered ensembles and the Code ones.

3.2 The analysis setting

Two different SRA have been performed, by adopting as much analytical procedures. The first one, applied by performing the software STRATA [15], works in the frequency domain and is based on the representation of ground motions through time series. The second analysis has been applied through the software DEEPSOIL [16,17], which adopts a nonlinear representation of the soil properties.

In both analyses the soil has been described by the relationships shown in Figure 5. The soils S1, S2 and R1 have been described after experimental tests made on samples taken in the surrounding area. Their dynamic curves have been determined by the laboratory ISMGEO (Istituto Sperimentale Modelli GEOtecnici, http://www.ismgeo.it/) through resonant column test. In Fig. 5 the web references of the experimental curves have been indicated.

The soil R2, instead, has been described through the relationships proposed by Idriss and Sun [24], since there were not available data. The bedrock has been assumed to have a visco-elastic behavior, with a shear velocity equal to 1000 m/s.

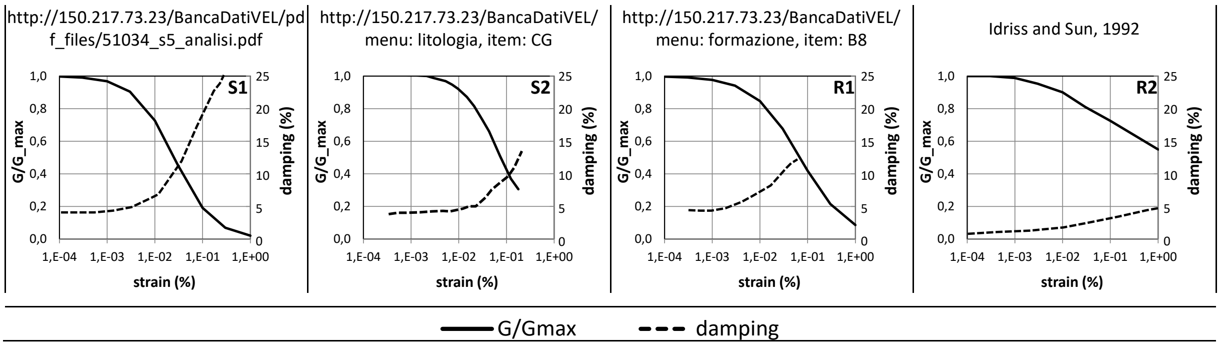


Figure 5. Assumed Geological Profiles.

All the assumed dynamic curves have been arranged through the masing option proposed by Matasovic [19], MRD and by the model introduced by Darandeli [18], DAR.

In the SRA, therefore, three different modeling choices have been done, respectively regarding the representation of the seismic input at the bedrock, the assumptions concerning the SRA and the dynamic curves arrangement. In Table 3 the considered assumptions have been resumed, and the code adopted to indicate the obtained results have been listed.

In all cases, the spectra of the surface records referred to the three soil profiles have been found through the software SeismoSignal 2016 [25].

Table 3. Codes adopted for the surface spectra.

Code	Software	Ensemble	Modeling of dynamic curves
S_S_MRD	Strata	Scalcona	Matasovic
S_S_DAR	Strata	Scalcona	Darandeli
S_R_MRD	Strata	Rexel	Matasovic
S_R_DAR	Strata	Rexel	Darandeli
D_S_MRD	Deepsoil	Scalcona	Matasovic
D_S_DAR	Deepsoil	Scalcona	Darandeli
D_R_MRD	Deepsoil	Rexel	Matasovic
D_R_DAR	Deepsoil	Rexel	Darandeli

4 RESULTS

Figure 6 shows the *mean* spectra obtained by performing the convolution analysis. For each soil profile and *RP*, 8 spectra have been found, according to the modeling option specified in Table 3. In Fig. 6 the surface represented spectra have been compared to the Code ones, i.e. the A-soil spectrum for the results found through the DTH profile, and the B-soil for the ones represented the SRT and the MASW/ESAC profiles. As can be noted, the results obtained by adopting the SRT and the MASW/ESAC profiles differ very much from the corresponding B-soil spectrum. Moreover, the *mean* spectra found through the two profiles largely differ each other, since the MASW/ESAC values of spectral accelerations are much larger than the SRT ones.

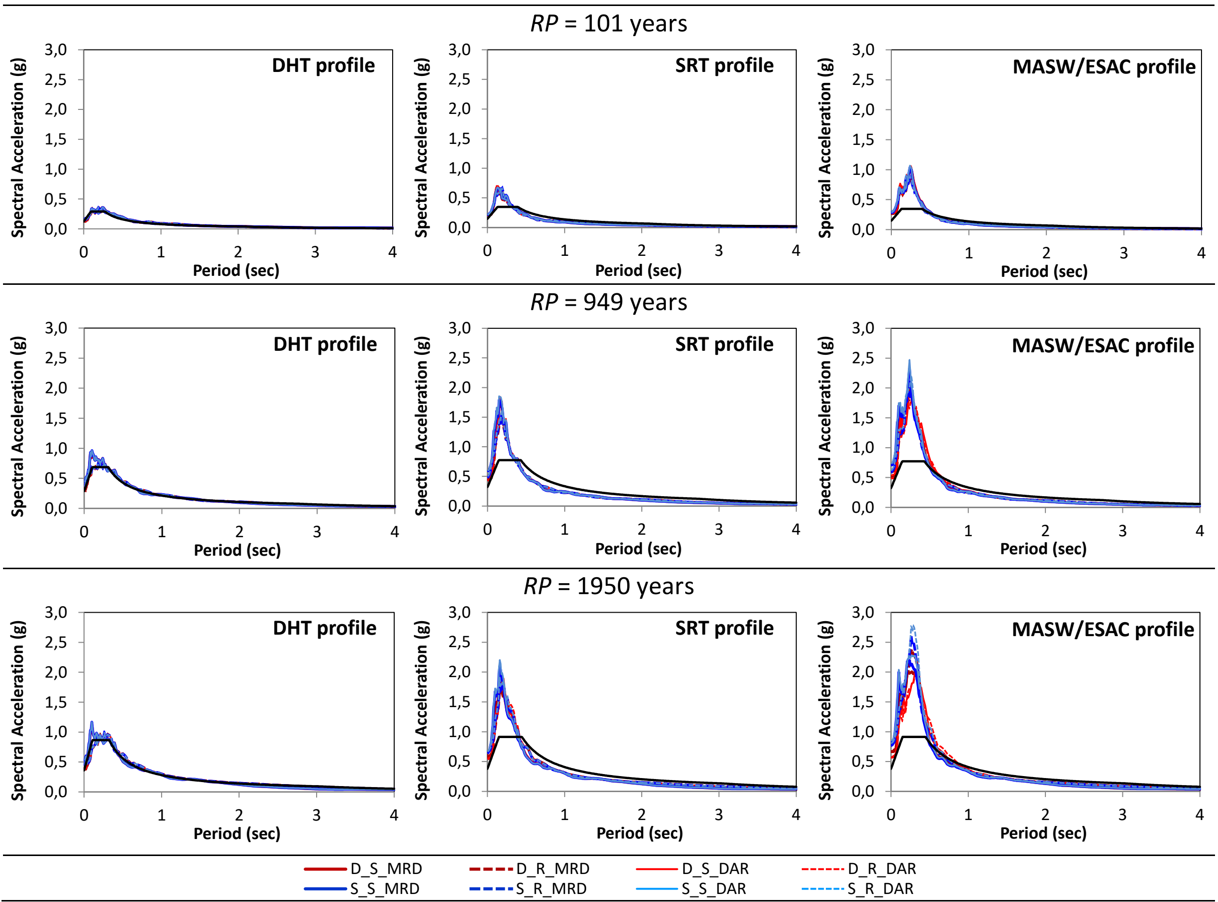


Figure 6. Surface spectra found by the convolution analysis.

The obtained spectra differ each other in shape and maximum spectral acceleration. In order to visualize the variability related to the modeling and to the intrinsic mechanical properties of the soil the maximum values provided by each analysis have been shown in Figure 7. As should be noted, the larger difference in the surface spectra is related to the soil profile; at the increase of the seismic intensity, however, the scatter related to the modeling increases as well; for *RP* = 1950 the effects of the modeling seem to overcome the difference between the SRT and the MASW/ESAC soil profiles.

In Figure 8 the *mean* amplification functions, AF, found as the ratio between the surface spectra and the bedrock ones, have been shown. As can be noted, the amplification is less sensitive to the seismic intensity; the maximum values of amplification factor, indeed, seem to be related more to the soil profile than to the Return Periods. Only the MASW/ESAC profile evidences a sensitivity to the seismic intensity, with an increasing role of the modeling assumptions for *RP* = 1950 years.

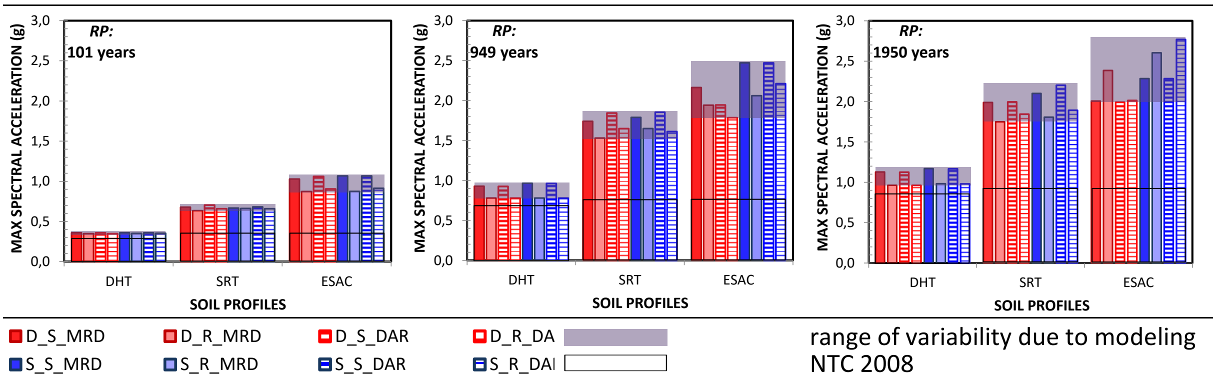


Figure 7. Maximum value of the spectrum

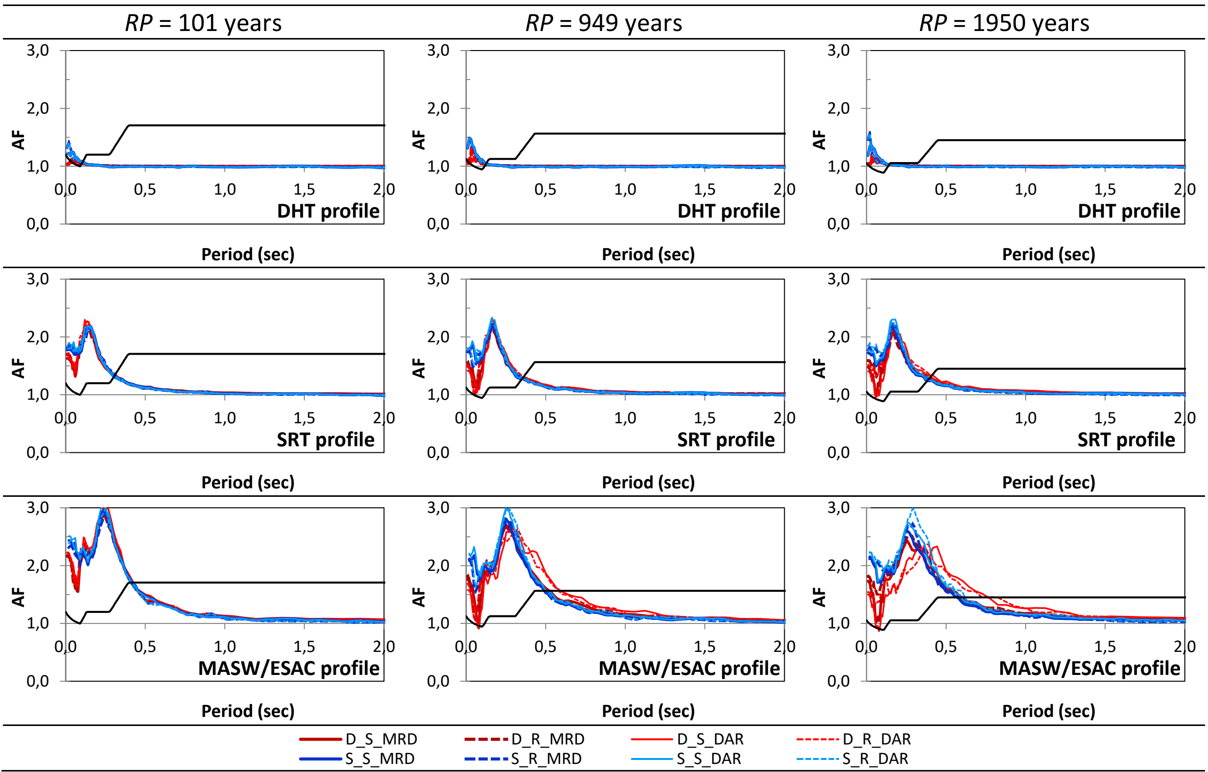


Figure 8. Maximum value of the spectrum

Figure 9 shows the maximum strain attained by the soil under the assumed ground motions. The Figure refers to the *mean* strain at the center of each layer: the reference depth of each layer is indicated in the graphs. As can be noted, the largest strain is attained by the silt layers. The MASW/ESAC soil profile is much more deformable than the other ones. Only for the MASW/ESAC profile, indeed, the strain exceeds 0.1%, achieving 0.25% in the more deformable layer (S2). In the more deformable soil layers, the effects of the modeling assumptions are larger; the choice of the convolution software is the most important, among the considered ones, whilst no substantial differences are noted between the strain found through the two alternative bedrock ensembles.

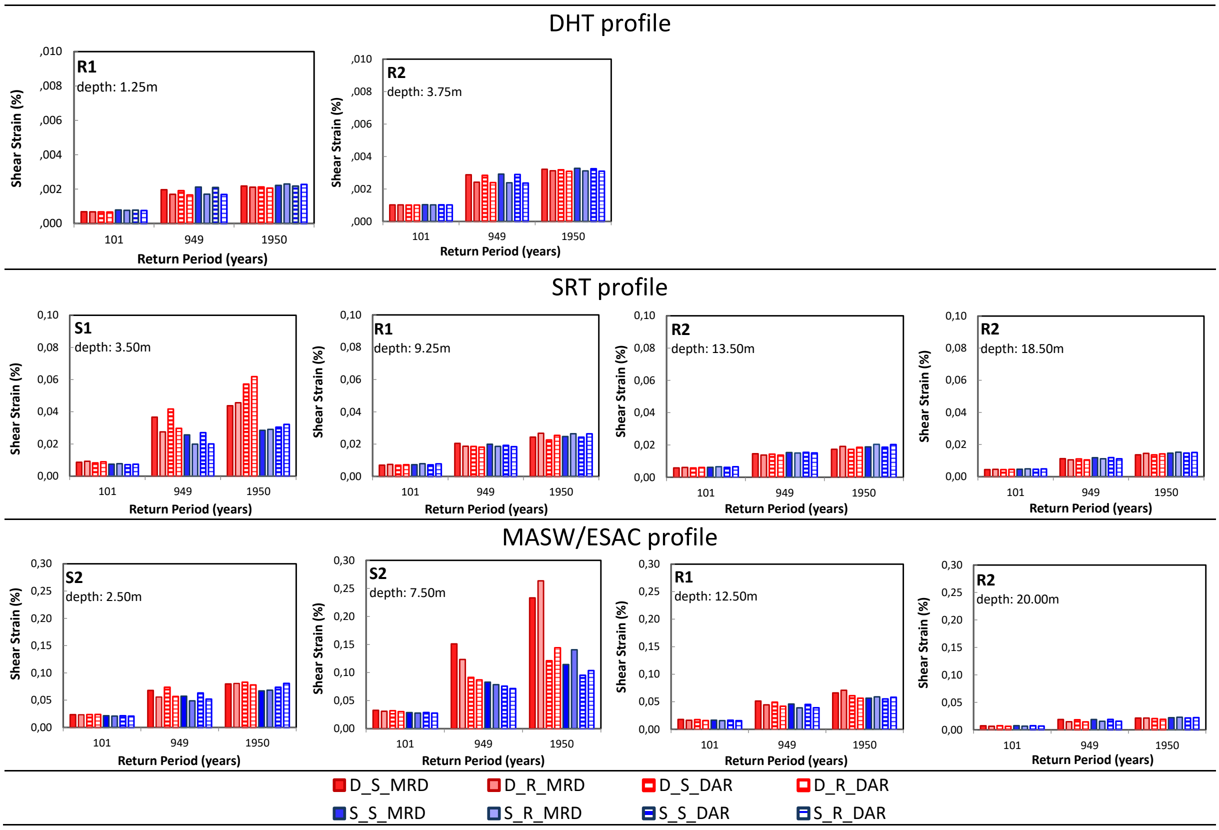


Figure 9. Mean shear strain in each soil layer.

5 CONCLUSIONS

In this work the effects of the soil mechanical properties on the seismic surface excitation have been evaluated in relation to a case study, i.e. a real site, located in Tuscany (Italy), which is the location of a Hospital complex. A detailed investigation has been made on the soil, mainly consisting of three different tests (DHT, SRT, MASW/ESAC), which have provided different mechanical properties within the same area. According to the EC8 classification, the soil resulted to belong to the A or to the B-classes, depending on the considered test.

The effects of the variability in the soil mechanical properties has been checked by evaluating the surface seismic input found by performing a SRA, where the soil stratigraphy has been described after the data provided by the investigation. Since the surface seismic input is found through numerical analysis, the work intended to evaluate even the role of the modeling choices, comparing their effects (epistemic uncertainty) to the ones related the soil variability (aleatory uncertainty).

The considered modeling choices concern the assumed seismic input at the bedrock (consisting of two alternative ensembles, selected by two different databases), the model applied to perform the convolution analysis (1D soil representation, respectively linear and not), and the arrangement of the dynamic curves describing the soil (proposed by Matasovic and Darandeli, respectively).

Three different seismic intensities, respectively corresponding to Return Periods equal to 101, 949 and 1950 years, have been considered.

The three soil sections provided mean surface spectra very different each other. The two soil profiles consistent to the B-soil type largely exceeded the Code spectral acceleration for low Periods (below 0.5 sec). The effects of the modeling assumptions on the surface spectra, especially regarding the considered convolution procedures, resulted to be considerable, especially for the most deformable soil profile. The two considered ensembles of ground motions selected to represent the bedrock seismic input, instead, have not affected the results.

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